INFLUENCE OF INDOOR ENVIRONMENT ON SICK BUILDING SYNDROME

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Degree of Doctor of Philosophy

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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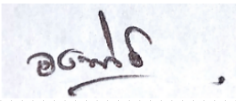

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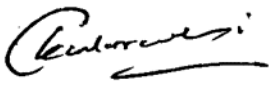
Perera T.M.

The above candidate has carried out research for the PhD thesis under our supervision.

Research Supervisors



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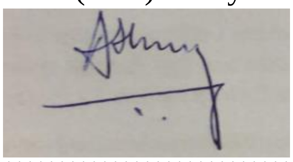
Prof. (Mrs.) C. Jayasinghe



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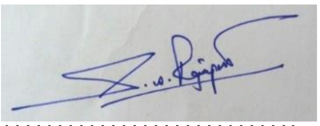
Prof. S.A.S. Perera



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Dr. S.W. Rajapaksa

ABSTRACT

Influence of indoor environment on sick building syndrome

People spend most of their time indoors, either at home or at work. Therefore, it is essential to maintain a high level of health and safety inside all types of buildings. The phenomenon where the health conditions of the occupants are adversely affected due to the indoor environment, it is called "Sick Building Syndrome" which is abbreviated as the SBS. The origin of indoor air pollutants is mainly categorized into three distinct sources. They are building materials and related human practices during construction and operation stages, outdoor sources and the prevailing ventilation condition of the structure in the discussion.

The importance of studying in-depth of the causes and prevention of SBS, lead this research to identify the effect of different building materials and operational practices on indoor air quality (IAQ) and quantify their impact with respect to its emission and the exposure of the occupants. Further, strategies have been determined to minimize the SBS while developing guidelines to create a healthier built environment.

In order to achieve these objectives, concentrations of Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Dioxide (NO_2), Total Volatile Organic Compounds (TVOCs) and Particulate Matter ($PM_{2.5}$) were measured using Indoor Air Quality Monitor (IQM60 Environmental Monitor V5.0) and Haz-Dust Particulate Air Monitor. A questionnaire survey was conducted to evaluate the satisfaction of the occupants with the indoor environment that they reside and obtain an idea on their reviews to formulate a relationship between the level of comfort and IAQ. At the same time, the effect of the ventilation condition was assessed using the IAQ results of each of these locations.

Out of all the building materials and related activities, solvent-based wall paint was selected for the detailed analysis due to the identification of a prominent contribution to the indoor air pollution with its usage. Results from the questionnaire survey were able to justify and present a relationship between the indoor air pollutants and the key symptoms related to SBS. At the same time, ventilation condition has been identified as a key factor that contributes to the betterment of IAQ. A Computational Fluid Dynamic (CFD) model was developed using ANSYS-Fluent software, which was used to predict the TVOCs concentration generated from solvent-based wall paint concerning the ventilation rates under the control of environmental and test conditions. The experimental results were used to validate the CFD model before it is recommended for future references. The validated CFD model could be used to predict the building flush-out period and appropriate ventilation condition to dilute the accumulated pollutants inside the buildings.

Keywords: Indoor Air Quality (IAQ), Sick Building Syndrome (SBS), Solvent-based paint, TVOCs dispersion, CFD model

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LIST OF ABBREVIATIONS

ACGIH	*American Congress of Governmental Industrial Hygienists*
ACH	*Air Changes per Hour*
ASHRAE	*American Society of Heating, Refrigerating and Air-Conditioning Engineers*
C	*Computer*
CDF	*Cumulative Distribution Function*
CF	*Carpeted Floor*
CFD	*Computational Fluid Dynamics*
CO	*Carbon Monoxide*
CO_2	*Carbon Dioxide*
dCO_2	*Difference between indoor and outdoor CO_2 concentrations*
DDT	*Dichlorodiphenyltrichloroethane*
DEHP	*Bis (2-ethylhexyl) Phthalate*
DPM	*Discrete Phase Model*
EDCs	*Endocrine Disruptive Chemicals*
EEA	*European Environmental Agency*
ETS	*Environmental Tobacco Smoke*
FIDOL	*Frequency, Intensity, Duration, Offensiveness and Location*
GC	*Gas Chromatography*
GHO	*Global Health Observatory*
GINA	*Global Initiative for Asthma*
H_2S	*Hydrogen Sulfide*
HCHO	*Formaldehyde*
HVAC	*Heating, Ventilation, and Air Conditioning*
IAP	*Indoor Air Pollution*
IAQ	*Indoor Air Quality*
IEQ	*Indoor Environmental Quality*
IPV	*Indoor Permissible Value*
IVC	*Inadequate Ventilation Condition*
MDF	*Medium Density Fiberboard*
MVSC	*Motor Vehicle Service Centre*
NCAR	*National Center for Atmospheric Research*
NIOSH	*National Institute for Occupational Safety and Health*
NO	*Nitric oxide*

NO_2	*Nitrogen Dioxide*
NPA	*Newly Painted Area*
OC	*Organic Carbons*
OSHA	*Occupational Safety and Health Administration*
P	*Probability*
PAHs	*Polyaromatic Hydrocarbons*
PB	*Particle board*
PBDEs	*Polybrominated Diphenyl Ethers*
PCBs	*Polychlorinated Biphenyls*
PM_{10}	*Particulate matter that have a diameter of less than 10 micrometers*
$PM_{2.5}$	*Particulate matter that have a diameter of less than 2.5 micrometers*
PM_5	*Particulate matter that have a diameter of less than 5 micrometers*
PMs	*Particulate matters*
PP	*Photocopiers and Printers*
PVC	*Polyvinyl Chloride*
QS	*Questionnaire Survey*
R^2	*Coefficient of determination*
RH	*Relative Humidity*
RI	*Retention Index*
RMSE	*Root Mean Square Error*
Rn	*Radon*
SBM	*Synthetic Building Materials*
SBS	*Sick Building Syndrome*
SO_2	*Sulfur dioxide*
SSE	*Sum of square Error*
TB	*Tuberculosis*
TF	*Tiled Floor*
TI	*Toxicity Index*
TVOCs	*Total Volatile Organic Compounds*
UDF	*User Defined Function*
USEPA	*United State Environmental Protection Agency*
USEPA IRIS	*United State Environmental Protection Agency -Integrated Risk Information System*
VOCs	*Volatile Organic Compounds*
WHO	*World Health Organization*

CHAPTER 1: INTRODUCTION

1.1 Background Information and context of the study

Indoor Air Quality (IAQ) is a phenomenon that has been receiving high significance from academic and commercial sectors, presenting a broader platform to study the adverse effects on building occupants when in a polluted environment. It has been found by a number of researches that, indoor air can be more polluted than the outdoor air due to the emissions from sources in a space with low ventilation conditions (Sun, Hou, Cheng , Sheng , & Zhan, 2019). The modern buildings have been made tighter and enclosed to save energy. While this serves one purpose, it opens up doors for the consequences such as Sick Building Syndrome (SBS) that results in an uncomfortable environment for its occupants (Persson, Wang, & Hagberg, 2019); (Sun, Hou, Cheng , Sheng , & Zhan, 2019); (Holøs, et al., 2018).

Indoor Air Pollution (IAP) is broadly studied in the current context, mainly focusing schools, homes, apartment buildings and offices (Branco, Alvim-Ferraz, Martin, & Sousa, 2019); (Sun, Hou, Cheng , Sheng , & Zhan, 2019); (Kelly & Fussell, 2019). Further, there have been studies on how indoor air quality affects the productivity and efficiency of its occupants (Mujan, Anđelković, Munćan, Kljajić, & Serbia, 2019). All these studies in the recent past dwell so hard on the fact that the ambience inside a building, affects significantly to the health conditions and efficiency of the residents. Mainly, prolonged exposure comes with the risk of chronic irregularities in the health aspects resulting in negative experiences and outcomes (Song, 2010); (Aun, et al., 2018); (Souza, et al., 2016). Therefore, it is important to note that the knowledge and awareness of IAQ and IAP are critical for the public to reduce their exposure to indoor air pollutants.

The concept of SBS describes the situations where building occupants experience acute health and comfort related effects that seem to be directly related to the time spent in buildings (Joshi, 2008); (USEPA, 1991). Over the years, the studies have identified symptoms such as fatigue, dizziness, nausea, respiratory diseases and asthma are due to this phenomenon called SBS. Therefore, this research primarily concentrates on the effect of IAPs and their dispersion characteristics to create a healthier built environment by further reducing the chances of SBS.

1.2 Problem Statement

As illustrated in the previous section, IAQ, IAP and SBS endure vital viewpoints in the current context, where the public requires the necessary knowledge and awareness regarding the space they live and work in. This phenomenon is even more excruciating when looked at on a global scale. To elaborate on, as per the World Health Organisation's (WHO) Global Health Observatory data (GHO), in 2016, 3.8 million deaths per annum were attributed to household air pollution, while 50% of the pneumonia deaths in children under 5 are due to the same (WHO, 2019(a)); (WHO, 2015). Further, 4.2 million deaths are attributed to ambient air pollution (WHO, 2019(b)). Sri Lanka is one of the several countries where more than 70 people per 100,000 population die due to household air pollution (Figure 1.1).

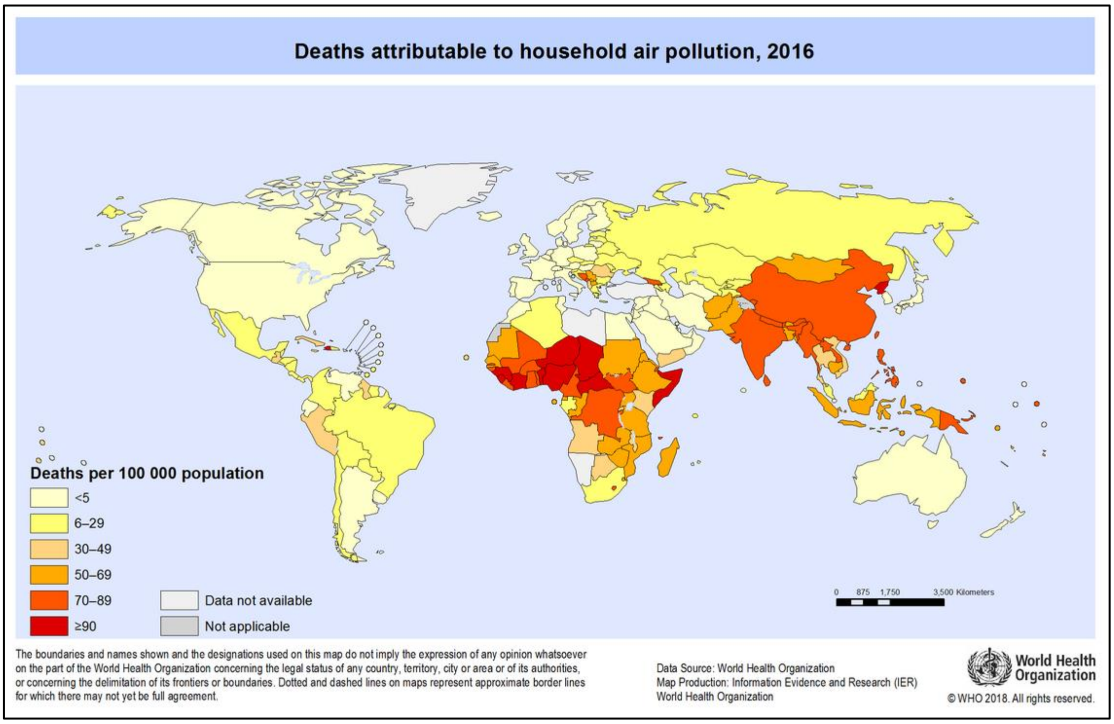


Figure 1.1: Deaths attributable to household air pollution

[Source: World Health Organization- published on the 29th Aug 2018 (WHO, 2019(c))**]**

Not only that, but also WHO claims that 92% of the world's population lives in places where air quality levels exceed WHO air quality guidelines (WHO, 2019(d)). As per USEPA (United State Environmental Protection Agency), nearly 1 in 13 children of school age has asthma due to their exposure to allergens as a result of poor air quality control in schools (USEPA, 2018).

To further understand where Sri Lanka stands on a global scale, Figure 1.2 provides a clear illustration on a death rate from indoor air pollution, compared with economically developed countries such as Germany, United Arab Emirates, United Kingdom, Australia, United States, France, Singapore, Japan and Canada. It is evident that in 2017, the age standardised number of deaths from indoor air pollution in Sri Lanka are comparatively five times larger than that of the countries above. This highlights the criticality of this research, specially for a country like Sri Lanka.

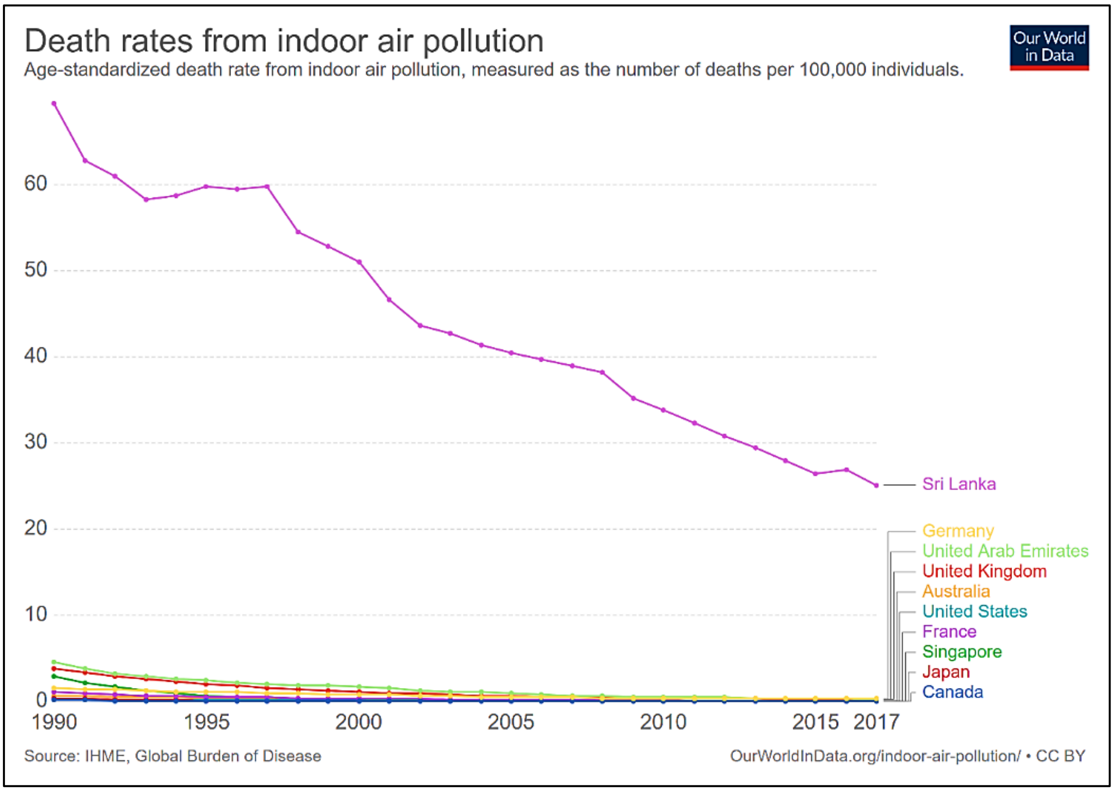


Figure 1.2: Comparison of age-standardised death rate from Indoor Air Pollution

[Source: World Health Organization- This article was last revised in April 2019 (WHO, 2019(e))**]**

With all these global as well as local conditions, it is evident that research in the arena of improving air quality and reducing the chances of SBS is vital and a need for academia as well as the industry in the current context. The following sections in this chapter will take you through the research gaps and justification, while elaborating how this research has been structured to achieve its objectives.

1.3 Research Gaps

When referring to available literature, it can be noted that there prevails an inadequacy of current information relevant to indoor air pollutants and the effects they have on the occupants. This might be due to the variability and complexity of indoor environments. Further, in relation to exposure, information on concentrations of indoor air pollutants and determinants of personal exposure seems circumscribed. The pollutants such as Carbon monoxide, Nitrogen oxide, Volatile Organic Compounds, radon and asbestos have been analysed in the past. However, in the current context, new sources have been emerging for these pollutants, opening up new pathways for research for quantification of the effects.

Moreover, due to the privacy of the indoor spaces (i.e. homes) enforceable indoor air quality standards were not preferred resulting in difficulties of systematic surveillance monitoring. Most importantly, even though literature presents outdoor air quality parameters for some pollutants, the problem exists with the unpredictability of pollutant concentration inside the buildings. This is mainly due to the specific local factors such as tightness of the building, that contribute to the prevalence of IAPs. Therefore, a gap of knowledge exists for a comprehensive review and quantification of the existing data on IAP, defining major pollutants and their concentrations. This limitation has resulted in a lack of evidence-based risk assessment approaches related to indoor air pollution that otherwise would have helped reduce similar types of problems.

Correspondingly, there seems to have a lot of opportunity for research in areas such as exposure patterns (short-term and long-term exposure levels in different environments), source apportionment of the pollutants, emissions of chemicals from consumer products, existing indoor air pollutants sources such as building materials and their related toxicities and potentially harmful emissions from indoor combustion processes. Furthermore, inadequate research conducted in areas such as health effects of combined exposure to indoor air pollutants and resulting chronic diseases has led to poor knowledge in the public and related industries to strive towards a healthier built environment.

Finally, at present, existing measurement standards for ambient air is applied for the measurement of the indoor environment. While some of the standards can be related, not all can be validated in the context of indoor air quality. Therefore, the development of new measurement standards or validation and harmonization of existing ones would be particularly important.

1.4 Research Justification

With the identification of the seriousness of the matter on hand and the prevailing research gaps, the aim and the scope of research can be justified as follows. This research mainly aims at quantifying toxicity levels of IAP and exposure periods by identifying the indoor pollutant sources and their concentrations as well as rates of dispersion. This quantification will enable the academia and the industry to obtain a clearer understanding based on numerical facts and figures resulting in better decision making in terms of minimising the IAPs, while addressing the research gap of inadequacy of quantitative information. Most importantly, as this research is conducted under several conditions of buildings based on occupancy, ventilation condition and polluting sources, etc. this will further facilitate any required extrapolation in terms of predicting pollutant concentrations in buildings based on a set of given conditions.

Secondly, an emphasis on the health effects due to air pollutants reduces the research gap of lack of knowledge in the said arena. The analysis of the health effects and symptoms has been conducted by an extensive literature review and a questionnaire survey for validation of the findings. Better knowledge of the health risks encourages the general public to take precautionary actions to reduce exposure by correctly identifying the pollutant sources.

Finally, this research investigates corrective measures that can be undertaken to mitigate the adverse effects of indoor air pollution. This has been carried out using an experimental as well as computational analysis. The research outcomes can be used to develop evidence-based risk assessment approaches to better design, remodel, or refurbish buildings, in a way that creates a healthier built environment. Moreover, the recommendations of this research can be used when standardising indoor air quality related parameters in construction codes.

1.5 The objectives

This research is structured and designed in a way that it will produce sufficient data and results to achieve the following objectives.

- Determination of the effect of building materials and building operational practices on Indoor Air Quality
- Determination of the strategies to minimize the Sick Building Syndrome

1.6 The methodology

This section presents the research design and methodology adopted to obtain the desired objectives while answering the research questions. Figure 1.3 illustrates the methodology in a flow chart for better representation and understanding of milestones related to the research.

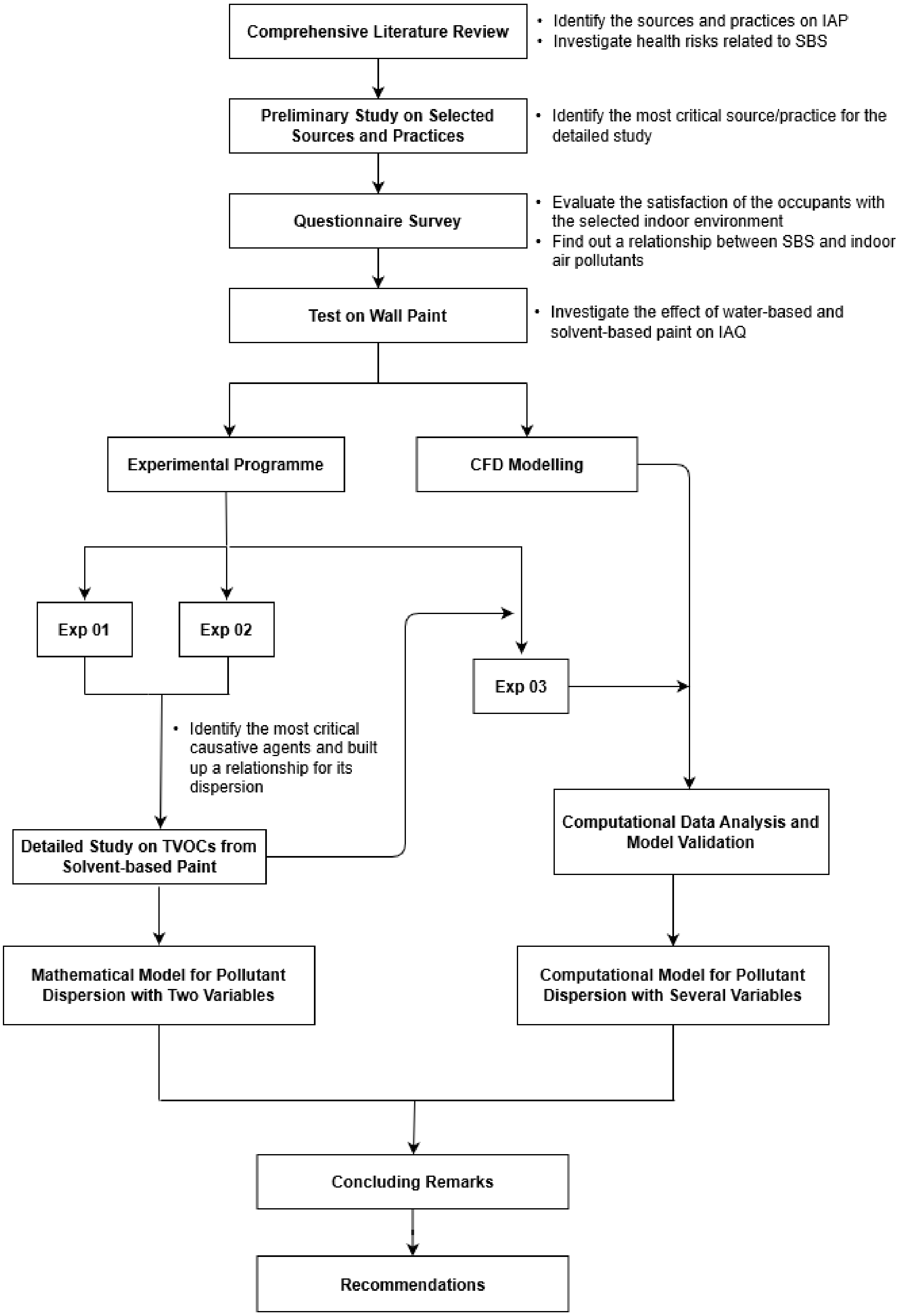


Figure 1.3: The methodology flow chart of the study

Note:

Exp 1*: - To quantify the effect of solvent based and water-based paints on IAQ*

Exp 2*: - To identify the one-dimensional spatial variation of pollutants generated from solvent based and water-based paints*

Exp 3*: - To investigate the effect of ventilation condition on dispersion of TVOCs generated from solvent based paint*

1.7 Equipment used

Equipment used in this study can be listed as follows.

- Indoor Air Quality Monitor (IQM60 Environmental Monitor V5.0)
- Haz-Dust Particulate Air Monitoring Equipment

Indoor Air Quality Monitor (Figure 1.4) was used to measure the concentrations of Carbon monoxide (CO), Nitrogen dioxide (NO_2), Carbon dioxide (CO_2), Total Volatile Organic Compounds (TVOCs), temperature and Relative Humidity (RH) while the Haz-Dust Particulate Air Monitoring Equipment (Figure 1.5) was used to measure the concentrations of particulate matter that have a diameter of less than 2.5 micrometers ($PM_{2.5}$) throughout the study. Both this equipment needed sufficient time for warming up, thus they were plugged into one-hour prior at the selected locations where measurements to be taken.

Figure 1.4: Air Quality Monitor (IQM60 Environmental Monitor V5.0)

Figure 1.5: Haz-Dust Particulate Air Monitoring Equipment

1.8 Content of the thesis

The thesis is structured in six chapters as follows.

Chapter 1 Introduction: Presents an overall introduction to the thesis topic while highlighting the keywords "IAQ", "IAP" and "SBS". It presents the research questions and objectives and summarises the methodology employed.

Chapter 2 Literature review: Provides an in-depth literature review of the sources of indoor air pollution, different types of pollutants and their health effects due to short-term and long-term exposure by occupants, corrective measures undertaken and an overview on computational fluid dynamics.

Chapter 3 Effect of different building operational practices on IAQ: Outlines the results and analysis of the study conducted to better understand which pollutants offer a severe negative impact on its occupants. Several indoor polluting sources and practices were taken into consideration to conduct the study, and by the end of the chapter, it has been justified that "wall paint" as the most detrimental cause on IAP among all.

Chapter 4 Questionnaire survey on occupant comfort and IAQ related health impacts: Evaluate the satisfaction of the occupants with the indoor environment and the building condition that they reside and build up a relationship between indoor air pollutant concentration with symptoms related to SBS.

Chapter 5 Experimental programme and a mathematical model on pollutants concentration due to wall paint: Addresses the effect of wall paints on indoor air quality, mainly focusing on the water-based and solvent-based paints. Subsequently, a mathematical model has been derived for pollutant dispersion, which is generated from solvent-based paints.

Chapter 6 Effect of ventilation on dispersion of TVOCs- Case study with solvent based paint: Computational Fluid Dynamic analysis has been carried out to predict the pollutant concentration under different ventilation conditions. Experimental data which were collected under the same environmental conditions were used to validate the computational model.

Chapter 7 Conclusions: Conclude all the findings of this research and portray opportunities for further research.

The next chapter provides a systematic review of the literature and further identifies research gaps that aligned this research.

CHAPTER 2: LITERATURE REVIEW

2.1 General

Most people spend around 90% of their time in indoor environments (Song, 2010). Therefore, it is essential to maintain a higher level of health and safety in all types of buildings. However, during the last several decades, the scientific evidence has indicated that the air within domestic and other buildings have been more seriously polluted than the outdoor air in most of the industrialized cities (U.S. Department of Housing , 2006). Thus, there are several health risks for occupants due to the various types of building environments.

Numerous pollutant sources are available in the indoor built environments can generate either short-term or long-term exposure levels for the occupants. Similarly, some human practices in construction and operation stages have also contributed to indoor air pollution. Apart from them, polluted outdoor air can be the main source of poor indoor air quality, as many of the houses located in the tropical zone is mostly rely on natural ventilation. Thus, the indoor sources, some human practices, outdoor pollutant levels, and air exchange rate have been identified as the main factors that could influence the indoor pollutant levels.

As mentioned in the previous chapter (Section 1.2), this research primarily concentrates on the effect of indoor pollutants and their dispersion characteristics in order to create a healthier built environment. Therefore, the literature review has been conducted on the following major topics.

1. Identification of indoor polluting sources and practices

2. The substances that can cause serious indoor air quality issues

3. The corrective measures which can be taken to mitigate indoor air pollution

4. Use of Computational Fluid Dynamics (CFD) modeling to assess the air movement characteristics

The above topics will be descriptively presented throughout this chapter.

2.2 Introduction to Indoor Air Quality

The good quality of air is recognized as a vital requirement for a society, considering the health, agricultural and industrial aspects (Wang & Zhang, 2009). It is essential to achieve a proper balance of life on earth as clean air is one of the basic needs for the survival of living organisms. The composition of dry air at sea level contains 78.084% Nitrogen, 20.946% Oxygen, 0.934% Argon, 0.031% Carbon dioxide, 0.00182% Neon, 0.00052% Helium, 0.00011% Krypton, 0.000125% Methane and 0.0000087% Xenon by volume (Mishra, 2008). Furthermore, air can be classified as ambient and indoor air depending on the surrounding environment. Ambient air refers to the outdoor environment, whereas the indoor refers to the air in enclosed spaces.

Over the past half-century, air pollution has taken persistent attention worldwide. This is mainly in developing countries which have confronted the air quality deterioration with the industrialization. Many of the developing countries consider economic development with little attention to environmental protection (Fang, Chan, & Yao, 2009). Thus, the ambient air pollutant levels of particulate matter, Sulfur dioxide, Nitrogen dioxide and Ozone, etc. have been elevated in many of the industrialized cities. As the main sources of ambient air pollution, emissions from synthetic material production, vehicular traffic, pesticides, environmental tobacco smoke and power plants which uses the coal as an energy source, etc. have been identified (Fredrick & Kenneth, 1974); (Thompson, Hensel , & Kats, 1973); (Wang & Zhang, 2009).

Indoor air pollution has also become an ever-increasing problem due to industrialization and ambient air pollution. At present, there are numerous types of indoor chemicals which were added from commonly used synthetic building materials and consumer products. According to Weschler (2009), “many of the chemicals presently found in indoor environments as well as in the blood and urine of occupants, were not present 50 years ago” (Weschler, 2009). Furniture made out from medium-density fiberboards (MDF) and particle boards (PB), synthetic carpets, scented cleaning agents, polymeric flooring, wallpapers and some mechanical and electrical appliances such as televisions, computers and printers, etc. have been identified as the sources for the indoor air pollution. Apart from the aforementioned sources, some of the personal habits and building operational practices such as indoor smoking and open waste burning, etc. can be mentioned as sources of indoor air pollution. Sometimes, ambient air pollution could also contribute to elevating the indoor pollutants' concentration masking the indoor polluting sources. Many of the buildings which are operated under natural ventilation condition and located in industrialized cities or close to the busy highways have been shown infiltration of outdoor air pollutants into the indoor environment. However, some studies have identified that indoor sources have contributed to outdoor air pollution, which is predominantly observed in highly populated areas (Rudel & Perovich, 2009). Thus, the outdoor/indoor pollutant concentration and air movement pattern should be carefully observed to select the ventilation condition for a better indoor environment.

In the mid-1970s, the concept of domestic energy conservation has emerged with the energy crisis in Western countries (Wang, Bai, Yu, Zhang, & Zhu, 2004). Thus, airtight buildings equipped with heating and cooling systems were introduced with the use of insulation materials to minimize the loss of energy (Rudel & Perovich, 2009). However, the modern building designs and operational practices such as enclosed environment with the air-conditioned environment is not only sufficient for many of the building environments as it causes to accumulate the pollutant concentrations emitted from synthetic materials. Also, many of the air conditioners operate with the recirculating of the high fraction of indoor air (Wang, Bai, Yu, Zhang, & Zhu, 2004). Thus, the pollutant concentrations are higher in indoors compared to the outdoors due to the limited degradation of indoor pollutant levels under minimum air exchange rates (Rudel & Perovich, 2009).

The interest in the indoor air quality has increased with its effect on the health, comfort and performance of occupants due to the considerable time spend by occupants in indoors (Singh, 1996); (Jones A. , 1999); (Deng & Zhang, 2004). Though some of the buildings do not have severe indoor air quality problems, there can be an episodic pattern of poor indoor air quality even in well-run buildings due to random operational practices or from the outdoor environment. Thus, awareness is the most important factor in reducing the risks of indoor air pollution. The next section (Section 2.3) will elaborate on the building-related symptoms and some of the identified causative agents for the sicknesses.

2.3 Sick Building Syndrome

The term "Sick Building Syndrome" (SBS) is used to describe situations in which building occupants experience acute health and comfort related effects that seem to be linked directly to the time spent in the building (Joshi, 2008); (USEPA, 1991). "A 1984 World Health Organization committee report suggested that up to 30 percent of new and remodeled buildings worldwide may be the subject of excessive complains related to indoor air quality" (USEPA, 1991). The symptoms due to Sick Building Syndrome are headache, fatigue, dizziness, nausea, congested nose, sneezing, irritability (eye, nose, or throat) and respiratory diseases as asthma. Also, long term exposure into the pollutants could cause more serious health effects (Canadian Center for Occupational Health and Safety, 2016); (University of Rochester Medical Center, 2016); (USEPA, 2016(a)); (Levin, 1989(a)). However, the effect of the indoor pollution on the occupants may depend on several factors such as source emission characteristics, ventilation condition and occupant's perception and susceptibilities, etc. Thus, this section explains several case studies which were carried out about the occupant's complains regarding their health problems and uncomfortableness while they spend their time in different indoor environments. Many of the studies have measured the indoor air quality parameters simultaneously in order to link the symptoms with causative agents. These studies revealed that TVOCs, CO_2, CO, $PM_{2.5}$, PM_{10}, SO_2 and NO_2, etc. as commonly found air pollutants in many of the indoors. Among these causative agents, TVOCs has taken higher attention considering its indoor toxicity levels and health effects. However, many of previous studies have used CO_2 in order to assess the occupants' complains related to indoor air quality and ventilation efficiency (ASHRAE, 2004); (ASTM, 2003); (CEN, 1999); (Wong & Mui, 2007). The severity of health problems due to the presence of indoor air pollutants could measure based on the pollutant's concentration and occupant's exposure period. The details of the building-related symptoms have been presented separately with respect to the selected indoor air pollutant.

The main source of indoor CO_2 is from human respiration where the CO_2 is continuously emitted as a bio effluent. The atmospheric concentration of CO_2 is in the range of 350 ~ 400 ppm or 0.03 ~ 0.04 by volume (Vaughan, 2015); (Dlugokencky & Tans, 2015). Detailed analysis of health effects related to CO_2 has identified that low concentration of CO_2 gas could have little toxicity effect, whereas the high concentration causes for an increase of respiratory rate, tachycardia, cardiac arrhythmias and impaired consciousness, etc. with reference to ambient CO_2 levels. Further, the concentration of CO_2 > 10% of volume may cause convulsions, coma and death (Langford , 2005). Seppänen et al. (1999) study illustrated that a typical range of CO_2 concentrations in many indoor environments could be from 350 to 2,500 ppm. Several case studies have reported a relationship between the elevated CO_2 level and the SBS (Backman & Haghighat, 1999); (Seppänen, Fisk , & Mendell , 1999); (Engvall, Norrby , & Norbäck , 2001).

The concentration of CO_2 and dCO_2 which is the difference between concentrations of CO_2 when indoor and outdoor is considered to have been used to establish a relationship with SBS symptoms. Some of the analyses were carried out by adjusting for influential factors in the above relationship, such as age, sex, smoking status, thermal comfort and presence of carpets in indoors, etc. (Erdmann, Steiner, & Apte, 2002). However, both high concentration of CO_2 or dCO_2 causes the headache, eye dryness, lethargy, dry throat, sore throat, wheeze, tiredness, dizziness, breathing difficulties and dryness in body mucous (Gupta, Khare, & Goyal, 2007); (Erdmann, Steiner, & Apte, 2002); (Yen Lu, Lin, Chen, & Chen, 2015). The study by Apte et al. (2000) has found that higher CO_2 concentration has resulted in SBS symptoms such as mucous membrane (i.e., irritated eyes, throat, nose, or sinus) and lower respiratory symptoms (i.e., breathing difficulties, chest tightness, cough, or wheeze). Furthermore, this study has suggested that the increase in the ventilation rate per person in a typical office building could be able to reduce the prevalence of SBS symptoms, although the particular building complies with the ASHRAE ventilation standards (Apte, Fisk, & Daisey, 2000). Measurement of the CO_2 taken in 21 studies with 30,000 subjects has identified a relationship between CO_2 concentration and ventilation rate. Twenty-Seven of the cases which all are with low ventilation rate out of 31 assessments (ventilation below 10 Ls^{-1}) were associated with at least one or more health problems. Thus, the productivity of occupants has also been reduced with elevated CO_2 concentration (Seppänen, Fisk , & Mendell , 1999).

The study by Tsai et al. (2012) has reported that the presence of eye and upper respiratory symptoms among the office workers when the indoor CO_2 concentration is greater than 800 ppm (Tsai, Lin, & Chan, 2012). One of the key factors that can be considered to measure the association between an exposure and an outcome as known as odds ratio (OR) which has increased from 1.1 to 1.5 for the respiratory symptoms with100 ppm increase in indoor CO_2 concentration (Yen Lu, Lin, Chen, & Chen, 2015). Many of the respondents have complained that the symptoms occur when they are indoors and the symptoms decrease while away from the buildings (Mendell, 1993). Hence, these symptoms can be considered as building-related symptoms. The comparative study of the sick building with the properly ventilated building has resulted that 40% to 50% of the decrease in sick building symptoms among the office workers due to the proper ventilation (Bourbeau, Brisson, & Allaire, 1997). Very large increases in ventilation rates could be sufficient to reduce indoor CO_2 concentrations to approximately outdoor levels and that would be expected to decrease the prevalence of selected symptoms by 85% (Erdmann, Steiner, & Apte, 2002). Furthermore, the analysis of CO_2 concentrations can be used to obtain information on building ventilation performance (Persily, 1996). The proper building design or ventilation system has been identified as a mandatory requirement to minimize the SBS as the elevated CO_2 concentration is significantly associated with occupant comfort and productivity. Thus, CO_2 has been categorized as an “indicator” for SBS (Gupta, Khare, & Goyal, 2007).

Endocrine (or hormone) disruptive chemicals (EDCs) are another substance that has become commonly available indoors from the building materials, furniture and consumer products, etc. These chemicals can affect endogenous hormones by indicating potential health problems. People can be exposed to EDCs by berating, drinking, eating or touching them as they can occur through air, water, soil, food and consumer products. During the past 15 years, several studies have found that EDCs have significantly increased with industrialization (Weschler, 2009); (Rudel & Perovich, 2009). Polychlorinated biphenyls (PCBs), Polybrominated diphenyl ethers (PBDEs), phthalates, dichlorodiphenyltrichloroethane (DDT), pyrethroids, etc. are the most commonly available EDCs. According to Hwang et al. (2008), PCBs are used in electrical equipment, caulking, paints, chlorinated or brominated flame retardants, furniture, textiles, pesticides, lawn maintenance, vinyl flooring, plastics, and fragrance products, etc. (Hwang, Park, Youn, & Hammock, 2008). PBDEs are in existing household items such as sofas, mattresses, carpets, air fresheners, vinyl flooring, adhesives, and detergents, etc. (Rudel & Perovich, 2009). Apart from the PCBs and PBDEs, phthalates are also frequently found in modern indoors since they are used as plasticizers in a variety of plastic polyvinyl chloride (PVC), food containers, toys, household goods and medical devices (e.g., intravenous bags and tubing) and as a solvent in fragranced personal care and household products (Rodgers, Rudel, & Just, 2014). The health effects from some of the EDCs are presented below.

The PCBs are an organic chlorine compound with low water solubility. Also, the dissipation of indoor PCBs is extremely slow due to lack of moisture, sunlight and microbial activities. Thus, they are to persist for a long period with a greater health risk for occupants (Erickson, 1997). The PCBs are recognized as developmental neurotoxins and also associated with effects on immune, reproductive, and endocrine systems (ATSDR, 2000); (Rudel & Perovich, 2009). USEPA Integrated Risk Information System (USEPA IRIS) has categorized PCBs as possible human carcinogens. Especially the risk for the prevalence of non-Hodgkin has elevated with exposure to PCBs (ATSDR, 2000); (Colt, et al., 2005).

In addition, the phthalate, which are esters of phthalic acid directly caused the respiratory system diseases such as asthma and allergies due to phthalate inhalation (Jaakkola & Knight, 2008). Also, it may cause cancers, birth defects, and reproductive and developmental disorders (ATSDR, 2002); (Hauser & Calafat, 2005). The study by Rodgers et al. (2014) has published that some of the phthalates, such as Bis (2-ethylhexyl) phthalate (DEHP) which is an organic compound and it can affect the development of the male reproductive system by interrupting the production of fetal testosterone and protein involved in testicular descent. According to Jaakkola and Knight (2008), phthalate in heated PVC fumes has contributed to the occurrence of asthma in adults. Further, DNA damage human sperm has been reported due to the phthalates exposure (Duty, et al., 2003). USEPA IRIS has classified DEHP as probable carcinogens (Group B). Also, DEHP has been suspected as a causative agent for asthma and allergic symptoms such as wheezing in children due to exposure of indoor dust (Kolarik, Naydenov, Larsson, Bornehag, & Sundell, 2008). Moreover, benzyl phthalate is also categorized as a cause for possible human carcinogens (Group C) (Bornehag, et al., 2004).

However, during the past years, it has been found that the number of carcinogens and anticipated carcinogens have decreased due to the regulatory actions and necessary attention given by several parties such as government, IAQ related and health concerned organizations in many developed countries. As mentioned in Weschler (2009), identified carcinogens are benzene, formaldehyde, asbestos, radon and environmental tobacco while the reasonably anticipated carcinogens are chloroform, trichloroethylene, carbon tetrachloride and naphthalene. These types of pollutants could still present in developing countries which are with insufficient policies and regulations considering the product's ingredients related to human health.

The other most frequent indoor health risk is asthma as a cause of respirable particle matters. The source of indoor particulate matter could be due to the presence of house dust mite, infiltration of contaminated outdoor air from vehicular traffic and re-suspension of particles from carpets (Wieringa, et al., 1997); (Stranger, Potgieter-Vermaak, & Grieken, 2007). In 1989, the Global Initiative for Asthma (GINA) program was started in order to make awareness about the increases of asthma among the people (Masoli , Fabian , Holt , & Beasley, 2004). However, a study by WHO has revealed that in the year 2016, nearly "235 million of people suffer from Asthma by recurrent attacks of breathlessness and wheezing, which vary in severity from person to person" (WHO, 2013); (WHO, 2016). Several researchers have emphasized that Asthma symptoms among pupils are considerably higher than the elders since their health is more susceptible to indoor air quality. Hence, several case studies have performed in a school environment to investigate the causative agents and remedial measures for asthma prevalence. Schools close to the highways have recorded considerable concentration of indoor particulate matters due to the infiltration of contaminated outdoor air which is generated from vehicular traffic. This situation could be increased with the accumulation of pollutant concentration due to the lack of ventilation. Many schools perform under the natural ventilation condition. Thus, pollutant removal is not continuously occurred with time (Yang, Sohn, Kim, Son, & Park, 2009). The study by Shaughnessy et al. (2006) has identified the ventilation rate as a factor that influences on the students' academic performance. According to this study, students' performances were increased in test scores when the ventilation rate increased from 3.5 to 6 l/s per person. However, minimum ventilation recommended by ASHRAE for the classroom is 8 l/s per person (Shaughnessy, Haverinen-Shaughnessy, Nevalainen , & Moschandreas , 2006).

The study by Kim et al. (2007) has investigated the allergen concentration in settled dust and in air samples at Korean and Swedish schools. The analysis highlighted that the high concentration of dog allergens and CO_2 levels were present in Korean schools and cat, dog and horse allergens were present in Swedish schools. As a result of this, many students who were suffering from asthma and respiratory symptoms such as breathlessness as a combination with wheeze (Kim , Elfman, & Norbäck, 2007). As per in Wickman et al. (2003) study, allergic diseases were increasing in recent years, for example, one out of four children is being suffered today. IAQ investigation in Korean schools has found that the presence of formaldehyde and particulate matter resulting several sick building symptoms among pupils and staff members during the first year from the renovation and reconstruction (Yang, Sohn, Kim, Son, & Park, 2009). Thus, the age of the building is another factor which might affect the SBS.

HVAC maintenance deficiencies and HVAC contamination have been suspected as other risk factors for building-related health symptoms. Yu et al. (2009) have referred to the study of Seppanen and Fick (2002) to mention an increase in the prevalence of SBS between 30 % to 200 % in the buildings with air-conditioning systems when compared with natural ventilation systems. Furthermore, death caused by

Legionnaires' disease which spread mainly by water droplets through air conditioning and similar systems, even occurred in an air-conditioned building (Yu, et al., 2009). The pollutant sources which were located near outside air intakes have increased the risk of adverse health effects (Kumar & Fisk, 2002).

The provision of sufficient daylight for an indoor environment has also been identified as an extremely important component that minimizes the SBS. According to ASHRAE (2002), daylighting had led to 20% of the increment in test scores within students while eliminating the SBS (ASHRAE, 2002).

The geothermal houses are a historical approach to heat the buildings with an eco-friendly concept of energy conservation. However, it was identified that seepage of Carbon dioxide (CO_2), Hydrogen Sulfide (H_2S), Radon (Rn) and other gasses from soil cavities directly into indoor air in the structures as a critical issue when considering air pollution. It was measured that 10-15% by volume, of CO_2 in enclosed ground floors of geothermal areas. This is a significant risk to the health as it is capable of asphyxiating at around 10% by volume of CO_2. Some other symptoms of eye irritation, chronic fatigue, headaches and migraines have reported due to H_2S concentration above 200 ppm in geothermal houses (Durand, 2006); (Durand & Scottb, 2005).

Considering the results obtained from all the SBS related case studies, it has been identified that any kind of indoor environment is really important in order to increase the comfort and productivity of occupants by minimizing absenteeism and health care costs from improved air quality. Moreover, better indoor environmental quality reduces the risk of litigation for any responsible parties such as employers and government, etc. (Kumar & Fisk, 2002). The USEPA estimates that poor indoor air may cost the nation, tens of billions of dollars in each year for the lost productivity and medical care (USEPA, 2015(a)). Thus, it has observed that building-related symptoms or SBS have led to introducing technical and policy approaches for improved air quality.

2.4 Sources and practices on Indoor Air Pollution

As mentioned in Section 2.2, there are numerous sources of indoor air pollution which are identified as causes for the human discomfort and degradation of their health. Some of the personal habits have also contributed to indoor air pollution. This section will explain the predominant sources and practices which could influence indoor air quality. The effect of these sources and practices can be quantified using the indoor toxicity level and the occupant's exposure period to an adverse environment. Source emission rate, pollutants transported rate from outside to inside, pollutants scavenged rate by indoor surfaces, indoor sink materials and ventilation rate are the key factors that could have an impact on the indoor environment (Weschler, 2009). According to the accomplished research studies, the followings are the selected sources and practices which could affect the indoor air pollution related to Sri Lanka.

- Building materials
- Combustion products
- Chemicals used in maintenance and operational periods
- Vehicular emission
- Environmental tobacco smoke
- Ventilation rate
- Outdoor air

The detailed descriptions of the above sources and practices are mentioned below.

2.4.1 Building materials

Building construction materials, interior decorations and furnishings are known sources which emit a large number of chemicals in indoor air (European Commision, 1997); (Alevantis, 1999); (USEPA, 2004). Many of the synthetic building materials have been identified which emit hazardous chemical components such as formaldehyde (HCHO) and VOCs as these building materials are manufactured by using several chemicals in order to achieve some of the advantages. For examples durability, cost-effectiveness, better finish and speedy construction, etc. could be mentioned as probable advantages of using various types of chemicals (Levin , 1989(b)). The products like partition boards, carpets, paints, wallpapers, furniture, interior decorations, cleaning products and floor finishes, etc. have been identified as known contributors to indoor air pollution (Guo, Murray, Lee, & Wilkinson, 2004); (Katsoyiannis, Leva, & Kotzias, 2008); (Plaisance, Blondel, Desauziers, & Mocho, 2014); (Nazaroff & Weschler, 2004); (Huang, et al., 2012); (NØrgaard, Kudal, Kofoed-SØrensen, Koponen, & Wolkoff, 2014).

One of the case studies of the IAQ investigation in schools which are constructed within one-year period with the presence of wooden desks, chairs and furnishings has identified that the elevate Formaldehyde with a mean concentration of 0.16 ppm. This study has measured the indoor to outdoor Formaldehyde ratio and it has found as 6.32 during the autumn season (Yang, Sohn, Kim, Son, & Park, 2009). Hence, the building materials have emitted the Formaldehyde to indoors as it is the only source present in the indoor environment to increase the concentration of the pollutants. The VOCs emission from building materials has been evaluated by several researchers with considering some of the environmental factors which could influence on emission and indoor air concentration, such as temperature, humidity, air change rate and surface air velocity (Haghighat & Bellis, 1998); (Kim, Kang, Choi, Yeo, & Kim, 2012). The obtained results can be used to achieve the benefits of economic performance evaluated by the developed environmental quality strategies. However, the low emitting materials and increased ventilation system have been recommended as the corrective measures to improve indoor air quality (Yang, Sohn, Kim, Son, & Park, 2009); (Alevantis, 1999).

2.4.2 Combustion products

In general, combustion is a chemical reaction in which a fuel combines with oxygen. When there is insufficient oxygen, incomplete combustion could emit several pollutants such as CO, NO_2, PMs, VOCs and SO_2, etc. (USEPA, 2016(c)). The sources of combustion products are open waste burning, wood stoves, gas stoves and fireplaces, etc. Open waste burning is a common method of disposing of waste, particularly in rural areas. However, the emission from this process pollutes the outdoor environment and polluted outdoor air could infiltrate into the indoor environment depending on the building ventilation system. A study led by the National Center for Atmospheric Research (NCAR) estimates that more than 40 percent of the world's garbage that is burnt, emit gases and particles which can substantially affect human health (NCAR, 2014). Therefore, even residential waste burning must be done with due care in order to minimize the emission from open waste burning. The environmentally feasible options like composting, recycling or disposing of allowable waste materials at a licensed landfill can be mentioned as the remedial measures to minimize air pollution.

2.4.3 Chemicals used in maintenance and operational periods

Different activities associated with buildings have a great impact on IAQ within those buildings. Many studies have been carried out to identify the effects of IAQ due to the maintenance and operational practices inside classrooms, residential buildings, office buildings, health care centres and hotels, etc. (Helmis, et al., 2007); (Dascalaki , Lagoudi , Balaras , & Gaglia, 2008). The obtained results from these studies have separately presented below with respect to the site location.

The studies were carried out by Lee et al. (2012) and Air Quality Sciences, Inc. (2007) in schools have revealed that the chemicals emitted from cleaning products, paints and floor finishes have increased VOCs in indoor environments (Lee, Yoon, Kim, Kim, & Kim, 2012). A proper ventilation system has been identified as a solution to dilute the accumulated indoor concentration. However, the ventilation system should be decided considering the suitability of outdoor air to provide for the in indoor environments. The effect of the activities associated with a hospital theatre has been examined regarding IAQ since the staff experience some discomfort while being inside the theatre. Significant variations were observed in the concentrations of TVOCs, CO_2, CO and PM inside the operation theatre due to the chemicals used and high occupant density under the improper ventilation system (Gunarathne, et al., 2013); (Helmis, et al., 2007). Some of the advances to the ventilation system have been recommended to improve the air quality inside the hospital theatre. A motor vehicle service centre is another place where large amounts of hazardous pollutants are generated with the potential to cause pollution in the vicinity area due to the handling of various chemicals and the generated waste during the operational stage. Crude oil, petroleum refined products, Trihalomethanes, Phenols, Inorganic fertilizers, Sulfides, Ammonia, Perchloroethylene, solvents like acetone, toluene, benzene and xylene have been classified as the most common use of chemicals in the motor vehicle service centre (Environmental Pollution Center, 2009). According to the ASHRAE minimum exhaust rate recommended for an auto-repair room is 7.5 L/s.m^2 (ASHRAE, 2004).

2.4.4 Vehicular emission

Motor vehicle emission produces severe pollutant types such as Hydrocarbons (which are organic compounds, including VOCs), CO, CO_2, SO_2, NO or NO_2 and PM. Many of these toxic chemicals are emitted from the partial burn of fuel and they can cause several health effects on occupants. Details of the health effects of these chemicals are presented in Section 2.5. The infiltration of the contaminated outdoor air into the indoor environment has observed in buildings which are located very close to the busy highways. Graham et al. (2004) study has shown that an attached garage has a higher impact on the indoor air quality in particular houses. VOC profiles obtained inside the house and vehicle emission profiles were identified as very similar to each other with the evidence of vehicular emission entered into the indoor environment (Graham, et al., 2004). The supply of a sufficient amount of fresh air into the attached garage or open garage design could lead to minimizing the pollutant accumulation inside such houses. Furthermore, the selection of a proper ventilation system, depending on the outdoor air quality could mitigate the infiltration of polluted air into indoor environments.

2.4.5 Environmental tobacco smoke

Smoking in an enclosed space leads to indoor air pollution due to the byproducts of tobacco combustion. The physical design of the cigar, leaf type, composition and wrapper type may all affect the cigar emissions. For a given composition, the mass of a cigar that is being consumed during smoking is a primary determinant of the number of its emissions (Repace, Ott, & Klepeis). Tobacco active smoking and passive smoking have been implicated as risk factors for most of the malignant diseases such as lip and oral malignancies, lung cancer, oesophageal cancers and also infectious diseases like tuberculosis (TB), and pneumonia. It has been revealed that tobacco smoke had led to the increment of permissible levels of VOCs and particulate matter in the ambient air. However, enhanced ventilation could reduce the concentration of environmental tobacco smoke pollutants and the exposure period to the above pollutants (Wang, et al., 2012). A designated smoking area in a building is another solution to reduce passive smoking and to improve indoor air quality.

2.4.6 Ventilation rate

Ventilation is the most important factor to reduce the effect of accumulated pollutants inside a building. Natural or mechanical ventilation systems can be adapted to control the air exchange rate inside a building. Natural ventilation systems provide openings such as windows and doors to dissipate the concentration of indoor air pollutants. In locations where openings are not possible, exhausted fans could be used to remove the pollutants from the indoor environment. The air conditioner is used to provide mechanical ventilation with controlled temperature and humidity to achieve a more comfortable indoor environment. It removes the indoor air and supplies filtered air into the indoors in a cyclical process. However, the proper maintenance of an air conditioner is mandatory for its better performance.

There are many case studies which have been done to investigate, the effect of ventilation systems on indoor air quality. The air quality measurements which were carried out in schools by Yang et al. (2009) have disclosed that the existence of Asthma symptoms among pupils is due to lack of ventilation and infiltration of contaminated outdoor air from vehicular traffic. Prevalence of sick building symptoms among office workers and occupants were also pointed out from several research studies due to the increase in pollutant concentration with poor ventilation condition (Joshi, 2008); (Amin, Akasah, & Razzaly, 2015); (Liddament, 1996); (Norhidayah, Chia-Kuang, Azhar, & Nurulwahida, 2013). Moreover, the importance of HVAC cleanliness and maintenance has been identified with the related health symptoms due to the air-conditioned environment. According to the results which were obtained from IAQ analysis regarding health conditions, the lower respiratory symptoms and asthma have been reported after the exposure to the poorly maintained air-conditioned environment

(Sieber, et al., 1996). Therefore, building design, HVAC system and their maintenance have been recognized as major factors which could affect the ventilation rate.

2.4.7 Outdoor air

Indoor air contaminants can originate within the building or they can be drawn inside from outdoors. Contaminated outdoor air could lead to indoor air quality problems even in properly ventilated buildings. The influence of outdoor pollution on indoor air quality, mainly depends on the variation of outdoor pollutant concentration, pollutants' transported rate from outside to the inside and ventilation condition of the building (Weschler, 2009). Gil et al. (1995) study have mentioned the relationship between the variation of indoor and outdoor pollutant concentrations of Carbon monoxide, Nicotine, particulate matter with a diameter of 5 µm (PM_5), total and carcinogenic polyaromatic hydrocarbons (PAHs). Results showed that the simultaneous variation of outdoor and indoor CO concentration had occurred, especially during traffic in between rush hours. Also, $PM_{5,}$ total and carcinogenic PAHs concentrations were very high in indoors and outdoors, illustrating infiltration as the main source for the indoor air pollution (Gil, Adonis, Cáceres, & Moreno, 1995). Particulate matter concentrations were measured in a school building that was located close to a busy commercial area with a natural ventilation system. It has found that the high concentration of particulate matter with the ratios of indoor to outdoor in the range of 0.69 to 0.88 (Yang, Sohn, Kim, Son, & Park, 2009); (Tippayawong, Khuntong, Nitatwichit, Khunatorn, & Tantakitti, 2009). Thus, the building ventilation system should be decided considering the outdoor air quality.

2.5 Different types of indoor pollutants

Indoor air quality and thermal comfort are the foremost requirements for a better indoor environment. Temperature, humidity, air exchange rate and indoor air pollutants have been identified as factors which may affect the quality of indoor air. The meteorological parameters such as temperature, relative humidity and wind speed and direction may influence on the concentration of air pollutants (Viswanathan & Murti, 1989); (Jayamurugan, Kumaravel, Palanivelraja, & Chockalingam, 2013); (Ocak & Turalioglu, 2008). In addition, inadequate ventilation can increase indoor pollutant levels as a result of not having sufficient outdoor air to dilute the emission from indoor sources (Refer Subsection 2.4.6 and 2.4.7).

This section discusses the causative agents of biological pollutants, particulate pollutants and gaseous pollutants which contribute to the degradation of indoor air quality (Yu, et al., 2009). The common types of indoor air pollutants are biological contaminants, VOCs, CO_2, CO, NO_2, SO_2, heavy metals, particulate matters, odour and undesirable temperature and details of them are discussed below.

2.5.1 Biological contaminants

Biological contaminants are living organisms or their products such as molds, bacteria, viruses, house dust, animal dander, pollen and mites, etc. These pollutants are quite adaptable to the indoor environment. However, some sources of biologicals can be minimized by controlling relative humidity. USEPA has suggested as 30-50% as a desirable humidity range for homes (USEPA, 2015(c)). Also, it is possible to limit the growth of these contaminants by removing the growing medium from the interior environment. Water damaged buildings, standing water in HVAC systems, plant debris, soil, people, animal and water bodies are some of the common sources inside buildings that would provide biological contaminants to the indoor air. Many of these biological contaminants are small enough to be inhaled. The identified health risks from these pollutants are fever, chills, cough, chest tightness, muscle aches and allergic reactions (USEPA, 2015(c)); (Joshi, 2008). However, there are no quantitatively presented guidelines for biological contaminant exposure and related health risks. Thus, it is recommended some ways and means to prevent the problems from main sources such as dampness and mold (WHO, 2009); (USEPA, 2015(c)).

2.5.2 Volatile Organic Compounds (VOCs)

Volatile Organic Compounds are emitted in the form of gases from the chemicals, which are mainly being used to manufacture building materials, interior furnishing, cleaning products and personal care products. Many synthetic building materials in the indoors, release various kinds of pollutants at room temperature. VOCs are the main constituent out of these building-related pollutants (Yang X. , 1999). Identified sources of indoor VOCs are paints, wallpapers, varnishes, lacquers, wood preservatives, cleaning products, disinfectants, air fresheners, plywood, particleboard, carpets, composite floors, printers, tobacco smoke and cosmetic products, etc. (Cincinelli, et al., 2016); (Kamal, Razzak, & Hossain, 2016); (Crump, Squire, & Yu, 1997).

VOCs could lead to both short-term and long-term adverse health effects. The health risks for cancers and respiratory tract irritations such as phlegm, chest tightness, sore throat, cough and asthma have been linked with the VOCs exposure (Guo, Murray, Lee, & Wilkinson, 2004); (Wahab, 2011). Moreover, VOCs are the main reason for the odour impact which could be experienced due to the industrial activities when factories are located close to the inhabited area (Gallego, et al., 2008). Norbäck et al. (1990) study has revealed that VOCs and respirable dust in primary school are the main causative agents which affect the pupil's health resulting in sick building syndrome. Formaldehyde emitted from particle board and medium-density fiberboard has been identified in many schools during the first year of the construction (Norbäck, Torgén, & Edling, 1990). Furthermore, Formaldehyde has been selected as a pollution index to measure the toxicity level of TVOCs considering its availability and percentage of the mixture of VOCs (Wang, Bai, Yu, Zhang, & Zhu, 2004). However, insufficient ventilation condition has aggravated the present situation with increasing indoor VOCs concentration.

Many research studies have been carried out to quantify the emission and dispersion of VOCs from building materials and interior decorations. As a result of it, numerical and computational models have been developed to predict the pollutant concentration and the exposure period (Kim, Brown, Hafner, & Hopke, 2005); (Haghighat & Huang, 2003); (Karlsson, Kalagasidis, & Hagentoft, 2005); (XinKe & YinPing, 2011); (Yang X. , Chen, Zeng, Zhang, & Shaw, 2001); (Wilke, Jann , & Brödner , 2004); (Murakami, Kato, Ito, & Zhu , 2003).

Table 2.1 presents the guideline used for VOCs during the study where Formaldehyde has been selected for guideline preparation considering the occupant's exposure period and health risks. The summary of the available guidelines for VOCs from several organizations is listed in Table C1.

2.5.3 Carbon dioxide (CO_2)

Carbon dioxide is a colourless and odourless gas that generally exists in the atmosphere with the concentration in the range of 350-400 ppm or 0.03-0.04% by volume (Vaughan, 2015); (Dlugokencky & Tans, 2015). It is mainly released during respiration and combustion process. The indoor CO_2 level is usually greater than outside, even in building with few complaints about indoor air quality.

If the indoor CO_2 level is more than 1,000 ppm, there would be inadequate ventilation with building-related occupant's complains such as headaches, fatigue, eye and throat irritation, etc. (Apte, Fisk, & Daisey, 2000). However, CO_2 itself is not responsible for the above complains as a high level of CO_2 may indicate the elevated levels of other contaminants in the building which could contribute to occupants complains (Occupational Health & Safety, 2016); (Illinois Department of Public Health , 2003). Shendell, et al. (2004) study has reported that the measured indoor CO_2 concentration above 1000 ppm has resulted in 10-20 % of the increment in student absenteeism in schools (Shendell, et al., 2004). Furthermore, Hedge and Erickson (1996) research results have emphasized that the perception of uncomfortableness has increased with decreasing mean air temperature, increasing mean relative humidity and CO_2 concentration (Hedge & Erickson, 1996). However, the buildings maintain an average CO2 level less than 800 ppm, with appropriate temperature and humidity has been minimizing the risk of sick building syndrome (Apte, Fisk, & Daisey, 2000); (Shahzad, Brennan, Theodossopoulos, Hughes, & Calautit, 2016). The CO_2 is used to assess the indoor air quality and building ventilation performance as the elevated CO_2 level is the indication of an inadequate amount of outside air being brought into a building (Persily, 1996); (ASHRAE, 2004); (ASTM, 2003); (CEN, 1999). ANSI/ ASHRAE 62-1989 "Ventilation for Acceptable Indoor Air Quality" provides the guidelines for indoor CO_2 concentration as 1000 ppm considering the human comfort with respect to the odour impact which is generated from emitted human bio effluent. Hence, this is considered as a target indoor concentration level since the occupant discomfort is directly linked with the Sick Building Syndrome criteria (ASHRAE, 2010); (Petty, P.E., & C.I.H., 2016).

2.5.4 Carbon monoxide (CO)

Carbon monoxide is a colourless, odourless and tasteless toxic gas. It is a by-product of the incomplete combustion of carbonaceous fuels such as wood, petrol, coal, natural gas and kerosene. The effects of CO exposure can vary greatly from person to person depending on age, overall health, concentration and exposure period. The sources of indoor CO are tobacco smoke, unvented space heaters, leaking chimneys and furnaces, gas stove, wood stove, fireplaces, generators, and other gasoline-powered equipment. CO pollution in urbanized areas is mainly caused by automobile and industrial processes.

When the CO enters into the bloodstream during inhalation, it binds chemically to haemoglobin which usually carries Oxygen to the cells. Thus, this situation reduces the Oxygen delivery to all tissues of the body, causing immediate health problems and even death. According to the Raub and Mathieu-Nolf (2000) study the early symptoms of headache, dizziness, body weakness, nausea, confusion, disorientation, chest pain and visual disturbances may take place as a result of CO exposure (Raub & Mathieu-Nolf , 2000); (WHO, 2010). Moreover, human death could cause at 250 ppm of CO concentration (Greiner, 1991). The Centers for Disease Control estimates that in each year, more than 400 Americans would die from unintentional CO poisoning, more than 20,000 visit the emergency care units, and more than 4,000 are hospitalized due to an excessive amount of CO exposure (Centers for Disease Control and Prevention, 2015). Especially, pregnant mothers could have a greater risk of CO poisoning and this would increase the short-term complication rate for them, fetal death and developmental disorders of the fetus (Raub & Mathieu-Nolf , 2000). The guideline for permissible indoor CO concentration defined by several organizations such as USEPA, WHO, OSHA and NIOSH are presented in Table C1 considering the effective occupational safety and health factors.

2.5.5 Nitrogen dioxide (NO_2)

Nitrogen dioxide is a highly reactive gas. It is being produced mainly as a result of emission from motor vehicles and other combustion processes. Therefore, near road measurements have exhibited a high concentration of NO_2 due to vehicular traffic (Smith, et al., 2015). Environmental tobacco smoke and unvented gas stoves and heaters are the indoor sources of NO_2. This gas is a precursor for a number of harmful secondary air pollutants such as ozone and particulate matter. Besides, NO_2 would lead to forming the acid rain and visibility degradation in the atmosphere.

NO_2 is linked with several health effects with an increase of respiratory symptoms such as asthma and wheeze. NO_2 will reduce the lung function and affect the cardiovascular systems as well as the birth outcome (Cibellaa, et al., 2015); (Smith, et al., 2015). The recommended indoor NO_2 levels are presented in Table C1 and the selected guideline for the study of indoor permissible value is mentioned in Table 2.1 considering the public health and welfare protection.

2.5.6 Sulfur dioxide (SO_2)

Sulfur dioxide is a colourless gas and it reacts easily with a variety of other substances of airborne solid particles. It is soluble in water and can be oxidized in airborne water droplets forming harmful compounds. SO_2 is being mainly created due to the industrial activity which processes materials with sulfur, e.g. the generation of electricity from coal, oil or gas that contains sulfur (Muller, Yua, & Zhu, 2015). Motor vehicle emission is the other source of SO_2 as a result of fuel combustion. Natural sources of SO_2 are volcanoes, forest fire, oceans and decaying of plant matter. The high concentration of SO_2 in the air leads to the formation of other Sulfur oxides (SO_X) which can generate the fine particulate matters contributing to particulate matter pollution and visibility degradation (USEPA, 2016(d)).

Exposure to SO_2 affects human health and this would make various respiratory problems such as nose, throat, and airway irritations to cause coughing, wheezing, shortness of breath, or a tight feeling around the chest. Also, it has been identified as a respiratory irritant that causes an asthma attack. The people who are suffered from asthma are particularly sensitive to the exposure of SO_2 with a great risk of developing health problems (Mabahwi, Leh, & Omar , 2014); (Department of Environment and Energy, 2005). The available air quality guidelines for SO_2 are presented in Table C1.

2.5.7 Heavy metals

The heavy metals of lead, cadmium, mercury and arsenic are mainly being emitted from the various industrial process such as energy-related sources associated with fuel combustion, smelting industries, abatement technologies for wastewater treatment, incinerators and metal refining, etc. Some of the domestic, agricultural, medical and technological applications also contribute to the distribution of these pollutants into the environment. According to the findings from the USEPA and the International Agency for Research on Cancer, heavy metals are classified as probable human carcinogens with the potential to cause damages to several organs (Tchounwou, Yedjou, Patlolla, & Sutton, 2012). The next paragraph will explain the applications and health risks with respect to the selected type of heavy metal.

Lead has been used in some paint as a pigment material which uses to increase the drying process and durability with a better appearance. Besides, people consume Lead unintentionally from drinking water as the lead pipes are used for the water supply system. It has also been identified that PVC products and vehicle emissions would contribute to indoor air pollution. However, WHO has reported that Lead exposure can cause kidney and bone damages, development and neurobehavioural effects on children, and high blood pressure in adults (WHO, 2007). The Cadmium is another kind of air pollutant that is mainly emitted from waste incineration, metal production and public electricity, heat production and environmental tobacco smoke. It can severely damage the lungs even causing death. The accumulated Cadmium in the body can affect the kidney by damaging the filtering mechanisms. The other health effects of Cadmium are bone fracture, reproductive failure or infertility, cancer development and damage central nervous system, immune system and DNA, etc. (WHO, 2007). Mercury is the only common metal which is found in liquid form at room temperature. It is being used in Fluorescent light bulbs, electrical fixtures, auto switches, thermostats, and medical equipment, etc. Acute exposure to the mercury vapour at high levels, which is more than 1000 $\mu g/m^3$ can cause irritation of the airways pneumonitis, pulmonary edema and damages in brain nerves, kidneys and lungs. It can lead to coma and/or death in extreme cases. Chronic exposure to the low level of mercury vapour (50 -100 $\mu g/m^3$) can result in adverse health effects to the nervous system and kidneys, thyroid to develop and short term memory loss in adults (WHO, 2007). The presence of Arsenic in the air could be due to special glass, semiconductors, paints, dyes, metals, soaps, drugs and treated wood. Arsenic may lead to health effects such as cancer development, lung irritation, skin disturbances, damage in DNA and brains (Pollution in People, 2006); (LENNTECH, 2016).

Several organizations have established regulatory measurements and guidelines to minimize exposure to heavy metals considering their extensive health risks. European Environmental Agency (EEA) has reported that across the EEA 32 countries, the emission of Lead, Mercury and Cadmium have been reduced by 91%, 68% and 70% respectively between 1999 and 2009 (European Environment Agency, 2011). However, these rules and regulations are properly being undertaken by developed countries whereas the developing countries are mainly focused on economic development rather than environmental pollution. Table C1 will reveal available air quality guidelines for Lead exposure.

2.5.8 Particulate Matter (PM)

Particulate matter refers to a mixture of solid particles and liquid droplets that are found in the air. The sources of indoor particles could be either indoor or outdoor sources of pollution. The concentration and composition of indoor particle pollutants may vary with respect to the polluting sources and ventilation conditions. In residential buildings, particles are mainly released from cleaning activities and combustion/thermal related activities such as cooking, smoking and incense or candle burning (Tunno, et al., 2015); (Geiss, Bianchi, & Barrero-Moreno, 2016); (Ozturk, 2006).

The sources such as sweeping and vacuum cleaning will also contribute to increasing the concentration of indoor particles (Howard-Reed, Wallace, & Emmerich, 2003). Many of these particles are considerably smaller in size. Thus, the majority of the particles are respirable and it can affect the respiratory system, causing serious health effects such as asthma and respiratory allergy (Isaxon, et al., 2015); (Hussein, et al., 2006). Tobacco smoke and re-suspension of dust particles from carpets are also taken as sources which may increase the indoor particulate matter concentration. The average increases in indoor $PM_{2.5}$ and PM_{10} have been recorded as 58 and 46% due to tobacco smoke emission. In some of the residential and school areas, indoor to outdoor ratio of $PM_{2.5}$ has exceeded the unity due to smoking and re-suspension of dust in indoor environments (Stranger, Potgieter-Vermaak, & Grieken, 2007). $PM_{2.5}$ mainly forms from Organic Carbons (OC). Therefore, the characteristics of $PM_{2.5}$ are influenced by OC. i.e., $PM_{2.5}$ structured from OC causes bacterial spread as it is inherited from the parental material (Shrimandilkar , 2013); (Kleindienst, et al., 2010). Morawska et al. (2002) study has found that the particulate matters emitted from motor vehicles are mostly found in the ultra-fine size (particle diameter size is < 100 nm) in many urban environments. Hence, the passengers and occupants inhabited close to busy highways would subject to severe health problems due to particulate matter pollution (Morawska, Jayaratne, Mengersen, Jamriska, & Thomas, 2002). In addition, dust that accumulated on hot surfaces such as heater and light fixtures is likely to emit harmful chemicals when they get heated. Yu, et al. (2009) study has found that VOCs are emitted from different types of heated dust. Table C1 depicts the guidelines which are given by USEPA and WHO for $PM_{2.5}$ and PM_{10} exposure (Yu, et al., 2009).

The summary of the IAQ guidelines defined by several organizations for permissible exposure limits of selected pollutants is presented in Table C1 in Annex C and the selected IAQ guidelines for the study is shown in Table 2.1.

Table 2.1: Selected IAQ guidelines for the study

Pollutant Name	Guidelines (Permissible Exposure Limits)		Averaging Time [a]	Organization	Selected Criteria for the Guideline Definition [b]	Source
	ppm	mg/m^3				
Carbon Monoxide (CO)	9		TWA (8 hrs)	USEPA	To protect against the occurrence of carboxyhemoglobi-n levels in human blood associated with health effects of concern	USEPA, Primary National Ambient Air Quality Standards- health based and Review of National Ambient Air Quality Standards for Carbon Monoxide; Final Rule (USEPA, 2018 (a)) and (USEPA, 2011)
Nitrogen Dioxide (NO_2)	0.1		TWA (1 hr)	USEPA	Public health protection, including the health of sensitive population such as asthmatics, children and elderly people	USEPA, Primary National Ambient Air Quality Standards- health-based (USEPA, 2018 (a))
	0.053		TWA (Annual)			
Carbon Dioxide (CO_2)	1000	1800	**Note 01**	ASHRAE	Human comfort or occupant odours	ANSI/ASHRAE 62-1989 standard (ASHRAE, 1995)
Formaldehyde (CH_2O)	0.75		TWA (8 hrs)	OSHA	Specific description is not given. Related health effects; HE2, HE4, HE6 and HE7	OSHA Occupational Chemical Database (OSHA, 2018 (d))
	0.5 (Action level)					
	2		STEL			
Particulate matter ($PM_{2.5}$)		0.025	TWA (24 hrs)	WHO	Relationship between 24-hour and annual PM levels	WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide (WHO, 2005)

a- **Type of exposure period (TWA**- Time Weighted Average. This refers to a concentration that a person has been exposed to average over some period, **C**- Ceiling, **STEL**- Short Term Exposure Limit, **REL**- Recommended Exposure Limit)

Note 01: -This is not a requirement of ASHRAE 62-1989. It can be considered as a target concentration level.

b- **Related health effects listed during the guideline's preparation (HE1**- Respiratory effects other than irritation- Cumulative lung damage, **HE2**- Irritation-Eyes, nose, throat, skin, **HE3**- Nervous system disturbances-Narcosis, **HE4**- Respiratory effects-Acute lung damage/edema or other, **HE5**- Asphyxiants, Anoxiants, **HE6**- Cancer- Currently regulated by OSHA as carcinogen, **HE7**- Respiratory effects other than irritation- Respiratory sensitization (asthma or other), **HE8**- Nervous system disturbances- Narcosis)

The air quality guidelines and regulations for Sri Lanka made by Minister of Environment and Natural Resources, Sri Lanka were gazetted in August 2008 and maximum permissible levels of pollutants are summarised in Table 2.2.

Table 2.2: Air quality guidelines and regulations for Sri Lanka

Pollutant	Averaging Time*	Maximum		+ Method of measurement
		μgm^{-3}	ppm	
Particulate Matter- Aerodynamic diameter is less than 10 μm in size (PM_{10})	Annual	50	-	Hi-volume sampling and Gravimetric or Beta Attenuation
	24 hrs	100	-	
Particulate Matter- Aerodynamic diameter is less than 2.5 μm in size ($PM_{2.5}$)	Annual	25	-	Hi-volume sampling and Gravimetric or Beta Attenuation
	24 hrs	50	-	
Nitrogen Dioxide (NO_2)	24 hrs	100	0.05	Colorimetric using Saltzman Method or equivalent Gas-phase chemiluminescence
	8 hrs	150	0.08	
	1 hr	250	0.13	
Sulphur Dixoxide (SO_2)	24 hrs.	80	0.03	Pararosaniliene Method or Equivalent Pulse Flourescent
	8 hrs	120	0.05	
	1 hr	200	0.08	
Ozone (O_3)	1 hr	200	0.10	Chemiluminescence Method or equivalent Ultraviolet
Carbon Monoxide (CO)	8 hrs	10,000	9.00	Non-Dispersive Infrared Spectroscopy
	1 hr	30,000	26.00	
	Any time	58,000	50.00	

*Minimum number of observations required to determine the average over the specified period-

03 hour average - 03 consecutive hourly average
08 hour average - 08 hourly average
24 hour average - 18 hourly average
Yearly average - 09 monthly average with at least 02 monthly average each quarter.
+ By using Chemicals or Automatic Analyser

2.5.9 Odour

Odour pollution of air could be a direct or indirect result of human activities. It can affect human comfort and enjoyment with the provision of annoyance from the environment. Since the outdoors is considered to be a contaminant due to its impact on nuisance conditions. However, it is not simply possible to assess the odour impact as the odour limit interacts with several factors such as Frequency, Intensity, Duration, Offensiveness and Location (FIDOL) (Nicell, 2009). National Environmental Act No.47 of 1980 has advised the relevant authorities to make all efforts for the removal of unpleasant odour as far as possible (The Asia Foundation, 2015).

2.5.10 Undesirable temperature

Although the temperature is not a direct indoor air pollutant, it can affect the pollutant concentration and degradation of human productivity and comfort leading to SBS. The undesirable temperature has been identified as a factor that was complained by many occupants regarding the human discomfort with respect to indoor air quality (Lai & Yik, 2009); (Kamaruzzaman, Egbu , Zawawi, Ali, & Che-Ani, 2011). The effects of global warming lead to elevated indoor temperature in recent years. Especially in tropical countries, this situation has resulted in extensive use of mechanical ventilation systems to bring back the human comfort.

During the 1970s, energy-efficient buildings have been introduced to minimize the energy crisis (Wang, Bai, Yu, Zhang, & Zhu, 2004). However, it was not effective to have airtight buildings as the occupants were not comfortable with the particular indoor environment and they tend to take alternative heating or cooling methods. The indoor comfort temperature could be related to several factors such as climate, seasons and region. Several researchers have published different relationships for indoor comfort temperature with the use of outdoor temperature and ventilation conditions (Ponni & Baskar, 2015). Jayasinghe and Attalage (1999) study has established the thermal comfort zones for Sri Lanka as shown in Figure 2.1 for various internal velocities. This study has revealed that Sri Lanka can be thermally comfortable at an elevated temperature like 30 ^{0}C with the availability of sufficient air movement (Jayasinghe & Attalage, 1999). Thus, the building with a proper ventilation system has to be maintained to enhance thermal comfort and building environmental performance.

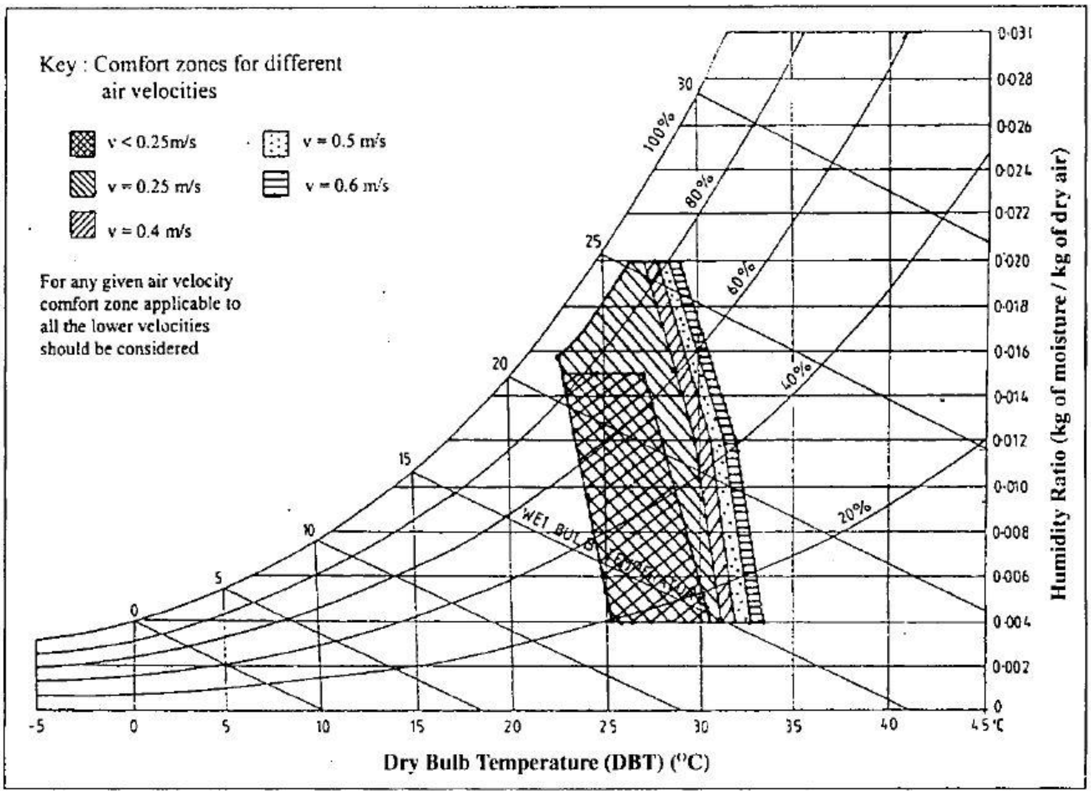


Figure 2.1: Psychrometric chart giving thermal comfort zones for Sri Lanka for various internal velocities (Jayasinghe, Priyanvada, & Jayawardena, 2002)

2.6 The corrective measures which have been taken to mitigate IAP

Previous sections in this chapter (Chapter 2) have been addressed about the indoor air quality with its related sickness and sources of indoor air pollutants, in order to emphasize the importance of IAQ for human survival and well-being. Many studies have revealed that air quality, thermal comfort, day-lighting, temperature, odour, noise, working environment, opportunities for social gathering, relaxation and exercises are as the factors that may affect on occupant's performance and level of satisfaction on the indoor environmental quality (Kamaruzzaman, Zawawi, Pitt, & Don, 2010); (Wong, et al., 2009); (Paul & Taylor, 2008); (Yavetz & Rafaeli, 2005). Among these factors, IAQ has been considered as a significant cause which can seriously affect human health and their productivity. Therefore, various researchers have come up with different solutions to improve air quality with the help of government or IAQ and health-related organizations. The following will explain the corrective measurements which were taken from several research studies to mitigate indoor air pollution.

The questionnaire survey is the most frequently performed basic method to investigate about the IAQ related problems directly from the occupant's responses. Based on the results obtained from this analysis, necessary actions could be suggested for rectification of identified problems. Kamaruzzaman, et al. (2011) research can be mentioned as an example for such a study where daylighting and thermal comfort have been identified as predominant factors that have been contributed towards a better indoor environment. Furthermore, it has highlighted the benefits which are gained from this particular analysis, such as healthy living with improved air quality and energy savings by use of a lesser number of electric lights (Kamaruzzaman, Egbu , Zawawi, Ali, & Che-Ani, 2011). However, Lai and Yik (2009) questionnaire study has found that noise propagation as a problem with the use of natural ventilation conditions depending on the site location to result in a low performing building (Lai & Yik, 2009). Hence, the questionnaire survey can be categorized as corrective measures that could be useful to get a decision for a better indoor environment.

The standard approaches to evaluate the benefits of air quality improvements can be mentioned as another action that was taken to make aware of the importance of the indoor air environment for human beings. As the other aspect, the standard evaluation method can be used to quantify the disadvantages of poor air quality with respect to the health and wealth conditions of the occupants. Based on the literature review, it was identified that there are three major evaluation methods which can be used for the indoor environmental quality assessment. They are namely, contingent, hedonic, and damage-cost approaches. Contingent valuation estimates the health benefits and determines the amount of money that individuals are willing to pay for improved air quality. The hedonic approach estimates the financial benefits by revealing the behaviour of people in the real market for air quality related issues. Moreover, this method also determines the amount of money that individuals are willing to pay for an enhancement in indoor air quality. In damage-cost approach, health benefits which are gained because of the reduction in pollutant levels, are estimated using two parameters. They are the "concentration-response" coefficient and predicted health outcomes with assigned economic values. "Concentration-response" coefficient quantifies a relationship between indoor air pollutant concentration and health responses. The results which are obtained from this analysis are being used to identify financial benefits which could be gained from the reduction in air quality related impacts (Chau, Hui, & Tse, 2007). Wang and Zhang (2009) study has reported that the contingent valuation for air quality assessment in Jinan, China has proven that 59.7% among the Chinese community have a positive answer for the willingness to pay in order to improve air quality. According to their responses, they agreed to pay 100 Chinese Yuan of the average amount of money per person per year. The rest of the respondents considered the air quality improvement as a government responsibility since the majority of them were not able to bear the cost due to their unprivileged living conditions (Wang & Zhang, 2009). Therefore, the decisions which were taken by standard evaluation methods could be used by any government, policymakers, researchers, or relevant institutes to regulate indoor air pollution.

Indoor and outdoor air quality monitoring sites can be mentioned as another effort which was performed to improve indoor air quality and public awareness about indoor air pollution. Mostly in urbanized areas, air quality monitoring stations are located near cities in order to measure the temporal variation of pollutant concentration in different places (Rudel & Perovich, 2009). Weschler (2009) study has highlighted that the details regarding air condition and/or daily air pollution could be led to an increase in the resident's perception of better indoor air quality. Subsequently, analytical instruments and their sensitivity were also improved by the identification of numerous types of pollutants. This could also be mentioned as an advancement in IAQ related industries (Weschler, 2009). Hence, the developments in research areas and public awareness of indoor air quality have exhibited with the use of sophisticated and portable IAQ meters for the respective applications.

As per the literature review, it was able to identify that the exposure levels of indoor chemicals are largely undocumented. Furthermore, limited toxicity data are available for commonly used indoor chemicals due to the weak regulatory requirement on chemical safety testing. Rudel and Perovich (2009) study has revealed that several regulatory policies are implemented by the European Union on commonly produced chemicals to disclose toxicity and exposure information on particular products. Such other organizations which are related to IAQ investigations are World Health Organization (WHO), United States Environmental Protection Agency (USEPA), United States Occupational Safety and Health Administration (OSHA), American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE), United States National Institute for Occupational Safety and Health (NIOSH) and American Congress of Governmental Industrial Hygienists (ACGIH), etc. These organizations serve to improve IAQ with necessary initiatives to maintain and to produce the policies for better environmental quality (Wong & Mui, 2007). They appreciably help developing countries to enhance the occupant's awareness of indoor air pollution due to existing insufficient information on exposure and health effects of many of the indoor chemicals (Rudel & Perovich, 2009). Therefore, ingredient disclosure and regulatory actions by several parties are also considered as corrective measures that were taken to mitigate indoor air pollution.

Computational modelling of indoor airflow is an evolutionary step that has been introduced to predict the concentration of the pollutants in indoors with the possible changes to the existing or newly designed buildings. The Computational Fluid Dynamic (CFD) technique has been developed by considering the five principal factors which could influence the generation and dispersion of pollutants in buildings. They are sources, sorption/ desorption, mixing volume, air exchange and removal (Panagopoulos, Karayannis, Kassomenos, & Aravossis, 2011). The detailed description of the CFD analysis is discussed in Section 2.7.

As mentioned in Weschler's (2009) study, the changes in the way that buildings are operated or constructed have also destroyed the quality of indoor air. For example, the presence of air conditioners in operation and intensive use of composite wood products during construction have been witnessing the above finding. The same study has suggested that some remedial measures to minimize indoor air pollution such as regulate the way that products are formulated and limit the use of certain products which are identified as the cause of IAP (Weschler, 2009). The results obtained from these studies could be used by researchers and decision makers to select effective environmental policies and practical applications to create a healthier built environment (Wang & Zhang, 2009).

2.7 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is used to analyse the fluid systems by means of computer-based simulation. Better solutions can be achieved by CFD analysis using high-speed supercomputers under the supervision of skilled personnel. CFD software is portable, easy to use, can be modified and it reduces the overall cost, which is required for experimentation and data acquisition. However, the results of CFD simulation depend on input data and assumptions made for the particular simulation. The accuracy of the results is limited by available computer power and mathematical models used in the solver for the simulation. Considering the advantages of CFD analysis, it is generally used in industries such as aerospace, automotive, heat ventilation and air condition (HVAC), biomedicine, chemical processing, hydraulics, power generation, ports and marine, etc. (Versteeg & Malalasekara, 2007); (Kuzmin, 2016); (Zuo , 2016).

There are several CFD software tools available for indoor air quality modelling such as ANSYS-CFX, ANSYS-Fluent, PHOENICS, AIRPAK, STAR-CD, CONTAM, IAQX, IAQUEST and INDAIR-2, etc. Analysis methods, results and accuracy are highly dependent on the software which is used for the project. Therefore, the selection of software should be done considering the project requirements and the available resources for the analysis. The applications of the CFD technique related to improvements in indoor air environments are presented in the below paragraphs.

AIRPACK 3.0 software and standard k-ε turbulence model were used for the CFD analysis in order to investigate the indoor thermal comfort in a test model building with the use of double-glazed windows including curtains. The suitability of this building material was predicted from the computational model considering the indoor temperatures in several locations of the building (Zhang, Huang, & Zhou, 2015). Prakash (2015) study is another research that was performed to examine the improvement for thermal comfort with the use of wood-wool insulation layer in an air-conditioned environment. ANSYS-Fluent software was used for the CFD analysis and it was used to predict the optimum temperature of supply air from an air conditioner. It has observed that the desired temperature is as 26-27 ^{0}C considering the thermal comfort of the occupants (Prakash, 2015). The same kind of study has been carried out by Yang et al. (2014) with the use of AIRPAK software as the CFD tool. In this research, the wind velocity field, temperature field and air age field are analyzed in a bedroom with wall -hanging air conditioning (Yang, Ye, & Jie he, 2014).

Hweij et al. (2016) research has evaluated the performance of ventilation with the use of chair fans. Validated CFD model and bioheat model were used to measure the airflow, temperature, and CO_2 concentration inside the building. ANSYS-Fluent software was used for the simulation (Hweij, Ghaddar, Ghali, & Habchi, 2016). The variation of indoor natural ventilation in the urban wind flow pattern has been studied with the use of a coupled CFD approach. The changes in the geometry of the building have shown an increase in ventilation conditions. The results obtained from the validated CFD model has revealed that an increase in opening size located near the roof can enhance the air exchange rate by up to 43% (Hooff & Blocken, 2010).

CFD software has also been used to quantify the emission from the building materials and the distribution of indoor pollutants. The followings are the selected studies that had used well-validated CFD software for the fluid analysis. Bourdin, et al. (2014) study has reported that Formaldehyde emission from the building materials has investigated by using ANSYS Fluent R15.0 software (Bourdin, Mocho, Desauziersa, & Plaisance, 2014). The traffic-related air pollution on indoor air quality of the naturally ventilated building has been evaluated using the CFD numerical simulation approach. The findings from this research have concluded that building envelop has restricted the dispersion and dilution of indoor particulate matter concentration (Tong, et al., 2016). The Reynolds Averaged Navier Stokes (RANS) k-ε (2 equation) model for turbulence has been used to study the mixing time of a pollutant with respect to the room airflow and source location. These equations were solved with a commercial code based on a finite-volume fully implicit method. Further, it has investigated the influence of the velocity and turbulence intensity at the source location on the mixing time (Gadgil, et al., 2003). Moreover, the CFD analysis was carried out to find out the pollutant transmission characteristics and personal exposure in office workstations under the combination of personalized ventilation with typical background ventilation systems. The Navier Stokes equations which are solved by the finite volume method was used to identify the advantages of personalized ventilation condition by combining the suitable background ventilation system (Shen, et al., 2013). Fan (1995) research can be mentioned as another study, which has used the k-ε model for the analysis of air contaminant distribution in the room. The above-mentioned case studies have shown the benefits of CFD software for indoor environment improvement (Fan, 1995). The predicted results from the software could be used by building planers to determine the building flush-out period or required minimum ventilation conditions to create a desirable indoor environment.

2.8 Summary

The comprehensive literature review was carried out on IAQ and SBS in order to understand its importance to human beings. Details of the air pollution have been examined over the past fifty years and its impact was able to identify on the indoor air quality as well. The summary of Chapter 02 is graphically presented in Figure 2.2.

As per the findings, the term “Sick Building Syndrome” was introduced as a result of the health complications and discomforts of the occupants due to the time spent indoors. Many researchers and IAQ related organizations have investigated the sources and practices of IAP. They are discussed in detail under Section 2.4. The ventilation rate was identified as a key factor in indoor air pollution as it can be used to disperse the accumulated indoor air pollutants with considering the quality of outdoor air. The types of indoor pollutants were deliberated with respect to their origins and related health effects due to the long-term and short-term exposure to the particular pollutants. Many researchers have investigated the health risks due to VOC exposure as it is the most common type of indoor air pollutant which was found in many indoor spaces.

However, the IAQ related organizations have introduced guidelines and regulations for the exposure of the occupants to indoor air pollutants. The definition of the guidelines for a pollutant was generated by considering several criteria such as the most vulnerable group of people to indoor air pollution and/or most alarming health conditions due to its exposure and occupant's comfortability.

The attention on the mitigation of IAP was increased when the gravity of better air quality is understood by many parties such as researchers, IAQ related organizations, governments and even by the occupants. Thus, they tend to find corrective measures to decrease the effect of this global issue. Based on the literature review, it was found out that the questionnaire survey was the most primitive step to investigate the occupants' comfort due to the indoor environment. Moreover, several standard evaluation methods were introduced to improve IAQ by emphasising the benefits of improved air quality and related costs due to its degradation. Since awareness is a predominant method to mitigate air pollution, many developed countries have established indoor and outdoor air quality monitoring sites in an accessible manner for the public. CFD modeling is also another technique which is used by researchers and policymakers to develop environmental policies to enhance the IAQ. This tool is used to predict the pollutant concentration or thermal comfort level with the presence of diverse environmental conditions while monitoring the pollutants' transportation inside the building. Thus, it is a pinnacle of success in the IAQ improvement as CFD analysis is capable to handle many factors at once which are influenced on the IAP.

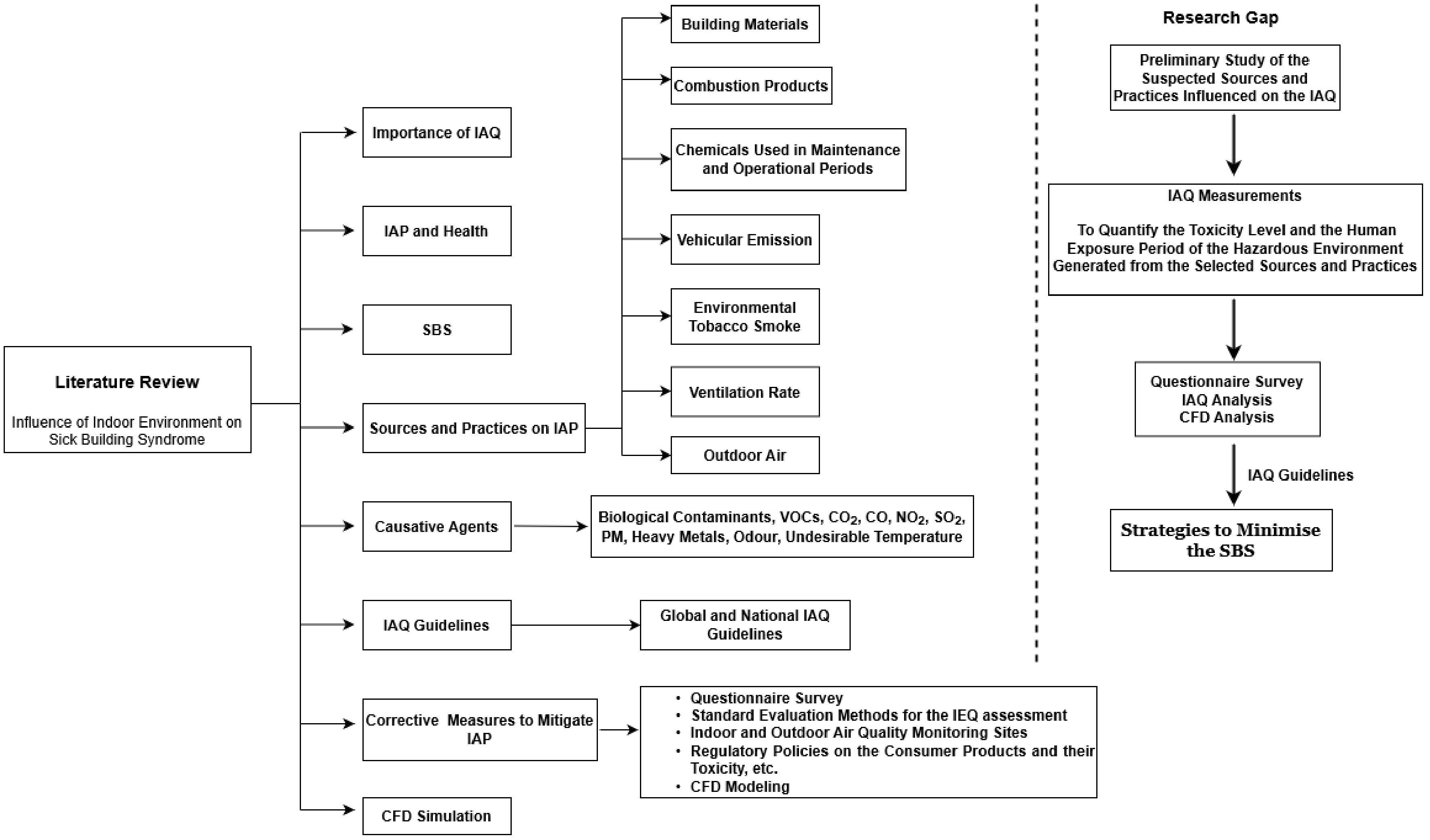


Figure 2.2: Summary of the literature review and identified research gap

CHAPTER 3: EFFECT OF CHEMICAL BASED HOUSEHOLD PRODUCTS AND PRACTICES ON IAQ

3.1 General

The findings of the previous chapters emphasized that indoor air pollution is broadly discussed in the current context, mainly due to the adverse effects it brings forth to the occupiers. As mentioned in Section 2.1, the concentration of air pollutants in indoors can be greatly influenced by the following three distinct sources namely,

- Building materials used and human practices in construction and operation stages
- Outdoor sources
- Ventilation condition of the environment

The above sources on IAP are briefly highlighted below in order to form the pathway for the study.

With reference to Subsection 2.4.1, the effect of building material on IAQ is closely related to the possible emissions of VOCs to the indoor environment including Formaldehyde. It has been found that most of the excess concentrations of VOCs were exclusively coming from building materials (Missia, Demetriou, Michael , Tolis, & Bartzis, 2010). Furthermore, there were concerns for harmful aldehydes prevailing in indoor environments, that have been identified as a result of building materials such as hardwood, plywood, laminated floorings, adhesives, paints and other household products (Marchand, Bulliot, Le Calvé, & Mirabel, 2006). Altogether, human practices are also considered as a source of IAP, which impact on IAQ in spaces with poor ventilation conditions. Many kinds of literature have supported illustrating the gravity of indoor air pollution due to the activities of using wood-burning stoves, open waste burning and environmental tobacco smoke, etc. (Refer Subsection 2.4.2 and 2.4.5). Thus, the usefulness of examining the emissions from building materials and human interventions, demonstrate a viable pathway to carry out the preliminary study for this research. The building materials and the types of human activities that are taken into consideration are illustrated in Section 3.2 with the specific reasons associated with the selection.

Furthermore, the contribution of outdoor activities such as ongoing constructions, industrial emissions and vehicular emissions is also paramount for air quality as described in Subsection 2.4.7. When considering the level of hazardous chemicals being released into the air from several sources, pollutants such as PM and NO_2 are of particular concern as they infiltrate from outdoors during prolong exposure to so-called outdoor activities as mentioned above (Kelly & Fussell, 2019). This can be further justified by the findings in Subsection 2.4.7 and recent researches, where they identified an enhanced proportion of PM in residences near roadwork sites, renovation activities and busy commercial areas with natural ventilation system (Stamatelopoulou, Asimakopoulos, & Maggos, 2019). These depict the importance of studying the impact of outdoor sources on indoor air quality that is under consideration.

As per the literature review on ventilation conditions towards indoor air quality, it has been found that emissions from building materials are highly dependent on the functionality of the ventilation system (Persson, Wang, & Hagberg, 2019). Further, there is an increased possibility of SBS at times where the ventilation system is malfunctioning. As brought forward in Norhidayah et al. study in 2013, the association between SBS and IAQ is closely related to the ventilation and possible accumulation of contaminants in the indoor environments (Norhidayah, Chia-Kuang, Azhar, & Nurulwahida, 2013). Therefore, it is evident that ventilation becomes a crucial factor to be studied and analysed in this research.

For the study, the ventilation conditions that prevail in spaces have been defined as “Proper ventilation” and “Poor ventilation”. “Proper ventilation” portrays a scenario where passive features are utilised to create a better ventilation system throughout the building with correct placement of doors, windows, shades, etc. “Poor ventilation” is either a properly designed building with restricted natural ventilation by closing all openings or poorly designed buildings in a way that does not suit the climatic conditions and zones of the country with no concern about passive features or air-conditioned buildings with poor maintenance. It is predominant to have a flow of fresh air to the indoors to have a favorable air quality within the space. Experiments were carried out to investigate the indoor environmental quality with scenarios of these different ventilation conditions is discussed in Chapter 4.

This chapter is arranged in a way that covers the experiments carried out to study the impacts of building materials, human practices and outdoor sources have on IAQ.

3.2 Details of the experimental programme

During this study, emissions from building materials used in construction and operational stages and human practices are identified and tested to determine their effect on IAQ. The building materials that take into consideration are listed below where the air quality in adverse indoor environments has been recognized for further investigation due to the excessive use of chemicals in the building operational cycle.

Building materials

- Air freshener, Wall paint, Synthetic building materials, Mosquito coil, Naphthalene ball, Incense sticks

Adverse indoor environments

- Hospital theatre, Motor vehicle service centre

The extensive literature review was carried out on the sources and practices of IAP was based to choose the above indoor sources for the research study (Ericson, et al., 2019); (O'Connor, et al., 2018); (Hicklin, Farrugia, & Sinagra, 2018); (Dai, et al., 2017); (Souza, et al., 2016); (Kim, Hong, Bong, & Cho, 2015); (Stabile, Fuoco, & Buonanno, 2012); (Batterman, et al., 2012); (See & Balasubramanian, 2011). Apart from that, the other reason behind the selection of these building materials is the fact that these are the common material to which occupants get daily encountered with, while due to the lack of knowledge and expertise, most of these have become everyday products that sometimes have an intense usage in the daily household, i.e., Mosquito coils, incense sticks, air freshener and synthetic building materials.

Simultaneously, the human activities below have been considered for the analysis, as they play the usual role in daily lives (Suryadhi, Abudureyimu, Kashima, & Yorifuji, 2019); (Stamatelopoulou, Asimakopoulos, & Maggos, 2019); (Kumar, et al., 2018).

- Open waste burning (Dry leaves and Polythene)
- Environmental tobacco smoke

The purpose of carrying out this exercise is to outline and illustrate the impact of these materials and human activities due to the research gap identified from the comprehensive literature review. As mentioned in Section 1.3, there is inadequate availability of data and information related to exposure and concentration of pollutants from the above-mentioned sources. Hence, the development and implementation of policies for risk assessment remain incomplete. Equally, there is a requirement to identify human exposure to indoor air pollutants and health effects as a result.

The outcome of this study enables identification and quantification of the effect of building materials and human practices with respect to its emission and the exposure of the occupants to the adverse environment of indoor air. The ventilation condition specified for each of these factors is dependent on how the most adverse effect of the specific component can be obtained. The effect of these building materials and human practices will be discussed in detail under Section 3.3.

The effect of outdoor sources of IAQ was investigated within a building which is closely located to an ongoing construction project. This construction project was in its latter stage of construction and building finishes were carried out during the experimentation. Initially, ventilation condition is natural during this experiment, and afterward, mechanical ventilation means were used to artificially improve the indoor environment. The effect of outdoor sources on IAQ would be further elaborated in Section 3.4.

Indoor Air Quality Monitor (IQM60 Environmental Monitor V5.0) and Haz-Dust Particulate Air Monitor were used to identify the air pollutants from the above sources. IAQ Monitor was used to measure the concentrations of CO, CO_2, NO_2, TVOCs, Temperature and RH. Haz- Dust Particulate Air Monitor was used to measure the concentration of the particulate matter which are having a diameter less than 2.5 μm. Instruments were placed at a height of 1m from the ground to simulate the working height of an occupant seated on a chair. The base case, that is considered during Section 3.3 and 3.4 is the average value of the measurements taken during one hour before the actual experiment (Refer to Table A1). For the Subsection 3.3.5, hence the air quality measurements depict the prevailing conditions of the indoor environment, the base case is defined as the average value of the causative agent outside the building over the above period.

Apart from the tests done for IAQ in hospital theatre and motor vehicle service centre in Section 3.3, all other experiments on building materials, human practices and outdoor sources were conducted inside the buildings of the University of Moratuwa, Sri Lanka. Details of the test chambers and other locations are described under the corresponding sections.

The study was structured in a way that the further experiments of the research would be directed upon the sources of IAP, which resulted in the highest impact on the occupant's health and comfort out of the identified sources for the preliminary study. Thus, the questionnaire survey is also performed in the environment of the selected sources under the different ventilation condition and it is discussed in Chapter 4. The data obtained from the questionnaire survey would be directly in correspondence with indoor air quality parameters measured during the experiment enabling quantification of the obtained results. The predictability of the exact conditions of the SBS has been enhanced by the specific symptoms identified from the occupants. The structure of the study is graphically presented in Figure 3.1.

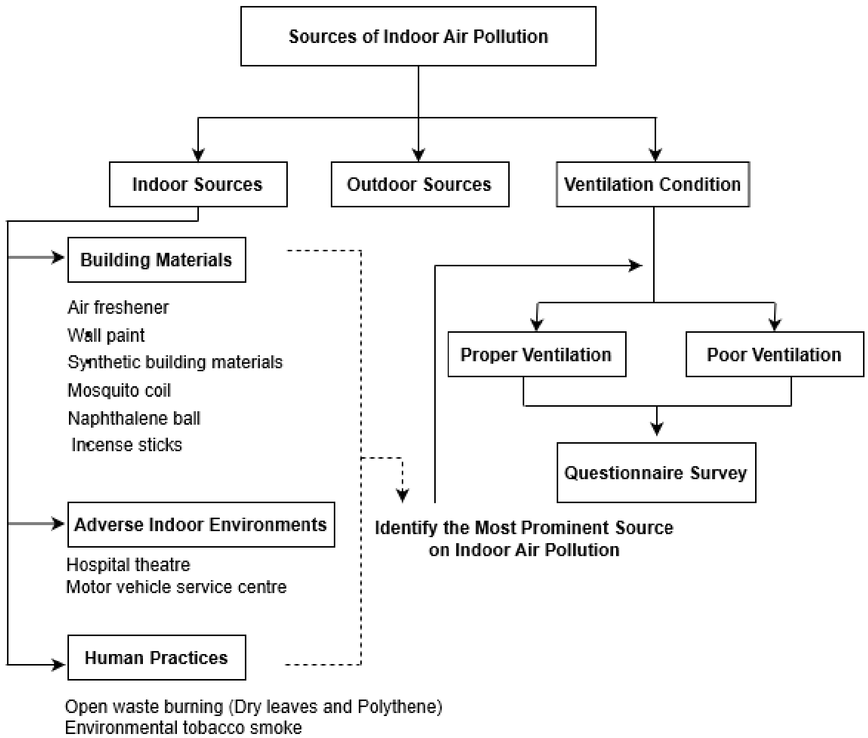


Figure 3.1: Structure of the preliminary study

3.3 Effect of indoor sources on indoor air quality

3.3.1 Air freshener

Air fresheners are consumer products that typically emit fragrance and used in houses, offices, stores, restrooms and commonly in public bathrooms with the promise of creating a clean, healthy, and sweet-smelling indoor atmosphere. Furthermore, there is a broad range of air fresheners such as traditional sprays, continuous release (Outlet and battery operated), solid gel dispensers, hanging car air fresheners and potpourri.

Based on the literature review, it was found that air freshener that we commonly use is a simple mask odour with chemicals and it is failed to remove contaminants in the indoor environment (Cohen, Janssen, & Solomon, 2007). They sometimes add toxic chemicals to the atmosphere that may lead to cause severe health problems for the occupants. Furthermore, many of these air fresheners contain Phthalates, which is a hazardous chemical known to be causing hormonal abnormalities, birth defects, and reproductive problems, although it helps to enhance and maintain the smell of the air freshener. According to the state of California notes that five common types of Phthalates found in air freshener product are Di-ethyl Phthalate (DEP), Di-n-butyl Phthalate (DBP), Di-isobutyl Phthalate (DIBP), Di-methyl Phthalate (DMP), Di- isohexyl Phthalate (DIHP) (NRDC, 2007).

The test chamber created for the experiment on air freshener is shown in Figure 3.2. It is an air-conditioned space located inside a building of the Department of Civil Engineering, University of Moratuwa. Since this building is older than three decades, there was no other effect of the building materials on IAQ which can be proven by the base case presented in Table A1. Therefore, pollutants generated in the experiment can entirely be from the selected source.

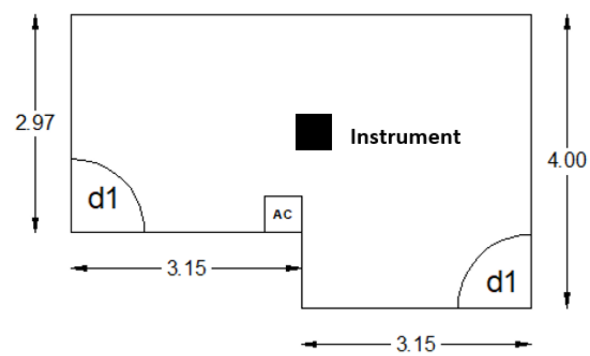


Figure 3.2: Plan view of the test chamber used for the experiment on air freshener (All the dimensions are in meters)

The traditional spray form of air freshener from a product type was used for the entire set of experiments and it was evenly sprayed inside the test chamber. The brand of air freshener was selected considering the high consumer demand for the product type as per the general observation. There were mainly two categories of test sets which used different volumes of air freshener as follows.

i. Test 01: 20 ml of air freshener spray
ii. Test 02: 40 ml of air freshener spray

Several experiments were conducted for each category and the overall results of Test 01 and Test 02 are presented below.

Results and Analysis – Air Freshener

The study revealed that the concentrations of CO, NO_2, TVOCs and $PM_{2.5}$ have increased after spraying of the air freshener. A significant effect was observed from the variation of TVOCs and $PM_{2.5}$ by considering the maximum concentrations and occupant's exposure times. According to the observed results from the experiment, maximum TVOCs concentration has appeared as 3.65 ppm and 10.66 ppm for 20 ml and 40 ml volume of air freshener, whereas the permissible exposure value of indoor TVOCs concentration is 0.75 ppm considering an 8-hour time-weighted average. Furthermore, the exposure time period beyond the permissible indoor value is more than one hour and two hours for the above volume of sprays respectively. Similarly, test 02 results represented that the maximum $PM_{2.5}$ concentration as 3.4 times higher than the permissible indoor value defined by the WHO. This scenario could be explained with the help of Kim et al. research in 2015. As per the study, many of the air fresheners release VOCs including terpene, aldehydes and esters, etc. which can react with ozone to produce secondary pollutants namely formaldehyde, secondary organic aerosol, oxidative product and ultrafine particles (Kim, Hong, Bong, & Cho, 2015). Thus, TVOCs and $PM_{2.5}$ have been escalated due to the use of air fresheners. Altogether, it has been highlighted that the potentially harmful health aspects due to emissions from air fresheners as sensory irritation, respiratory symptoms and dysfunction of the lungs, although the air freshener manufacturers advertise the air freshener as air purifiers (Kim, Hong, Bong, & Cho, 2015); (Nazaroff & Weschler, 2004). Temperature and RH inside the test chamber did not show any significant variation due to the air freshener.

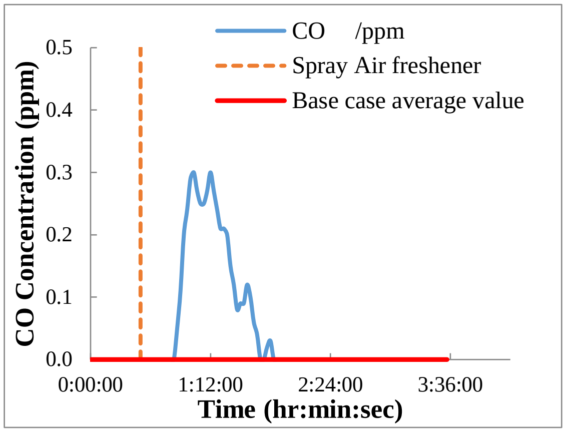


Figure 3.3: CO variation- Air freshener (20 ml)

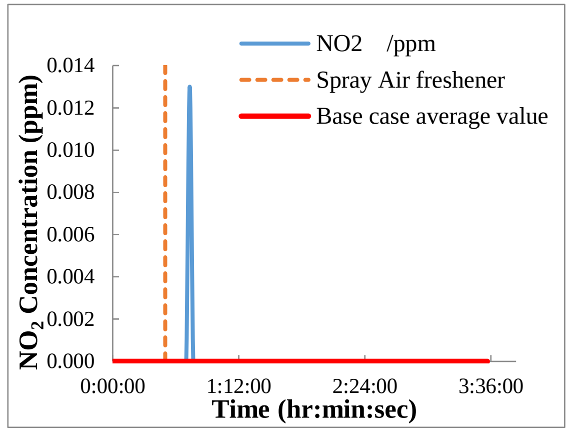


Figure 3.4: NO_2 variation- Air freshener (20ml)

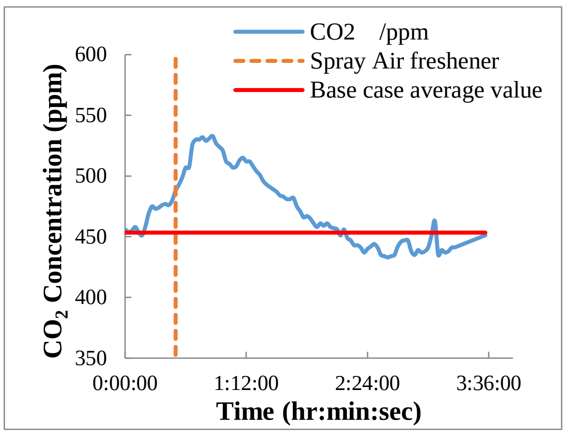


Figure 3.5: CO_2 variation- Air freshener (20 ml)

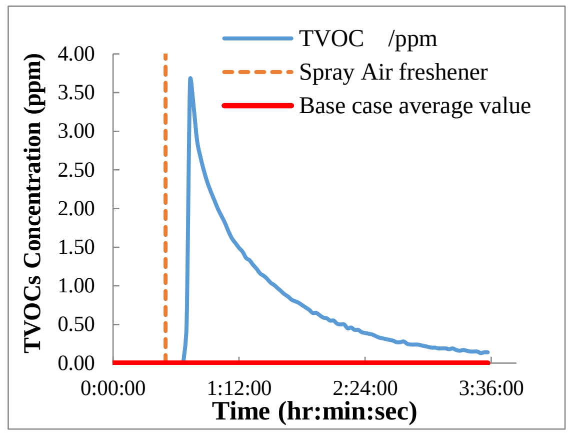


Figure 3.6: TVOCs variation- Air freshener (20 ml)

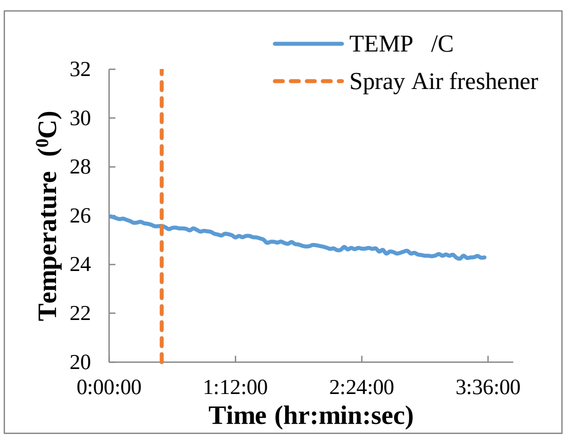


Figure 3.7: Temperature variation- Air freshener (20 ml)

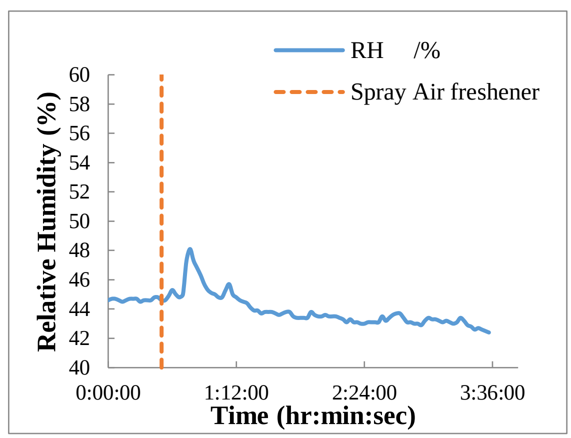
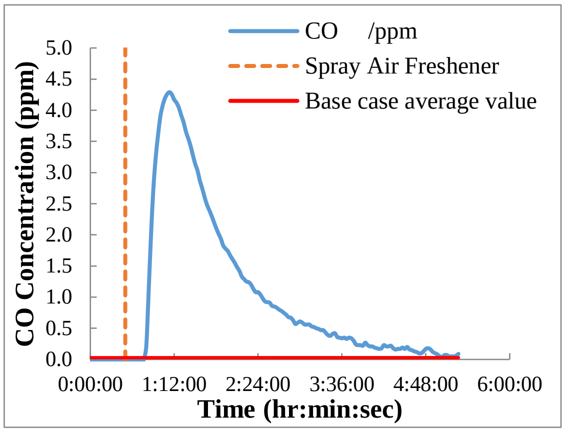


Figure 3.8: RH variation- Air freshener (20 ml)



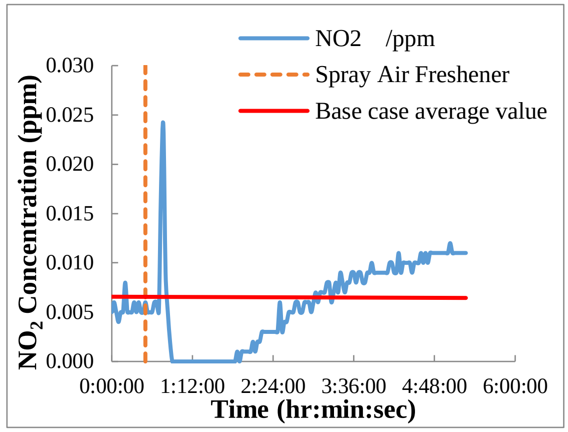
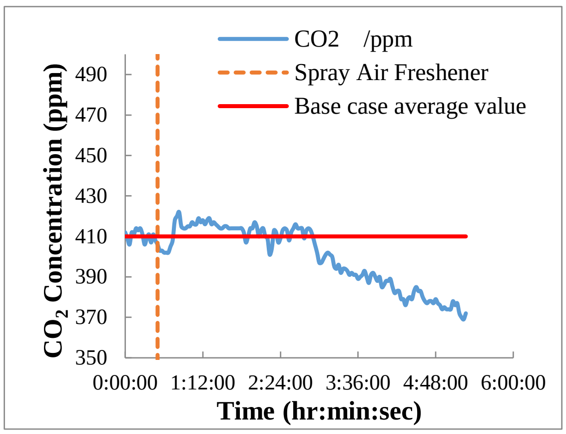


Figure 3.9: CO variation- Air freshener (40ml)

Figure 3.10: NO_2 variation- Air freshener (40ml)



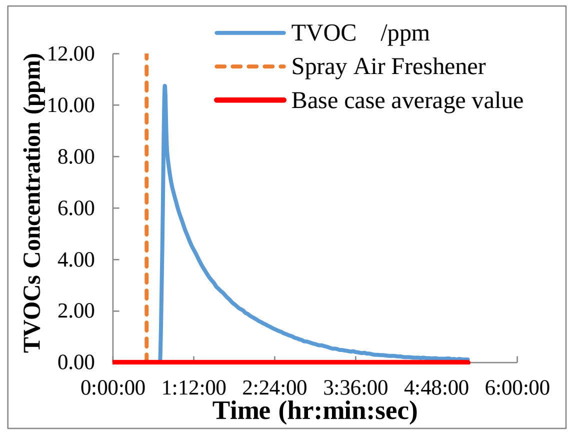


Figure 3.11: CO_2 variation- Air freshener (40ml)

Figure 3.12: TVOCs variation- Air freshener (40ml)

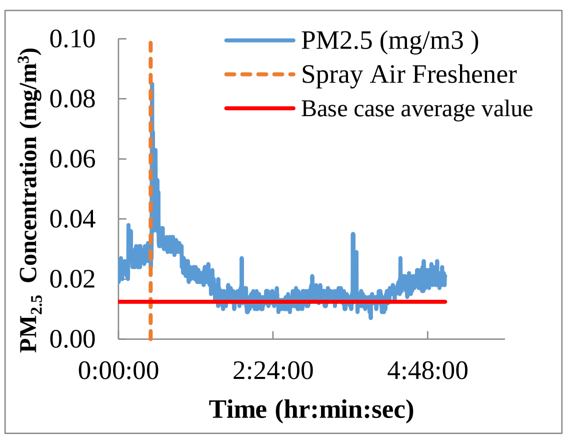


Figure 3.13: $PM_{2.5}$ variation- Air freshener (40 ml)

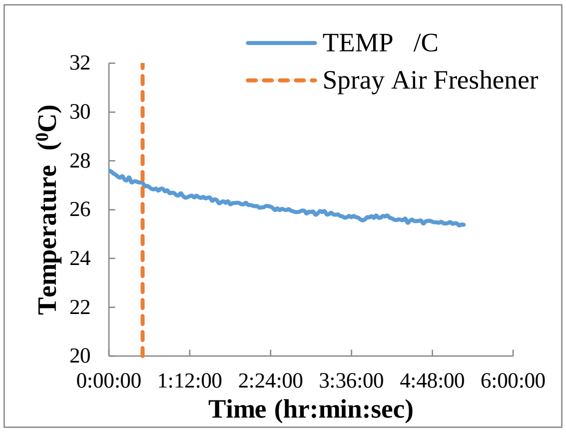


Figure 3.14: Temperature variation- Air freshener (40 ml)

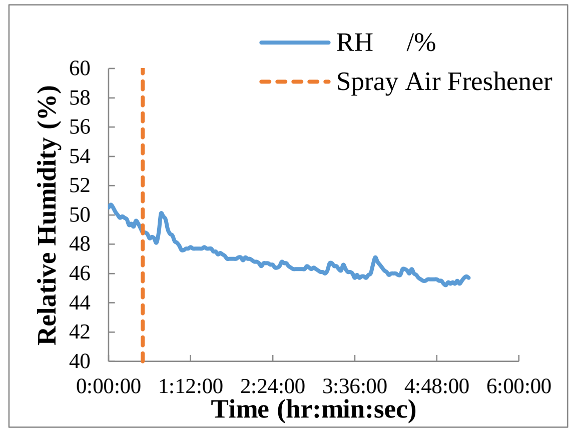


Figure 3.15: RH variation- Air freshener (40 ml)

The summary of the above experiments on air freshener is presented below in Table 3.1.

Table 3.1: Summary of the experimental results- Air Freshener

Name of the causative agent	**Test 01**			**Test 02**		
	(i)	**(ii)**	**(iii)**	**(i)**	**(ii)**	**(iii)**
CO (ppm)	0.3	-	0	4.29	-	0
NO_2 (ppm)	0.013	-	0	0.024	-	0.005
CO_2 (ppm)	533	-	467	422	-	410
TVOCs (ppm)	3.65	64 min	0	10.66	132 min	0
$PM_{2.5}$ (mg/m^3)	Refer "**Note 02**"			0.085	35 min	0.012
Temperature (^{0}C)			25.6- 26	Temperature (^{0}C)		27.1- 27.6
RH (%)			44.5- 44.8	RH (%)		48.8- 50.7

(i) Maximum concentration

(ii) Exposure time beyond the permissible indoor limit (**Note 01**)

(iii) Base case average value

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

Note 02: PM meter was not available for measurement

3.3.2 Wall paint

Wall paint is used to protect and decorate all types of buildings and structures and acts as a barrier against environmental conditions. Many researchers have identified paint as one of the building materials, that pollute the indoor air, adversely affecting the health of the painters as well as the occupants (Xiong, Wang, Bai, & Zhang, 2013); (Wieslander, Norbäck, & Edling, 1994). The major environmental impact of paint application is the emission of VOCs and heavy metals such as Mercury, Cadmium, Lead, Arsenic and Zinc (Malakootian, Nouri, & Hossaini, 2009); (Sorme & Lagerkvist, 2002); (Martin & Griswold, 2009); (United States Patent No. 5,637,355, 1997). As per Liang et al. study in 2014, VOCs such as propylene glycol, has shown a significant increase after wall paint application (Liang, Wang, Yang, & Yang, 2014).

However, VOCs are identified as a major group of air pollutants that associate with a significant number of health problems, even to the extent of cancer risk (Can, Özden Üzmez, Döğeroğlu, & Gaga, 2015). Likewise, the study carried out by Ericson et al. in 2019 portrays the risks of lead-based paint that has on the health of occupants and painters itself. It is further depicted that due to the lack of laws and regulations emplaced in low to medium income earning countries, there seems to still have a common availability of lead-based paint despite having banned in high-income countries (Ericson, et al., 2019). These illustrate the importance of studying wall paints and the effect it has on indoor air quality.

When studying the impact of wall paint, the intensity of the solvent-based paint and water-based paint is of a question before carrying out the experiments. As presented in most of the literature, due to the prevalence of high lead content in enamel-based paints which is one of the solvent-based paints, it enhances the negativity of the consequences when exposed to, in contrast with the water-based paints (Kumar & Gottesfeld, 2008), (Clark, et al., 2014), (O'Connor, et al., 2018). Therefore, the experiments conducted were aligned to analyse the impact of solvent-based paint.

The test chamber used for this experiment of the impact of wall paints on IAQ is presented in Figure 3.16. For this study, a nearly enclosed area which was under natural ventilation was selected inside the Department of Civil Engineering, University of Moratuwa. Two painters were employed in painting the area, which took approximately one hour and twenty minutes for the task to be completed. The results of the experiments were presented in Figure 3.17 to 3.23.

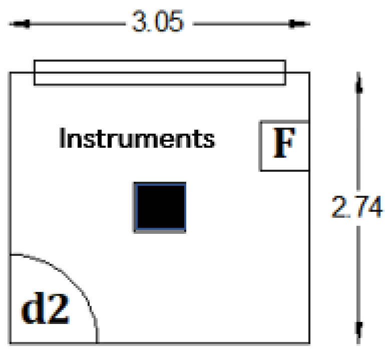


Figure 3.16: Plan view of the test chamber used for the experiment on wall paint (All the dimensions are in meters)

Results and Analysis – Wall paint

With reference to the graphs in Figure 3.17 to 3.23, the concentrations of CO, NO_2, CO_2, TVOCs and $PM_{2.5}$ have varied in different magnitudes due to the effect of wall paint. A huge impact was observed in the variation of TVOCs concentration as its maximum value was 45.58 ppm, which is 60 times higher than the indoor permissible value. Also, the exposure period for this adverse environment has been witnessed as more than 4 hours under the minimum ventilation condition. Paint ingredients that were used during the manufacturing process and some of the secondary pollutants generated due to the paint application could be mentioned as reasons for the high VOCs levels measured during the experimentation. Similarly, the variation of $PM_{2.5}$ concentration has also exhibited the same pattern, where its maximum concentration is far beyond the permissible indoor value over one and a half hours. Thus, the health impacts due to the inhalation of the following pollutant levels could result in severe damages to the pulmonary and cardiovascular system, etc. (Pronk, et al., 2009); (Kim, Hong, Bong, & Cho, 2015) . The concentration of NO_2 and CO were also increased due to the paint application. The CO level was slightly raised from the ambient condition, whereas the NO_2 has violated the indoor guideline over eight minutes of the period. However, the pollutants of VOCs, NO_2 and CO have led to creating sick buildings due to the formation of tropospheric Ozone which is described in detail in Subsection 4.3.1. Finally, the variation of CO_2 in Figure 3.19 has revealed that its concentration has also gone beyond the ambient condition during the paint drying process. Thus, many of the paint manufacturers are under consideration to reduce the emission of VOCs as well as CO_2 by reducing the drying time. The temperature inside the test chamber did not show any significant variation, which was varying between a few degrees. RH was also varying between 75-80% without showing abrupt changes.

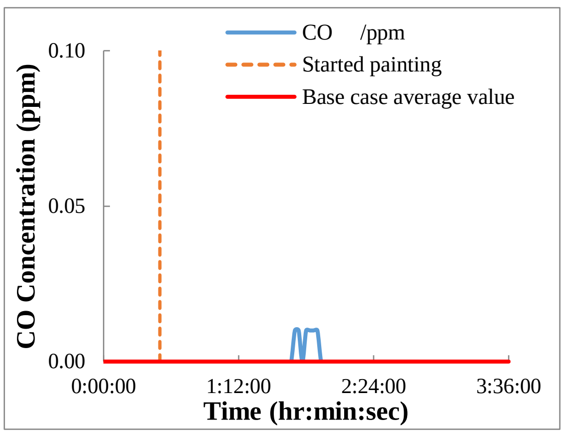


Figure 3.17: CO variation- Wall paint

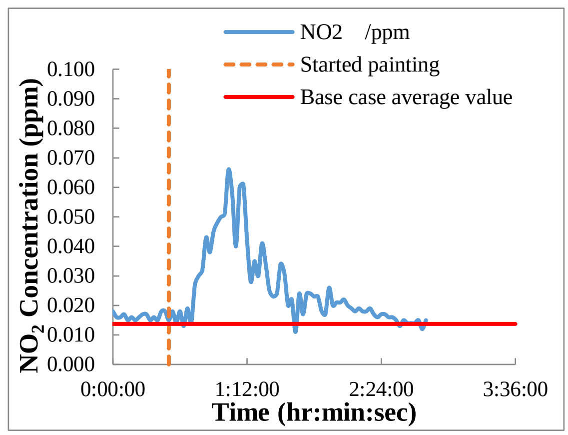


Figure 3.18: NO_2 variation- Wall paint

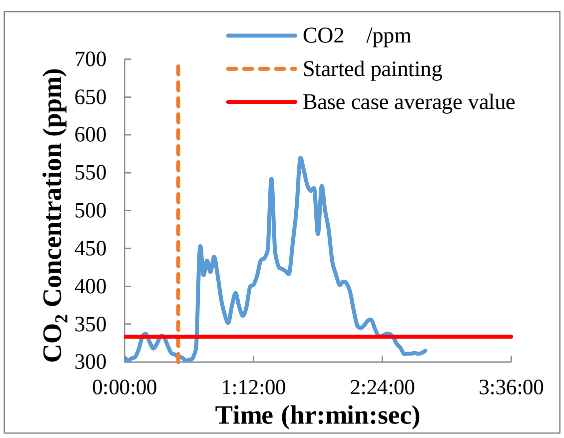


Figure 3.19: CO_2 variation- Wall paint

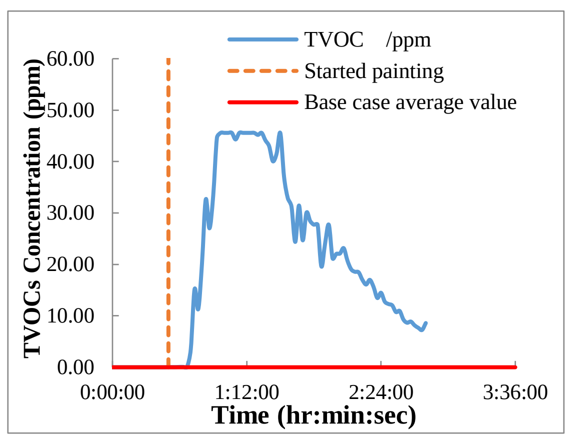


Figure 3.20: TVOCs variation- Wall paint

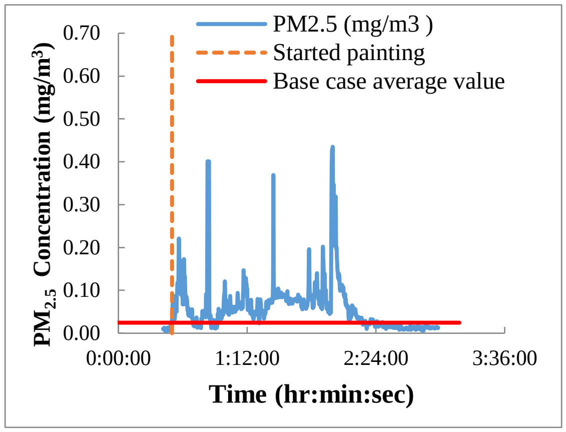


Figure 3.21: $PM_{2.5}$ variation- Wall paint

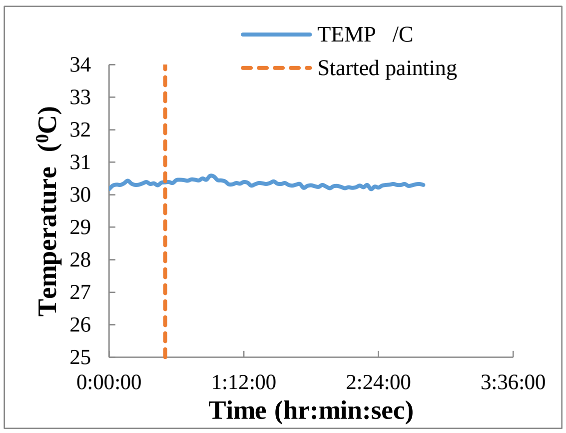


Figure 3.22: Temperature variation- Wall paint

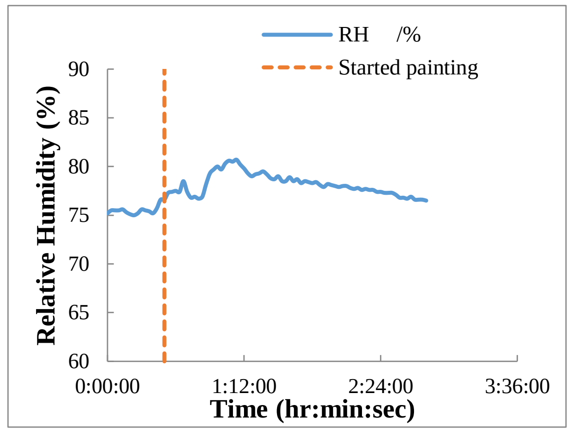


Figure 3.23: RH variation- Wall paint

The summary of the above experiments on wall paint is presented below in Table 3.2.

Table 3.2: Summary of the experimental results- Wall paint

Name of the causative agent	(i)	(ii)	(iii)
CO (ppm)	0.01	-	0
NO_2 (ppm)	0.066	8 min	0.014
CO_2 (ppm)	568	-	327
TVOCs (ppm)	45.58	244 min	0
$PM_{2.5}$ (mg/m^3)	0.435	87 min	0.009
Temperature (^{0}C)			29.9- 30.2
RH (%)			74.6- 75.4

(i) Maximum concentration

(ii) Exposure time beyond the permissible indoor limit (**Note 01**)

(iii) Base case average value

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

3.3.3 Indoor air quality in a hospital theatre

The attention on the IAQ inside hospitals and healthcare facilities has increased in the recent past due to the experience of discomforts which were complained by the staff members during the surgeries and afterward. Indoor air of a theatre contains various traces of chemicals used for purposes such as anesthesia, disinfecting and sterilizing, etc. (Mierdl, Byhahn, Abdel-Rahman, Matheis, & Westphal, 2003; Panni & B. Corn, 2002). As the building environment is an enclosed place, the stagnation of the pollutants could lead to high concentrations of pollutant levels resulting potential of health aspects among the occupiers. A research that was undertaken to measure the impact of prolonged exposure to anesthetic gases has highlighted that even the exposure to low dose anesthetic gases could influence some haematochemical hepatic and hematopoietic parameters in the health of the subjects (Casale et al., 2014). Likewise, it has been found that even though the exposure to modern waste anesthetic gases did not induce systemic DNA damage, it did result in genomic instability, cytotoxicity and proliferative changes, which were detected in the exfoliated buccal cells of anesthesiologists (Souza, et al., 2016). Therefore, these professionals can be considered at risk for developing genetic alterations resulting from occupational exposure to these gases, suggesting the need to minimize this exposure. Thus, IAQ in hospital theatres is paramount for medical practitioners as well as patients, thus mandating the use of efficient ventilation systems for proper air circulation and purification (Dascalaki, Lagoudi, Balaras, & Gaglia, 2008).

Because of the seriousness of the issue, hospital theatres are the most important and complex zones of a hospital, which require careful control of the aseptic and ventilation conditions (Khalil, 2012). Hence, factors such as ventilation system, door opening /closing rates, building age, possible sources of infiltration, the number of people present in the operating area will play a role in influencing pollutant concentrations in operating theatres (Nimra et al., 2015). To better understand the actual impact, the experiments were conducted at a leading hospital in Sri Lanka, during several days under differing conditions such as the type of surgery and the total number of surgeries.

Experiments were carried out in three different days inside the hospital theater, which is labelled as Day_1, Day_2 and Day_3. Details of the experiment related to a particular day are mentioned in Table 3.3, such as the number of surgeries and their time durations. The base case measurement was taken on the same day at outside, in the vicinity of a hospital building as the indoor environment of the hospital was influenced by the activities associated with the hospital theater. The test chamber used, for these experiments is presented in Figure 3.24. The following graphs in Figure 3.25 to 3.52 portray the impact of the used chemicals had on the indoor air quality inside the theatre.

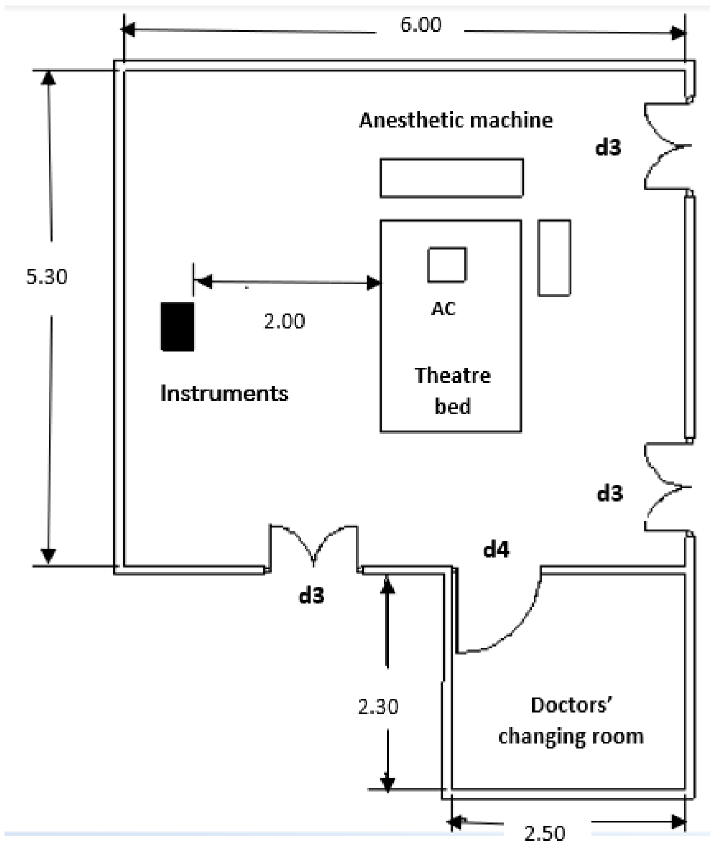


Figure 3.24: Plan view of the test chamber used for the experiment on IAQ inside the hospital theatre (All the dimensions are in meters)

Table 3.3: Details of the experiments in hospital theatre

Name of the Experiment	Number of surgeries	Time duration
Day_1	Surgery_1 Surgery_2	4 hours 3 hours 18 min
Day_2	Surgery_1 Surgery_2 Surgery_3 Surgery_4 Surgery_5	20 mins 2 hours 40 min 1 hour and 14 min 56 min 1 hour 16 min
Day_3	Surgery_1	7 hours 48 min

Results and Analysis – Hospital theatre

The concentration of CO was recorded between 0 ppm to 2 ppm depending on the activities which were carried out in the hospital theatre. As per the observation made during the experiments (Figure 3.25 to 3.27), it has been identified that the CO concentration was increased after each use of "*Surgical Diathermy*", which is also known as "*Electrosurgery*". Thus, *Surgical Diathermy* could be the main source to release CO to the indoor environment. The mechanism of the *Surgical Diathermy* is to induce heat or high-frequency electromagnetic currents to use as a cutting utensil and/or to burn the veins to seal them and stop bleeding. However, incomplete combustion could be taken place during this process. As a result, CO is emitted to the indoors and recorded a high concentration of CO beyond the ambient condition (Figure 3.28). Nevertheless, the maximum concentrations are within the permissible indoor value which is defined by the USEPA (9 pm). Other than the use of *Surgical Diathermy*, CO concentration was increased during the laparoscopic surgeries as the combustion that occur in low oxygen environments could result in the formation of CO and that is common in the laparoscopic environment (Society of Laparoendoscopic Surgeons, 2006).

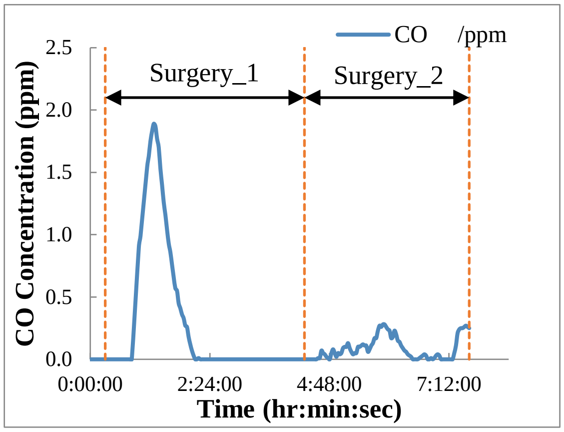


Figure 3.25: CO variation- Hospital theatre (Day_01)

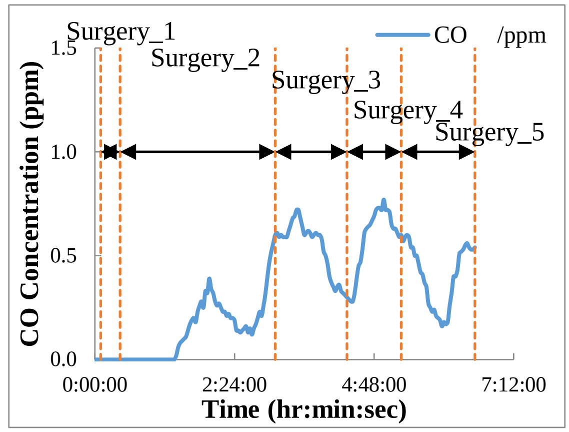


Figure 3.26: CO variation- Hospital theatre (Day_02)

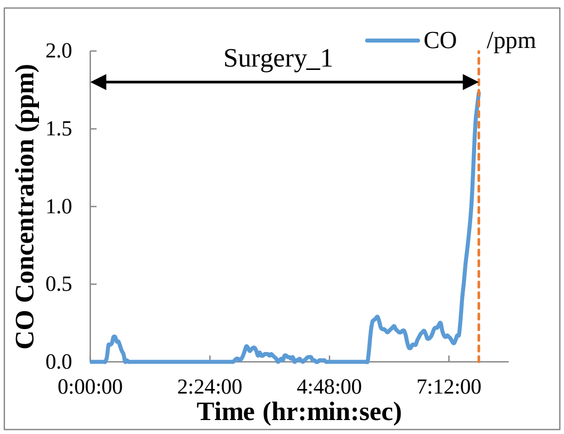


Figure 3.27: CO variation- Hospital theatre (Day_03)

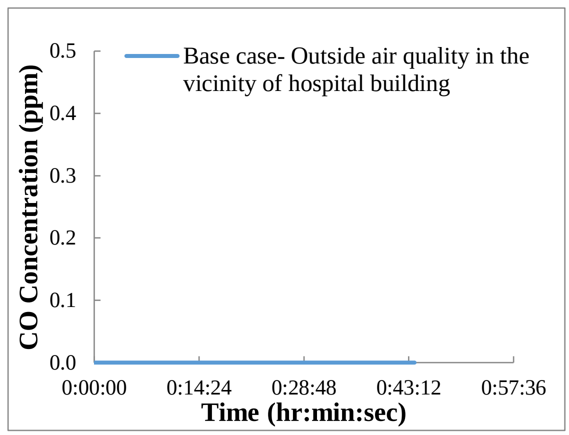


Figure 3.28: CO variation- Hospital theatre (Base case)

Regarding the Figure 3.29, 3.30 and 3.31, there was no significant variation in NO_2 concentrations inside the hospital theatre. Furthermore, it is observed that the average NO_2 concentration was very similar to the ambient condition (Refer to Figure 3.32). Thus, it can be concluded that there is no effect on NO_2 concentrations of the activities related to hospital theatre.

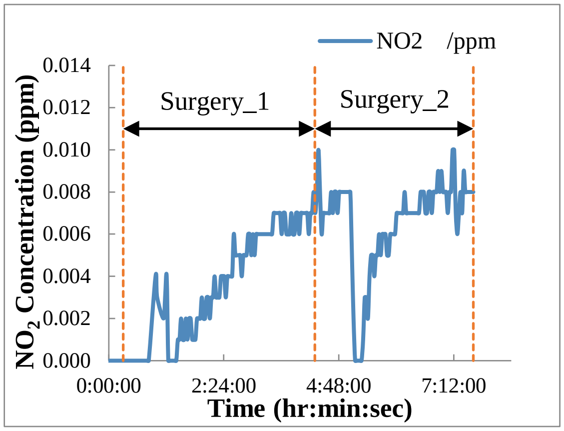


Figure 3.29: NO_2 variation- Hospital theatre (Day_01)

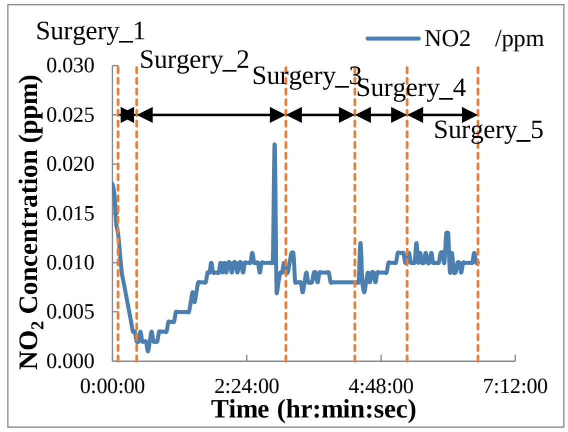


Figure 3.30: NO_2 variation- Hospital theatre (Day_02)

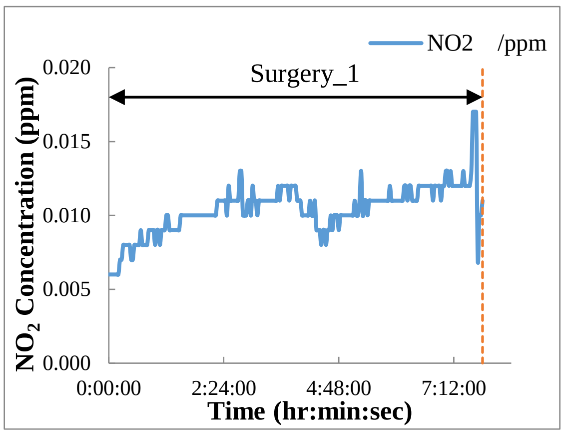


Figure 3.31: NO_2 variation- Hospital theatre (Day_03)

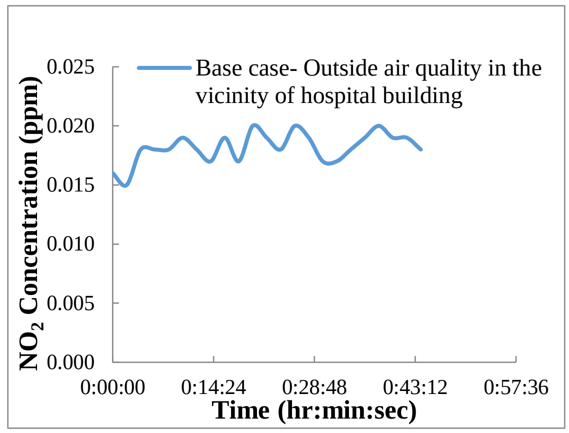


Figure 3.32: NO_2 variation- Hospital theatre (Base case)

According to the Figures, in 3.33 to 3.35, CO_2 concentrations were exceeded the average ambient condition which is 340 ppm as presented in Figure 3.36. Likewise, Figure 3.33 shows the concentration of CO_2, which was increased even beyond the permissible indoor value (1000 ppm) defined by ASHRAE. During the experiments, it has been identified that occupant density as the main source of the CO_2 emission to the indoors. Corresponding to recorded data, there was a high occupant density at the commencement of each surgery as well as the end of it. Hence, it has been noted high CO_2 concentration at the beginning and the end of the surgeries. Further to that, the results have interpreted that the type of surgery is also matters on the CO_2 accumulation. In detail, *Surgery_3* and *Surgery_5* which were carried out in *Day_2* are "Laparoscopic surgeries" where the CO_2

levels were recognised to escalate during the surgeries. This is because CO_2 was used for insufflation of the abdominal cavity. However, an effective ventilation system is required to rectify this problem as the occupant density and type of surgery are not controlled factors to minimize the CO_2 emission.

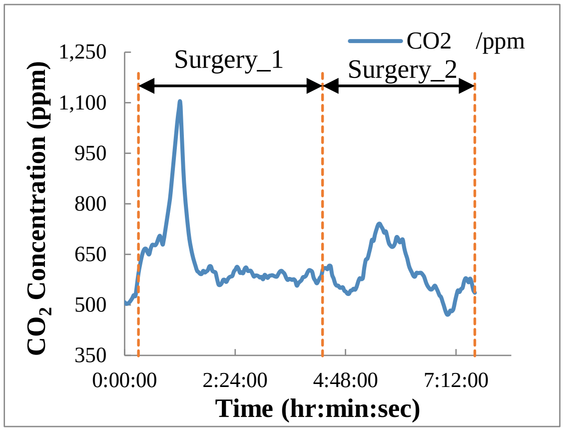


Figure 3.33: CO_2 variation- Hospital theatre (Day_01)

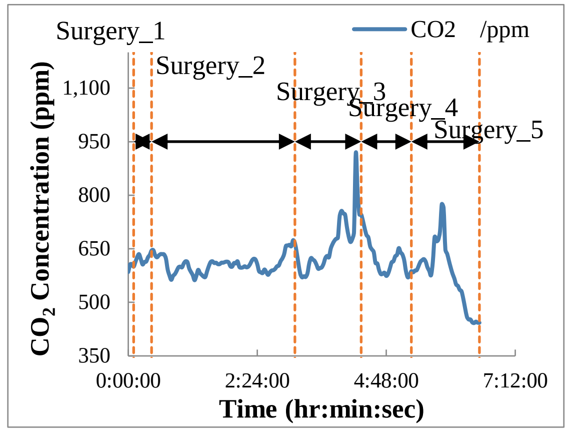


Figure 3.34: CO_2 variation- Hospital theatre (Day_02)

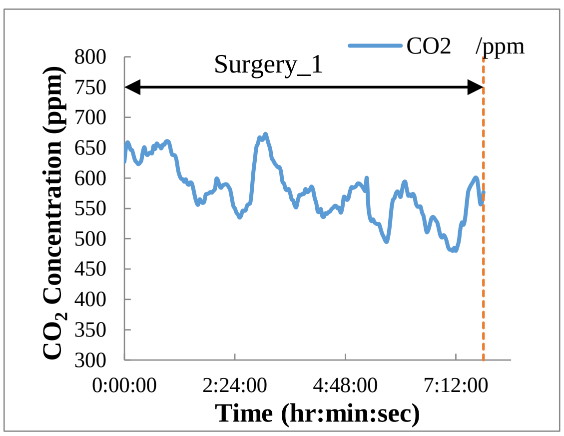


Figure 3.35: CO_2 variation- Hospital theatre (Day_03)

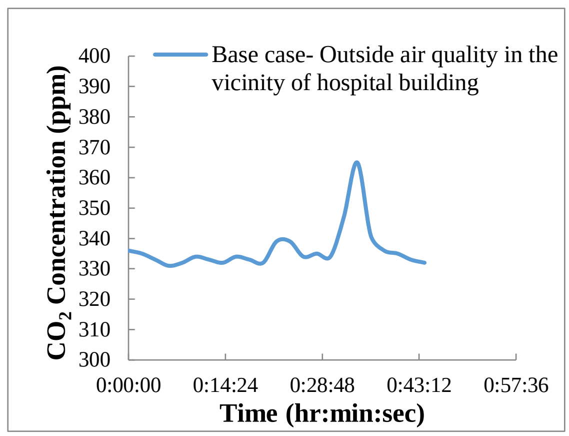


Figure 3.36: CO_2 variation- Hospital theatre (Base case)

Volatile organic compounds are under major consideration related to the IAQ in hospital theatre as many of the activities would contribute to increase their concentration. This is mainly due to the disinfectants such as "*Ether*" and "*Surgical spirit*" which is used before and after surgeries as well and some of the utensils used during the operations such as "Diathermy" and/or "Ultrasonic scalpel dissection", etc. The variation of TVOCs concentration inside the theatre has shown several high points, especially during the start and end of the surgeries due to the use of disinfectants. By considering Figure 3.37, 3.38 and 3.39, it has been observed that these maximum concentrations are 20 to 60 times higher than the indoor permissible value defined by OSHA (0.75 ppm). Exposure periods are also more than one hour and forty minutes from the permissible exposure limits during an entire day. However, the ambient condition was recorded as 0 ppm as in Figure 3.40. Thus, the pollutants generated inside the hospital theatre is purely due to the activities which are carried out in the indoor environment. The study by Edward et al. in 2011 has also revealed that the presence of several VOCs such as benzene, ethylbenzene, styrene, toluene, heptane, and methylpropene in surgical smoke. These pollutants are identified as potentially carcinogenic irritant chemical, deteriorating human health even due to the short term exposure period (Edward, Malik, & Ahmed, 2011); (Sisler, et al., 2018).

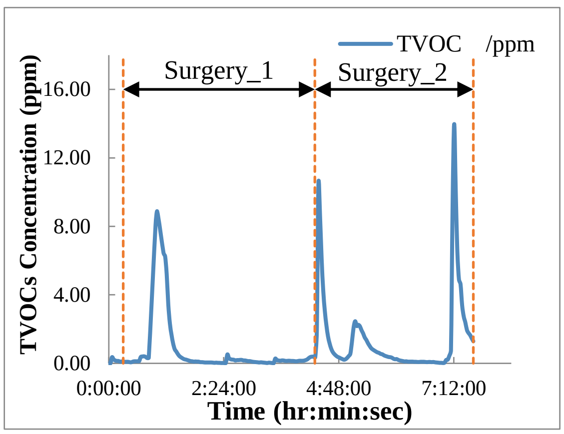


Figure 3.37: TVOCs variation- Hospital theatre (Day_01)

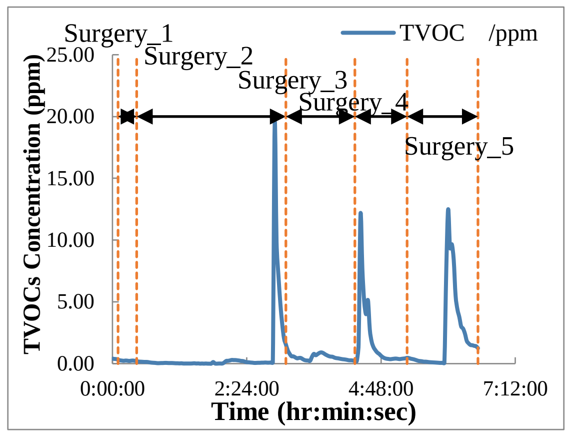


Figure 3.38: TVOCs variation- Hospital theatre (Day_02)

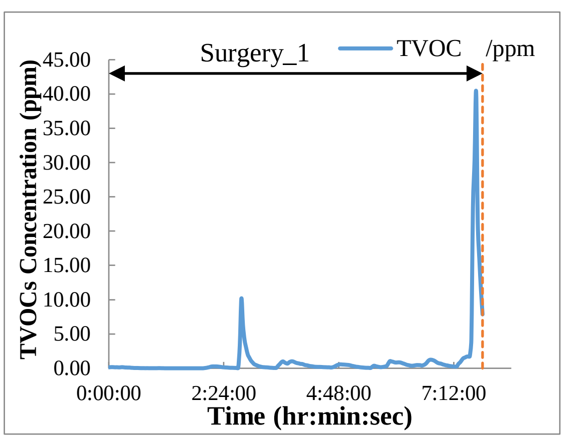


Figure 3.39: TVOCs variation- Hospital theatre (Day_03)

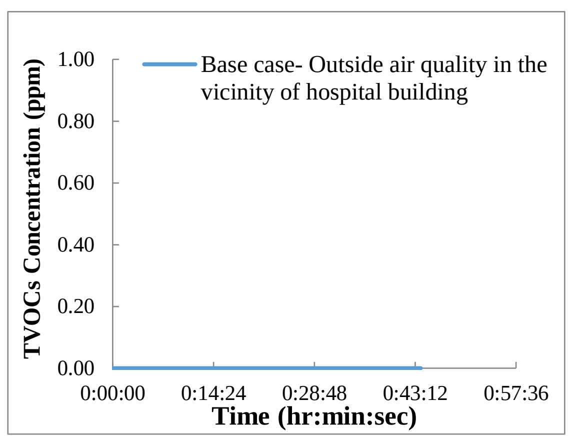


Figure 3.40: TVOCs variation- Hospital theatre (Base case)

The variation of $PM_{2.5}$ has shown the rapid fluctuations in the concentration with time due to the practices operated in the hospital theatre. Furthermore, it has been recorded that $PM_{2.5}$ concentration was close to the indoor permissible value even prior to the surgeries taken place. As presented in Figure 3.41, 3.42 and 3.43, the maximum concentration of $PM_{2.5}$ has increased to o.14 ~ 0.15 mg/m^{3}during the experiments, which is 6 times higher than to the pertain indoor guideline by WHO (0.025 mg/m^3). Thus, medical professionals and patients are exposed to this adverse environment over a considerable period. Several researchers have highlighted that the surgical smoke which is produced from *Surgical Diathermy* resulted in particulate matters causing the respiratory effects among the hospital theatre personnel (Brace, et al., 2014); (Karjalainen, et al., 2018); (Sisler, et al., 2018).

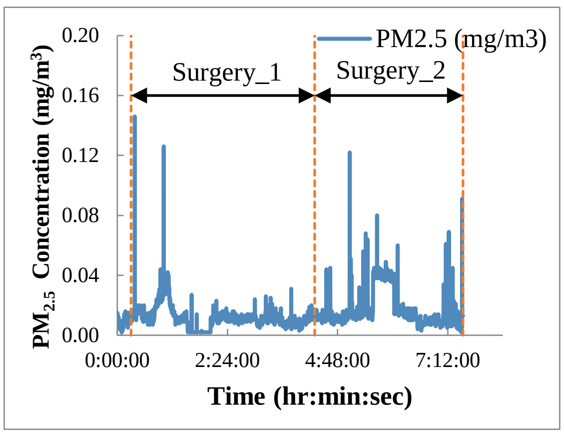


Figure 3.41: $PM_{2.5}$ variation- Hospital theatre (Day_01)

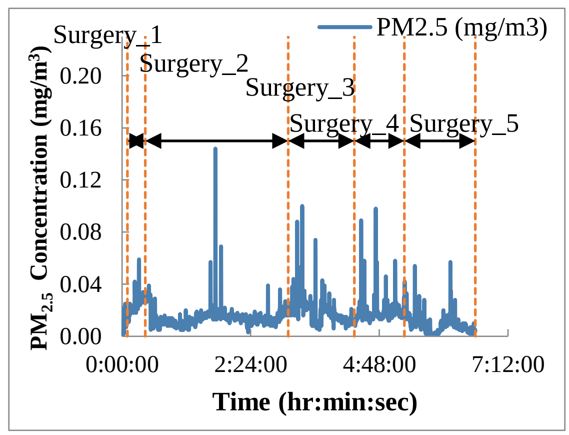


Figure 3.42: $PM_{2.5}$ variation- Hospital theatre (Day_02)

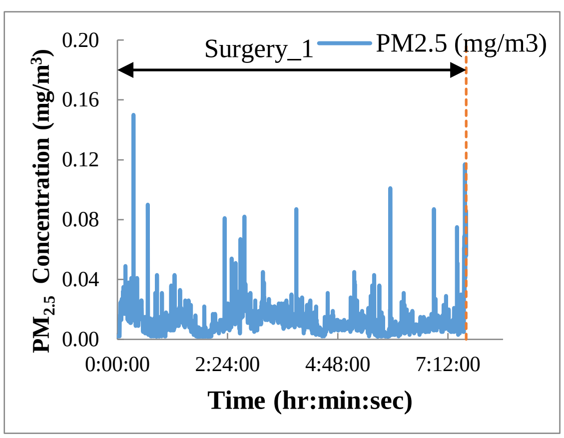


Figure 3.43: $PM_{2.5}$ variation- Hospital theatre (Day_03)

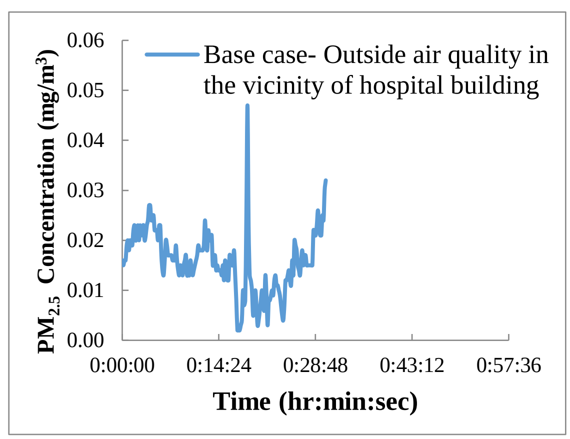


Figure 3.44: $PM_{2.5}$ variation- Hospital theatre (Base case)

A significant variation of temperature and RH did not record due to the activities related to hospital theatre. The temperature was controlled and maintained in the range of 22.5 ^{0}C to 24.5 ^{0}C with the use of the central air conditioning system and RH was also slightly varying between 65-70% without showing abrupt changes. The following graphs, Figure 3.45 to 3.52 portray the timely variation of the above two parameters during the experiments.

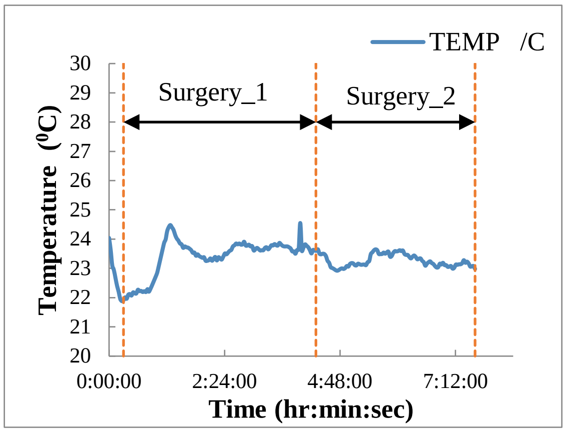


Figure 3.45: Temperature variation- Hospital theatre (Day_01)

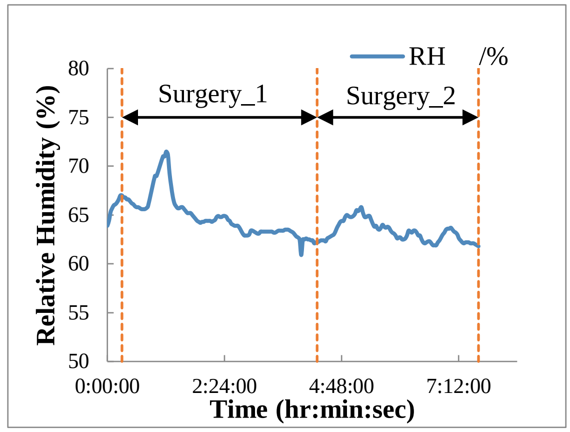


Figure 3.46: RH variation- Hospital theatre (Day_01)

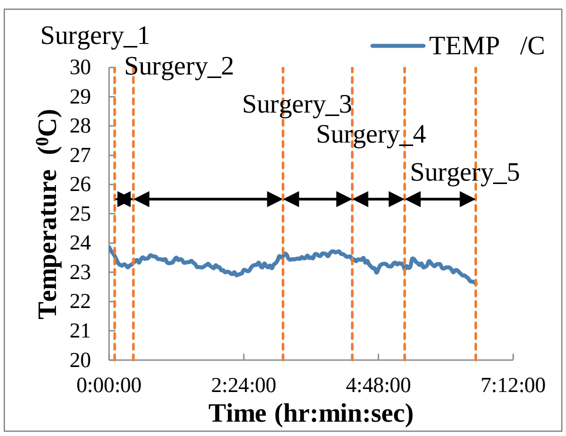


Figure 3.47: Temperature variation- Hospital theatre (Day_02)

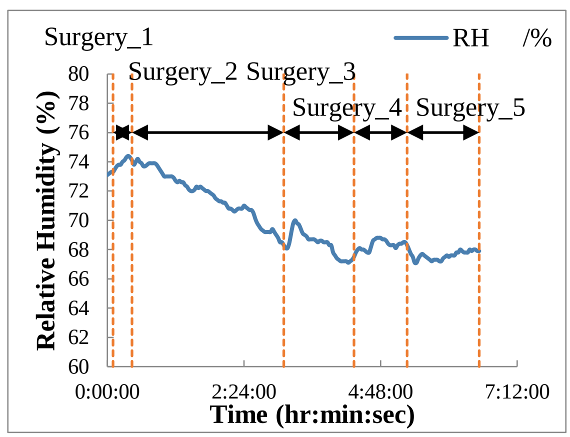


Figure 3.48: RH variation- Hospital theatre (Day_02)

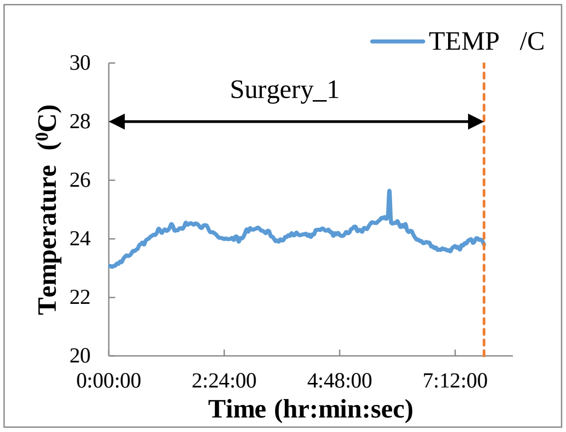


Figure 3.49: Temperature variation- Hospital theatre (Day_03)

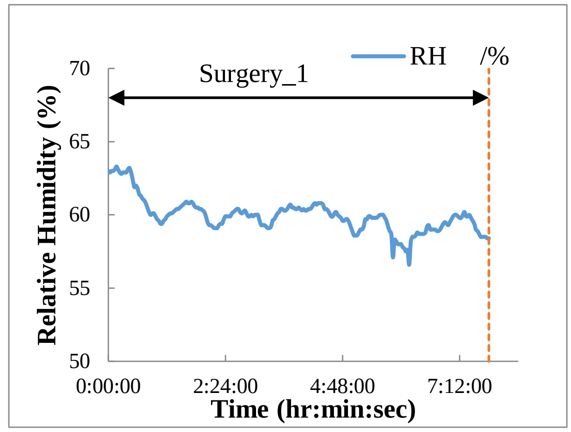


Figure 3.50: RH variation- Hospital theatre (Day_03)

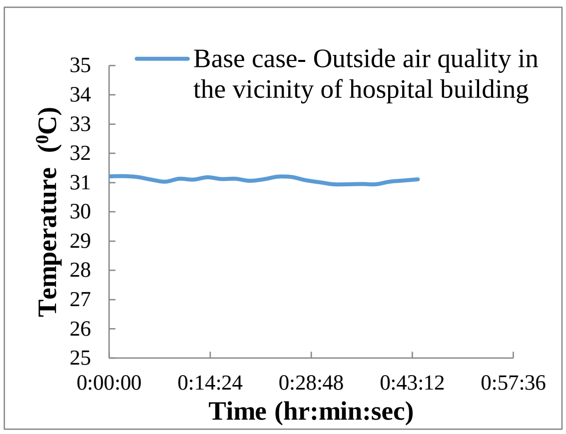


Figure 3.51: Temperature variation- Hospital theatre (Base case)

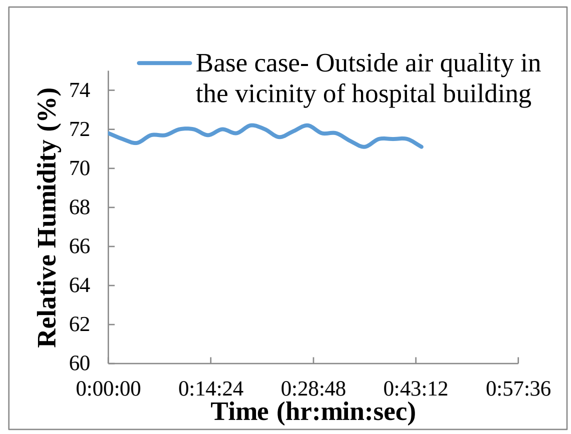


Figure 3.52: RH variation- Hospital theatre (Base case)

The summary of the above experiments on IAQ inside the hospital theatre is presented below in Table 3.4.

Table 3.4: Summary of the experimental results- Hospital Theatre

Name of the causative agent	Day_01		Day_02		Day_03		(iii)
	(i)	(ii)	(i)	(ii)	(i)	(ii)	
CO (ppm)	1.89	-	0.77	-	1.73	-	0
NO_2 (ppm)	0.01	-	0.022	-	0.017	-	0.018
CO_2 (ppm)	1102	6 min	918	-	673	-	336
TVOCs (ppm)	13.97	102 min	19.37	83 min	40.31	104 min	0
$PM_{2.5}$ (mg/m^3)	0.146	44 min	0.144	42 min	0.15	23 min	0.016
Temperature (^{0}C)							30.9- 31.2
RH (%)							71.1- 72.2

(i) Maximum concentration

(ii) Exposure time beyond the permissible indoor limit (**Note 01**)

(iii) Base case average value

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

3.3.4 Indoor air quality in a motor vehicle service centre

Motor vehicle service centres generate large amounts of hazardous pollutants and they have the potential of causing pollution in the vicinity due to the handling of various chemicals and waste generated during the operational stage. Crude oil, petroleum refined products, solvents like acetone, toluene, benzene and xylene, trihalomethanes, phenols, inorganic fertilizers, sulphides, ammonia and perchlorate can be classified as the most commonly used chemical pollutants in motor vehicle service centres (Centers, 2017). As identified in the literature, a large part of hydrocarbon emissions originate from motor vehicles (Jensen & Grant, 1964). Moreover, as identified by Hicklin et al. in 2018, the VOC emissions from service stations have been found to affect the ambient air including the surrounding buildings as well (Hicklin, Farrugia, & Sinagra, 2018). However, it is important to note that, there are not many types of research undertaken to quantify the impact of emissions from vehicle service centres in the recent past.

This experiment was carried out to identify the IAQ parameters inside the motor vehicle service center during the operation period. Measurements were taken at three different locations on the ground floor level of a reputed motor vehicle service centre in the Colombo district, Sri Lanka, which are namely service area, workshop, and office. The service area is an open zone with nearly 30 m width and 75 m length under natural ventilation condition. Figure 3.53 and 3.54 show the plan view of the other two locations which were allocated for the workshop and to the office respectively. The ventilation condition of these two locations was with an air-conditioned environment using the split type of air conditioner. This office was only allocated for the documentation related to the service center, where there were four occupants inside the room during the experimentation.

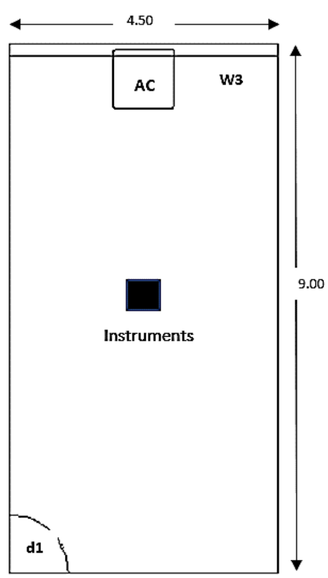


Figure 3.53: Plan view of the test chamber used for the experiment on IAQ in the vehicle service centre (Workshop- All the dimensions are in meters)

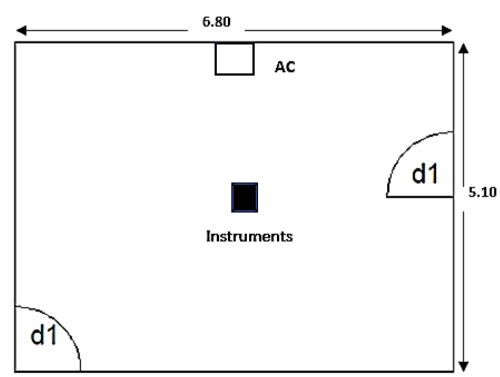


Figure 3.54: Plan view of the test chamber used for the experiment on IAQ in the vehicle service centre (Office- All the dimensions are in meters)

The results obtained from these experiments are shown in Figure 3.55 to 3.75.

Results and Analysis – Motor vehicle service centre

The results obtained from the IAQ measurements inside the vehicle service area have revealed that the concentrations of CO, CO_2, TVOCs and $PM_{2.5}$ were increased during the experimental period depending on the indoor activities. Although the CO and CO_2 variations were within the indoor permissible guidelines; TVOCs and $PM_{2.5}$ concentrations have exceeded, resulting in maximum concentrations of 1.5ppm and 0.055 mg/m^3 respectively. However, as illustrated in Figure 3.55 and 3.59, a rapid dispersion was observed in the pollutants' concentration due to the natural ventilation condition at this location. A significant level of variation was not observed for NO_2, temperature and RH during the time of measurement.

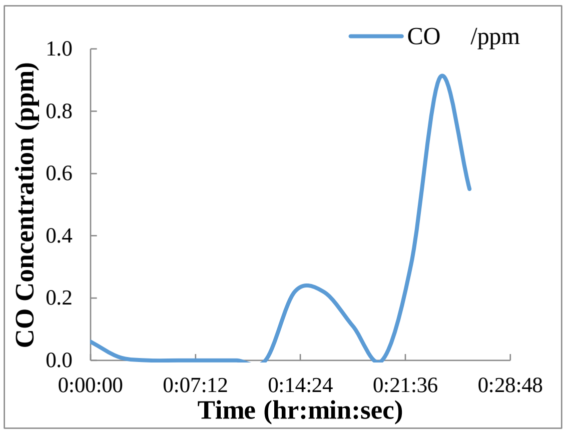


Figure 3.55: CO variation-

Vehicle service centre (Service area)

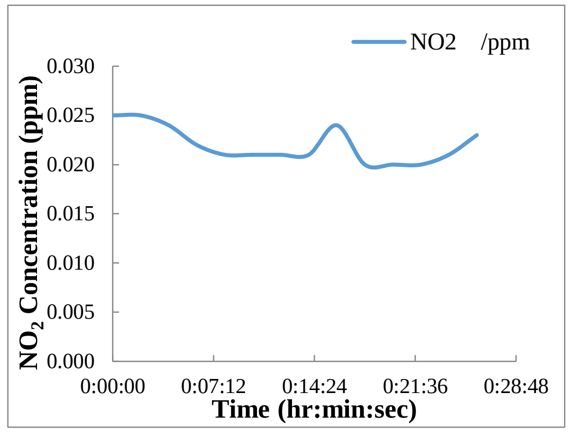


Figure 3.56: NO_2 variation-

Vehicle service centre (Service area)

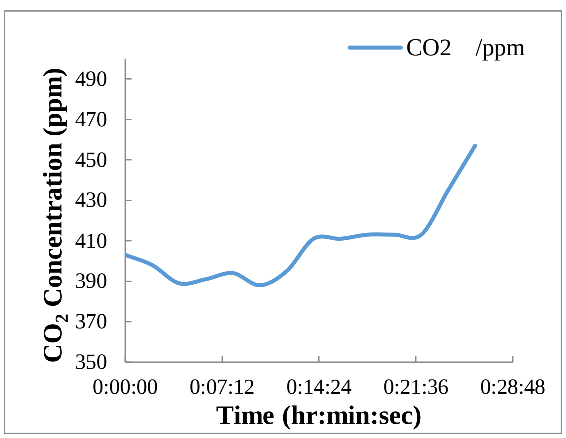


Figure 3.57: CO_2 variation-

Vehicle service centre (Service area)

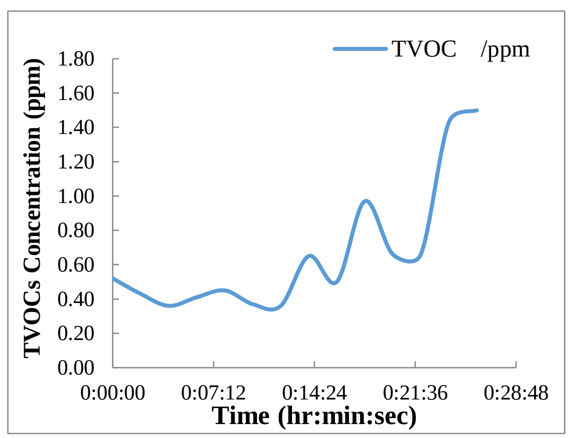


Figure 3.58: TVOCs variation-

Vehicle service centre (Service area)

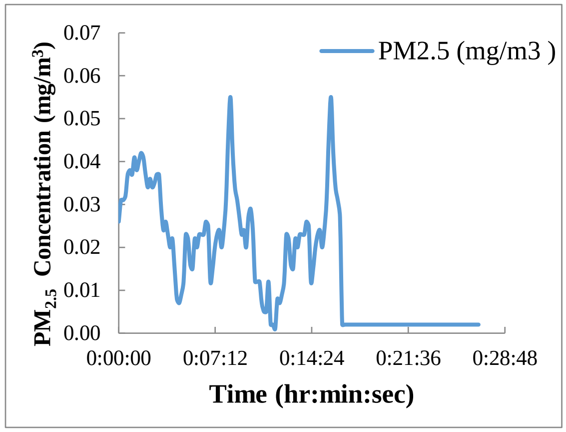


Figure 3.59: $PM_{2.5}$ variation- Vehicle service centre (Service area)

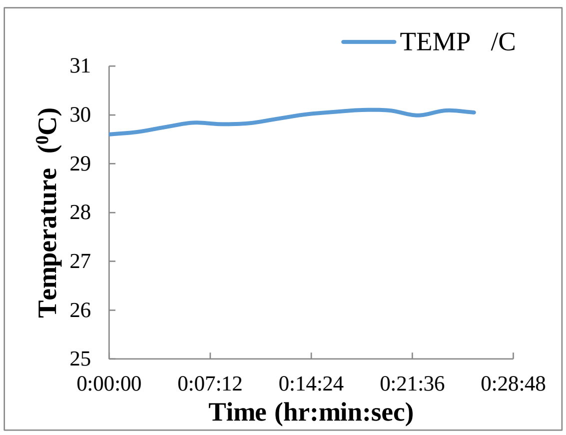


Figure 3.60: Temperature variation- Vehicle service centre (Service area)

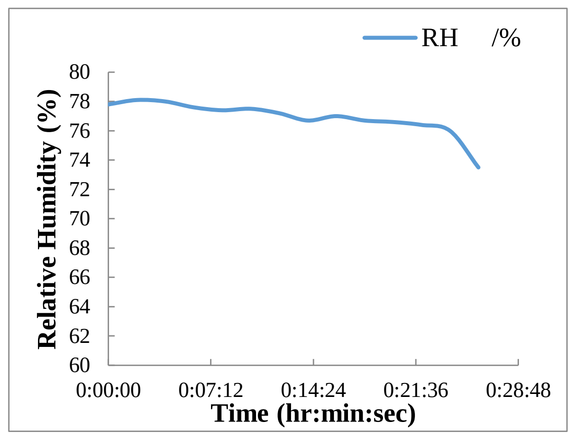


Figure 3.61: RH variation- Vehicle service centre (Service area)

Similar patterns of variation were observed for CO, CO_2, TVOCs and $PM_{2.5}$ concentrations at the workshop of vehicle service centre. The concentrations of TVOCs and $PM_{2.5}$ were overreached the permissible exposure limit, where the other two pollutants were within the guidelines pertain for indoor spaces. A substantial impact was identified from the TVOCs accumulated inside the workshop. As in Figure 3.65, average TVOCs concentration was 7 ppm, which is ten times the permissible exposure limit of 0.75 ppm defined by OSHA. Furthermore, it has been noticed that the dispersion rate of TVOCs is very low under the air-conditioned environment. Thus, it is paramount to take necessary precautions to maintain a good quality of air while monitoring the IAQ parameters. The concentration of NO_2 was also influenced by the indoor practices and slightly increased up to 0.04 ppm as revealed in Figure 3.63. The variation of temperature and RH did not influence by indoor activities during the experimental programme.

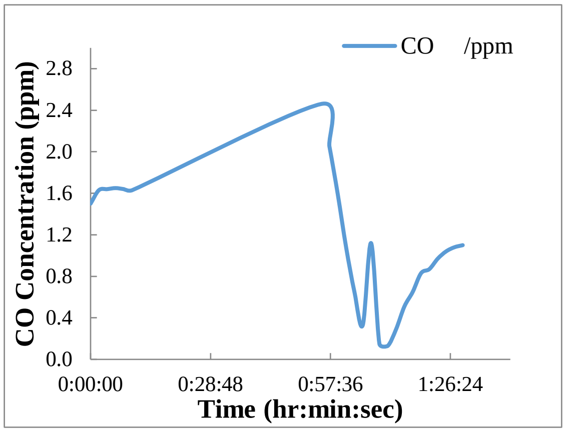


Figure 3.62: CO variation-

Vehicle service centre (Workshop)

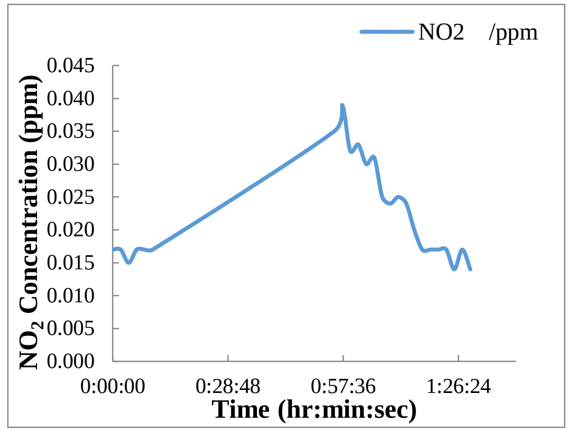


Figure 3.63: NO_2 variation-

Vehicle service centre (Workshop)

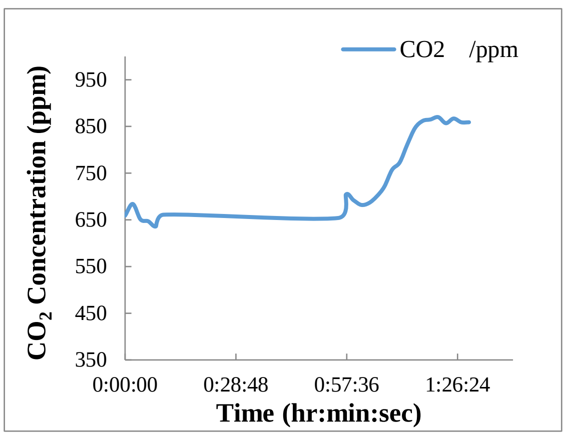


Figure 3.64: CO_2 variation-

Vehicle service centre (Workshop)

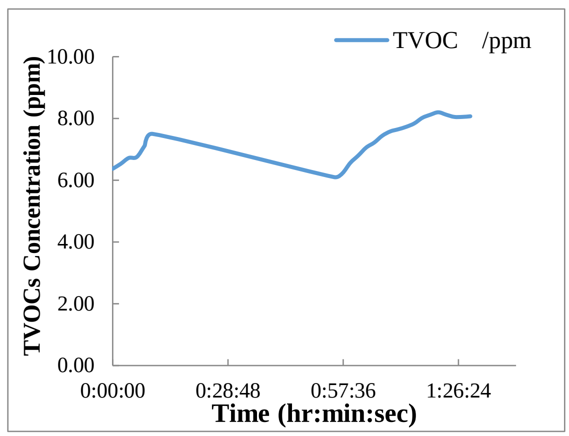


Figure 3.65: TVOCs variation-

Vehicle service centre (Workshop)

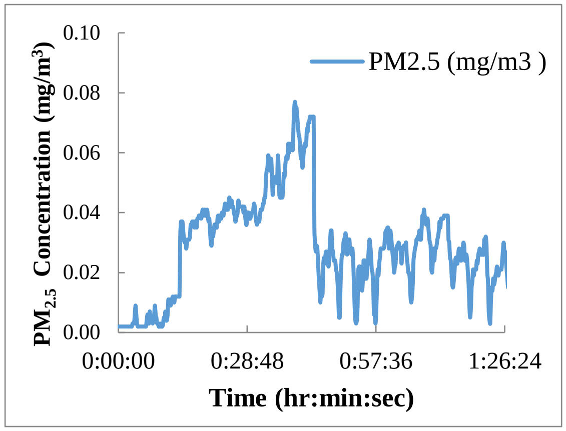


Figure 3.66: $PM_{2.5}$ variation- Vehicle service centre (Workshop)

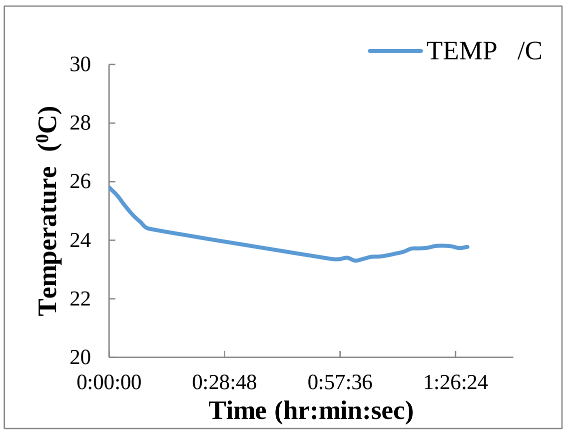


Figure 3.67: Temperature variation- Vehicle service centre (Workshop)

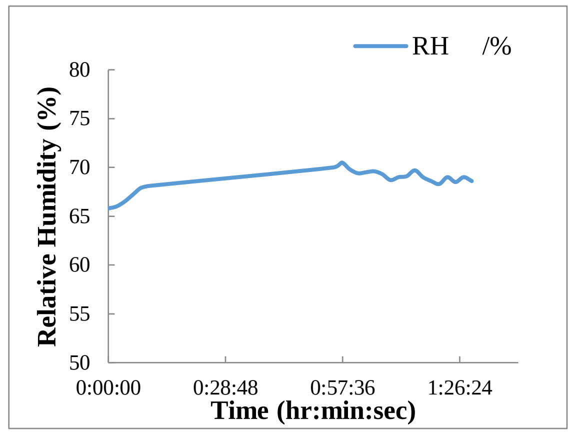


Figure 3.68: RH variation- Vehicle service centre (Workshop)

Concerning Figure 3.69, 3.71 and 3.72, it has been observed that the concentration of CO, CO_2 and TVOCs were recorded far beyond the average ambient condition [Refer I], though the CO was only within the permissible exposure limit defined by ASHRAE. It is particularly important to highlight that the above pollutants' variation was exhibited a very low dispersion rate. Thus, the exposure period to this adverse environment is quite high, which could result in several health problems among the inhabitants. Furthermore, there were no sources related to CO and TVOCs inside the office room. Hence, this could be due to the infiltration of pollutants from outdoor through the openings such as doors and ducts of air conditioner, etc.

***Refer I: The average ambient condition, which is defined by considering more than 50 measurements carried out in Colombo district, Sri Lanka** (CO- 0 ppm, NO_2 – 0.022 ppm, CO_2- 340 ppm and TVOCs- 0 ppm)*

Further to that, a high concentration of CO_2 is mainly due to the population density inside the room, while the polluted outdoor air could also contribute to an acceleration of the indoor concentration. $PM_{2.5}$ concentration was also fluctuating between 0 to 0.03 mg/m^3 and reached to the indoor permissible value in several times. However, there is no noticeable variation in NO_2, temperature and RH inside the office during the experiment.

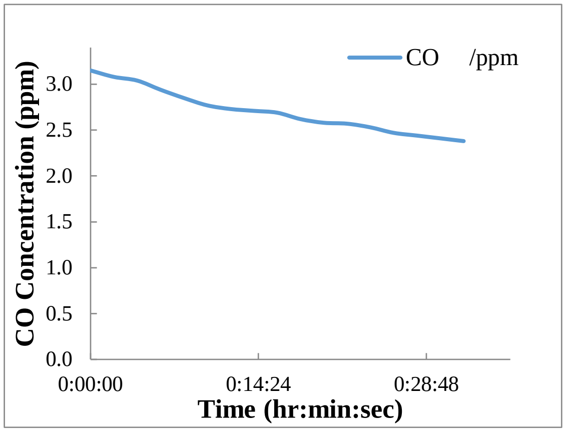


**Figure 3.69: CO variation-
Vehicle service centre (Office)**

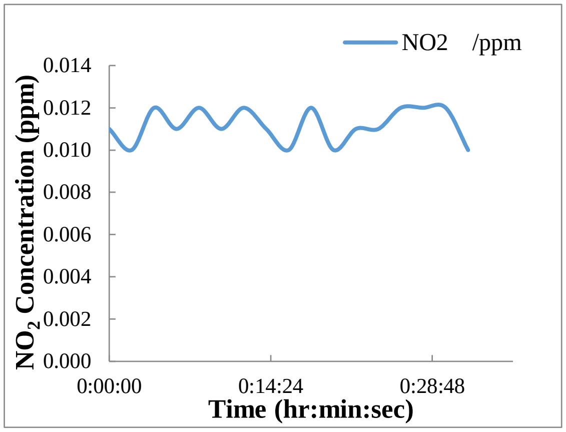


**Figure 3.70: NO_2 variation-
Vehicle service centre (Office)**

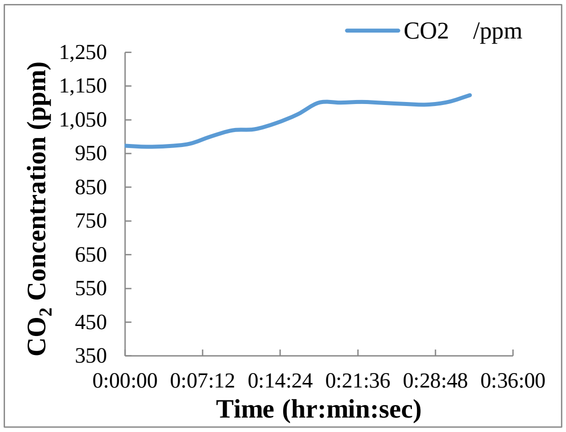


**Figure 3.71: CO_2 variation-
Vehicle service centre (Office)**

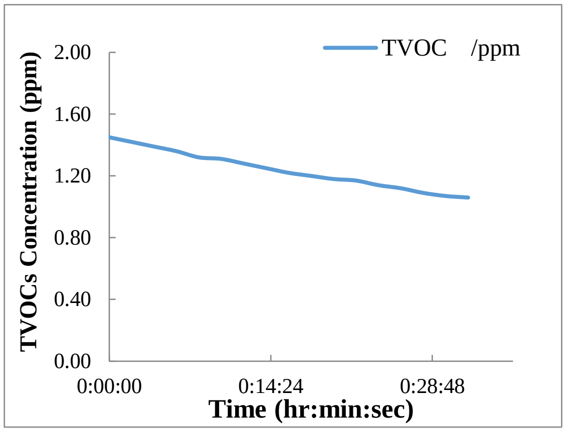


**Figure 3.72: TVOCs variation-
Vehicle service centre (Office)**

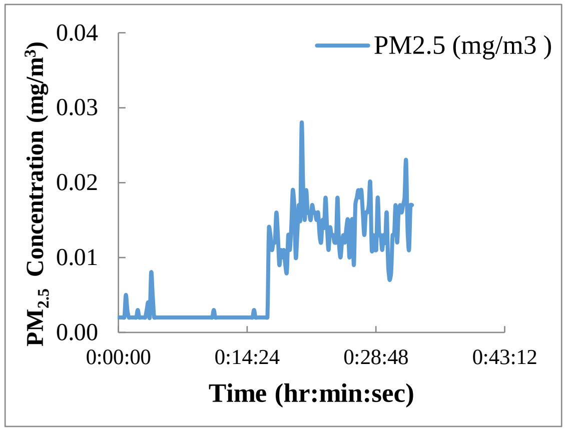


Figure 3.73: $PM_{2.5}$ variation- Vehicle service centre (Office)

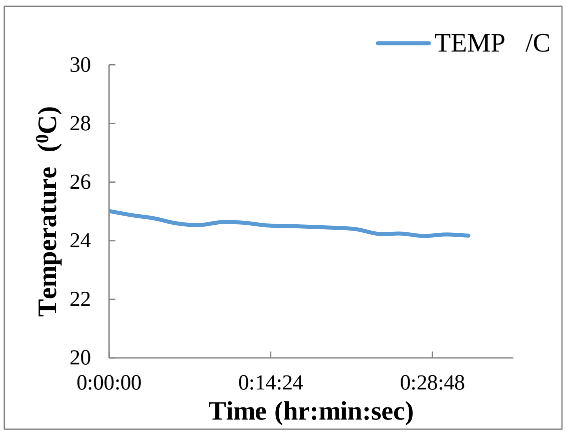


Figure 3.74: Temperature variation- Vehicle service centre (Office)

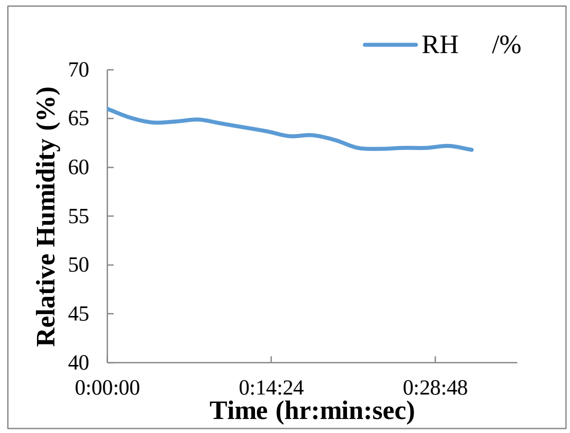


Figure 3.75: RH variation- Vehicle service centre (Office)

According to the IAQ analysis in three different locations of the motor vehicle service centre, it can be concluded that the measured IAQ parameters were influenced due to the activities in service area as well as in the workshop. As a result, the other parts of the building and the surrounding area were also polluted and thus, their IAQ parameters were also recorded above the average ambient condition.

The summary of the above experiments on IAQ inside the motor vehicle service center is presented below in Table 3.5.

Table 3.5: Summary of the experimental results- Motor vehicle service centre

Name of the causative agent	Service area		Workshop		Office		(iii)
	(i)	(ii)	(i)	(ii)	(i)	(ii)	
CO (ppm)	0.91	-	2.46	-	3.15	-	Refer "**Note 03**"
NO_2 (ppm)	0.025	-	0.039	-	0.012	-	
CO_2 (ppm)	457	-	870	-	1123	Refer "(iv)"	
TVOCs (ppm)	1.5	Refer "(iv)"	8.2	Refer "(iv)"	1.45	Refer "(iv)"	
$PM_{2.5}$ (mg/m^3)	0.055	Refer "(iv)"	0.077	Refer "(iv)"	0.028	Refer "(iv)"	
Temperature (^0C)							
RH (%)							

(i) Maximum concentration

(ii) Exposure time beyond the permissible indoor limit (**Note 01**)

(iii) Base case average value

(iv) (i) and (ii) values are based on the activities which are carried out in the vehicle service centre. Therefore, it is not precise enough to mention value for the exposure time instead of identifying the worst-case scenarios from the study of IAQ parameters vs activities of service centres. Further to that, measurements were taken over a period of 1 hour at each location due to the practical issue and it is not adequate to present an average value for the exposure time to particular causative agent beyond its permissible indoor value.

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

Note 03: IAQ was measured outside the vehicle service centre as for the base case scenario. However, the values are beyond the average ambient condition and the pollutants' concentrations were varied with time as per the activities which were carried out in the service area. Therefore, the base case scenario was not present here since the air quality in the vicinity of the particular area was affected by its activities.

3.3.5 Synthetic building materials

Synthetic building materials are present in most of the building products ranging from household products to furnishings. These building materials potentially bestow in chemical reactions that therefore results in unwanted side reactions emitting VOCs that are harmful for inhalation (Uhde & Salthammer, 2007). It has been found that in a newly renovated house, especially within initial months, the VOC concentrations are generally high. Therefore, ventilation has to be controlled in such a way that it manages the decay rates of unwanted air pollutants (Dai, et al., 2017), (Holøs, et al., 2018).

When we think about the usual building materials we live with, partition boards, wood-based panels, furniture and even machines like photocopiers and printers contributes significantly to the release of VOCs and formaldehyde (Elango, Kasi, Vembhu , & Poornima, 2013); (Luisser & Rosen, 2009). Furthermore, even the use of carpets, contribute to a significant amount of VOCs emissions in a household due to carpet cushions and adhesives used during installation (USEPA, 1992). Therefore, it is important to study the impact of synthetic building materials that all of us come across in a day-to-day basis.

The test chamber used for this experiment was an air-conditioned space located in one of the administrative buildings at the University of Moratuwa. Tests were carried out in three administrative buildings for better representation and verification of the data obtained. The layouts of the test chambers are presented in Figure 3.76, 3.77 and 3.78. IAQ was measured at three different locations with the only presence of synthetic building materials such as partition boards, fabric chairs, new MDF furniture, blinds, carpeted floor, photocopiers, printers and computers, etc. IAQ monitor was utilized to obtain the air quality parameters that are shown in the graphs from Figure 3.79 to 3.102.

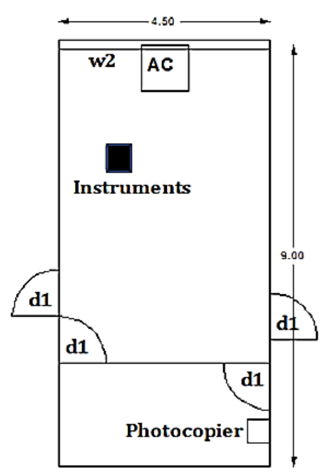


Figure 3.76: Plan view of the test chamber used for the experiment on synthetic building materials (Location_01- All the dimensions are in meters)

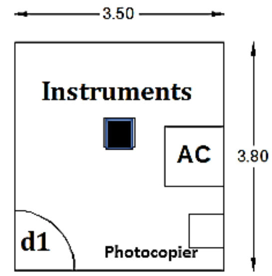


Figure 3.77: Plan view of the test chamber used for the experiment on synthetic building materials (Location_02- All the dimensions are in meters)

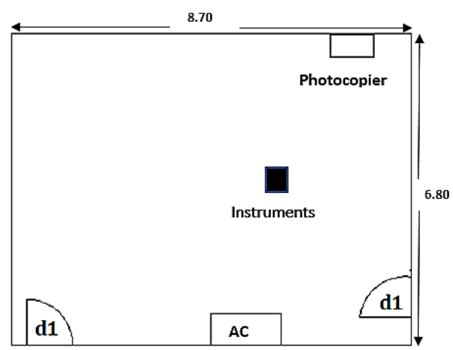


Figure 3.78: Plan view of the test chamber used for the experiment on synthetic building materials (Location_03- All the dimensions are in meters)

Results and Analysis – Synthetic building materials

Results obtained from the three different locations revealed that the diurnal variation of CO, CO_2 and TVOCs were above the ambient conditions, which are presented in Figure 3.82, 3.90 and 3.94. Descriptively, the concentration of CO was varied from 0 ppm to 0.5 ppm and TVOCs was in between 0 ppm to 0.04 ppm at each location. However, the indoor CO_2 concentration drastically exceeded the indoor permissible value (1000 ppm) defined by ASHRAE, during the entire working hours. Thus, the occupants may experience discomfort when they spend their time indoors and that could lead to reducing of the efficiency and productivity of workers as well. Moreover, several health problems may also cause occupants such as respiratory effects due to the prolonged exposure period to this adverse environment. It has been identified that the population density with poor ventilation systems to be the main source of CO_2. The recorded data on the population density of Location_01, Location_02 and Location_03 are disclosed as 8 m^2/person, 7 m^2/person and 10 m^2/person respectively. According to Location_03 results, it can be concluded that although the building is complying with the building regulations, there are some situations that could influence the indoor environment due to the presence of indoor sources and operational practices. Thus, it is very important to maintain an appropriate ventilation system of natural ventilation, a well-maintained air conditioning system or both ways in order to diminish the accumulated polluted air in the buildings. The variation of indoor NO_2, temperature and RH did not show any differences corresponding to the base case scenario.

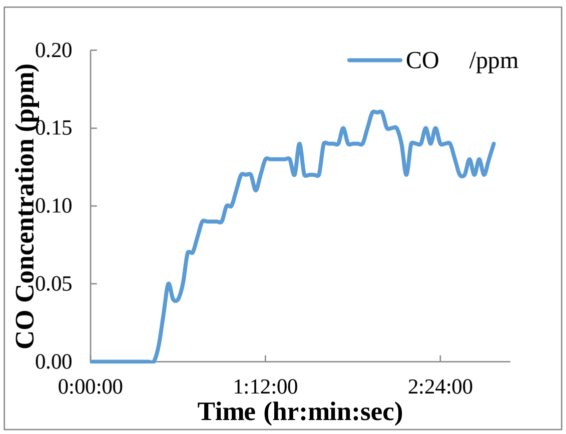


Figure 3.79: CO variation- Synthetic building materials (Location_01)

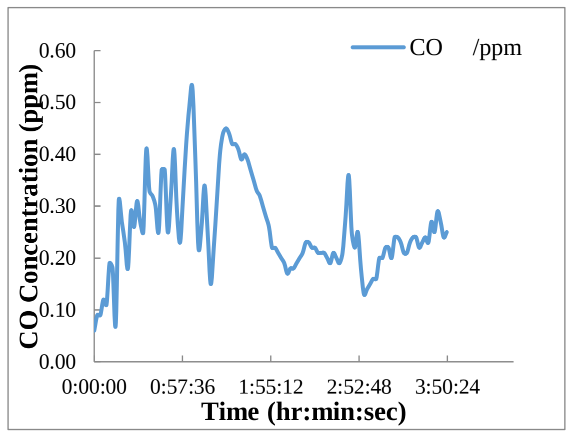


Figure 3.80: CO variation- Synthetic building materials (Location_02)

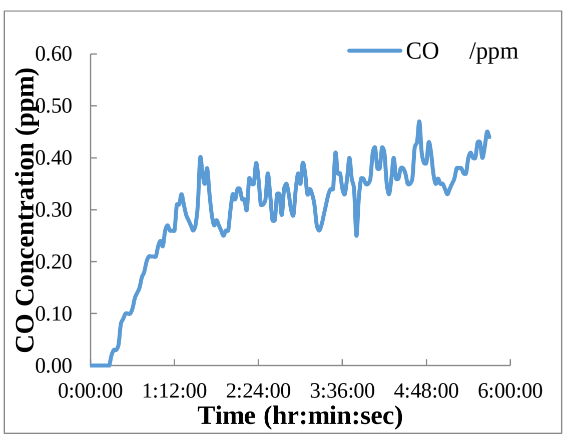


Figure 3.81: CO variation- Synthetic building materials (Location_03)

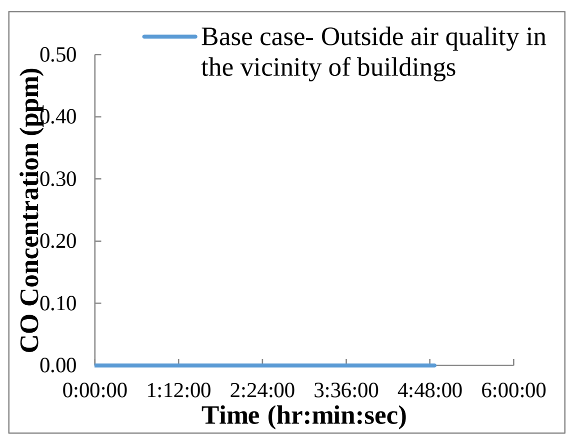


Figure 3.82: CO variation- Synthetic building materials (Base case)

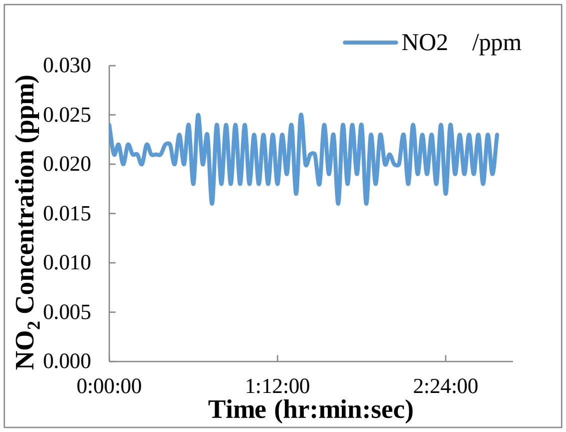


Figure 3.83: NO_2 variation- Synthetic building materials (Location_01)

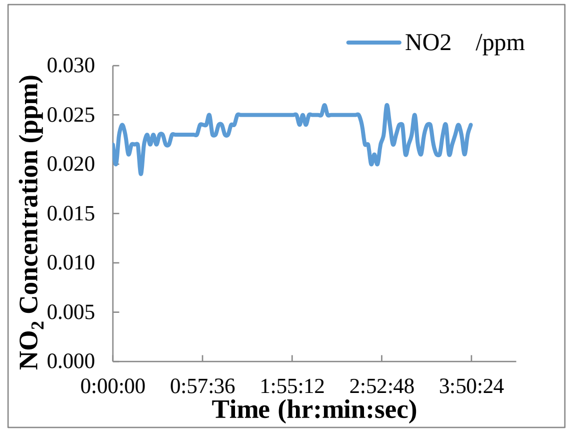


Figure 3.84: NO_2 variation- Synthetic building materials (Location_02)

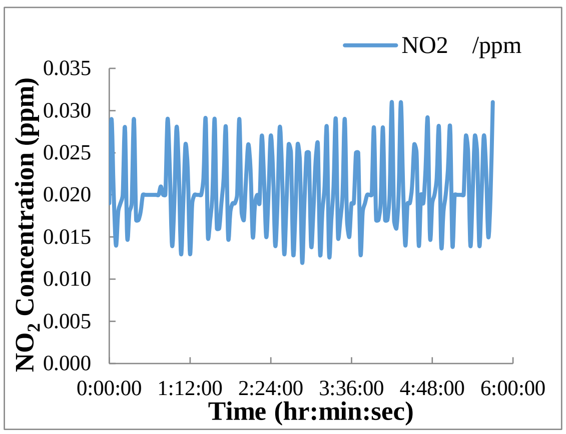


Figure 3.85: NO_2 variation- Synthetic building materials (Location_03)

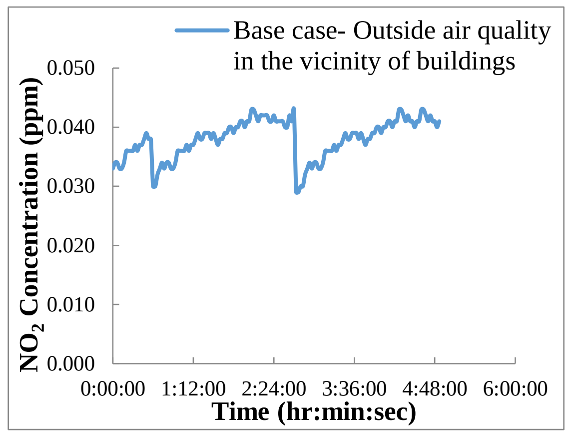


Figure 3.86: NO_2 variation- Synthetic building materials (Base case)

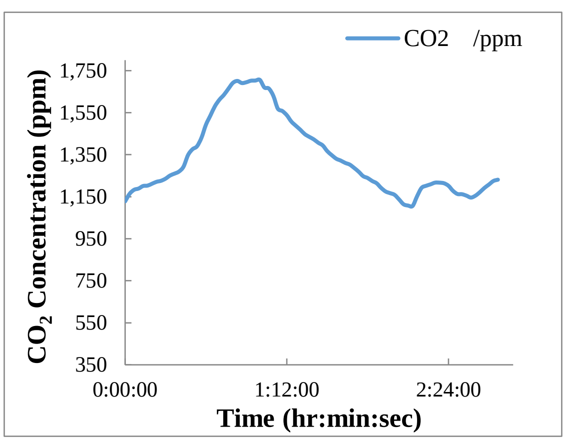


Figure 3.87: CO_2 variation- Synthetic building materials (Location_01)

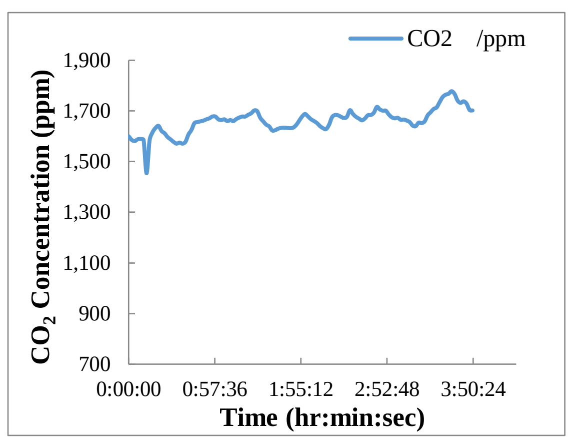


Figure 3.88: CO_2 variation- Synthetic building materials (Location_02)

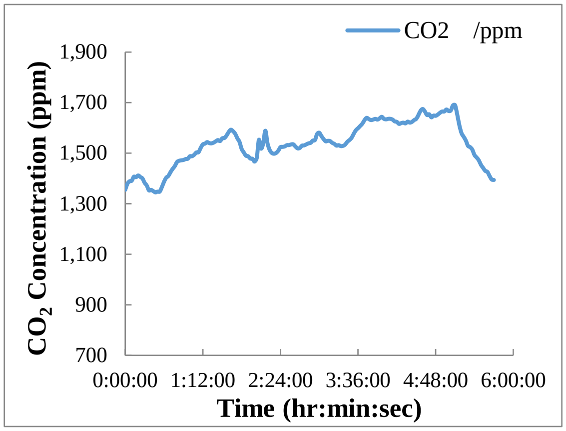


Figure 3.89: CO_2 variation- Synthetic building materials (Location_03)

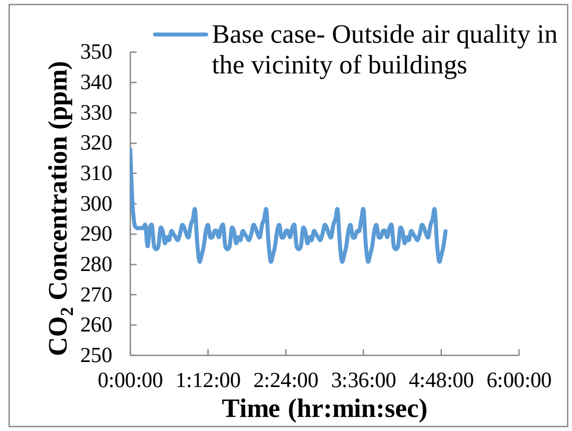


Figure 3.90: CO_2 variation- Synthetic building materials (Base case)

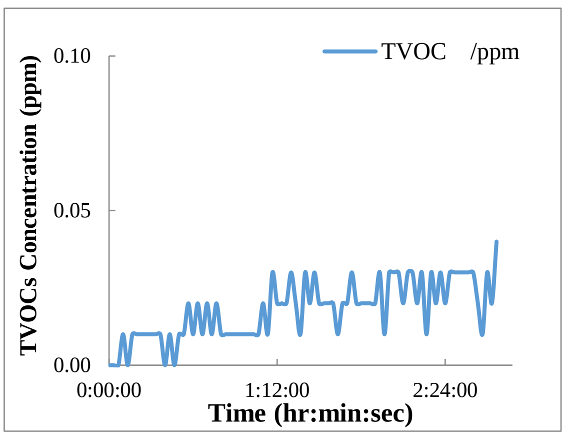


Figure 3.91: TVOCs variation- Synthetic building materials (Location_01)

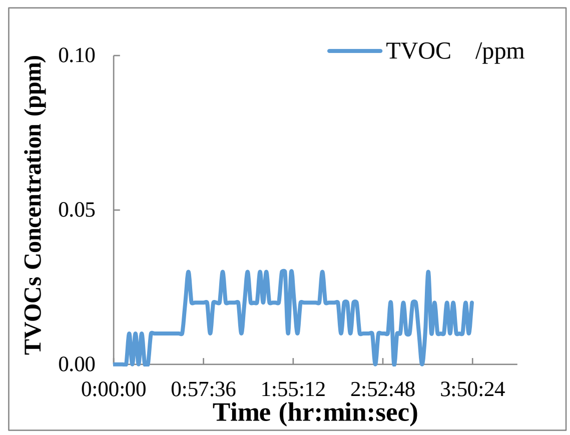


Figure 3.92: TVOCs variation- Synthetic building materials (Location_02)

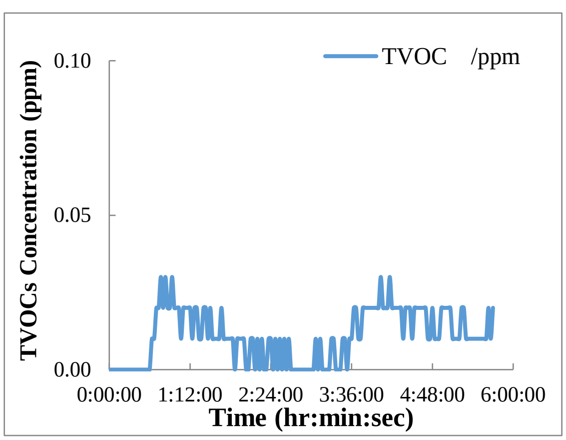


Figure 3.93: TVOCs variation- Synthetic building materials (Location_03)

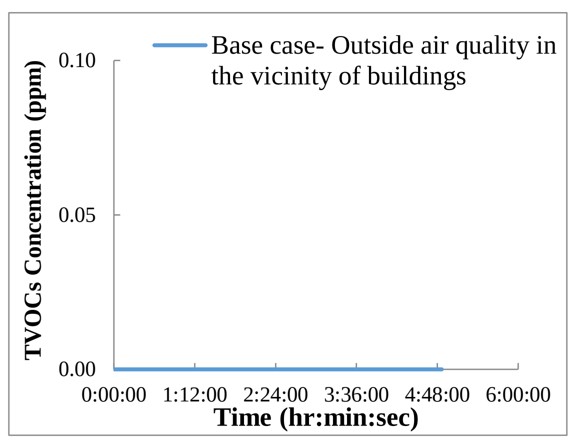


Figure 3.94: TVOCs variation- Synthetic building materials (Base case)

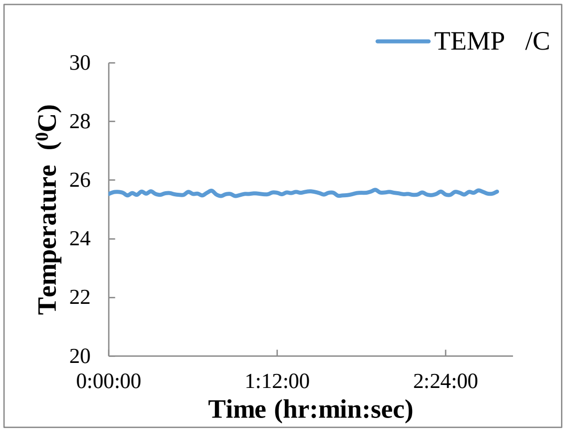


Figure 3.95: Temperature variation- Synthetic building materials (Location_01)

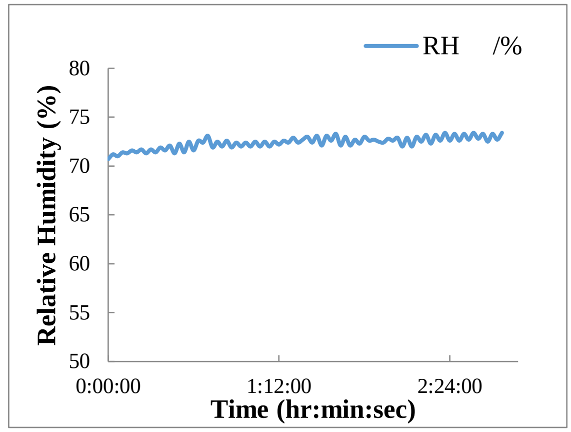


Figure 3.96: RH variation- Synthetic building materials (Location_01)

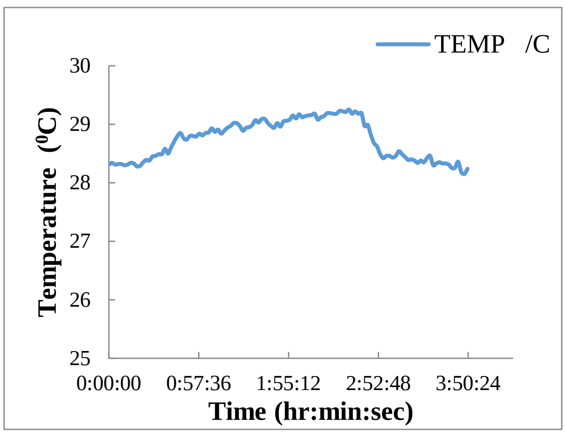


Figure 3.97: Temperature variation- Synthetic building materials (Location_02)

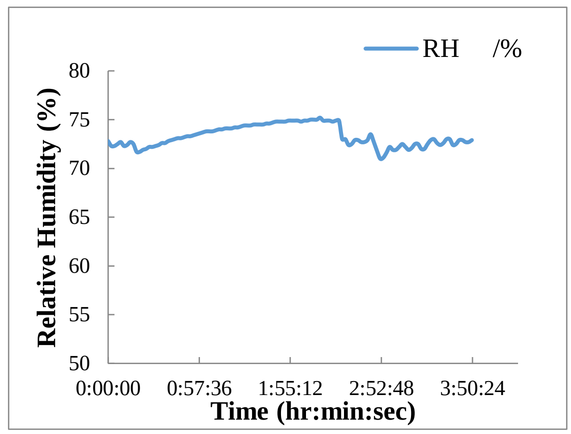


Figure 3.98: RH variation- Synthetic building materials (Location_02)

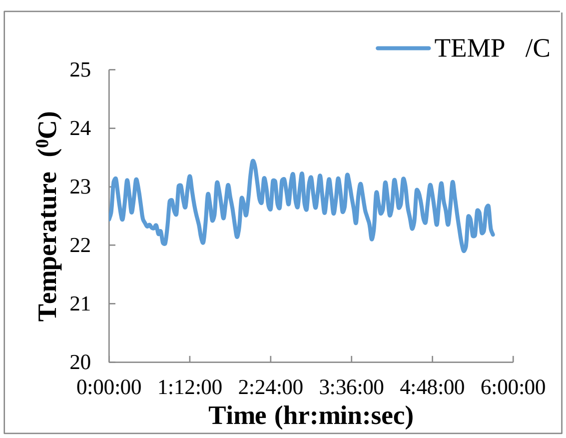


Figure 3.99: Temperature variation- Synthetic building materials (Location_03)

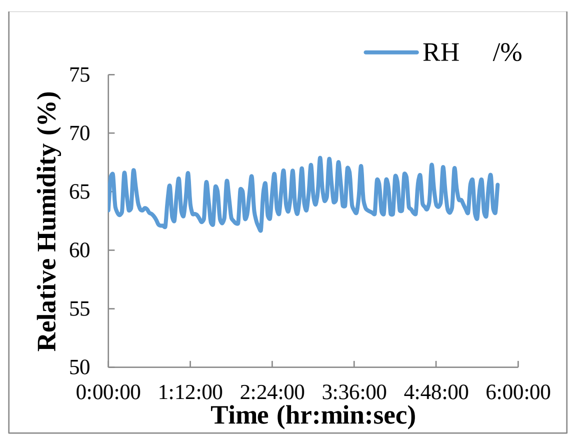


Figure 3.100: RH variation- Synthetic building materials (Location_03)

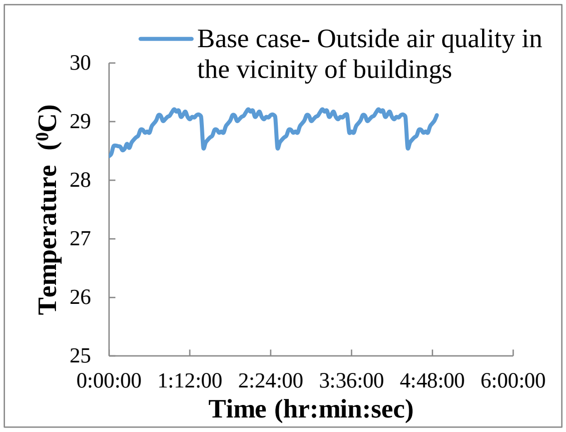


Figure 3.101: Temperature variation- Synthetic building materials (Base case)

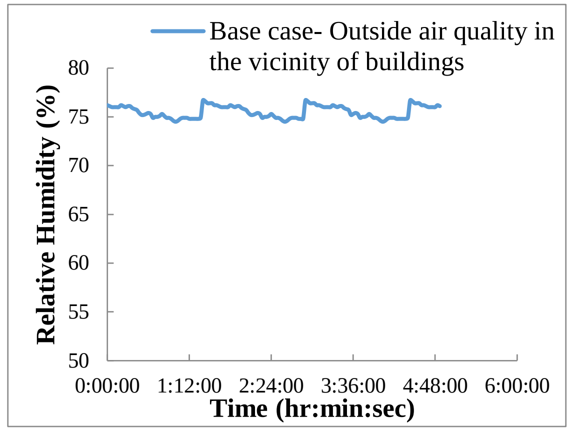


Figure 3.102: RH variation- Synthetic building materials (Base case)

The summary of the above experiments on synthetic building materials is presented below in Table 3.6.

Table 3.6: Summary of the experimental results- Synthetic building materials

Name of the causative agent	**Location_01**		**Location_02**		**Location_03**		
	(i)	**(ii)**	**(i)**	**(ii)**	**(i)**	**(ii)**	**(iii)**
CO (ppm)	0.16	-	0.53	-	0.47	-	0
NO_2 (ppm)	0.025	-	0.026	-	0.031	-	0.038
CO_2 (ppm)	997	-	1778	330 min	1690	330 min	290
TVOCs (ppm)	0.04	-	0.03	-	0.03	-	0
$PM_{2.5}$ (mg/m^3)	Refer "**Note 02**"						-
Temperature (^{0}C)							28.4- 29.2
RH (%)							74.5- 76.7

(i) Maximum concentration

(ii) Exposure time beyond the permissible indoor limit (**Note 01**)

(iii) Base case average value

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

Note 02: PM meter was not available for measurement

3.3.6 Mosquito coil

Mosquito coil is widely known as an efficient mosquito repellent. It is usually shaped into a spiral, and typically made from a dried paste of pyrethrum powder which is the major active ingredient of the mosquito coil and nearly used about 0.3 -0.4% of the coil mass (Liu, et al., 2003); (Lukwa & Chandiwana, 1998). According to the investigation of Liu et al., combustion of mosquito coils could generate particles containing heavy metals such as Cd, Zn and Pb, allethrin, and other organic compounds e.g. phenol and O-cresol (Lee & Wang, 2006); (Liu, Wong, & Mui, 1987). Further, a couple of researchers have identified organic compounds such as black carbon particles, allethrin and phenol from the mosquito coil smoke by gas chromatography-mass spectrometry (Stabile, Fuoco, & Buonanno, 2012); (Liu & Sun, 1988).

The experiment was carried out in an enclosed space which was located in the Department of Civil Engineering, University of Moratuwa. The test chamber shown in Figure 3.103 was used under the minimum ventilation condition to witness the maximum effect from the source. The coil was lit for approximately 1.5 hours in the test chamber and kept 0.4 m away from the instrument.

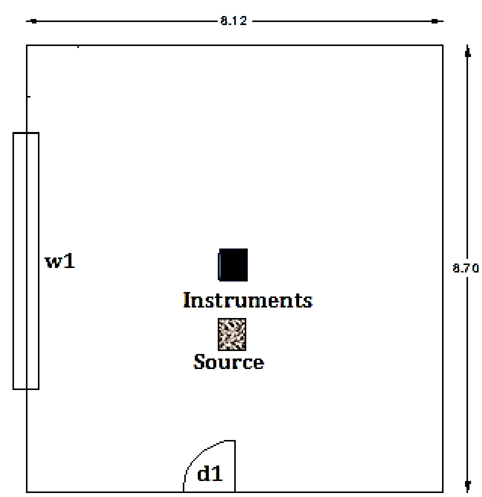


Figure 3.103: Plan view of the test chamber used for the experiment on mosquito coil (All the dimensions are in meters)

Results and Analysis – Mosquito coil

Figure 3.104 to 3.110 shows the variation of selected pollutants due to the emission from the mosquito coil during the 1.5 hours of the burning period. According to Figure 3.104, the concentration of the CO has increased drastically beyond the permissible value defined by the ASHRAE (9 ppm) and the time taken to disperse to the ambient condition was more than 5 hours. Therefore, occupants are exposed to this adverse environmental condition during this period. Since there are severe health risks from CO exposure like reducing oxygen delivery to the body's organs and death due to the extremely high levels of CO, the occupant awareness is highly essential (Raub & Mathieu-Nolf , 2000).

The concentration of NO_2, CO_2 and TVOCs varies with time is presented in Figure 3.105, 3.106 and 3.107 respectively. According to the results, the concentrations have increased due to the mosquito coil smoke. However, it was found all the values are less than the permissible indoor values.

As illustrated in Figure 3.108, the concentration of $PM_{2.5}$ has also uprisen significantly and the maximum concentration is 3.8 mg/m^3 due to the mosquito smoke over a period of 1.5 hours. However, the permissible indoor values defined by the WHO is 0.025 mg/m^3 based on the relationship between 24 hours and annual PM levels. Thus, the maximum concentration is 150 times of the permissible indoor value and the exposure time beyond the permissible value is more than 8.5 hours. Among the above all the pollutants, $PM_{2.5}$ causes a substantial impact on human health since particle size is very small, it contains small microscopic solids or liquid droplets that they can get deep into the lungs and cause serious health problems (WHO, 2005).

The results shown in Figure 3.104 and 3.110 represent the effect of mosquito coil smoke on IAQ during the 1.5 hours of its burning period. However, the actual scenario could be more than this period and also the magnitudes. The result obtained from this experiment did not show any difference in the variation of temperature and RH due to the mosquito smoke.

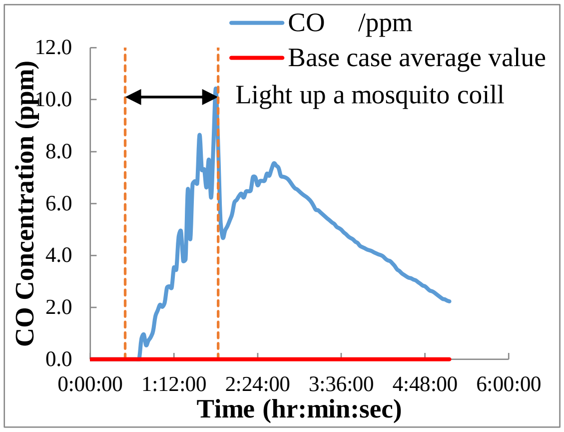


Figure 3.104: CO variation- Mosquito coil

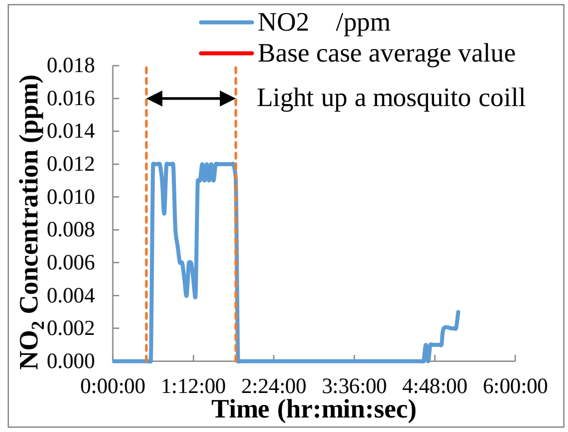


Figure 3.105: NO_2 variation- Mosquito coil

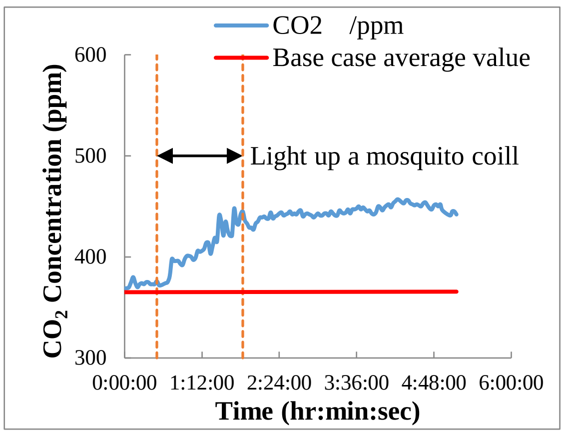


Figure 3.106: CO_2 variation- Mosquito coil

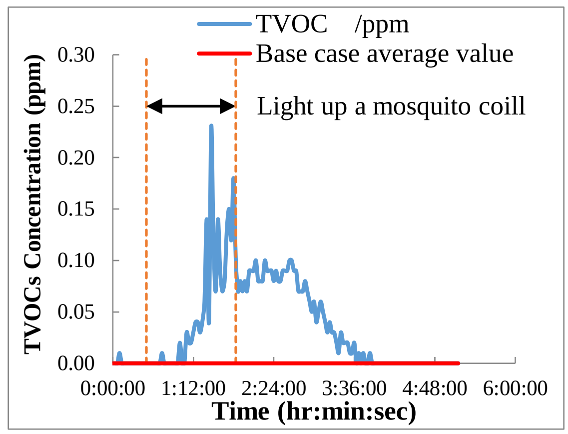


Figure 3.107: TVOCs variation- Mosquito coil

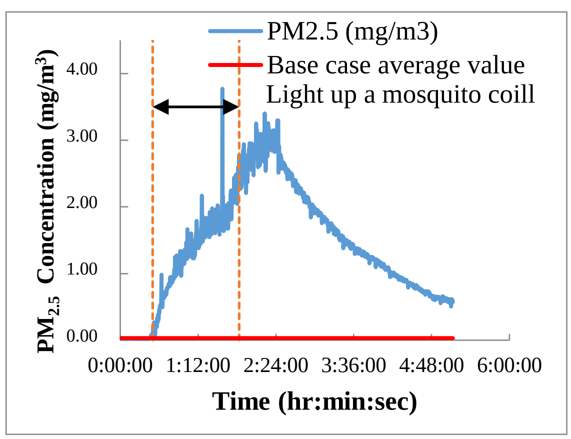


Figure 3.108: $PM_{2.5}$ variation- Mosquito coil

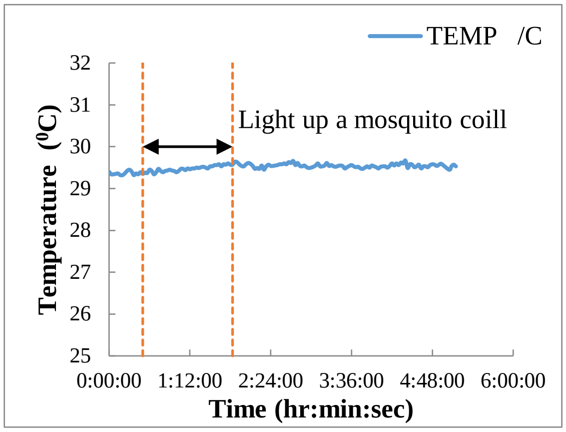


Figure 3.109: Temperature variation- Mosquito coil

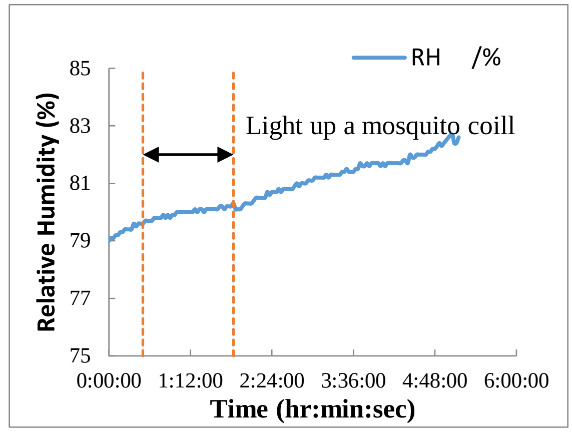


Figure 3.110: RH variation- Mosquito coil

The summary of the above experiment on mosquito coil is presented below in Table 3.7.

Table 3.7: Summary of the experimental results- Mosquito coil

Name of the causative agent	(i)	(ii)	(iii)
CO (ppm)	10.43	2 min	0
NO_2 (ppm)	0.012	-	0
CO_2 (ppm)	457	-	365
TVOCs (ppm)	0.23	-	0
$PM_{2.5}$ (mg/m^3)	3.772	510 min	0.031
Temperature (^{0}C)			29.2- 29.4
RH (%)			77.8- 78.9

(i) Maximum concentration

(ii) Exposure time beyond the permissible indoor limit (**Note 01**)

(iii) Base case average value

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

3.3.7 Naphthalene ball

Naphthalene is both a volatile organic compound and polycyclic aromatic hydrocarbon ($C_{10}H_8$), which may exist as white crystalline plates, balls, power or solvent with a distinct and easily detectable odour (WHO, 2010); (Jia & Batterman, 2010). Naphthalene is widely used as a moth and insect repellent in building operational stage, whereas emissions from attached garages, cigars and vehicles could also be mentioned as other sources of naphthalene in indoors (Batterman, et al., 2012). Moreover, Naphthalene acts as a solvent and is used in the production of automobile paint, driveway sealants, various chemicals in the dye and synthetic leather tanning industries, lubricants, motor fuel and toilet deodorizers. Batterman et al study in 2012 has identified that average naphthalene concentrations ranged from 0.18 to 1.7 $\mu g/m^3$ in the non-smoker's homes, and from 0.02 to 0.31 $\mu g/m^3$ outdoors in urban areas. However, WHO has defined the indoor guideline of 10 $\mu g/m^3$ for long term exposure to the toxicity of naphthalene with considering respiratory tract lesions, including tumors in the upper respiratory tract (Batterman, et al., 2012). Most importantly, the study by Sudakin et al. in 2011 has highlighted toxicological effects and injuries to the respiratory tract been occurred by prolonged exposure to naphthalene (Sudakin , Stone, & Power, 2011). Further to that, due to the lack of awareness of people of proper use of naphthalene balls, they tend to ignore the instructions on the packaging that eventually expose them to hazardous chemicals and particulate matter. However, studies carried out on the personal exposure of naphthalene is very limited by considering the review of available facts.

The experiment was done in order to quantify the effect of smoke coming out from the burning naphthalene balls on IAQ. The same test chamber, which is shown in Figure 3.103 was used for this experiment as described in Subsection 3.3.6. Commonly available two naphthalene balls of standard size were lit one after the other inside the test chamber. The source was located 0.4m distance from the centrally mounted instruments. The data obtained are plotted in the graphs presented in Figure 3.111 to 3.116.

Results and Analysis – Naphthalene ball

Figure 3.111 to 3.114 displays the variation of the concentration of CO, NO_2, CO_2 and TVOCs from the ambient condition after the burning of the two Naphthalene balls. Although the concentrations of NO_2, CO_2 and TVOCs were increased from the ambient condition, they all are well below the respective permissible indoor values. However, the concentration of CO has increased beyond the permissible value over half an hour due to the incomplete combustion process taken at the place. The results obtained from this experiment did not show any difference in the variation of temperature and RH due to the smoke from the two Naphthalene balls.

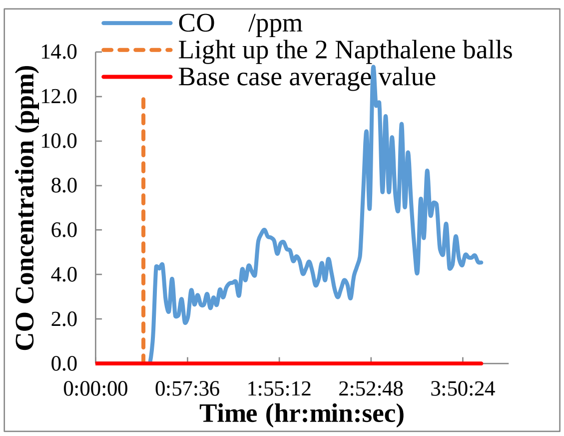


Figure 3.111: CO variation- Naphthalene balls

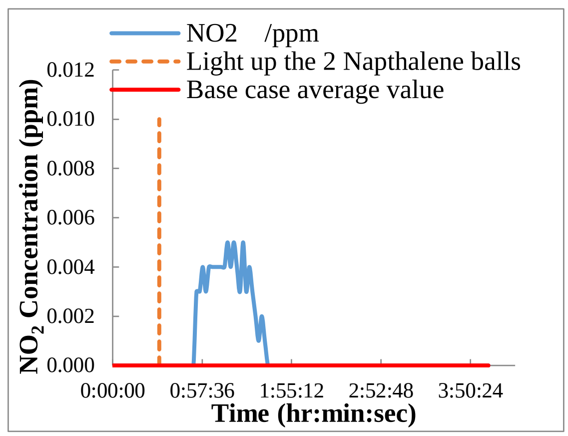


Figure 3.112: NO_2 variation- Naphthalene balls

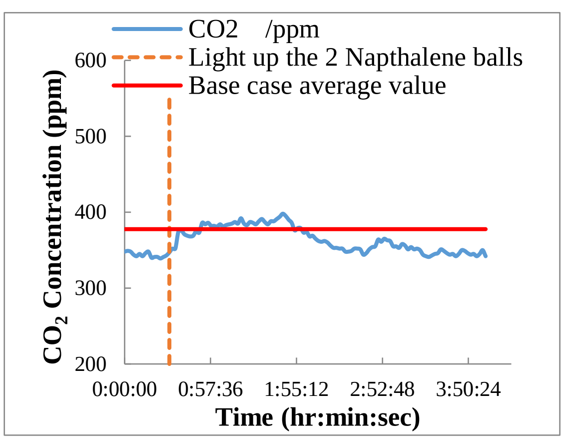


Figure 3.113: CO_2 variation- Naphthalene balls

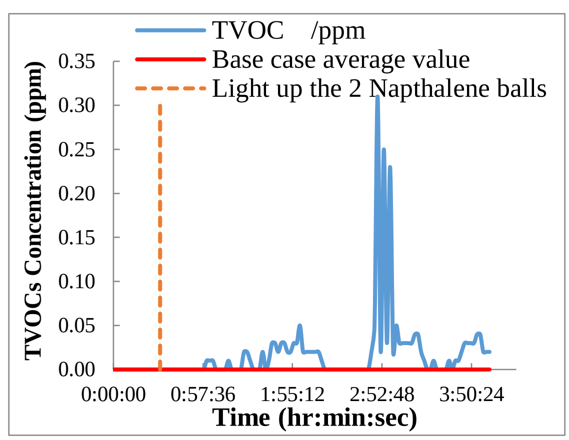


Figure 3.114: TVOCs variation- Naphthalene

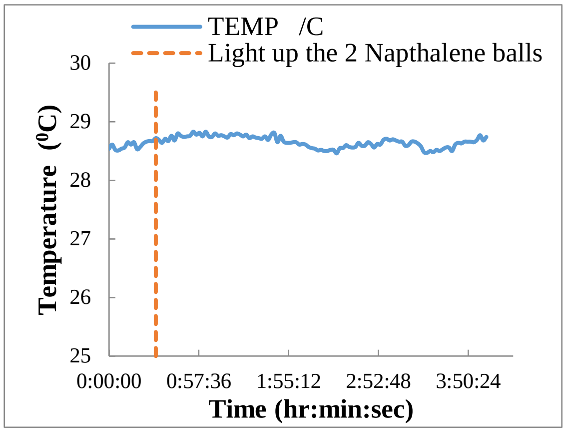


Figure 3.115: Temperature variation- Naphthalene balls

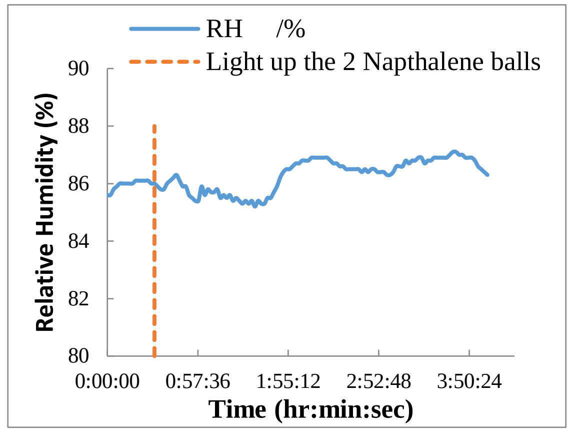


Figure 3.116: RH variation- Naphthalene balls

The summary of the above experiment on naphthalene ball is presented below in Table 3.8.

Table 3.8: Summary of the experimental results- Naphthalene ball

Name of the causative agent	(i)	(ii)	(iii)
CO (ppm)	13.17	26 min	0
NO_2 (ppm)	0.005	-	0
CO_2 (ppm)	398	-	378
TVOCs (ppm)	0.31	-	0
$PM_{2.5}$ (mg/m^3)	Refer "**Note 02**"		-
Temperature (^{0}C)			28.4- 28.8
RH (%)			84.8- 85.6

(i) Maximum concentration

(ii) Exposure time beyond the permissible indoor limit (**Note 01**)

(iii) Base case average value

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

Note 02: PM meter was not available for measurement

3.3.8 Incense sticks

Incense burning is a traditional and common practice of various religious devotees in many Asian nations. It is mostly used in temples, churches and residential homes to fragrance the environment. Several ingredients which are used to manufacture the incense could be mentioned as resins (such as frankincense and myrrh), spices, aromatic wood and bark, herbs, seeds, roots, flowers, essential oils, and synthetic substitute chemicals which are used in the perfume industry (Wang, Lee, Ho, & Kang, 2007); (Cheng Lee & Wang, 2004). However, incense sticks have been identified as the most significant source of air pollution due to the combustion derived particulate matters which are in submicron sizes, including ultrafine and nanoparticles (See, Balasubramanian, & Joshi, 2007). Moreover, the studies carried out by several researchers on incense burning have recognized the emission of gas products like CO, CO_2, NO_2, SO_2, and volatile organic compounds of benzene, toluene, and xylenes, as well as aldehydes and polycyclic aromatic hydrocarbons (PAHs) (Wang, Lee, Ho, & Kang, 2007); (Cheng Lee & Wang, 2004); (See, Balasubramanian, & Joshi, 2007); (Lin, Krishnaswamy, & Chi, 2008). The air pollution in and around the temples is also documented in order to understand its impact on human health (Wang, Lee, Ho, & Kang, 2007). Greater particle mass generation was identified in outdoors as well as indoors due to the incense burning causing a potential health risk depending on the exposure duration and the intensity. The presence of ultrafine particles in incense smoke has been led to pose a greater risk to health as they can penetrate deep into the respiratory tract triggering respiratory system dysfunction (Ji, et al., 2010); (Lin, Krishnaswamy, & Chi, 2008); (See & Balasubramanian, 2011). Further to that, Lin et al. study in 2008 has revealed that “On average, incense burning produces particulates greater than 45 mg/g burned as compared to 10 mg/g burned for cigarettes” (Lin, Krishnaswamy, & Chi, 2008). Thus, public awareness should be improved on the incense burning while minimizing the exposure period to heavy incense smoke at outdoor religious places. Considering the residential exposure, it can be mentioned that the provision of proper ventilation and the use of smokeless incense to dilute the pollutants accumulated in indoor spaces (Lin, Krishnaswamy, & Chi, 2008); (See & Balasubramanian, 2011) .

The test chamber which is shown in Figure 3.103 was used to quantify the emission from incense burning on IAQ. The area was made fully enclosed with minimum ventilation in order to witness the maximum effect of the incense sticks. The commonly used brand, type of incense was used for the experiment considering the consumer demand for the particular product. Twenty no of incense sticks were lit at once inside the test chamber and IAQ measurements were taken at 0.4 m distance from the source. The results are graphically presented in Figure 3.117 to 3.123.

Results and Analysis – Incense sticks

According to the figures shown below, all the indoor air quality parameters were increased due to the incense burning. A significant effect was observed in the variation of CO, TVOCs and $PM_{2.5}$ as in Figure 3.117, 3.120 and 3.121, where the three pollutant concentrations were well above the indoor permissible values during the entire experimental programme. Regarding the variation of CO, maximum concentration and exposure time beyond the permissible indoor value were recorded as 54 ppm and five hours respectively due to the incredibly low dispersion rate prevailed in the experiment. Likewise, TVOCs has also appeared in the same pattern with 3.87 ppm maximum value and more than four hours dispersion time. Besides, $PM_{2.5}$ variation has been even further life-threatening since its dispersion time to the permissible indoor limit is more than nineteen hours, which is obtained from the rate of dispersion of the curve as in Figure 3.121. Thus, the burning of incense sticks should be done with due care to mitigate this air pollution with the use of precautionary actions. As in Figure 3.118 and 3.119, although the NO_2 and CO_2 concentrations were influenced due to the incense burning, their concentrations were maintained within the permissible indoor values as portrayed below. Temperature and RH did not show any alteration due to the incense smoke.

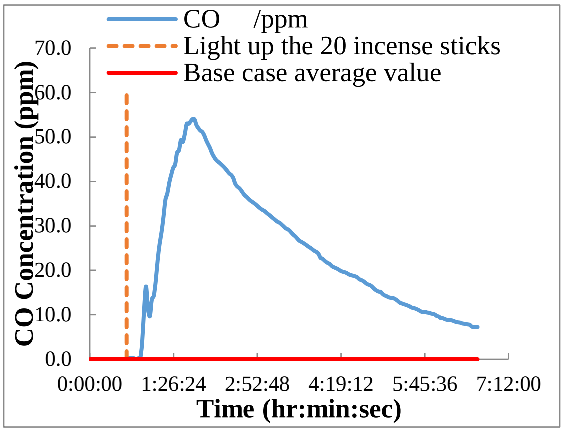


Figure 3.117: CO variation- Incense sticks

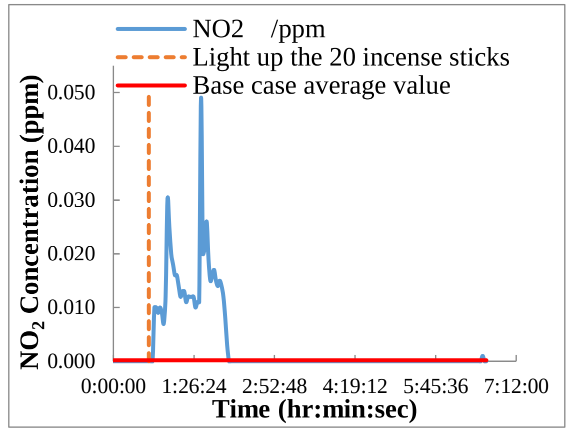


Figure 3.118: NO_2 variation- Incense sticks

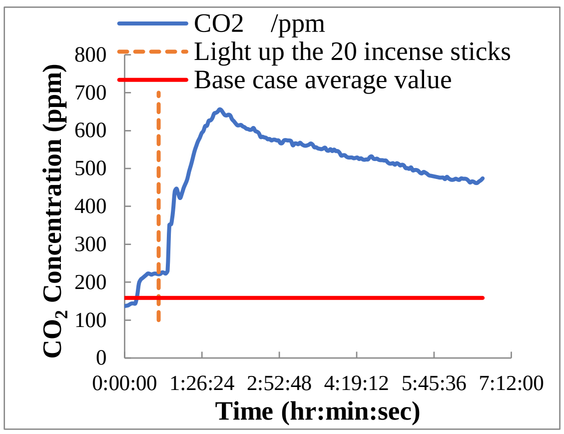


Figure 3.119: CO_2 variation- Incense sticks

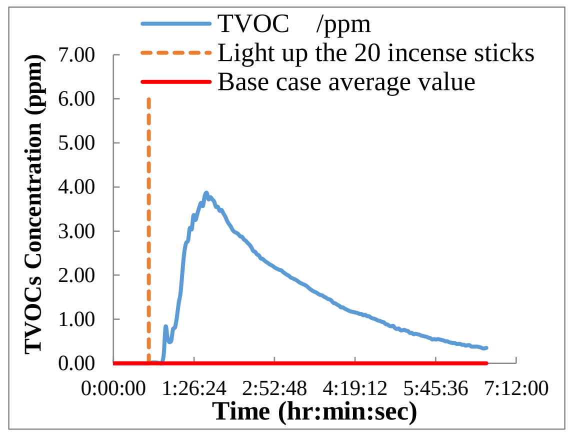


Figure 3.120: TVOCs variation- Incense sticks

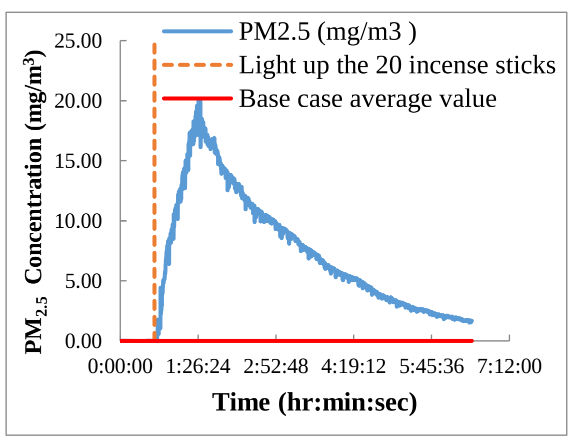


Figure 3.121: $PM_{2.5}$ variation- Incense sticks

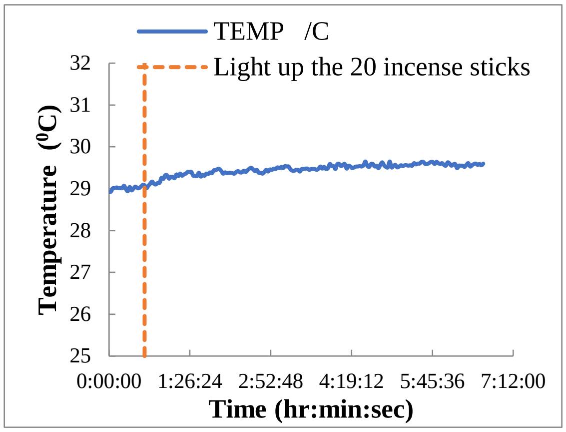


Figure 3.122: Temperature variation- Incense sticks

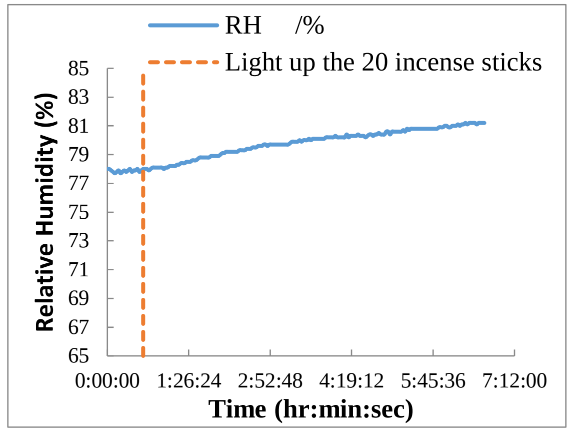


Figure 3.123: RH variation- Incense sticks

The summary of the above experiment on incense burning is presented below in Table 3.9.

Table 3.9: Summary of the experimental results- Incense sticks

Name of the causative agent	(i)	(ii)	(iii)
CO (ppm)	54.02	310 min	0
NO_2 (ppm)	0.049	-	0.0002
CO_2 (ppm)	656	-	159
TVOCs (ppm)	3.87	256 min	0
$PM_{2.5}$ (mg/m^3)	20	>19 hrs	0.008
Temperature (^{0}C)			27.2- 28.9
RH (%)			57.2- 78

(i) Maximum concentration

(ii) Exposure time beyond the permissible indoor limit (**Note 01**)

(iii) Base case average value

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

3.3.9 Open waste burning (Dry leaves and Polythene)

Open waste burning generally refers to an uncontrolled burning of any waste, including agricultural waste and crop residues (Kumar, et al., 2018). It is a common way of disposing household waste, particularly in rural areas in countries like Sri Lanka. Not only that, but also in 2006, 12-40% of the US households were estimated to burn garbage in their backyard (Christian, et al., 2010). Further, it has been estimated globally, that 2400 Tg of waste is generated annually out of which 970 Tg (41%) is burned openly in the residential areas and dumpsites or landfills combined together (Kumar, et al., 2018). Correspondingly, phthalates and bisphenol A have been found to be more abundant in New Delhi, mostly due to high emissions from the open burning of plastic and other solid wastes (Li et al., 2014). All these statistics enhance the importance of further study that is related to the impact of open waste burning has on indoor air quality

Typical household waste consists of items such as paper, cardboard, food scrap, plastic, leaves, etc. A study led by the National Center for Atmospheric Research (NCAR) estimates that more than 40 percent of the world‘s garbage that is burnt, is emitting gases and particles that can substantially affect human health (Wiedinmyer, Yokelson, & Gullett, 2014). Further, it is brought forward that garbage burning is globally a significant source of particles and trace gases and maybe a major global source of HCl (Christian, et al., 2010).

The test chamber shown in Figure 3.124 was used for this experiment and garbage was burnt at a 3m distance from the instruments. The experiment was conducted under natural ventilation condition and all the windows were opened to facilitate the cross-ventilation across the test chamber. The measured quantities of dry leaves (2.1 kg) and Polythene (2.75 kg) were burnt separately for several days and the IAQ parameters were measured from the two equipment.

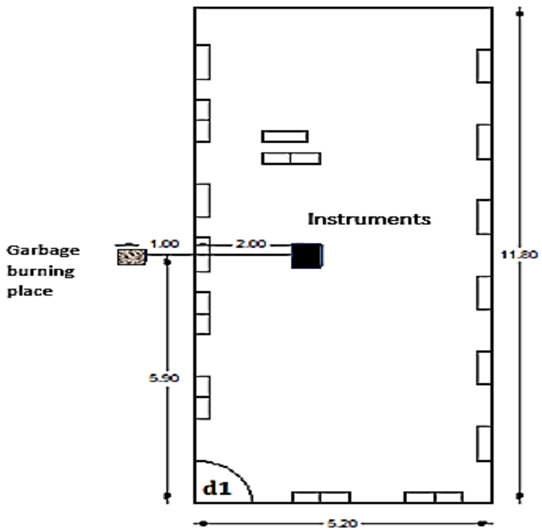


Figure 3.124: Plan view of the test chamber used for the experiment on open waste burning (All the dimensions are in meters)

Results and Analysis – Open waste burning (Dry leaves)

Figure 3.125 to 3.129 demonstrates the variation of the pollutants due to the smoke coming out from the burning of dry leaves. According to the Figures, the concentrations of CO, TVOCs and $PM_{2.5}$ were increased beyond the indoor permissible values, whereas the NO_2 and CO_2 variations were within the pertain guidelines for indoors. $PM_{2.5}$ was identified as the foremost pollutant type on the indoor air pollution due to the open waste burning as its concentration remained around the forty minutes exceeding the permissible exposure limit of 0.025 mg/m^3 defined by the WHO. Temperature and RH did not indicate any difference in the variation due to the dry leaves burning.

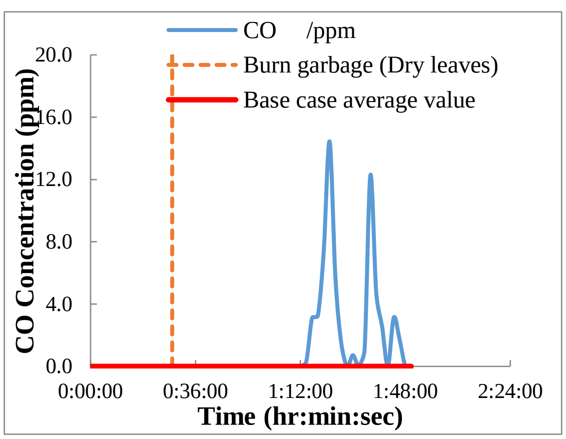


Figure 3.125: CO variation- Burning dry leaves

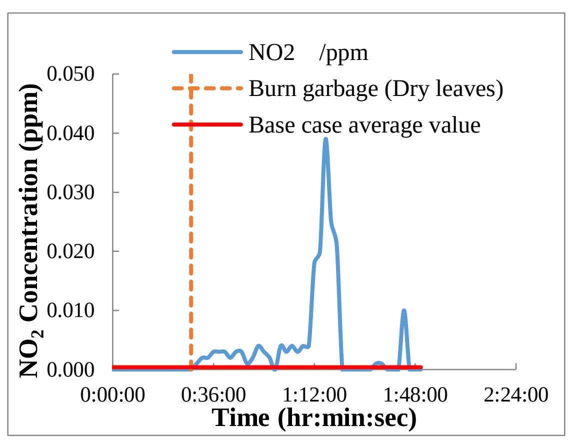


Figure 3.126: NO_2 variation- Burning dry leaves

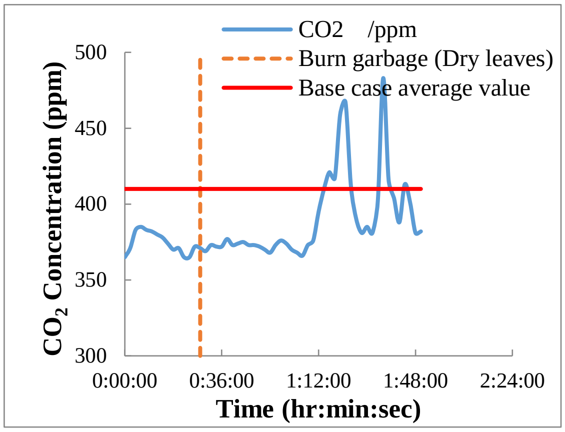


Figure 3.127: CO_2 variation- Burning dry leaves

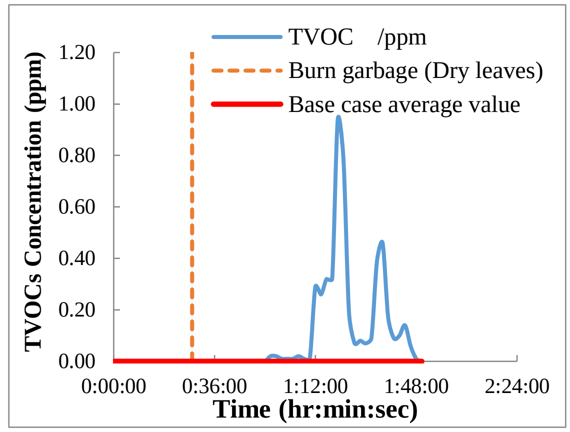


Figure 3.128: TVOCs variation- Burning dry leaves

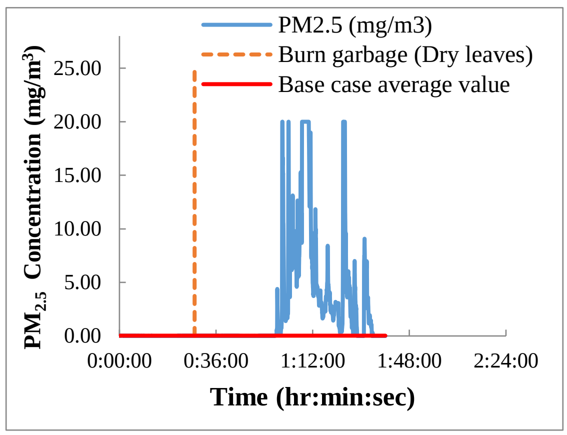


Figure 3.129: $PM_{2.5}$ variation- Burning dry leaves

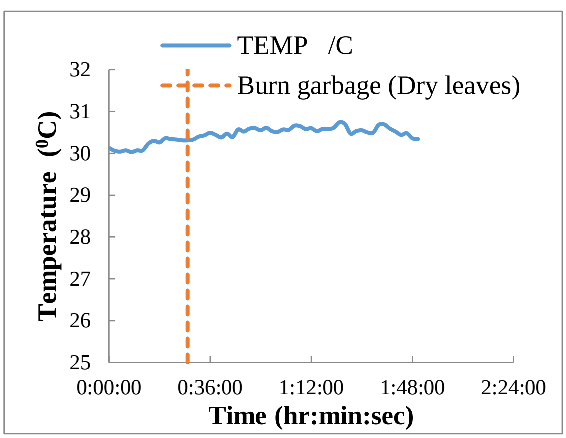


Figure 3.130: Temperature variation- Burning dry leaves

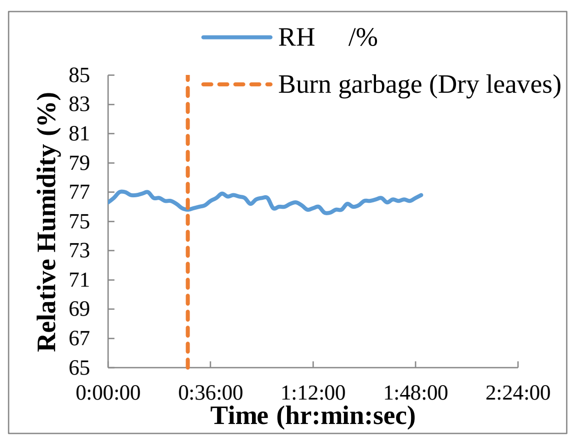


Figure 3.131: RH variation- Burning dry leaves

Results and Analysis – Open waste burning (Polythene)

Similar to the burning of dry leaves, concentrations and dispersion curves were obtained for the emission from Polythene burning. The concentration variation of CO, CO_2, NO_2, TVOCs and $PM_{2.5}$ were presented in Figure 3.132 to 3.136 consecutively. The results obtained were revealed that the emission of CO, CO_2 and $PM_{2.5}$ were very low during the experiment compared to the dry leaves burning. However, NO_2 and TVOCs were recorded above the ambient condition during the entire experimental period due to the smoke generated from the Polythene burning.

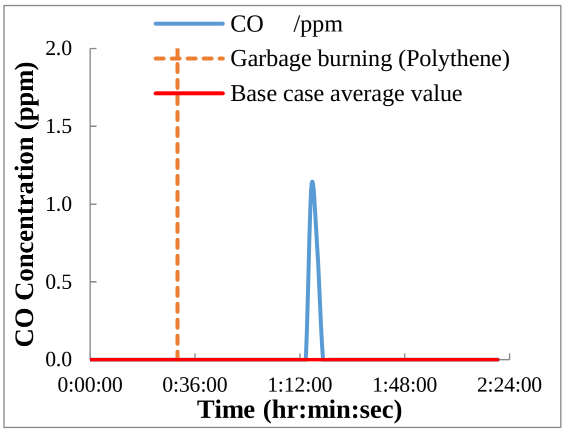


Figure 3.132: CO variation- Burning polythene

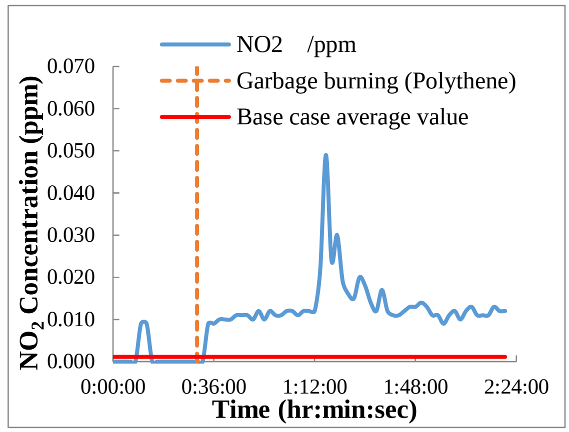


Figure 3.133: NO_2 variation- Burning polythene

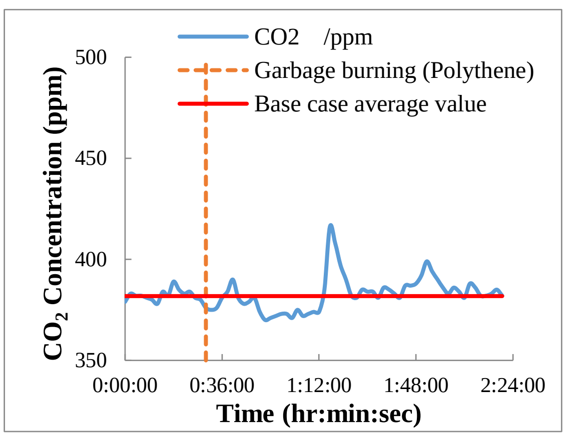


Figure 3.134: CO_2 variation- Burning polythene

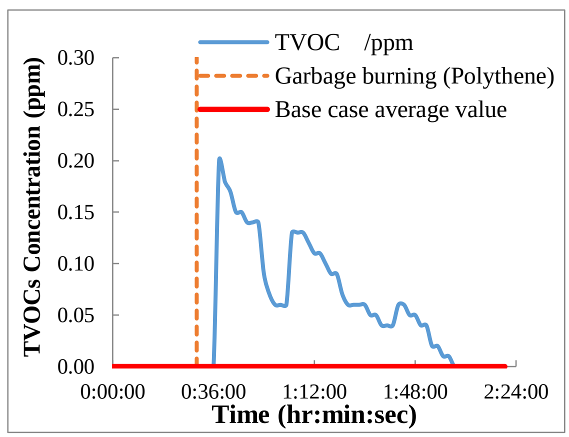


Figure 3.135: TVOCs variation- Burning polythene

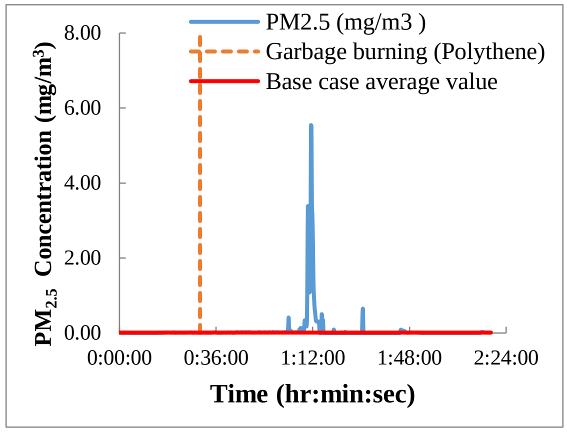


Figure 3.136: $PM_{2.5}$ variation- Burning polythene

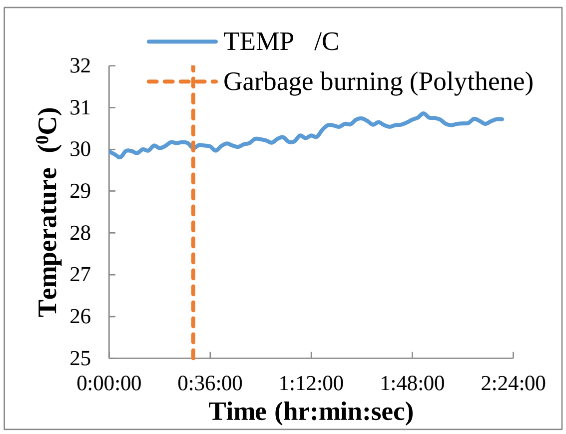


Figure 3.137: Temperature variation- Burning polythene

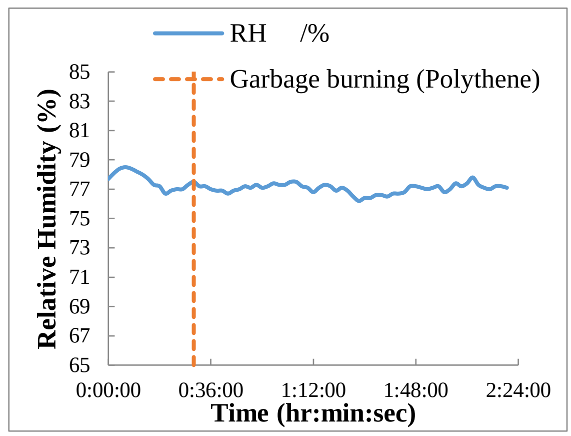


Figure 3.138: RH variation- Burning polythene

The summary of the above experiments on open waste burning is presented below in Table 3.10.

Table 3.10: Summary of the experimental results- Open waste burning

Name of the causative agent	Dry leaves			Polythene		
	(i)	(ii)	(iii)	(i)	(ii)	(iii)
CO (ppm)	14.44	14 min	0	1.12	-	0
NO_2 (ppm)	0.039	-	0.0004	0.049	-	0.001
CO_2 (ppm)	483	-	410	416	-	382
TVOCs (ppm)	0.94	2 min	0	0.2	-	0
$PM_{2.5}$ (mg/m^3)	20	36 min	0.010	5.54	15 min	0.011
Temperature (^0C)			30- 30.4	Temperature (^0C)		29.8- 30.1
RH (%)			75.8- 77	RH (%)		76.7- 78.5

(i) Maximum concentration

(ii) Exposure time beyond the permissible indoor limit (**Note 01**)

(iii) Base case average value

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

3.3.10 Environmental tobacco smoke

Environmental tobacco smoke is a phenomenon that almost everyone gets exposed to daily. Especially, people who work in the hospitality industry have a higher vulnerability due to a lack of smoking restrictions and regulations such as smoke-free areas (Johnsson, et al., 2005). Being exposed to particulate matter and volatile organic compounds released by tobacco smoke on a daily basis may have serious health repercussions that will ultimately threaten the life expectancy of the subjects (Jamrozik, 2005); (Johnsson, et al., 2005).

It has been estimated that the fatality rate due to environmental tobacco smoke exposure at work in Finland was 0.9% of the total fatality rate of the Finnish population in the relevant disease and age categories in the year 1996 (Nurminen & Jaakkola, 2001). Further, it has been highlighted that in the UK, the deaths due to passive smoking each year adds up to 617 people, including around 54 worker deaths in the hospitality sector (Jamrozik, 2005). Higher PM levels have been identified in houses when the presence of one or more smokers in sites (Stamatelopoulou, Asimakopoulos, & Maggos, 2019). Moreover, as per the latest research, exposure to environmental tobacco smoke increased the risk of acute lower respiratory infection of children (Suryadhi, Abudureyimu, Kashima, & Yorifuji, 2019). Thus, how the indoor air quality depreciates with the addition of toxins from tobacco smoke is, stand crucial to be studied.

The test chamber used for the experiment is presented in Figure 3.103, which was an air-conditioned space in the Department of Civil Engineering, University of Moratuwa. Two categories of experiments were carried out, one for active smoking, and another for burning cigars. There was one smoker inside the enclosed chamber during the first experiment, three cigarettes were used continuously for each test. The obtained results are presented below.

Results and Analysis –Environmental tobacco smoke (Active smoking)

Figure 3.139 to 3.142 interprets the variation of CO, NO_2, CO_2 and TVOCs concentration due to active smoking. As the results emphasize, all four types of pollutant concentrations were increased during active smoking, whereas the CO, CO_2 and TVOCs were exceeded the relevant indoor permissible values as well. However, temperature and RH did not show any difference in their variation during the experiment.

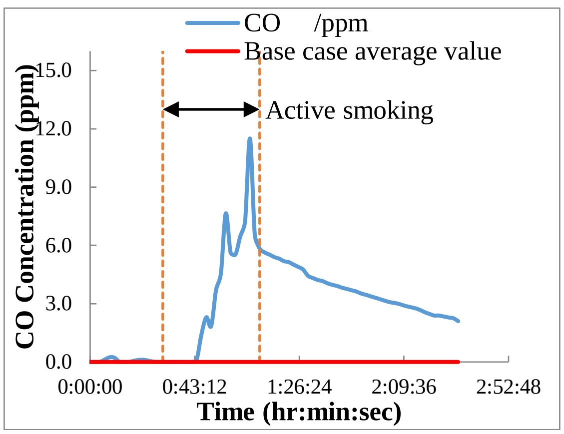


Figure 3.139: CO variation- ETS (Smoking 3 cigars continuously)

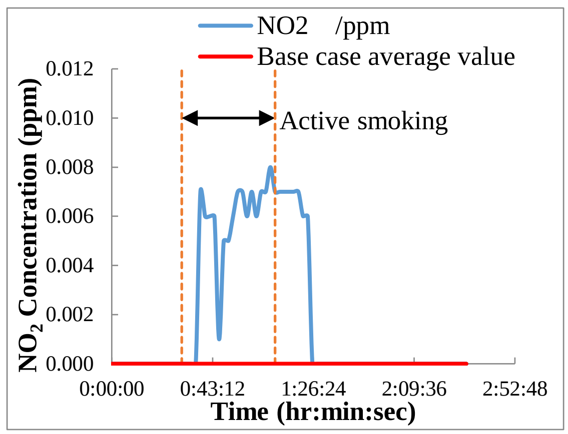


Figure 3.140: NO_2 variation- ETS (Smoking 3 cigars continuously)

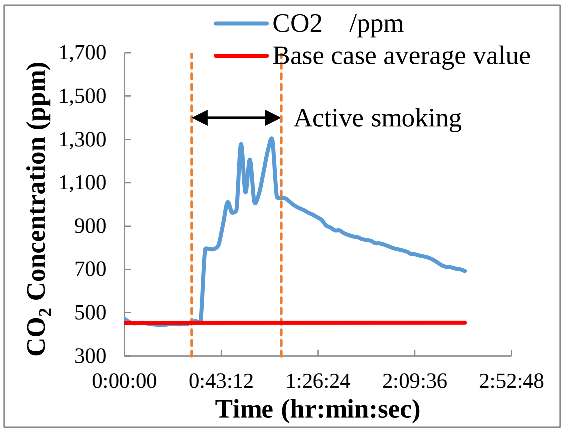


Figure 3.141: CO_2 variation- ETS (Smoking 3 cigars continuously)

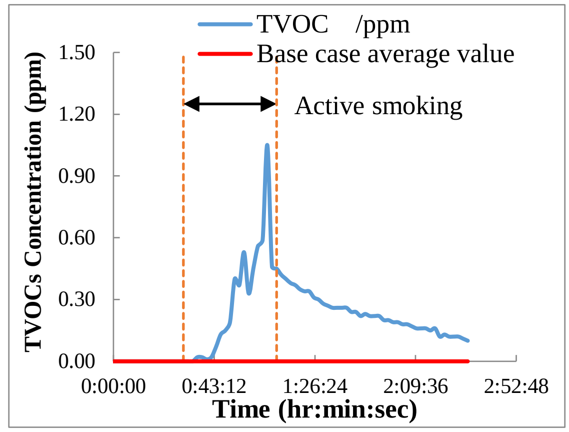


Figure 3.142: TVOCs variation- ETS (Smoking 3 cigars continuously)

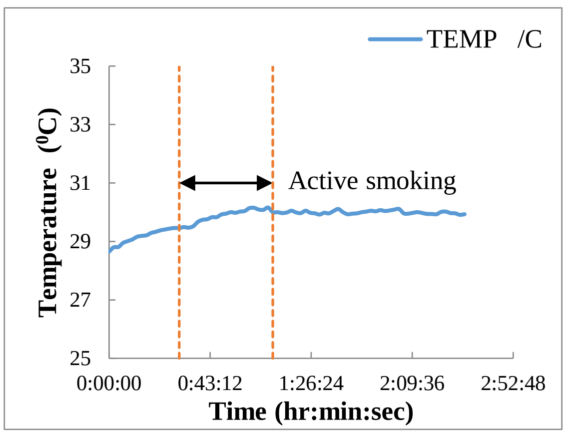


Figure 3.143: Temperature variation- ETS (Smoking 3 cigars continuously)

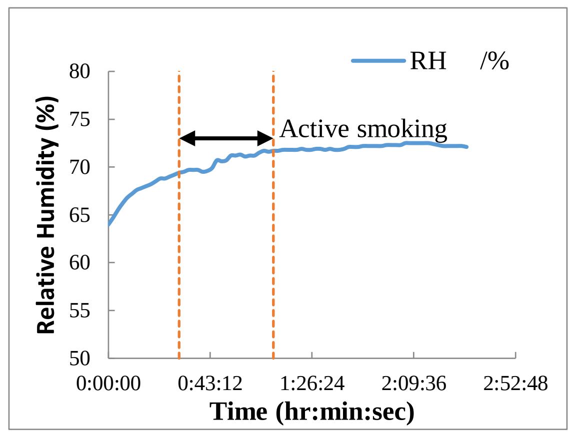


Figure 3.144: RH variation- ETS (Smoking 3 cigars continuously)

Results and Analysis –Environmental tobacco smoke (Burning cigars)

A similar variation in pollutant concentration was observed for burning cigar in an enclosed chamber, with different magnitudes from that of experiment on active smoking. Figure 3.145 to 3.149 indicates the variation of CO, NO_2, CO_2, TVOCs and $PM_{2.5}$ concentrations and they all were increased beyond the ambient condition due to the tobacco smoke. A significant effect was noted from $PM_{2.5}$ concentration, as its maximum value is 3.5 mg/m^3 with the exposure period of three hours above the permissible indoor value. Temperature and RH variations are presented in Figures 3.150 and 3.151, did not have any influence from the emission of burning cigars.

However, tobacco active smoking and passive smoking have been implicated as risk factors for most of the malignant diseases such as lip and oral malignancies, lung cancer, oesophageal cancers, infection diseases like tuberculosis (TB), and pneumonia. Thus, it is paramount to consider the IAP due to the environmental tobacco smoke and necessary precautions should be taken to minimize its adverse effects on human health.

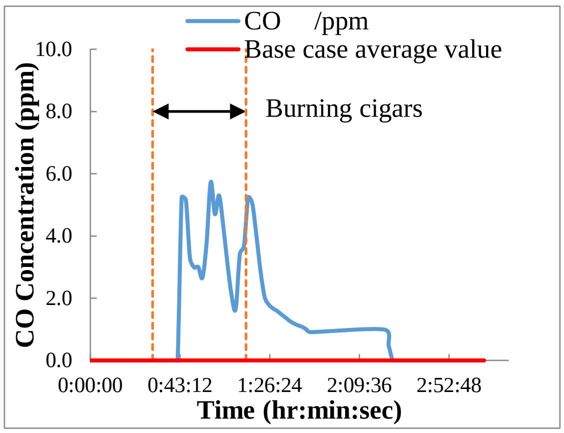


Figure 3.145: CO variation- ETS (Burning 3 cigars continuously)

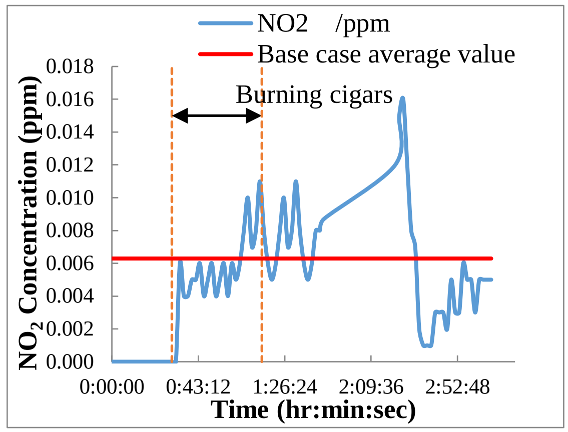


Figure 3.146: NO_2 variation- ETS (Burning 3 cigars continuously)

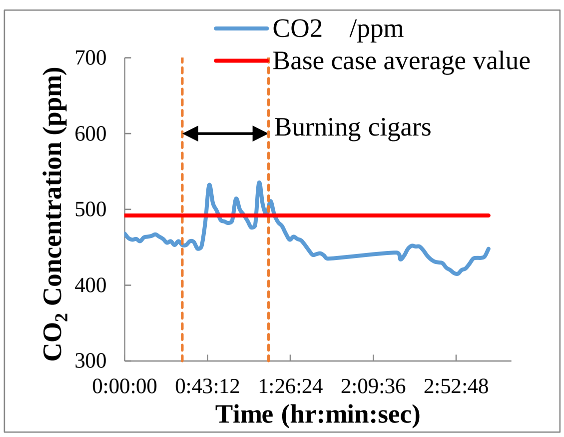


Figure 3.147: CO_2 variation- ETS (Burning 3 cigars continuously)

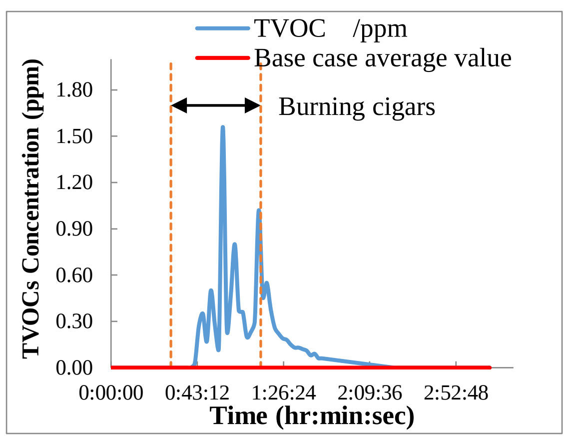


Figure 3.148: TVOCs variation- ETS (Burning 3 cigars continuously)

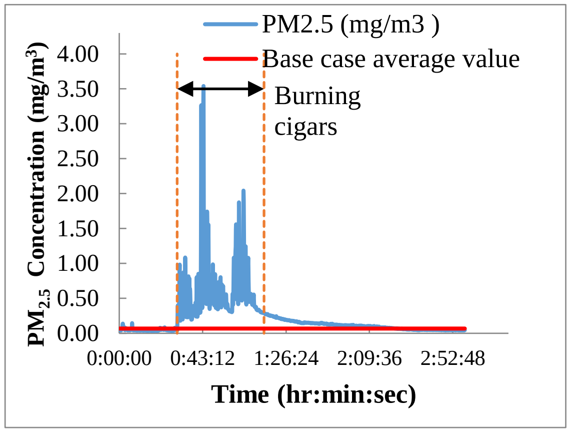


Figure 3.149: $PM_{2.5}$ variation- ETS (Burning 3 cigars continuously)

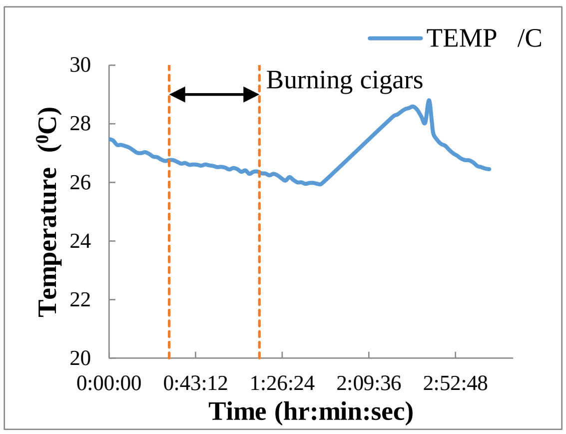


Figure 3.150: Temperature variation- ETS (Burning 3 cigars continuously)

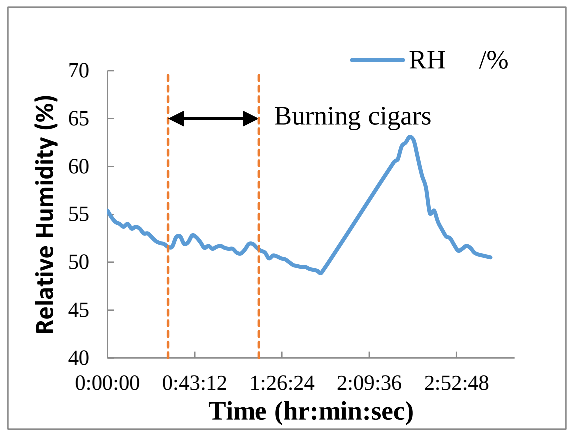


Figure 3.151: RH variation- ETS (Burning 3 cigars continuously)

The summary of the above experiments on environmental tobacco smoke is presented below in Table 3.11.

Table 3.11: Summary of the experimental results- Environmental tobacco smoke

Name of the causative agent	**Smoking cigars**			**Burning cigars**		
	(i)	**(ii)**	**(iii)**	**(i)**	**(ii)**	**(iii)**
CO (ppm)	11.5	2 min	0	5.73	-	0
NO_2 (ppm)	0.008	-	0	0.016	-	0.006
CO_2 (ppm)	1298	28 min	454	535	-	492
TVOCs (ppm)	1.05	2 min	0	1.56	18 min	0
$PM_{2.5}$ (mg/m^3)	Refer "**Note 02**"		-	3.504	180 min	0.049
Temperature (^{0}C)			28.0- 29.9	Temperature (^{0}C)		27.5- 30.2
RH (%)			51.5- 71.2	RH (%)		55.4- 73.2

i. Maximum concentration
ii. Exposure time beyond the permissible indoor limit (**Note 01**)
iii. Base case average value

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

Note 02: PM meter was not available for measurement

3.3.11 Comparison and analysis of the experimental results of indoor sources on IAQ

As mentioned in Section 3.2, frequently used building materials, adverse indoor environments and some human practices were tested to quantify their effect on IAQ. The summary of results is presented in Table 3.12, where maximum concentration and exposure period beyond the indoor permissible value are considered in the comparison. With reference to the Table 3.12, the following indoor sources which are presented in Table 3.13, exceeded the pertain indoor air quality guidelines over a considerable time period. Thus, it is considered in the further analysis with the use of statistical tools and exposure parameters to identify the most critical source or practice on IAP.

Table 3.12:Summary of the experimental results- Building materials, adverse indoor environments and human practices on IAQ

Source	Causative agent									
	CO (ppm)		NO_2 (ppm)		CO_2 (ppm)		TVOCs (ppm)		$PM_{2.5}$ (mg/m^3)	
	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)	(i)	(ii)
Air freshener-20 ml	0.3	-	0.013	-	533	-	3.65	64 min	Refer "**Note 02**"	
Air freshener-40 ml	4.29	-	0.024	-	422	-	10.66	132 min	0.085	35 min
Wall paint	0.01	-	0.066	8 min	568	-	45.58	244 min	0.435	87 min
Hospital theatre - Day_1	1.89	-	0.01	-	1102	6 min	13.97	102 min	0.146	44 min
Hospital theatre - Day_2	0.77	-	0.022	-	918	-	19.37	83 min	0.144	42 min
Hospital theatre - Day_3	1.73	-	0.017	-	673	-	40.31	104 min	0.15	23 min
MVSC- Service area	0.91	-	0.025	-	457	-	1.5	Refer "**Note 03**"	0.055	Refer "**Note 03**"
MVSC- Workshop	2.46	-	0.039	-	870	-	8.2		0.077	
MVSC -Office	3.15	-	0.012	-	1123	Refer "**Note 03**"	1.45		0.028	
SBM- Location_01	0.16	-	0.025	-	1706	186 min	0.04	-	Refer "**Note 02**"	
SBM- Location_02	0.53	-	0.026	-	1778	330 min	0.03	-	Refer "**Note 02**"	
SBM- Location_03	0.47	-	0.031	-	1690	330 min	0.03	-	Refer "**Note 02**"	
Mosquito coil	10.43	2 min	0.012	-	457	-	0.23	-	3.772	510 min
Naphthalene balls	13.17	26 min	0.005	-	398	-	0.31	-	Refer "**Note 02**"	
Incense sticks	54.02	310 min	0.049	-	656	-	3.87	256 min	20	>19 hrs
Open waste burning- Dry leaves	14.44	14 min	0.039	-	483	-	0.94	2 min	20	36 min
Open waste burning- Polythene	1.12	-	0.049	-	416	-	0.2	-	5.54	15 min
ETS- Smoking cigars	11.5	2 min	0.008	-	1298	28 min	1.05	2 min	Refer "**Note 02**"	
ETS- Burning cigars	5.73	-	0.016	-	535	-	1.56	18 min	3.504	180 min

MVSC *Motor Vehicle Service Centre* ***SBM*** *Synthetic Building Materials* ***ETS*** *Environmental Tobacco Smoke*

(i) Maximum concentration

(ii) Exposure time beyond the permissible exposure limit (**Note 01**)

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

Note 02: PM meter was not available for measurement

Note 03: The measurements were taken over a period of 1 hour at each location of the motor vehicle service centre due to the practical issue. Thus, it is not adequate to present an occupant's exposure time of particular causative agent beyond its permissible exposure limit.

Table 3.13 presents the pollutants to be considered in further analysis since their huge impact on indoor air pollution.

Table 3.13: Selected indoor sources and causative agents on IAP for the detailed analysis

Indoor sources	Causative agents
Air freshener	TVOCs and $PM_{2.5}$
Wall paint	TVOCs, $PM_{2.5}$ and NO_2
Hospital theatre	TVOCs, $PM_{2.5}$ and CO_2
Motor vehicle service centre	TVOCs, $PM_{2.5}$ and CO_2
Synthetic building materials	CO_2
Mosquito coil	$PM_{2.5}$ and CO
Naphthalene ball	CO
Incense sticks	CO, TVOCs and $PM_{2.5}$
Open waste burning	TVOCs, $PM_{2.5}$ and CO
Environmental tobacco smoke	TVOCs, $PM_{2.5}$, CO and CO_2

The empirical cumulative distribution function (CDF) was used for the statistical analysis and obtained results are shown in Figure 3.152 to 3.178. The main advantage of the empirical CDF is much more suitability of the comparison of several data sets, which can be plotted into the same axes irrespective of the amount of data contained in each set. Moreover, direct quantitative reading of essential key values such as "*Cumulative probability relevant to indoor permissible value (P)*" can be mentioned as another benefit related to CDF analysis. Subsequently, the severity of the occupant exposure to the adverse environment was also estimated using the time-weighted average of the selected pollutant with respect to the indoor sources in Table 3.13. The measured occupant exposure levels were compared with the international indoor air quality guidelines defined by the several organizations on human safety and health to identify the impact on the SBS.

The empirical cumulative distribution functions for the above pollutants are presented below.

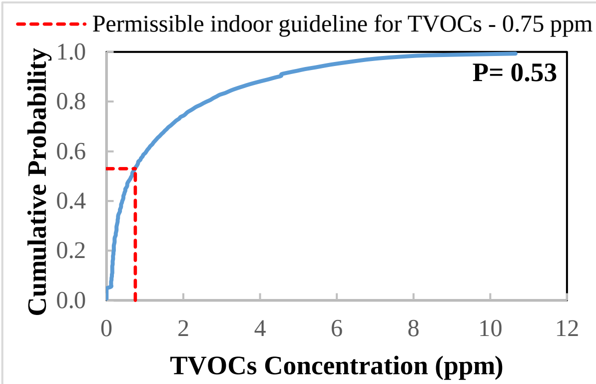


Figure 3.152: Empirical CDF of TVOCs from air freshener

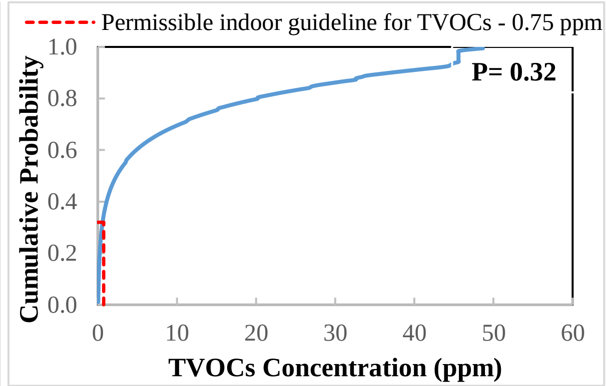


Figure 3.153: Empirical CDF of TVOCs from wall paint

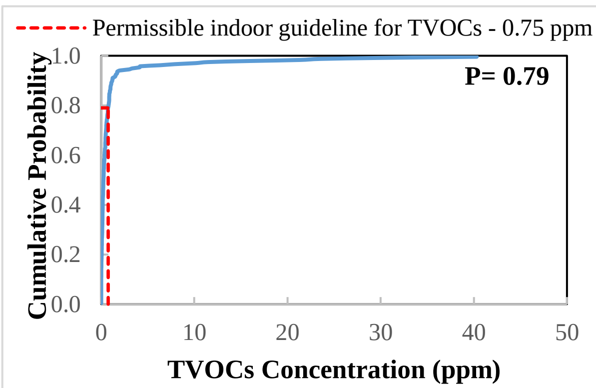


Figure 3.154: Empirical CDF of TVOCs from hospital theatre- Day_3

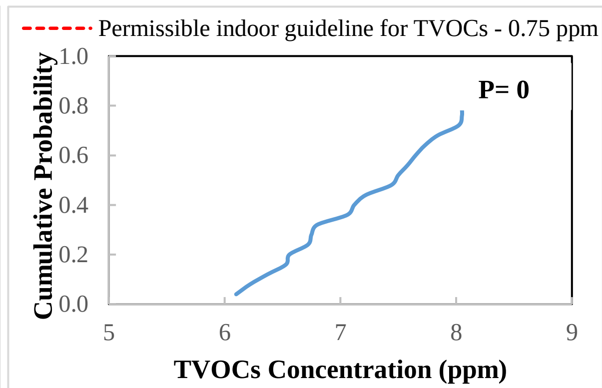


Figure 3.155: Empirical CDF of TVOCs from motor vehicle service centre- Workshop

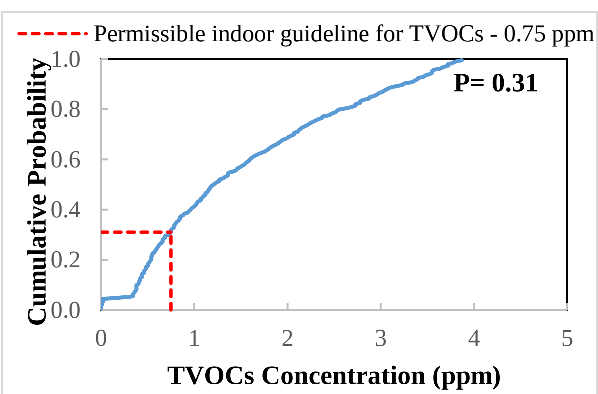


Figure 3.156: Empirical CDF of TVOCs from incense sticks burning

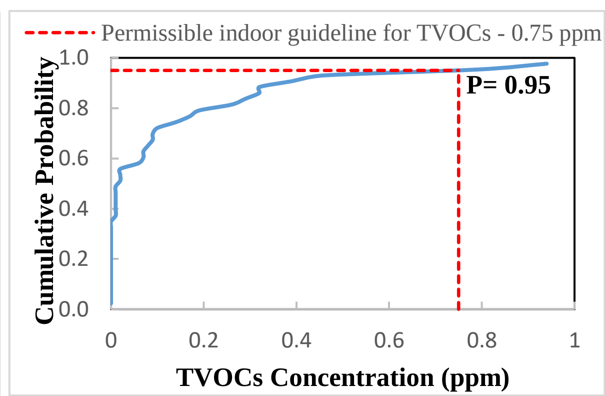


Figure 3.157: Empirical CDF of TVOCs from open waste burning- Dry leaves

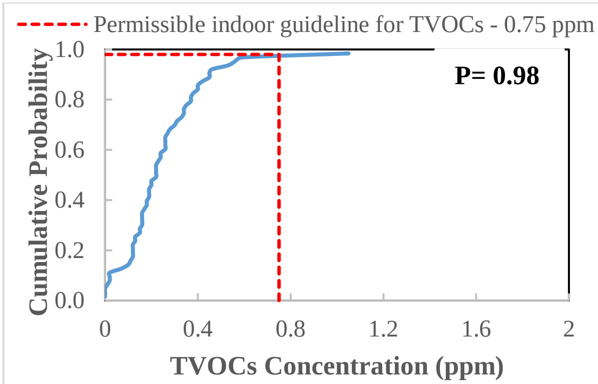


Figure 3.158: Empirical CDF of TVOCs from environmental tobacco smoke – Active smoking

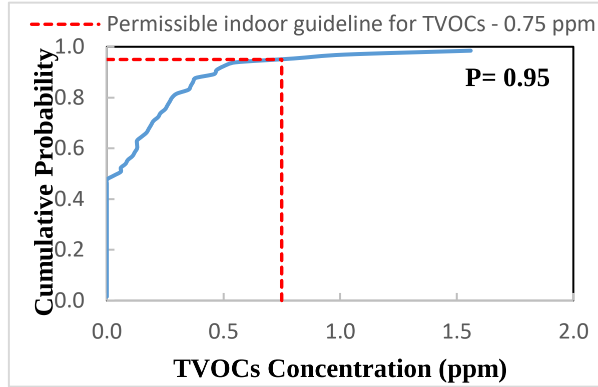


Figure 3.159: Empirical CDF of TVOCs from environmental tobacco smoke - Burning cigars

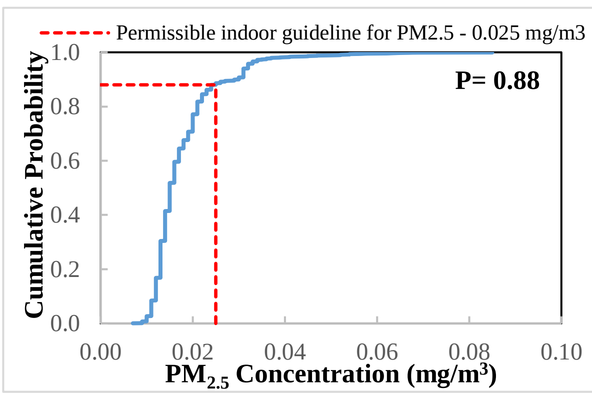


Figure 3.160: Empirical CDF of $PM_{2.5}$ from air freshener

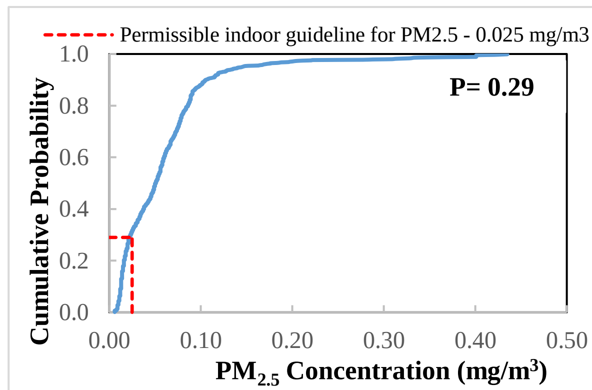


Figure 3.161: Empirical CDF of $PM_{2.5}$ from wall paint

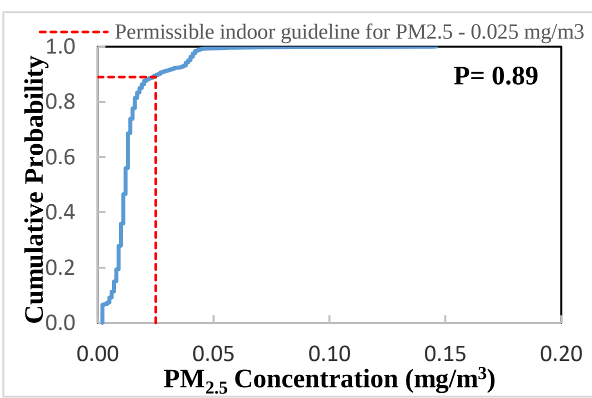


Figure 3.162: Empirical CDF of $PM_{2.5}$ from hospital theater- Day_1

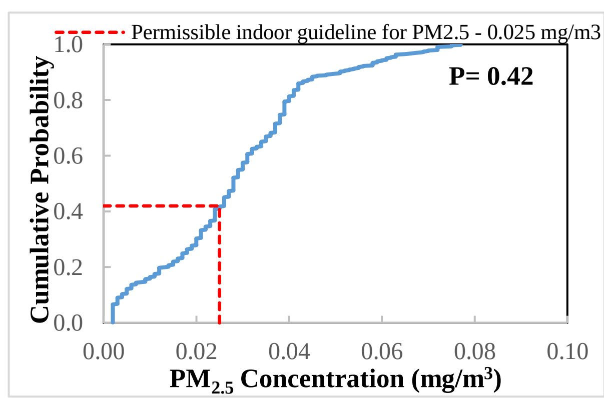


Figure 3.163: Empirical CDF of $PM_{2.5}$ from motor vehicle service center- Workshop

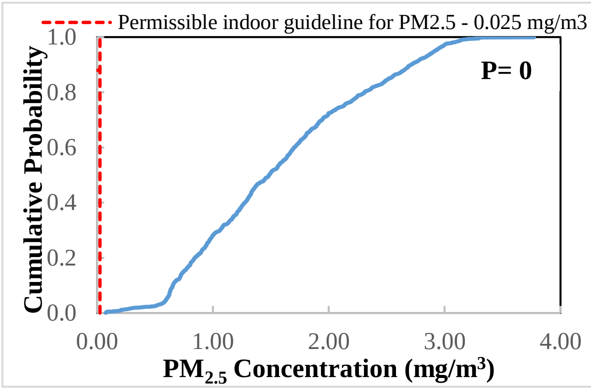


Figure 3.164: Empirical CDF of $PM_{2.5}$ from mosquito coil

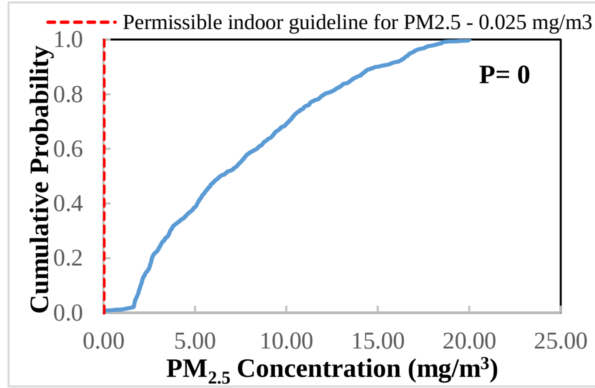


Figure 3.165: Empirical CDF of $PM_{2.5}$ from incense sticks

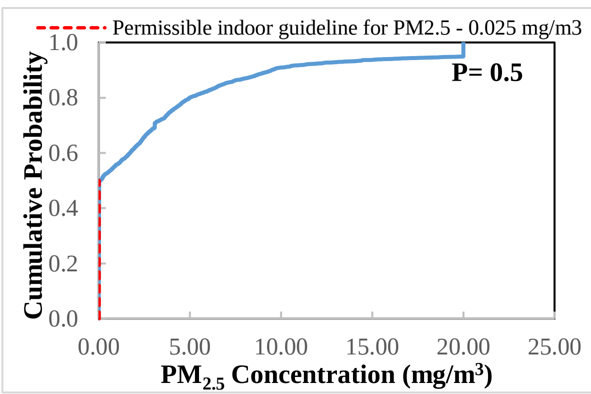


Figure 3.166: Empirical CDF of $PM_{2.5}$ from open waste burning- Dry leaves

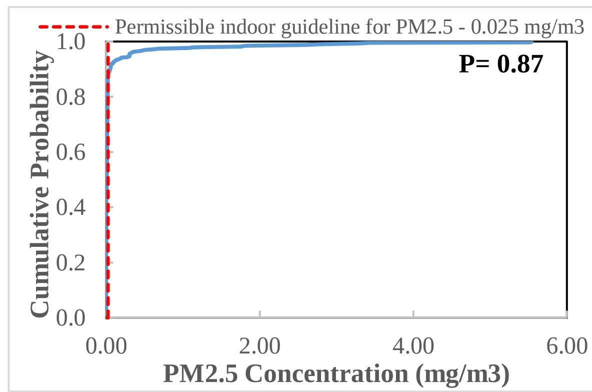


Figure 3.167: Empirical CDF of $PM_{2.5}$ from open waste burning- Polythene

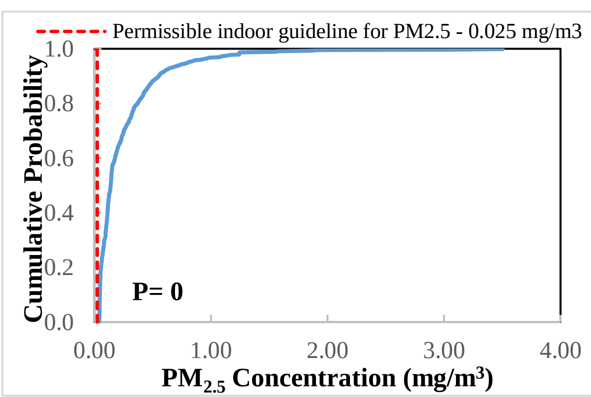


Figure 3.168: Empirical CDF of $PM_{2.5}$ from environmental tobacco smoke Burning cigars

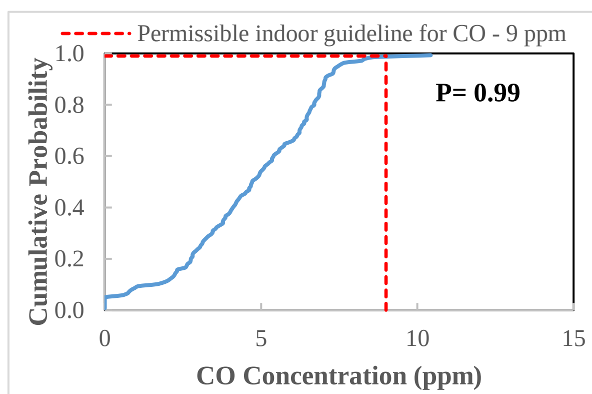
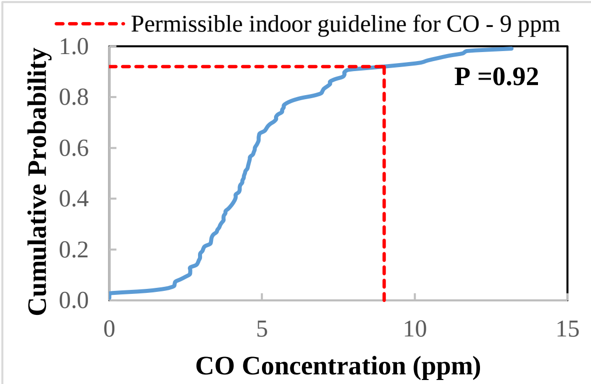


Figure 3.169: Empirical CDF of CO from mosquito coil



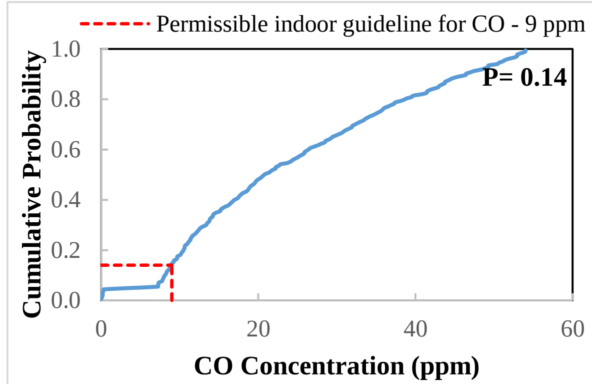
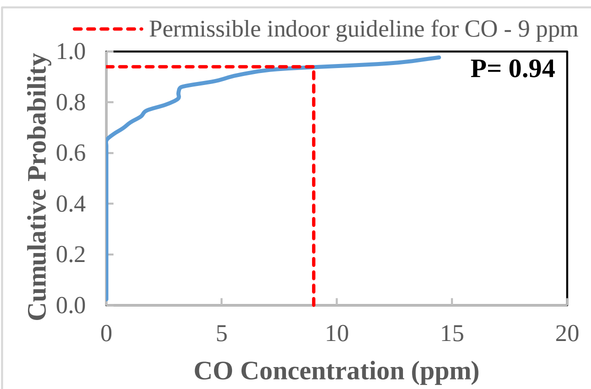


Figure 3.170: Empirical CDF of CO from naphthalene ball

Figure 3.171: Empirical CDF of CO from incense sticks burning



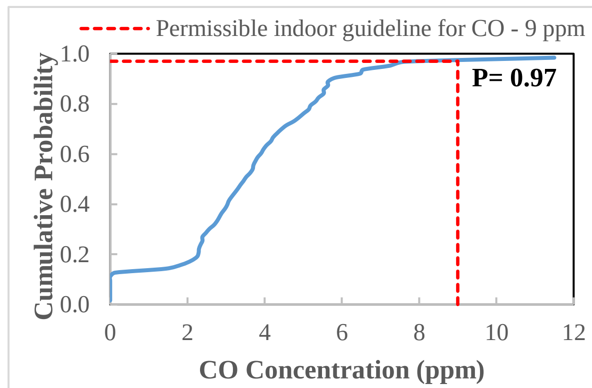
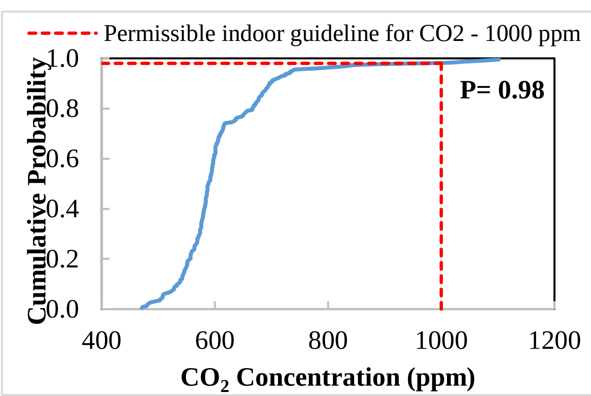


Figure 3.172: Empirical CDF of CO from open waste burning- Dry leaves

Figure 3.173: Empirical CDF of CO from environmental tobacco smoke – Smoking cigars



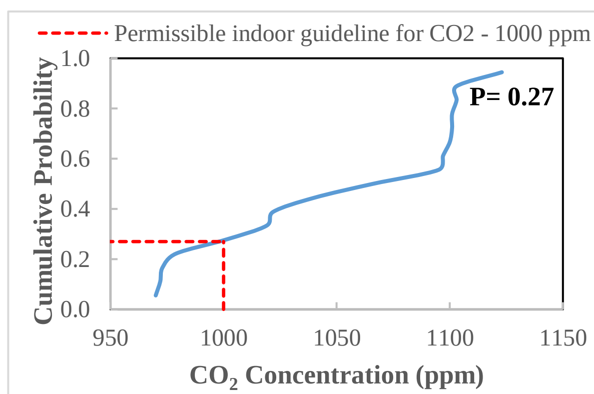


Figure 3.174: Empirical CDF of CO_2 from hospital theater- Day_1

Figure 3.175: Empirical CDF of CO_2 from motor vehicle service centre- Office

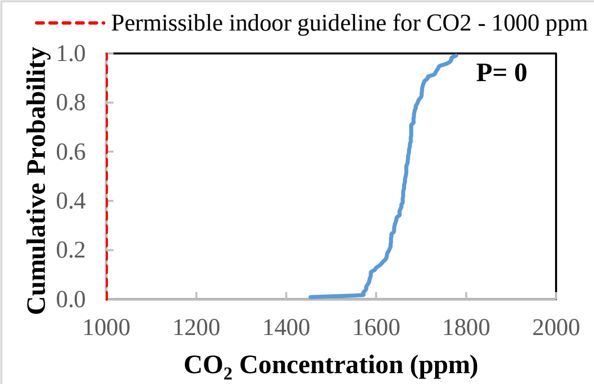


Figure 3.176: Empirical CDF of CO_2 from synthetic building materials- Location_02

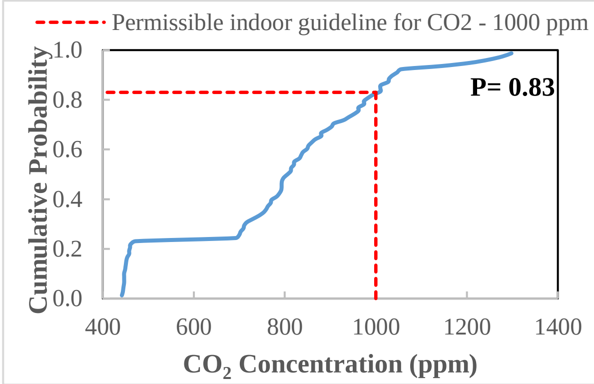


Figure 3.177: Empirical CDF of CO_2 from environmental tobacco smoke – Smoking cigars

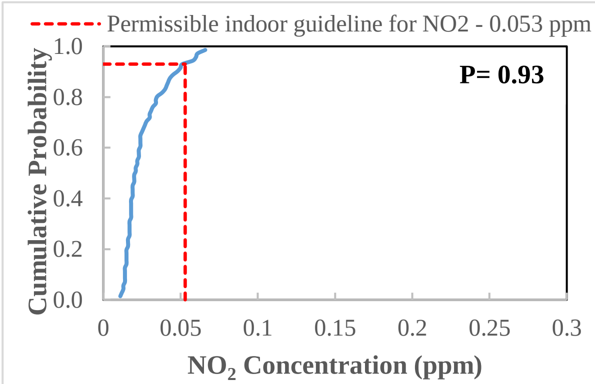


Figure 3.178: Empirical CDF of NO_2 from wall paint

A comparison of the results obtained from subsection 3.3.1 to 3.3.10 is carried out using the listed summary in Table 3.14, where the CDFs and occupant exposure parameters were derived to quantify the toxicity level of the sources for the selected pollutants. The pollutant dispersion until the indoor permissible value or the ambient condition was considered in Table 3.14 with the time-weighted average concentration of the pollutants during the experiments.

Table 3.14: Summary of the CDFs and occupant exposure parameters for the selected pollutants

Pollutant type (i)	Indoor source	(ii)	(iii)	(iv)	(v)	(vi)
TVOCs **(0.75 ppm)**	Air freshener	0.53	0.47	132 min	1.52 ppm	10.66 ppm
	Wall paint	0.32	0.68	244 min	14.61 ppm	45.58 ppm
	Hospital theatre- Day_03	0.79	0.21	104 min	1.12 ppm	40.31 ppm
	Motor vehicle service centre-Workshop	0.00	1.00	Refer "(vii)"	3.95 ppm	8.20 ppm
	Incense sticks	0.31	0.69	256 min	1.53 ppm	3.87 ppm
	Open waste burning -Dry leaves	0.95	0.05	2 min	0.12 ppm	0.94 ppm
	Environmental tobacco smoke-Active smoking	0.98	0.02	2 min	0.25 ppm	1.05 ppm
	Environmental tobacco smoke-Burning cigars	0.95	0.05	18 min	0.11 ppm	1.56 ppm
$PM_{2.5}$ (**0.025** mg/m^3)	Air freshener	0.88	0.12	35 min	0.012 mg/m^3	0.085 mg/m^3
	Wall paint	0.29	0.71	87 min	0.061 mg/m^3	0.435 mg/m^3
	Hospital theatre- Day_01	0.89	0.11	44 min	0.014 mg/m^3	0.146 mg/m^3
	Motor vehicle service centre-Workshop	0.42	0.58	Refer "(vii)"	0.029 mg/m^3	0.077 mg/m^3
	Mosquito coil	0.00	1.00	510 min	1.576 mg/m^3	3.772 mg/m^3
	Incense sticks	0.00	1.00	>19 hrs	7.55 mg/m^3	20 mg/m^3
	Open waste burning -Dry leaves	0.50	0.5	36 min	2.9 mg/m^3	20 mg/m^3
	Open waste burning - Polythene	0.87	0.13	15 min	0.087 mg/m^3	5.54 mg/m^3
	Environmental tobacco smoke-Burning cigars	0.00	1.00	180 min	0.249 mg/m^3	3.504 mg/m^3
CO **(9 ppm)**	Mosquito coil	0.99	0.01	2 min	4.57 ppm	10.43 ppm
	Naphthalene ball	0.92	0.08	26 min	4.91 ppm	13.17 ppm
	Incense sticks	0.14	0.86	310 min	24.2 ppm	54.02 ppm
	Open waste burning -Dry leaves	0.94	0.06	14 min	1.55 ppm	14.44 ppm
	Environmental tobacco smoke-Active smoking	0.97	0.03	2 min	3.61 ppm	11.5 ppm
CO_2 **(1000 ppm)**	Hospital theatre- Day_01	0.98	0.02	6 min	612 ppm	1102 ppm
	Motor vehicle service centre-Office	0.27	0.73	Refer "(vii)"	1117 ppm	1123 ppm
	Synthetic building materials-Location_02	0.00	1.00	330 min	1545 ppm	1778 ppm
	Environmental tobacco smoke-Active smoking	0.83	0.17	28 min	3.61 ppm	1298 ppm
NO_2	Wall paint	0.93	0.07	8 min	0.26 m	0.066 ppm

(i) Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)
(ii) Cumulative probability relevant to the indoor permissible value
(iii) Probability of exposure period beyond the indoor permissible value
(iv) Exposure period beyond the indoor permissible value ($EP_{>IPV}$)
(v) Time-weighted average of pollutant concentration (TWA)
(vi) Maximum concentration (Max C)
(vii) The measurements were taken over a period of 1 hour at each location of the motor vehicle service centre. Therefore, the results were only used to interpret the IAQ status inside the motor vehicle service centre as the diurnal variation of the pollutant concentration was not able to study during the experimentation.

With reference to the indoor sources of TVOCs in Table 3.14, the huge impact can be observed from the wall paint and incense sticks on the IAP. The occupant exposure period beyond the indoor permissible value is more than 4 hours for wall paint as well as for incense sticks. However, the time-weighted average concentration and maximum concentration of TVOCs for wall paint are much higher than those from incense sticks. Thus, wall paint can be chosen as the most significant source of indoor TVOCs among others.

Considering the variation of $PM_{2.5}$ concentration of the selected sources, the substantial influence on IAQ was noticed from the wall paint, mosquito coil, incense sticks, open waste burning (dry leaves) and environmental tobacco smoke (burning cigars) resulting in an adverse environmental exposure for the occupants. Although the maximum effect on indoor particulate pollution has occurred from the incense sticks, the contribution of the aforesaid other sources could not be negligible due to their long exposure period and high-level of maximum concentration recorded in the experiments.

According to the results of the other pollutants, remarkable consequences on IAQ was reported for incense sticks from the CO concentration. Further to that, the measurements carried out in the "Synthetic building materials" were interpreted that the time-weighted average concentration of CO_2 is beyond the permissible indoor guideline defined by ASHRAE. However, the measured CO_2 concentration was identified as not from the synthetic building materials emission and it is due to the high occupant density during the operational period. The wall paint was the only source of indoor NO_2 that exceeded the pertain indoor air quality guideline during the study.

Based on the comparison of the indoor sources on IAP, the wall paint and incense sticks burning can be determined as the most influential sources on IAP since the other sources were dominated only for the one pollutant type exceeding its permissible indoor value.

The wall paint is an essential building material in construction and operational periods, and it cannot be avoided during any stage of the building, although the only possibility is to improve the technology to minimize its effect on IAQ. Moreover, the present regulations do not require disclosure of all the ingredients of wall paint, even if there is sufficient evidence to witness its toxicity on human health. However, the incense sticks burning can be used in the outside or in the indoor spaces which are opened to the outdoors. As per in Section 3.3.8, twenty numbers of incense sticks were burnt under the minimum ventilation condition with the high intensity of incense smoke simulating the air quality inside a religious place rather than that for residential places. Thus, the impact of incense burning in residential, commercial, and public buildings would not be much significant as the obtained results for incense sticks burning in the preliminary study. Lack of awareness is a common fact for both types of sources concerning the Sri Lankan context. Considering the severity of the concentration and the application of the sources in the buildings, wall paint has been selected for the detailed analysis with different ventilation conditions.

3.4 Effect of outdoor sources on indoor air quality

As elaborated in Section 3.1, the effect of outdoor sources on IAQ was investigated by monitoring the parameters inside a building which is in close vicinity to a construction site. The project was in the late stages of its construction, where the main tasks that were carried out were related to its finishes.

IAQ was measured inside the building which is located close to the ongoing construction project in the University of Moratuwa. The selected building was an empty building without any goods inside. Thus, there were no other sources of indoor air pollution other than the effect from the outdoor source under consideration. The plan view of the test chamber is presented in Figure 3.179 below. Initially, ventilation condition is natural during this experiment, and afterward, mechanical ventilation means were used to artificially improve the indoor environment. The different ventilation conditions, which were maintained in the experiment is described in Table 3.15.

Table 3.15: Different ventilation conditions maintained in the experiment on outdoor sources

Ventilation condition	Description
VC1	All windows are closed
VC2	Windows are 50% opened
VC3	All windows are opened
VC4	All windows are opened+ Fan is in operation

Experiments were carried out in two days and the results are plotted in Figure 3.180 to 3.193.

Figure 3.179: Plan view of the test chamber used for the experiment on outdoor sources on IAQ (All the dimensions are in meters)

The measured IAQ parameters have interpreted that the very similar pattern of variation of CO, NO_2, CO_2 and TVOCs in two different days. The concentration of CO, CO_2 and TVOCs values did not vary with the ambient condition, whereas the NO_2 concentration is slightly above the base case as shown in Figure 3.181 and 3.188. The $PM_{2.5}$ concentration has been identified as the most dominant pollutant type related to this experiment, as there is a significant effect of its variation with time, where its maximum values are varying from 0.2- 0.5 mg/m^3. It is clearly portrayed in Figure 3.184 and 3.191, $PM_{2.5}$ concentration was almost in the surrounding condition during the initial period of the experiment, their outdoor air supply was restricted by closing all the windows. However, the concentration of $PM_{2.5}$ was recorded above its indoor permissible value when the supply of outdoor air into the indoors. Thus, it can be concluded that the increase of $PM_{2.5}$ is certainly due to the infiltration of polluted outdoor air into the test chamber. This can be further justified by the results obtained by Stamatelopoulou et.al in 2019, where they identified an enhanced proportion of particulate matter in residences near roadwork sites and renovation activities (Stamatelopoulou, Asimakopoulos, & Maggos, 2019). However, temperature and RH did not show any difference in the variation during the experiment.

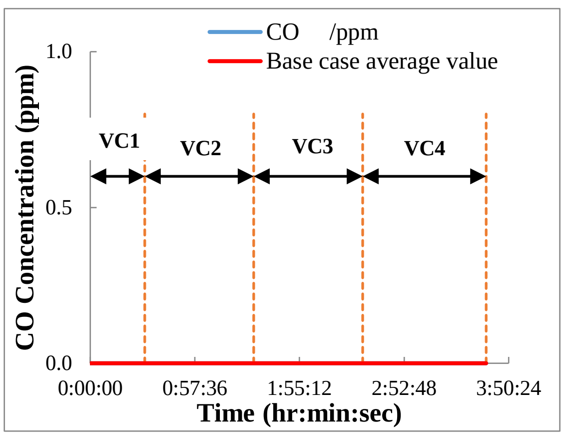


Figure 3.180: CO variation- Outdoor source (Day-01)

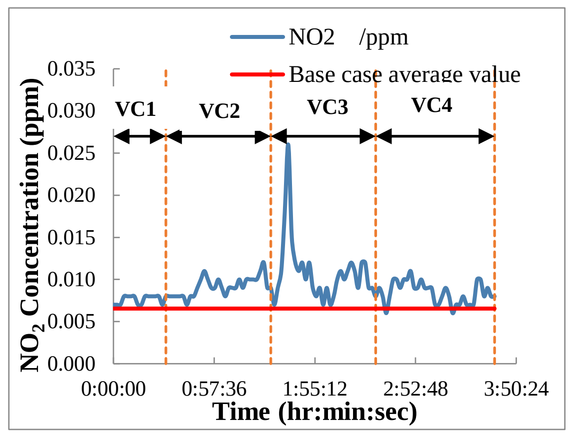


Figure 3.181: NO_2 variation- Outdoor source (Day-01)

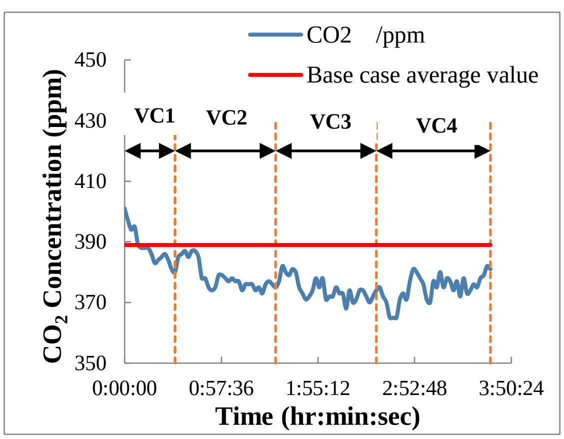


Figure 3.182: CO_2 variation- Outdoor source (Day-01)

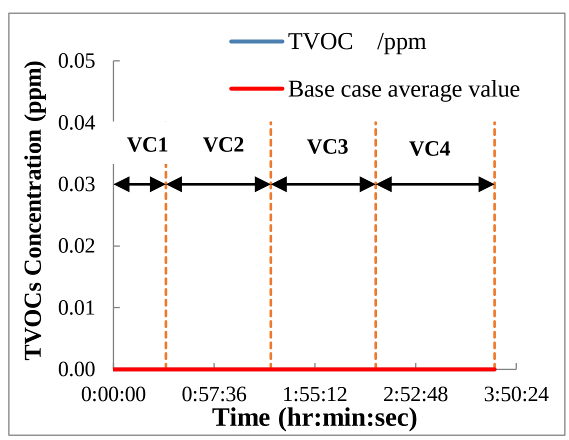


Figure 3.183: TVOCs variation- Outdoor source (Day-01)

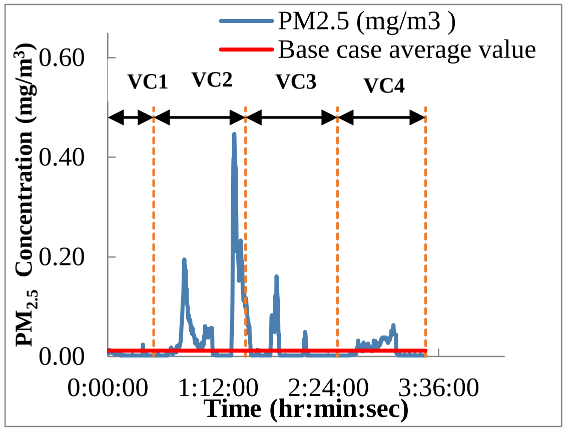


Figure 3.184: PM2.5 variation- Outdoor source (Day-01)

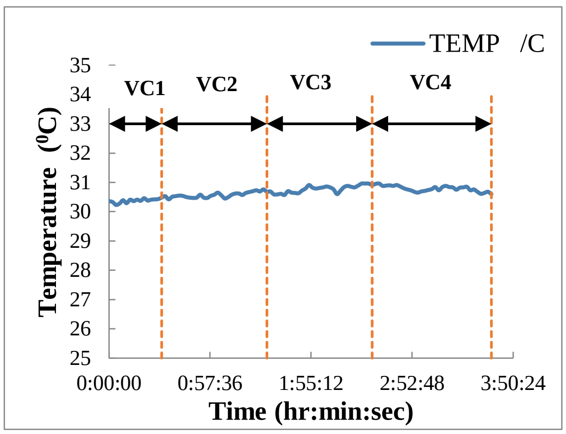


Figure 3.185: Temperature variation- Outdoor source (Day-01)

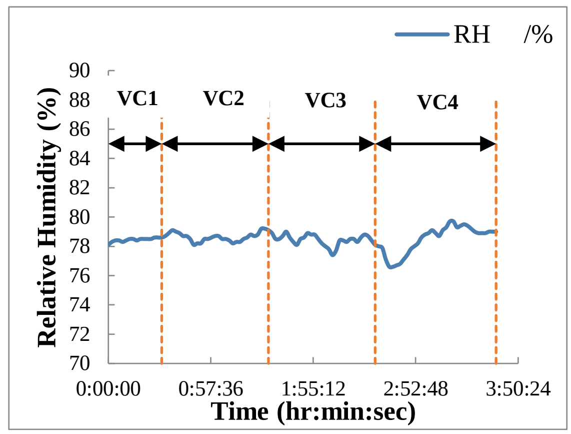


Figure 3.186: RH variation- Outdoor source (Day-01)

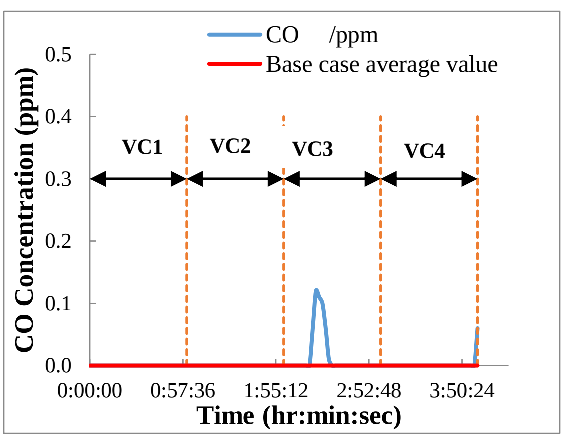


Figure 3.187: CO variation- Outdoor source (Day_02)

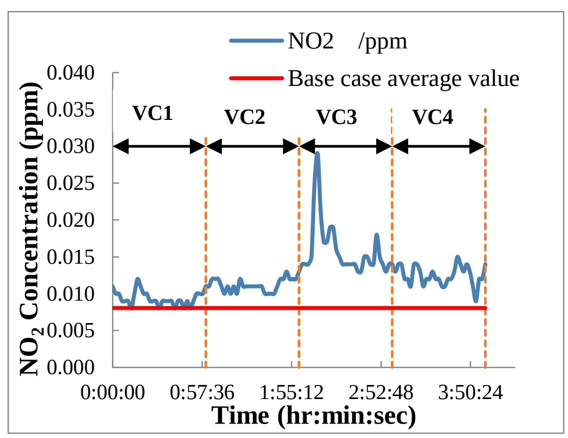


Figure 3.188: NO_2 variation- Outdoor source (Day-02)

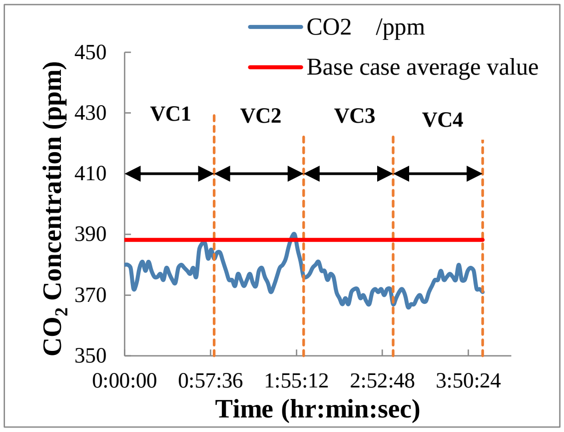


Figure 3.189: CO_2 variation- Outdoor source (Day_02)

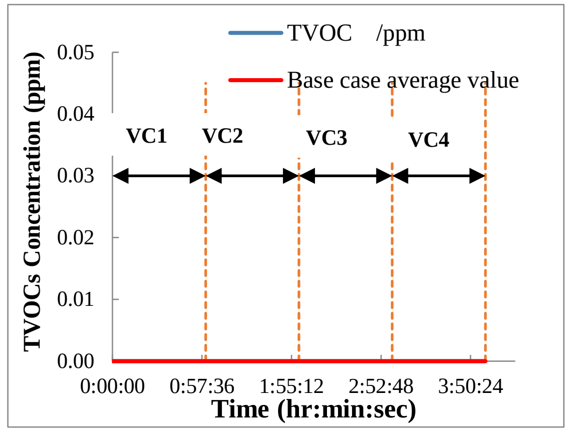


Figure 3.190: TVOCs variation- Outdoor source (Day-02)

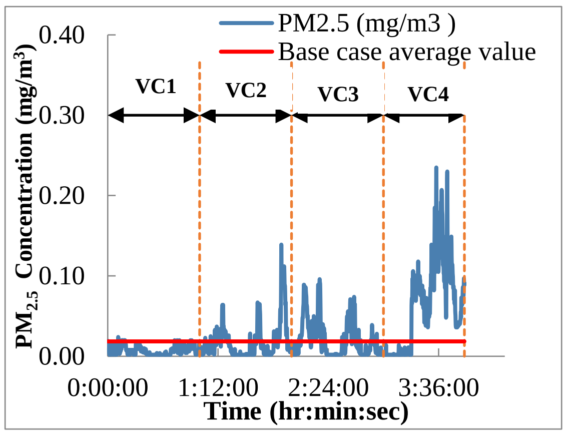


Figure 3.191: $PM_{2.5}$ variation- Outdoor source (Day-02)

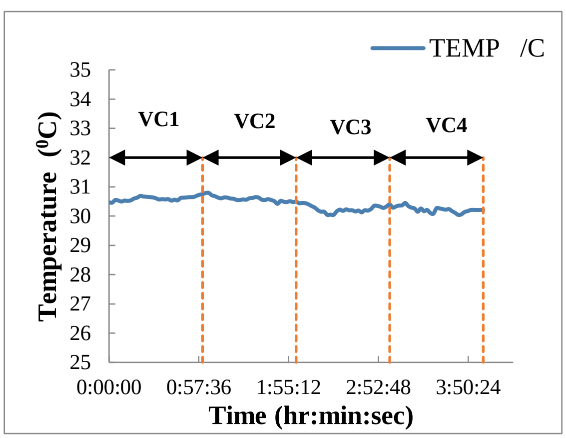


Figure 3.192: Temperature variation- Outdoor source (Day_02)

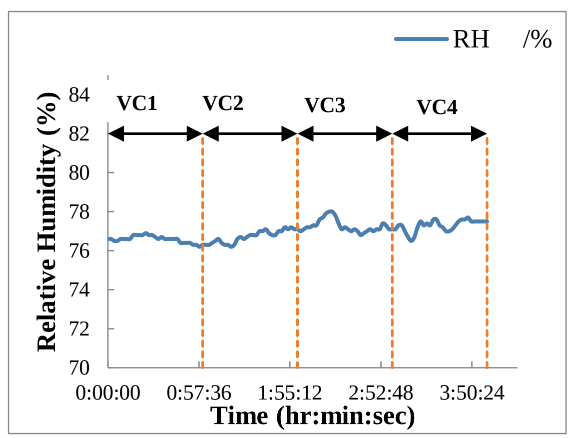


Figure 3.193: RH variation- Outdoor source (Day_02)

The summary of the above experiments on outdoor sources is presented below in Table 3.16.

Table 3.16: Summary of the experimental results- Outdoor sources

Name of the causative agent	**Day_01**		**Day_02**		**(iii)**
	(i)	**(ii)**	**(i)**	**(ii)**	
CO (ppm)	0	-	0.12	-	0
NO_2 (ppm)	0.026	-	0.029	-	0.01
CO_2 (ppm)	401	-	390	-	390
TVOCs (ppm)	0	-	0	-	0
$PM_{2.5}$ (mg/m^3)	0.447	48 min	0.235	76 min	0.011
Temperature (^{0}C)					29-30
RH (%)					77-78

(i) Maximum concentration

(ii) Exposure time beyond the permissible indoor limit (**Note 01**)

(iii) Base case average value

Note 01: Permissible exposure limits; CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

3.5 Summary

In this chapter, numerous pollutant sources and human practices were measured in order to quantify their effect on IAQ. The selection of these pollutant sources was done by considering the literature review and their frequency of usage among the general public in the course of days. TVOCs and $PM_{2.5}$ have been identified as the most critical causative agents which were emitted from many of the selected indoor air polluting sources. Air freshener, wall paint, incense sticks and IAQ in hospital theatre and motor vehicle service centre have been recorded the highest values of TVOCs and exposure period exceeding the pertain indoor guidelines for a considerable time period. Including the above building materials and practices, mosquito coil, dry leaves burning, and environmental tobacco smoke have also contributed to increase in the concentration of $PM_{2.5}$ drastically. The huge impact was observed from the elevated concentration of CO, which is generated from naphthalene ball and incense sticks during the process of partial burning. The IAQ measurements carried out in different locations with synthetic building materials have revealed a high concentration of CO_2 in all the places due to the high population density with the poor ventilation condition. Empirical CDF was used to analyses the data obtained for the toxicity of pollutants from selected sources and, the probability of exposure period beyond the indoor permissible value has also been considered as a criterion for the comparison. The results analysis and the application of the sources were led to choose the "Wall Paint" as the most controversial source on IAP out of the others. The effect of outdoor sources on IAQ was studied and realized its impact on IAP, to maintain a desirable ventilation condition for healthy indoor environments.

The detailed analysis of wall paint on IAQ will be discussed in the upcoming chapters.

CHAPTER 4: QUESTIONNAIRE SURVEY ON OCCUPANT COMFORT AND IAQ RELATED HEALTH IMPACTS

4.1 General

Questionnaire Survey (QS) was conducted to study the occupants' perception of the built environment as well as their symptoms related to SBS. The main purpose of this study is to evaluate the satisfaction of the occupants with the indoor environment that they reside and obtain an idea of their reviews on the level of comfort with the building condition. For the differentiation of sample types along with the objectives of this research, paint has been selected for the detailed study with different ventilation conditions. IAQ was measured simultaneously while the QS was ongoing for the better representation and analysis of survey data. Equally, this facilitates finding out the relationship between indoor air pollutants and the symptoms related to SBS. The effect of ventilation condition was also assessed from the IAQ measurements at each location.

4.2 Details of the questionnaire survey

QS was conducted in four sample locations, defined based on prevailing building material and ventilation conditions. In order to isolate the effect of paint from other building materials, QS was carried out in old buildings which were constructed with conventional building material. As mentioned above, IAQ measurements were taken at every location while the QS was ongoing.

The selection of the sample locations was done with due care to maintain the consistency of data collection during the QS. Accordingly, the building type, number of respondents, population density, potential pollutant sources and ventilation condition were considered during their selection. As in Table 4.1, QS was conducted in office and educational buildings, whereas the recreational building was used to identify the effect of ventilation condition on IAQ, as described in Section 3.1. The number of respondents was in the same range. Thus, the percentage of the respondents can be used to interpret the results obtained from QS. Further elaboration on sample selection is presented in Figure 4.1.

Table 4.1: Details of the selected locations for questionnaire survey

Details related to QS	Sample Name				
	A	B	C	D	E
Building type	Office	Office	Educational	Educational	Recreational
Number of respondents	23	24	23	21	-
Population density (m^2/ person)	4.5	5	6	8.3	-
Potential pollutant sources	SBM, CF, PP, C, IVC, NPA	SBM, CF, PP, C	SBM, TF, PP, C, NPA	SBM, CF, PP, C	SBM, CF
Ventilation condition	Air-conditioned with poor maintenance	Air-conditioned with poor maintenance	Air-conditioned environment	Naturally ventilated environment	An improved air-conditioned system with fresh air recharge

SBM- Synthetic building materials (fabric chairs, partition boards, blinds, new MDF furniture, etc.), **CF**- Carpeted floor, **TF-** Tiled Floor, **PP**- Photocopiers and printers, **C-** Computers, **IVC-** Inadequate ventilation condition, **NPA-** Newly painted area (One month before the experimentation)

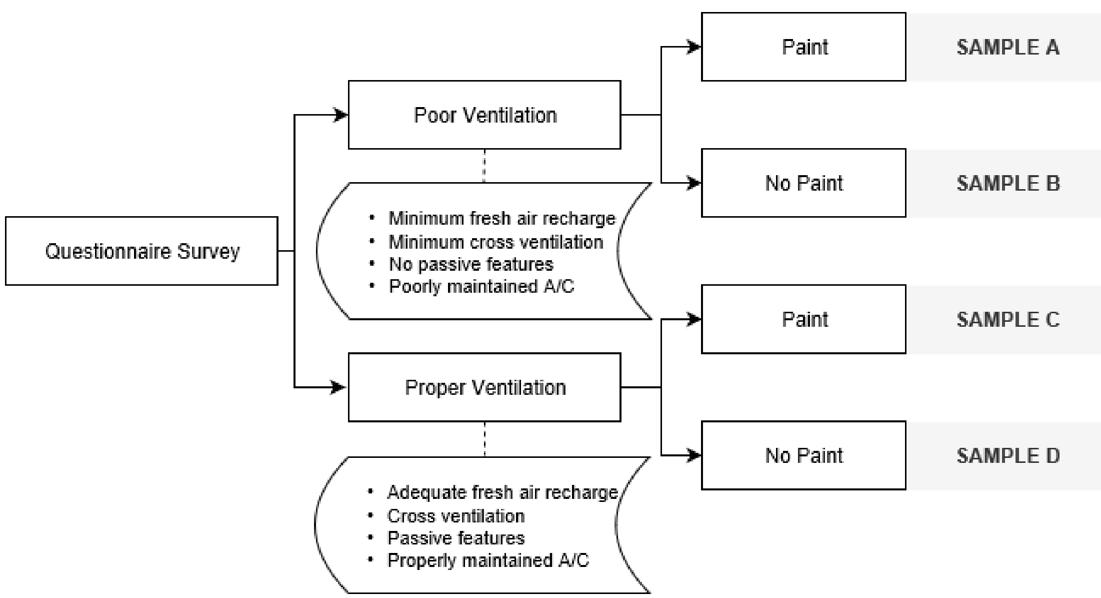


Figure 4.1: Structure of the questionnaire survey

All the above samples are located with no outdoor polluting sources in the near vicinity. Thus, all these had a similar quality of ambient air. The table below (Table 4.2) represents the average concentrations of causative agents in ambient air.

Table 4.2: Average concentrations of causative agents in ambient air

Name	**Average concentration**
CO (ppm)	0
NO_2 (ppm)	0.04
CO_2 (ppm)	290
TVOCs (ppm)	0
Temperature (^{0}C)	28.4 ^{0}C-29.2
Relative Humidity (%)	74.5 %-76.7

4.3 Questionnaire survey template

The questionnaire survey template was prepared in a way of collecting data such as, personal details, medical symptoms and respondents' perception of symptoms existence, suspected sources, and the time of the day when they feel less comfortable, etc. The template consists of two pages, which are presented in Figure D1 and D2 of Annex D. The recorded data were converted into meaningful facts and they are discussed in Section 4.4.

4.4 Results of the questionnaire survey

The response rate of QS was presented in Figure 4.2 and it is > 90% in all four samples by fulfilling the requirement of response rate > 80% defined by American Journal of Pharmaceutical Education (Fincham, 2008). The rate of validity is 95% in sample A, while the other three samples express 100%.

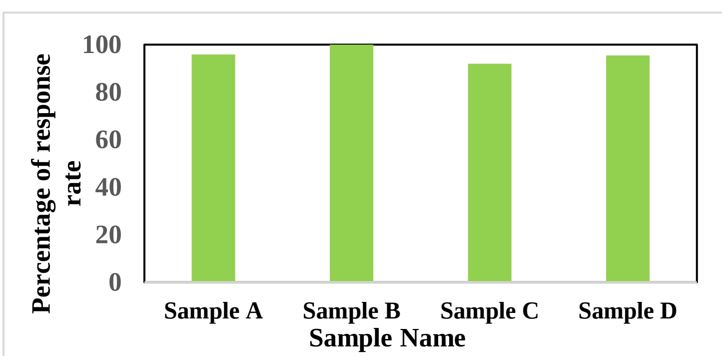


Figure 4.2: Response rate of the questionnaire survey

As in Figure 4.3, the respondent's age group distribution has an arithmetic mean value of 30 as the target group in based on office and educational buildings.

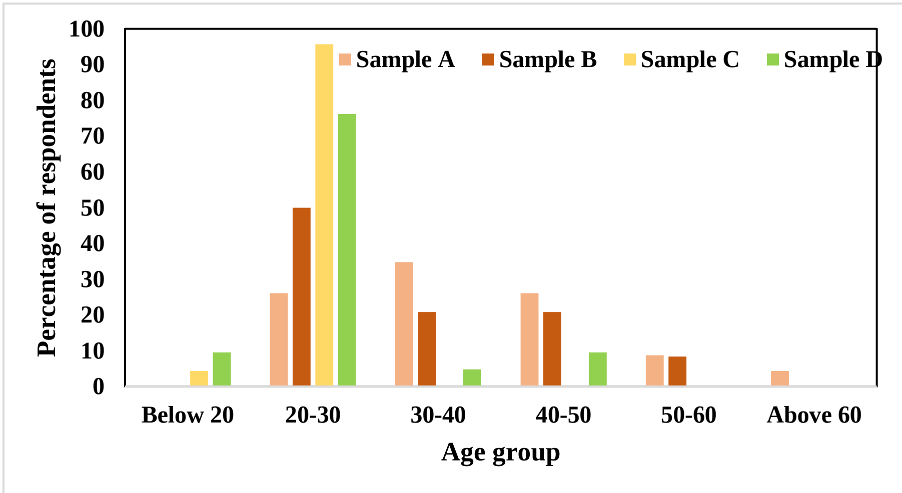


Figure 4.3: Respondent's age group distribution

Gender distribution illustrated in Figure 4.4 has established the equal distribution in male and female of the overall result in an accidently that could lead to conclude the decisions irrespective of the gender of the targeted group (Male 48% and Female 52 %).

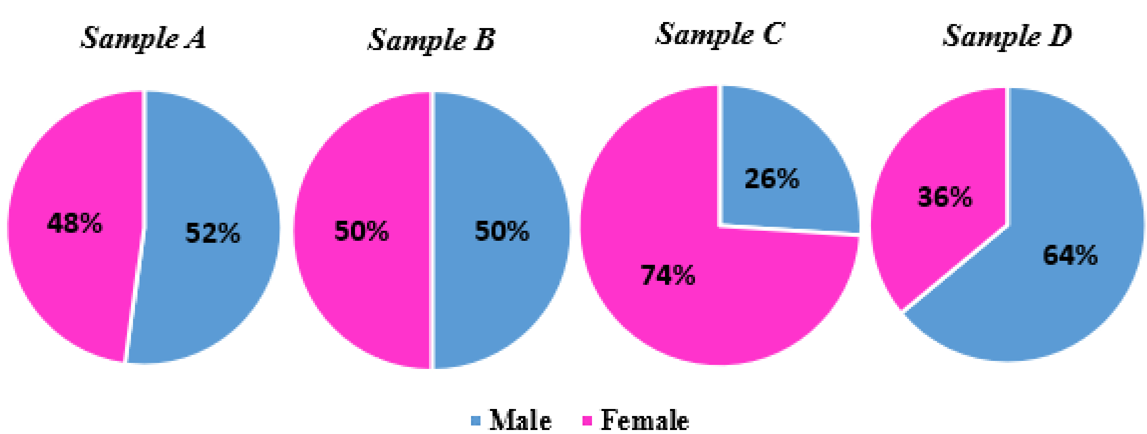


Figure 4.4: Respondent's gender distribution

The symptom existence among the respondents is plotted in Figure 4.5. According to the comparison of results with respect to the samples, Sample D has the lowest percentage in the response of the symptom existence as the presence of good ventilation with no paint condition. The highest percentage was recorded in Sample A, in an office with very poor ventilation condition and the newly painted area which is applied one month prior to the experiment. Considering all four samples, it has been identified as the most common type of symptoms as sleepiness, headache, and thermal discomfort among the targeted group of people. However, Sample A and C exhibited the odour/ smell and shortness of breath as the common symptoms in greater extend, which are only specific to those two samples. Moreover, the percentage of complaints related to eye and throat irritation are also under consideration as it is moderately particular to these two samples.

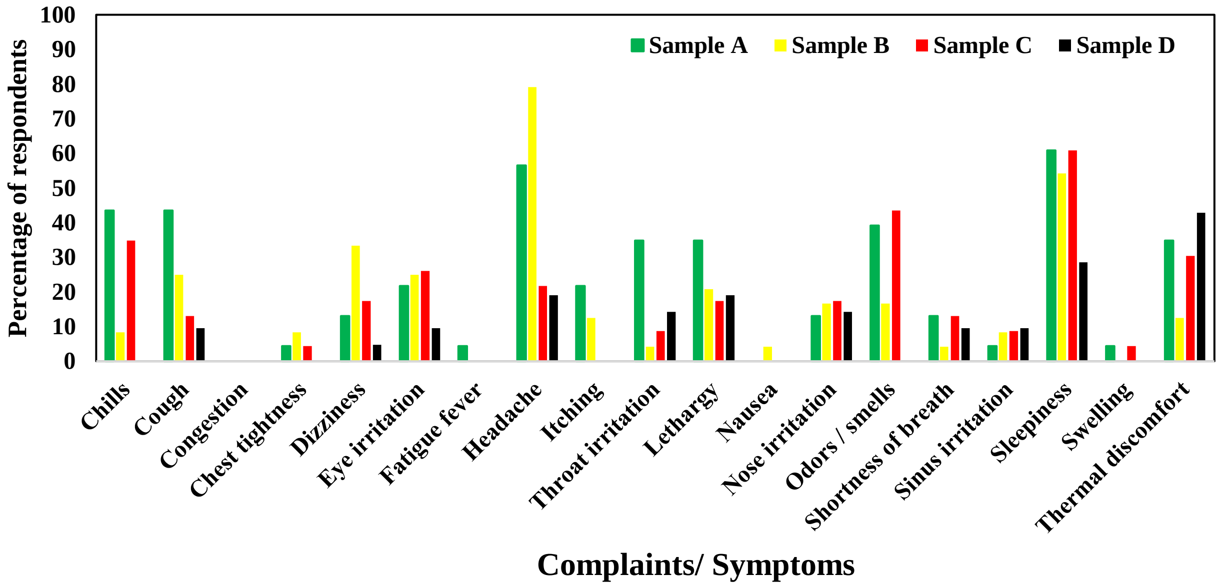


Figure 4.5: Percentage of responses vs Complaints/ Symptoms

As in Figure 4.6, 90% of the average in samples A, B and C realized that the above symptoms are occurred due to the indoor environment. In sample D, many of the respondents did not feel any discomfort (19 % of its sample size) while they are in the indoor environment and thus, their percentage of perception about symptom existence due to the indoor environment is 67%. Hence, it can be concluded that many of the symptoms which are presented in Figure 4.5, are related to the indoor environment, emphasizing Sample A, B and C are as sick buildings.

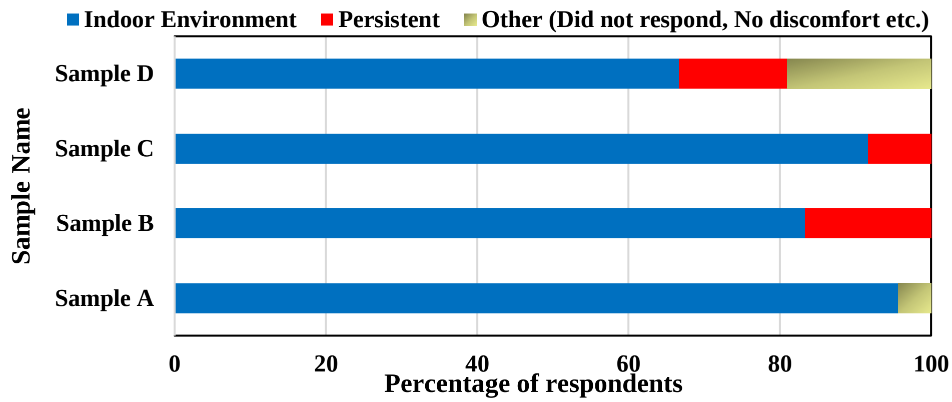


Figure 4.6: Respondent's perception of symptom existence

The respondent's perception about the time of the day when they feel discomfort is presented in Figure 4.7. The results revealed that many of the occupants experienced discomfort while they are inside the room, although some of them were replied that they got the above symptoms just after the exposure as well as the indoors. However, Sample A and B were reported that these symptoms were persisted for some period, even after leaving the room.

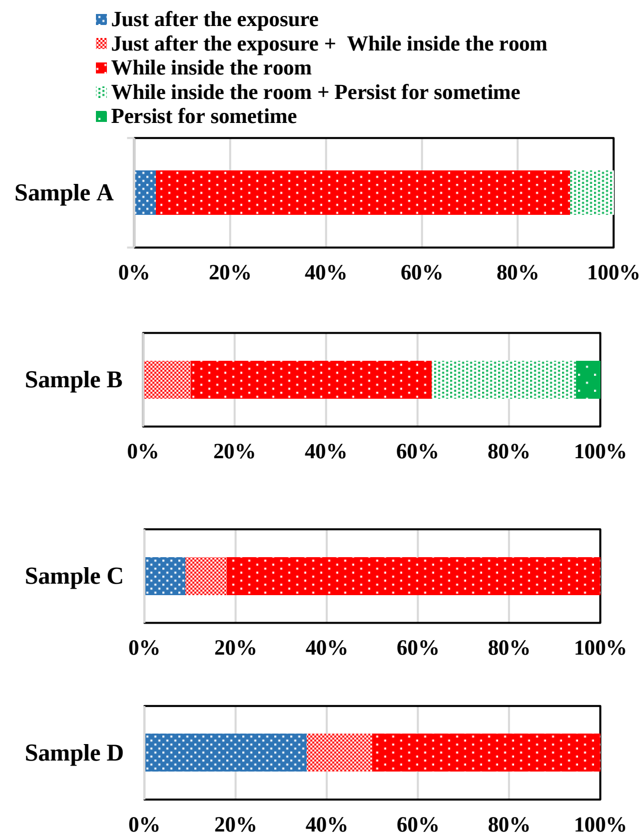


Figure 4.7: Respondent's perception about the time of the day when they feel discomfort-Sample A, B, C and D respectively

4.5 Indoor air quality of selected locations

With reference to Figure 4.1, the measurements were taken under four different conditions which are namely samples A, B, C and D. IAQ parameters were taken at each place at least two times in two consecutive days to make sure the results are not due to any special circumstances. After obtaining a clear understanding of the level of indoor air pollutants, the graphs have been plotted using the most average scenario. This section will reveal the determinants of the experiments conducted under each sample of its respective locations. The base case is derived from the average value of the causative agents outside the building over the period of one hour and it is marked on each graph which are presented below.

<u>Sample A</u>

In this sample, IAQ was measured at three different locations, namely, A_1, A_2 and A_3. The locations were defined by considering the activity spaces in order to cover a large floor area. It is important to note that there were some synthetic building materials present in these locations as well. IAQ monitor was utilized to obtain the air quality parameters that are shown in the graphs from Figure 4.8 to 4.13 in location A_1, Figure 4.14 to 4.19 in location A_2 and Figure 4.20 to 4.25 in location A_3 of the Sample A. The floor plan view is presented in Figure B1-i in Annex B. The summary of the IAQ parameters are listed in Table 4.3.

<u>Location A_1</u>

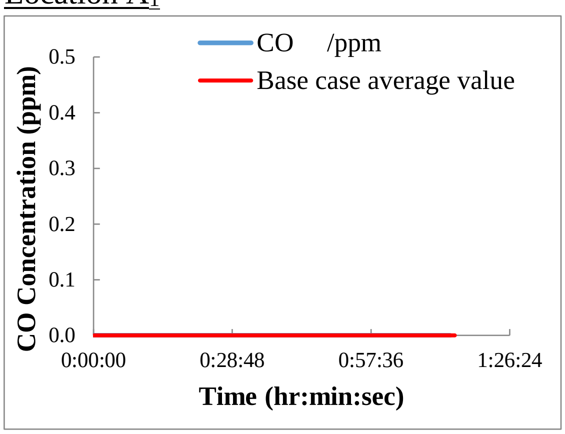


Figure 4.8: CO variation- Sample A (Location A_1)

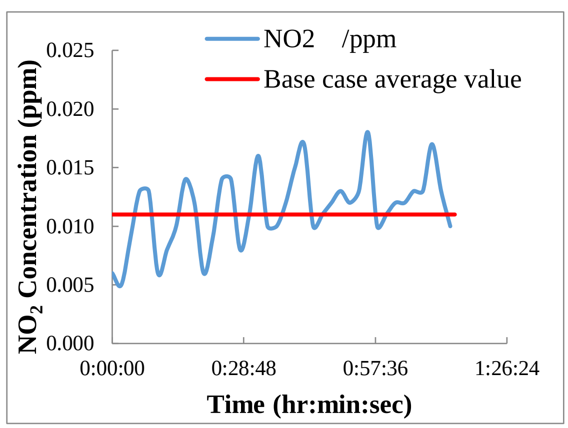


Figure 4.9: NO_2 variation- Sample A (Location A_1)

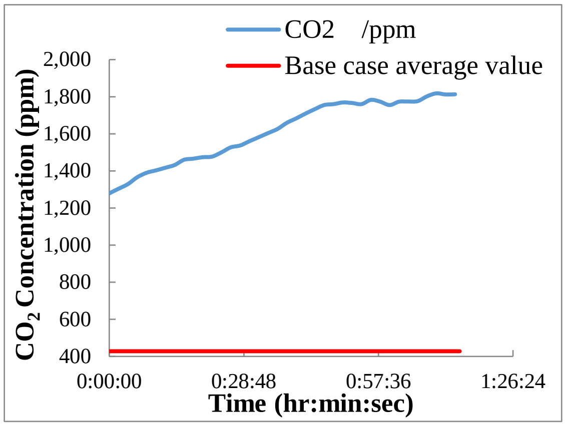


Figure 4.10: CO_2 variation- Sample A (Location A_1)

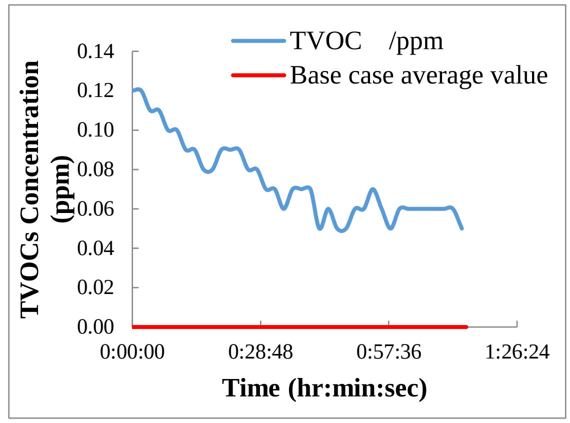


Figure 4.11: TVOCs variation- Sample A (Location A_1)

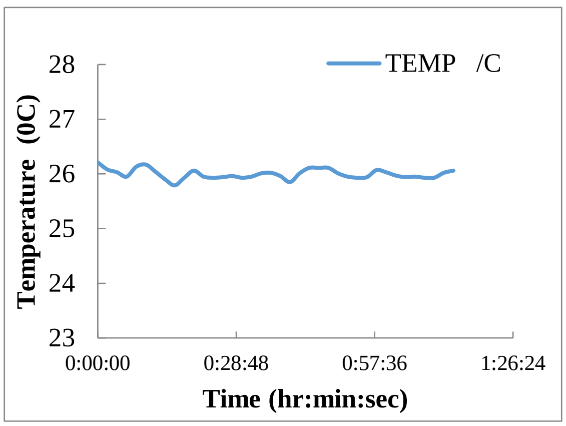


Figure 4.12: Temperature variation- Sample A (Location A_1)

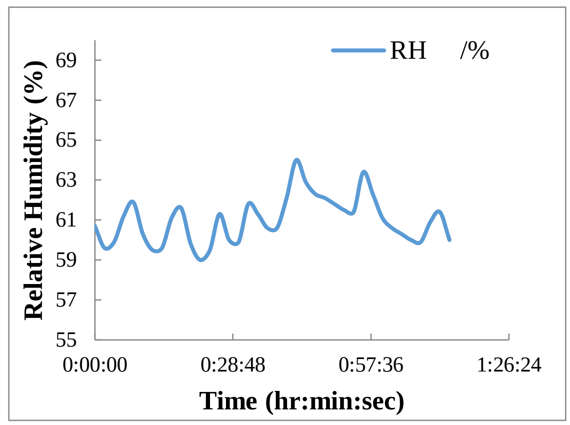


Figure 4.13: RH variation- Sample A (Location A_1)

<u>Location A_2</u>

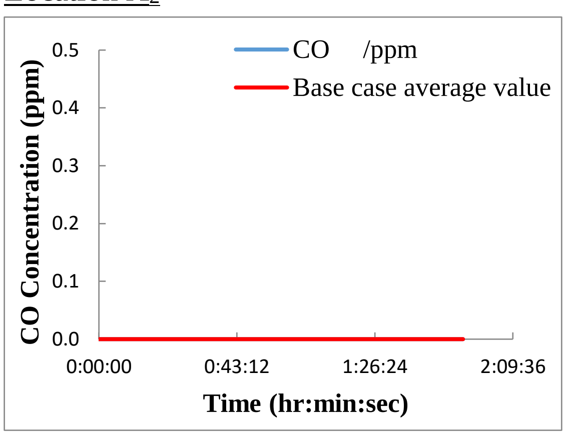


Figure 4.14: CO variation- Sample A (Location A_2)

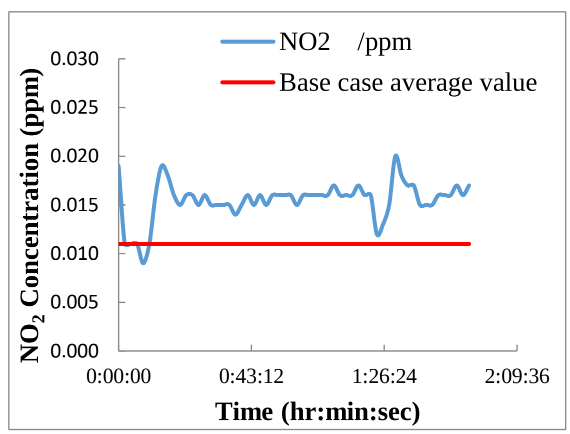


Figure 4.15: NO_2 variation- Sample A (Location A_2)

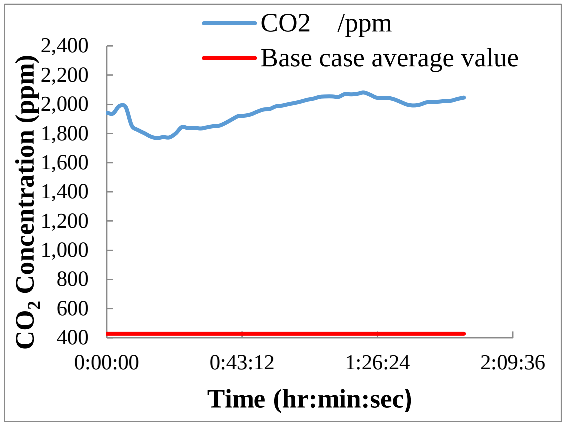


Figure 4.16: CO_2 variation- Sample A (Location A_2)

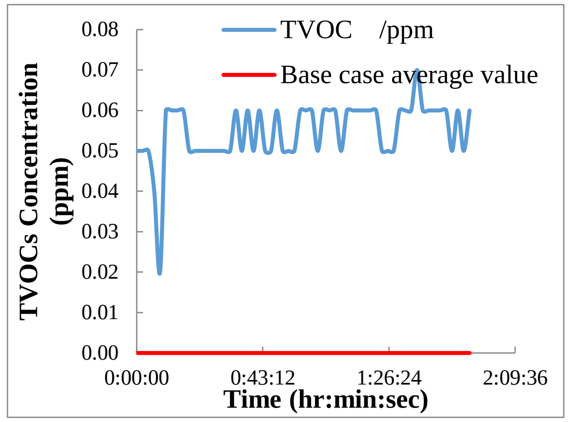


Figure 4.17: TVOCs variation- Sample A (Location A_2)

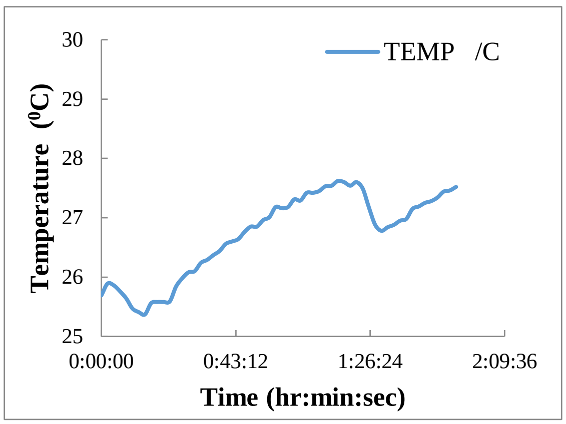


Figure 4.18: Temperature variation- Sample A (Location A_2)

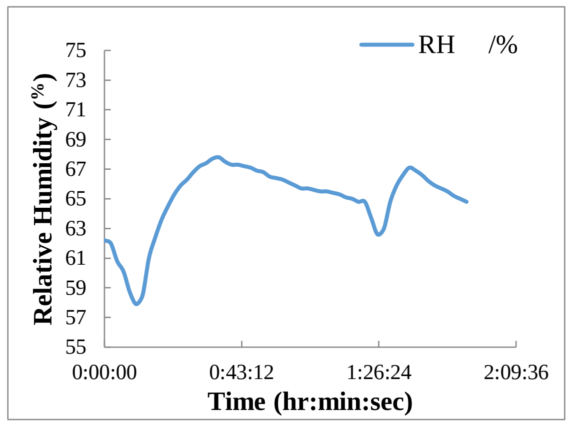


Figure 4.19: RH variation- Sample A (Location A_2)

Location A_3

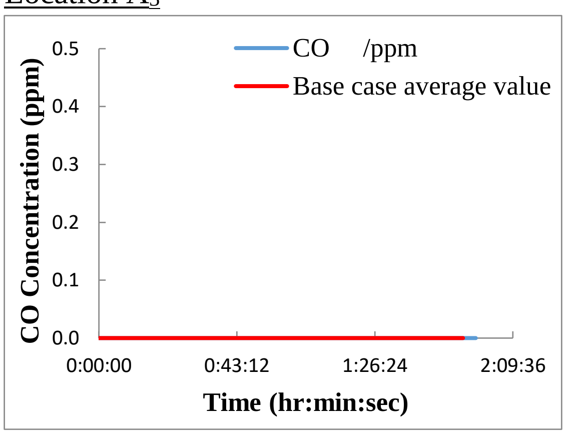


Figure 4.20: CO variation- Sample A (Location A_3)

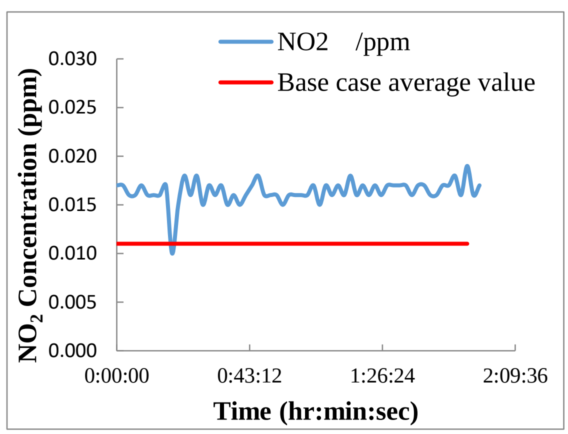


Figure 4.21: NO_2 variation- Sample A (Location A_3)

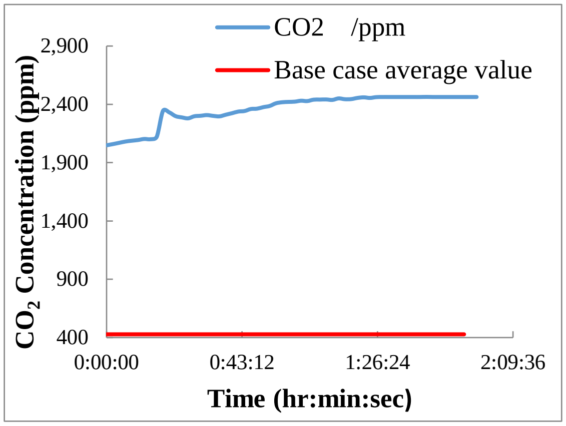


Figure 4.22: CO_2 variation- Sample A (Location A_3)

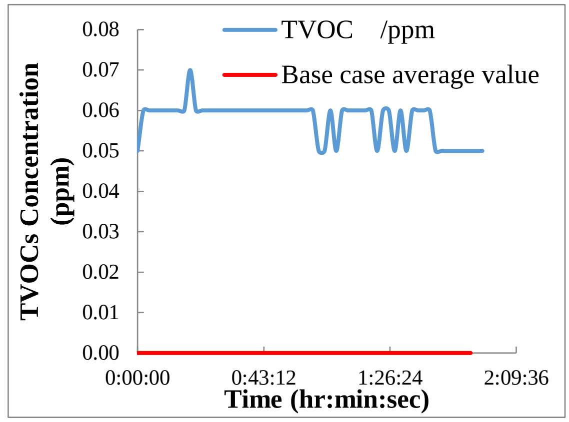


Figure 4.23: TVOCs variation- Sample A (Location A_3)

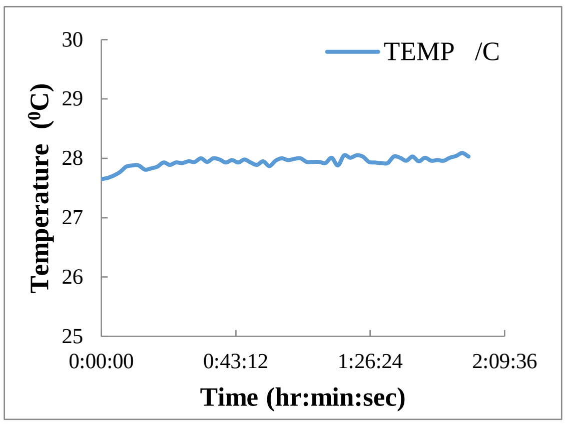


Figure 4.24: Temperature variation- Sample A (Location A_3)

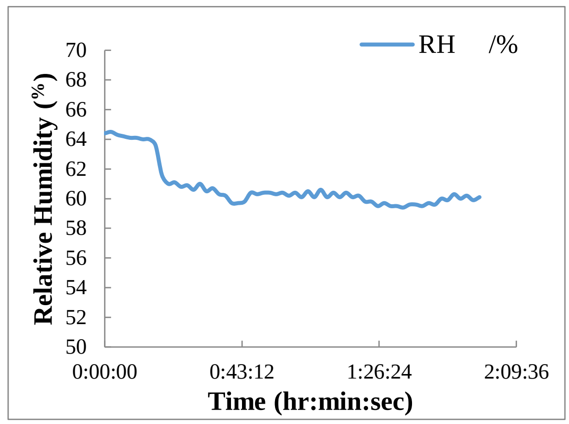


Figure 4.25: RH variation- Sample A (Location A_3)

<u>Sample B</u>

Under this scenario, QS was conducted in five different places namely, B_1, B_2, B_3, B_4 and B_5 which have not been recently painted. Ventilation condition could be considered as inadequate under the poor maintenance in the air conditioners and the presence of synthetic building material were also evident. The floor plan view of each location is attached in Annex B, from Figure B1- ii to B1- vi.

The results are presented in the graphs from Figure 4.26 to 4.31 in location B_1, Figure 4.32 to 4.37 in location B_2, Figure 4.38 to 4.43 in location B_3, Figure 4.44 to 4.49 in location B_4

and Figure 4.50 to 4.55 in location B_5 of the Sample B. The summary of the results is presented in Table 4.3.

<u>Location B_1</u>

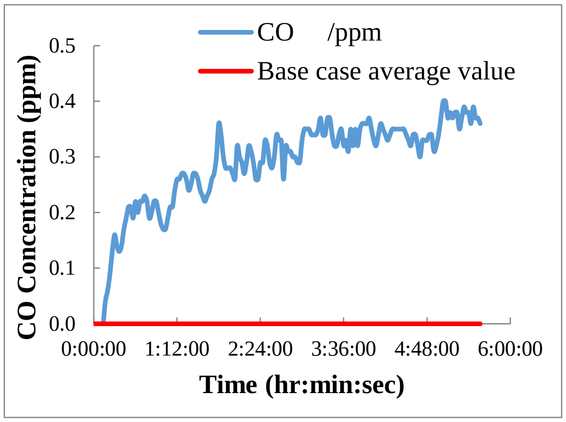


Figure 4.26: CO variation- Sample B (Location B_1)

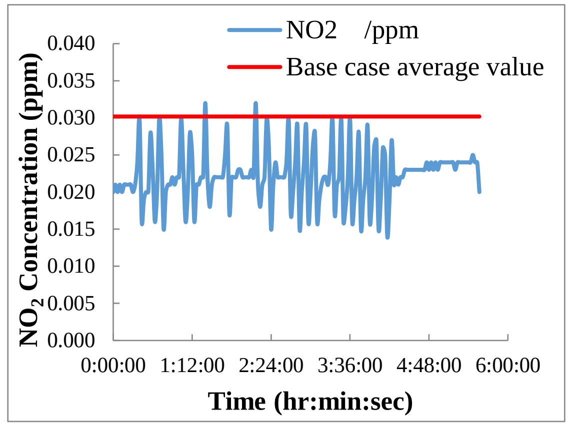


Figure 4.27: NO_2 variation- Sample B (Location B_1)

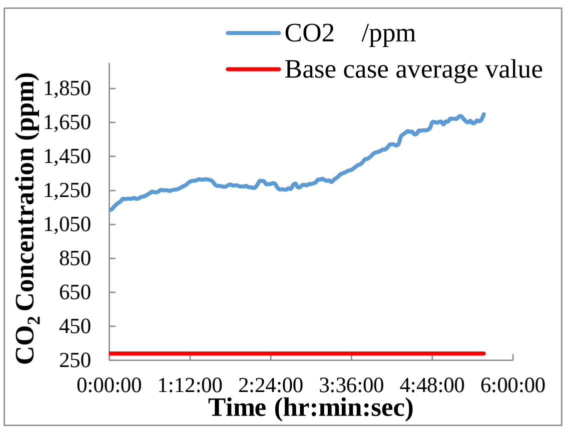


Figure 4.28: CO_2 variation- Sample B (Location B_1)

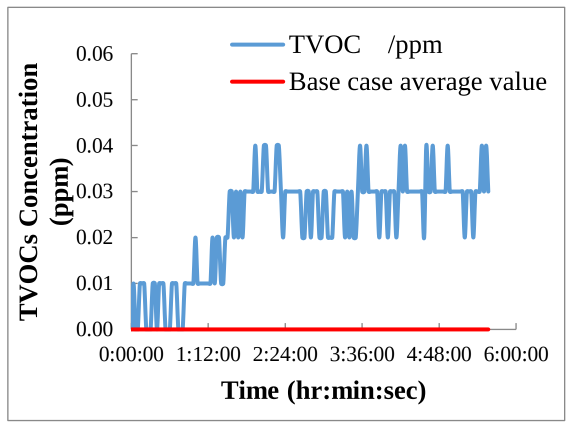


Figure 4.29: TVOCs variation- Sample B (Location B_1)

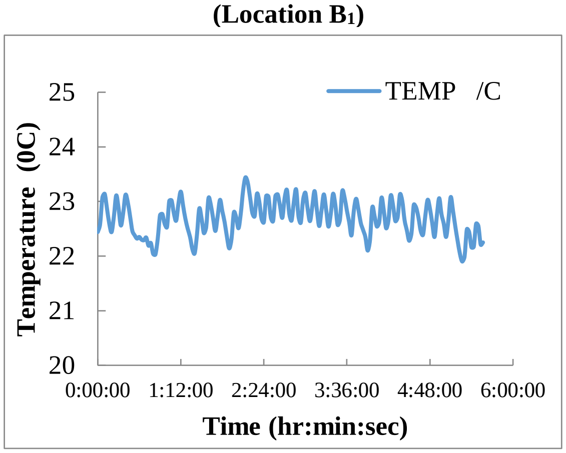


Figure 4.30: Temperature variation- Sample B (Location B_1)

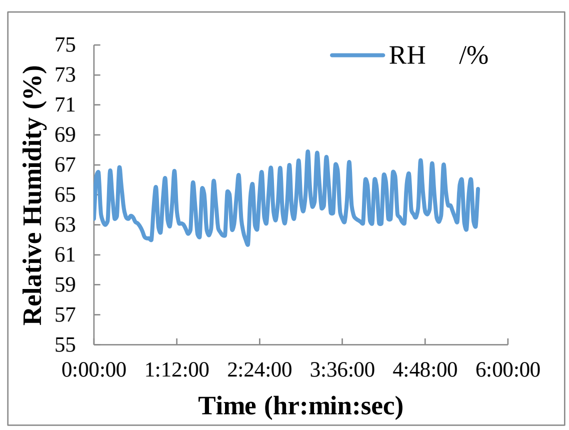


Figure 4.31: RH variation- Sample B (Location B_1)

<u>Location B_2</u>

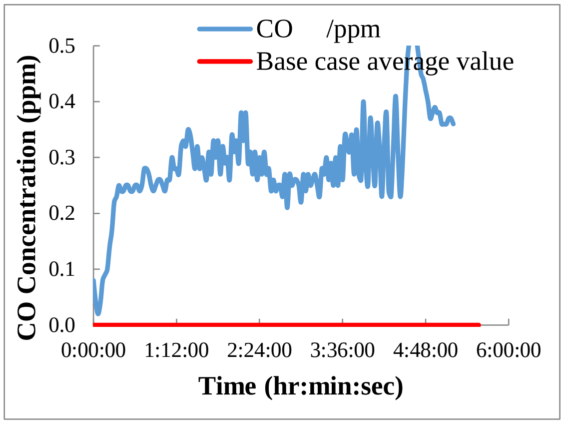


Figure 4.32: CO variation- Sample B (Location B_2)

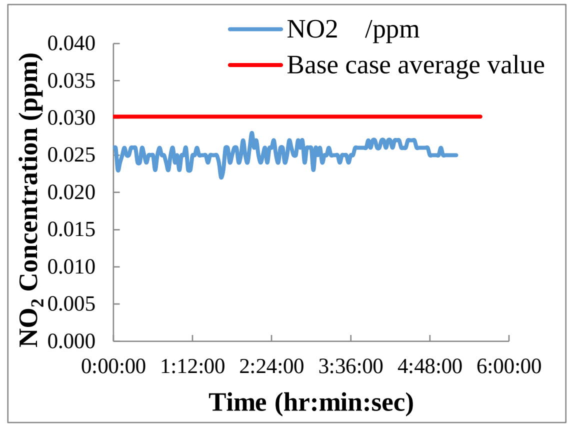


Figure 4.33: NO_2 variation- Sample B (Location B_2)

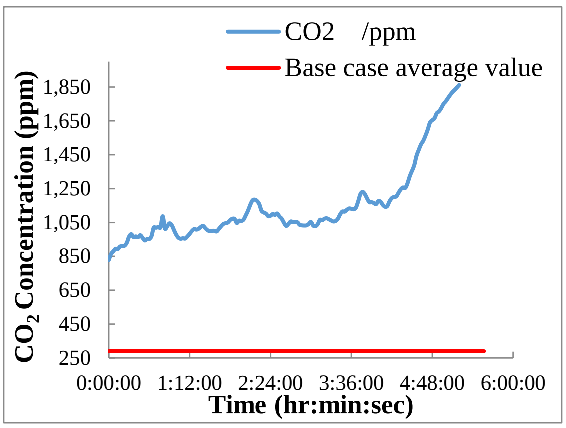


Figure 4.34: CO_2 variation- Sample B (Location B_2)

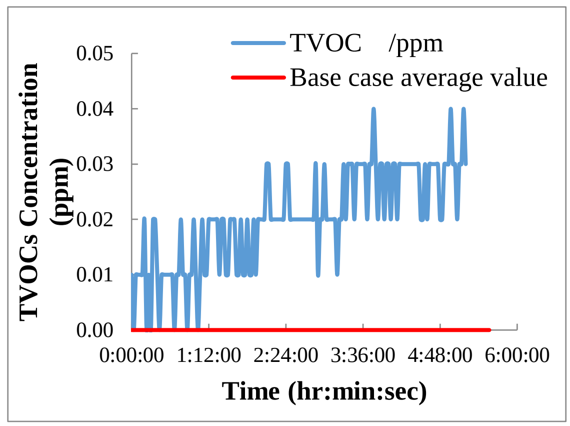


Figure 4.35: TVOCs variation- Sample B (Location B_2)

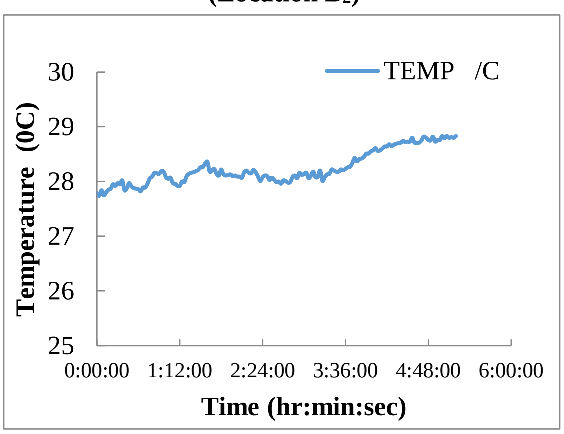


Figure 4.36: Temperature variation- Sample B (Location B_2)

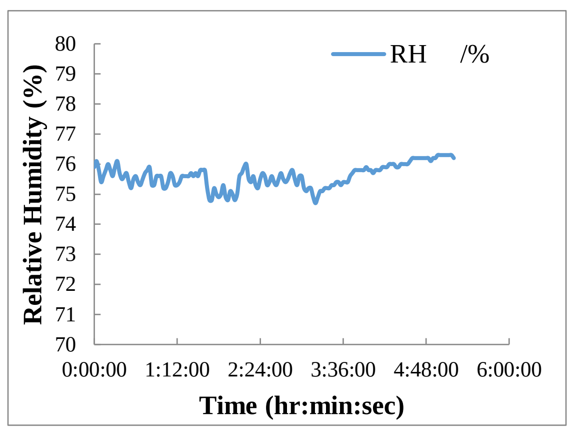


Figure 4.37: RH variation- Sample B (Location B_2)

Location B_3

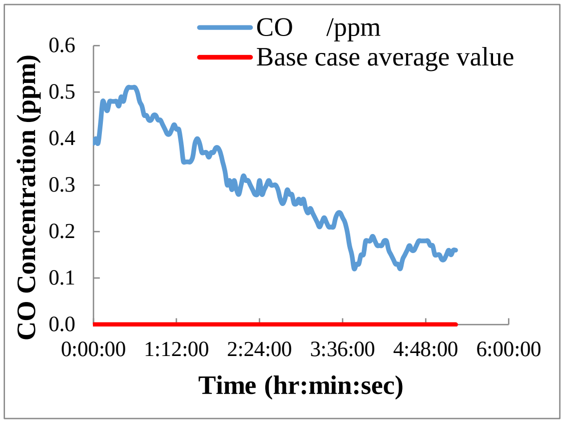


Figure 4.38: CO variation- Sample B (Location B_3)

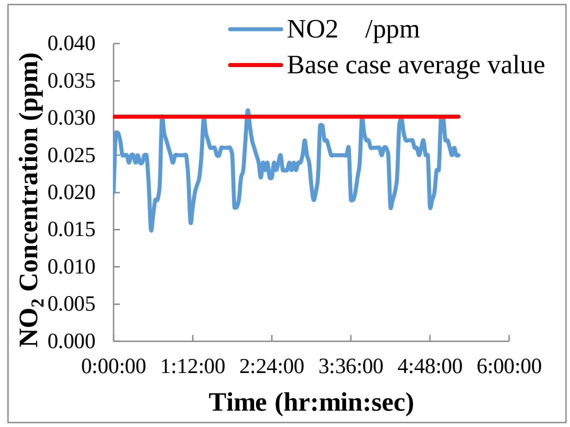


Figure 4.39: NO_2 variation- Sample B (Location B_3)

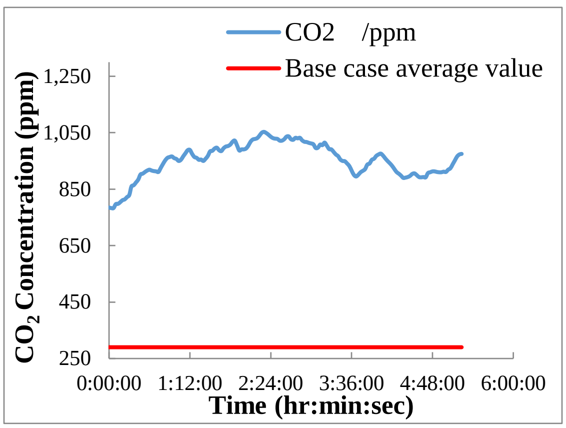


Figure 4.40: CO_2 variation- Sample B (Location B_3)

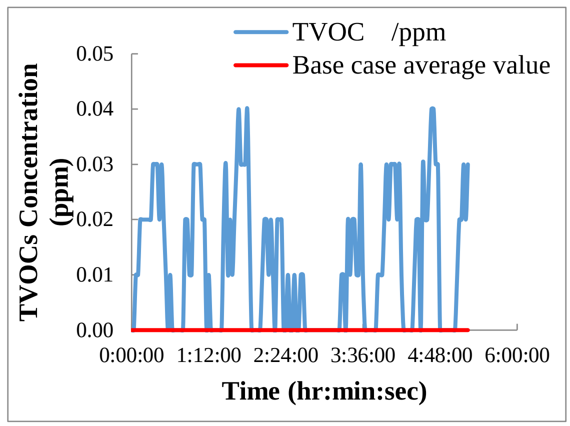


Figure 4.41: TVOCs variation- Sample B (Location B_3)

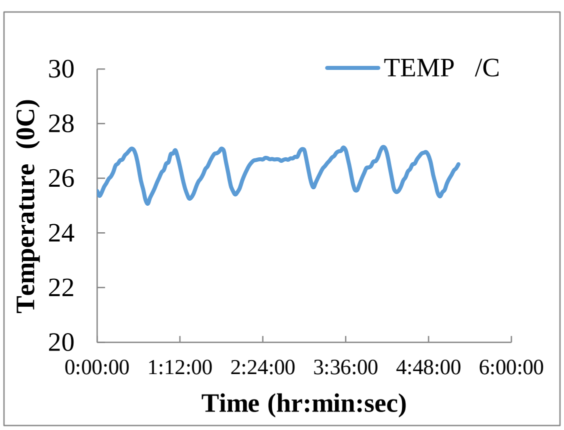


Figure 4.42: Temperature variation- Sample B (Location B_3)

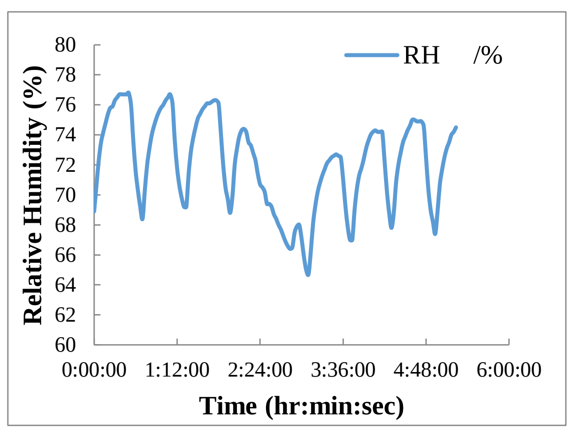


Figure 4.43: RH variation- Sample B (Location B_3)

Location B_4

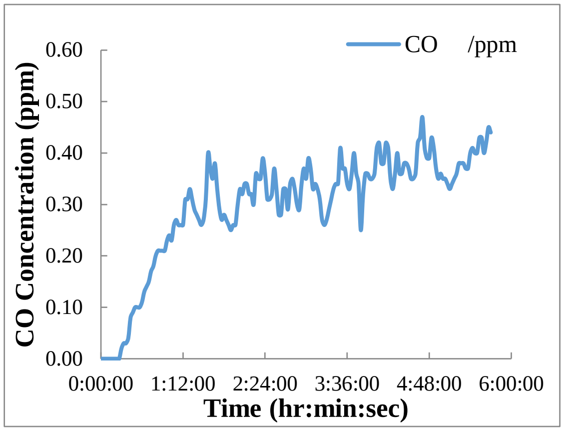


Figure 4.44: CO variation- Sample B (Location B_4)

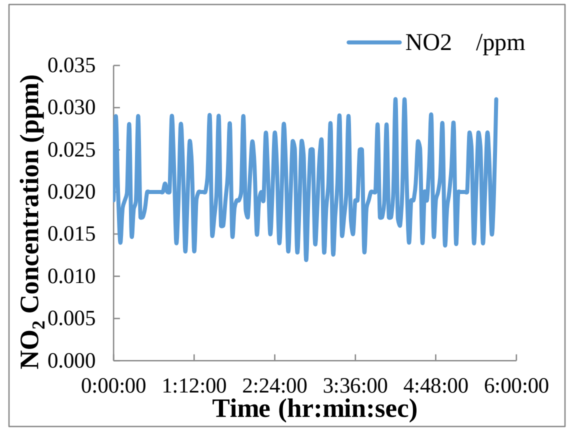


Figure 4.45: NO_2 variation- Sample B (Location B_4)

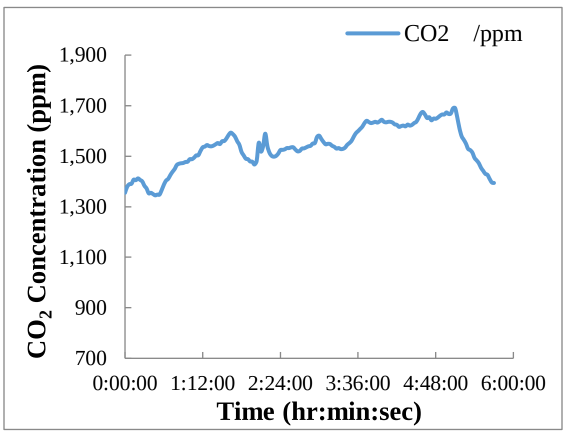


Figure 4.46: CO_2 variation- Sample B (Location B_4)

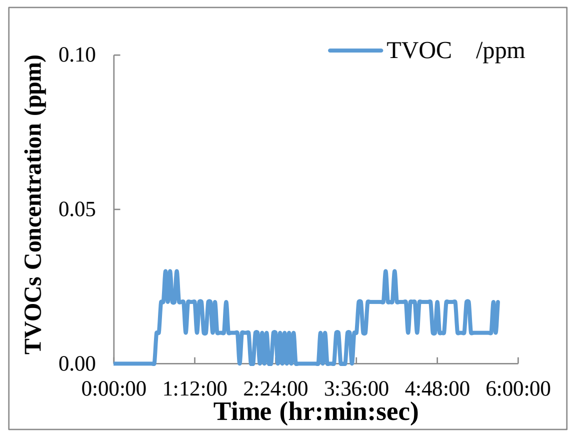


Figure 4.47: TVOCs variation- Sample B (Location B_4)

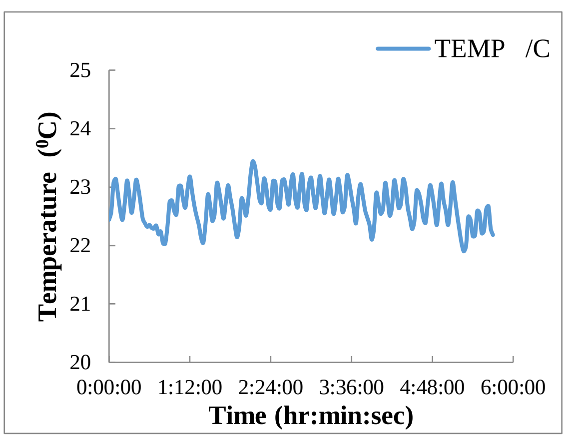


Figure 4.48: Temperature variation- Sample B (Location B_4)

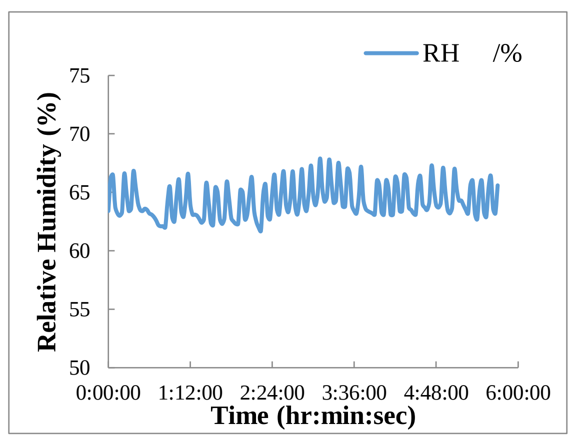


Figure 4.49: RH variation- Sample B (Location B_4)

Location B_5

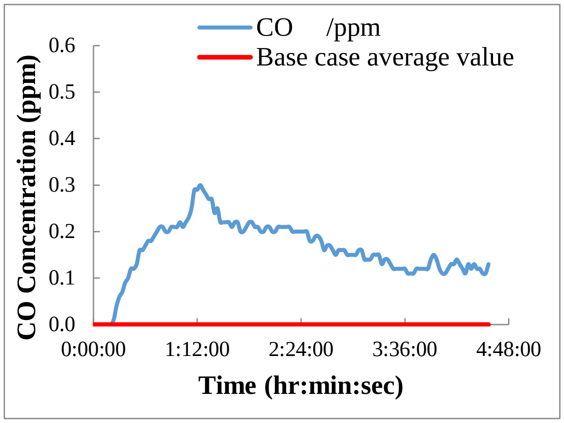


Figure 4.50: CO variation- Sample B (Location B_5)

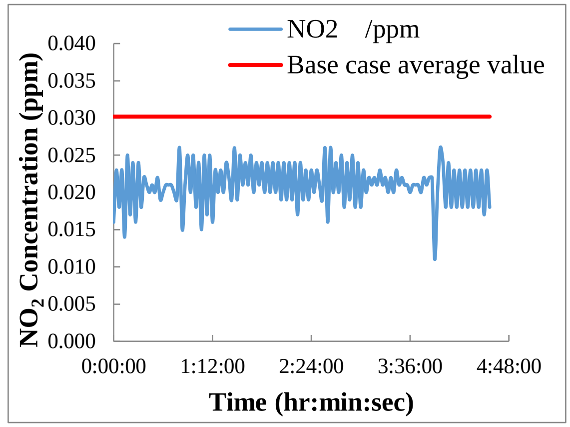


Figure 4.51: NO_2 variation- Sample B (Location B_5)

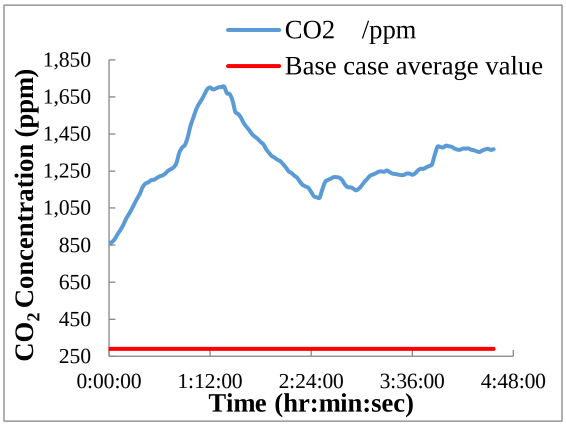


Figure 4.52: CO_2 variation- Sample B (Location B_5)

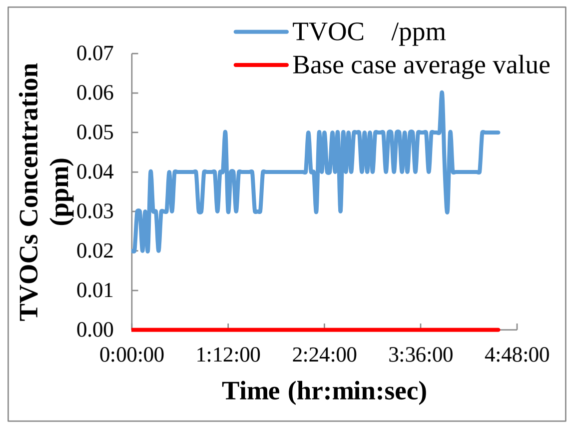


Figure 4.53: TVOCs variation- Sample B (Location B_5)

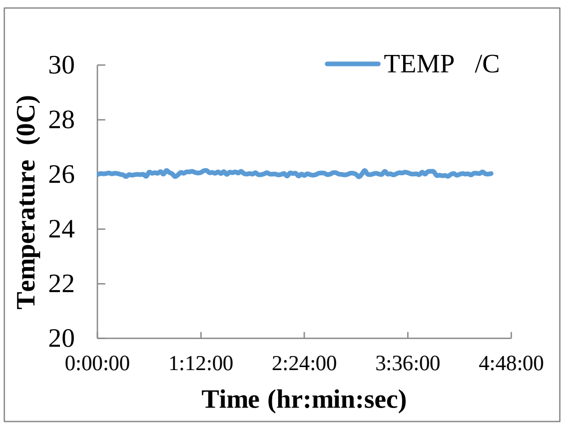


Figure 4.54: Temperature variation- Sample B (Location B_5)

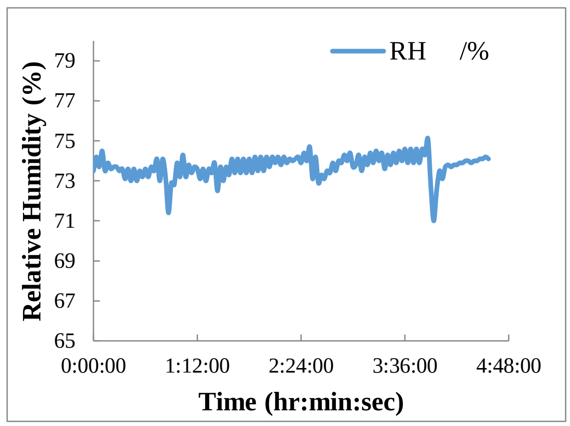


Figure 4.55: RH variation- Sample B (Location B_5)

Sample C

In this sample, IAQ measurements were taken in a building that was painted one month prior to the experiment. This location was an air-conditioned space with properly maintained air conditioner and the synthetic building materials were present in the building. The floor plan view of the location is illustrated in Figure B1-vii. The summary of the results is presented in Table 4.3.

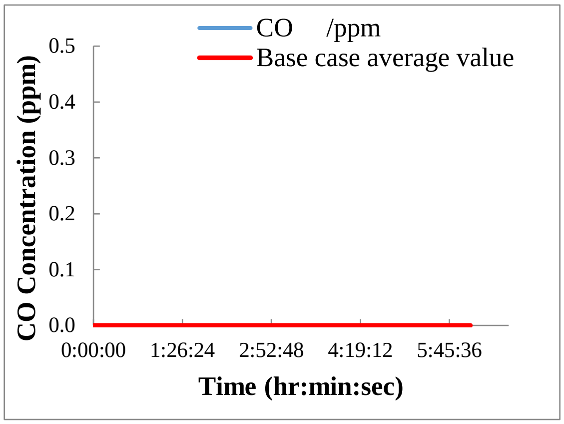


Figure 4.56: CO variation- Sample C

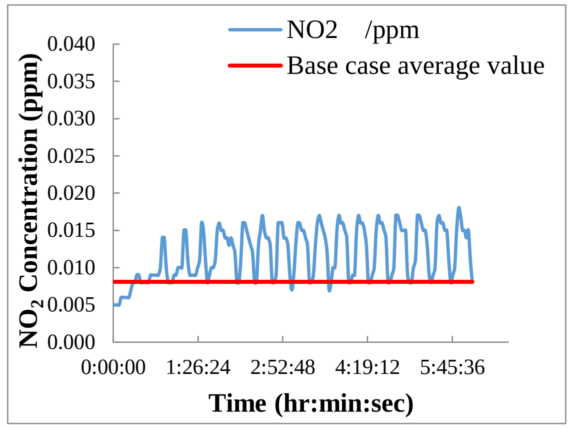


Figure 4.57: NO_2 variation- Sample C

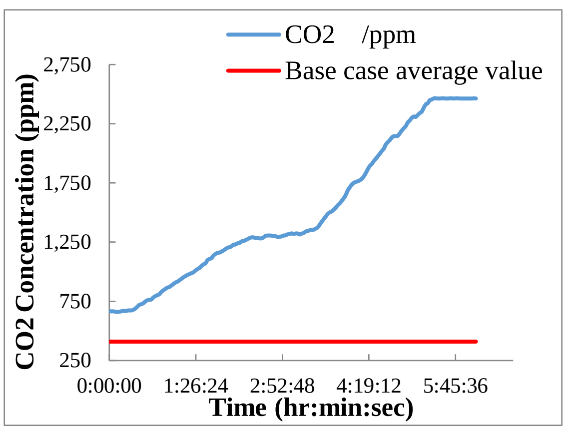


Figure 4.58: CO_2 variation- Sample C

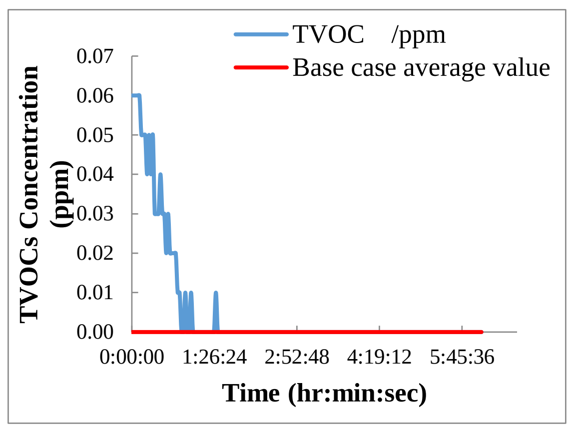


Figure 4.59: TVOCs variation- Sample C

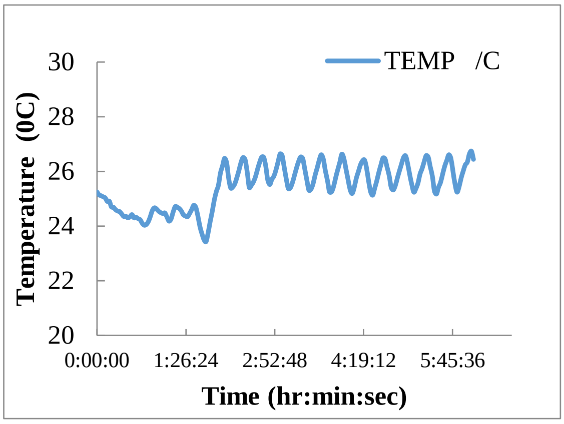


Figure 4.60: Temperature variation- Sample C

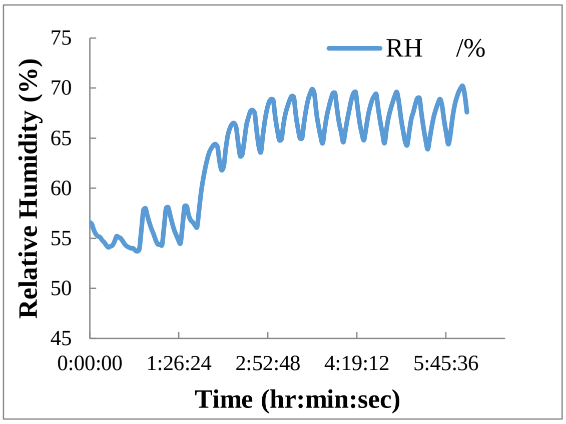


Figure 4.61: RH variation- Sample C

Sample D

In this scenario, QS and IAQ measurements were conducted at a location under natural ventilation conditions. The floor plan view of Sample D is shown in Figure B1- viii in Annex B. As illustrated in the figure, this space was provided with cross ventilation during the experiment. Similar to the other three samples where the QS was conducted, synthetic building materials were evident in this location as well.

The graphs of the obtained results are presented in Figures 4.62 to 4.67. The summary of the IAQ parameters is presented in Table 4.3.

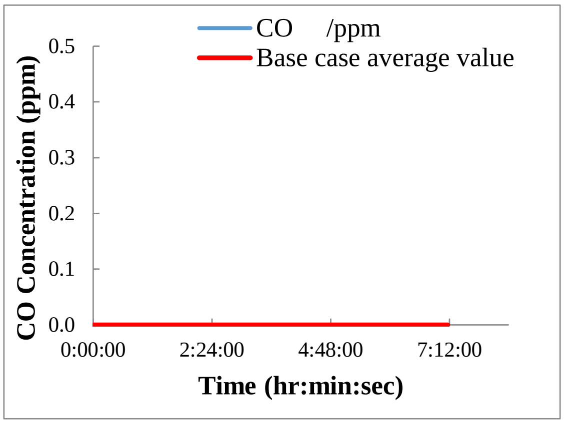


Figure 4.62: CO variation- Sample D

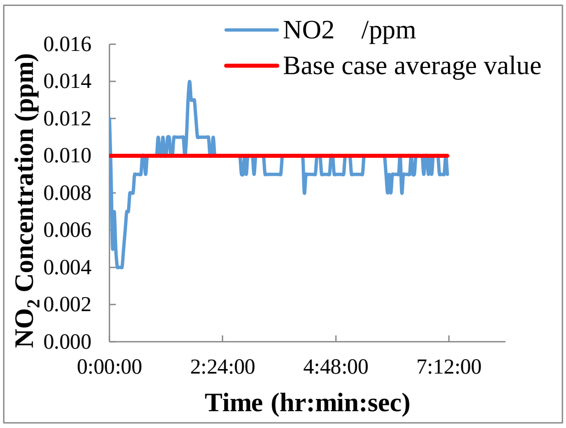


Figure 4.63: NO_2 variation- Sample D

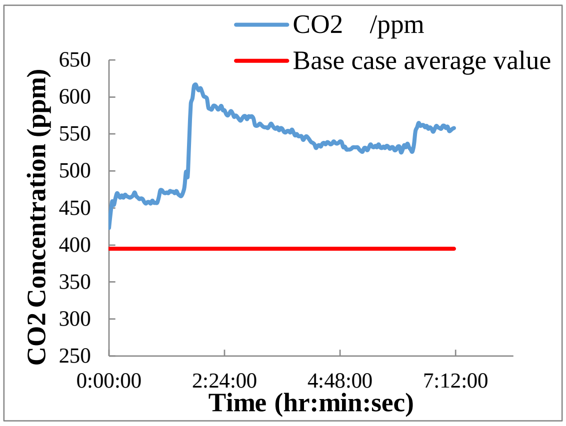


Figure 4.64: CO_2 variation- Sample D

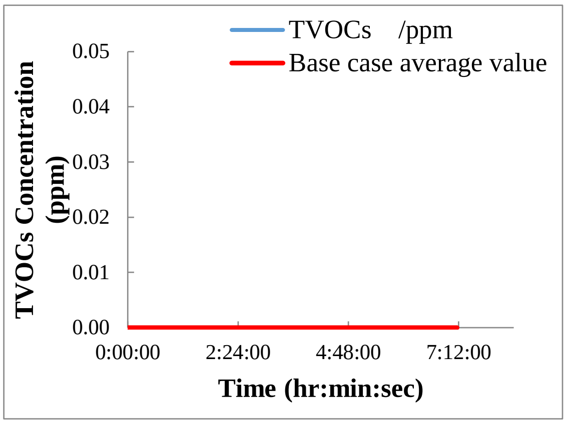


Figure 4.65: TVOCs variation- Sample D

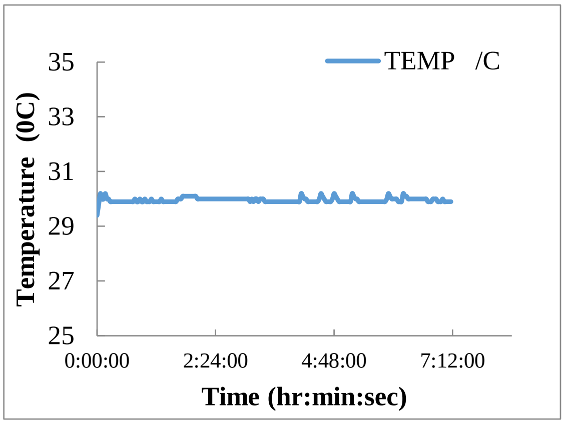


Figure 4.66: Temperature variation- Sample D

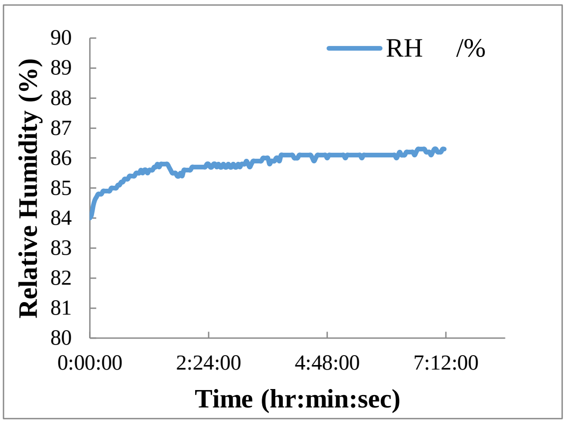


Figure 4.67: RH variation- Sample D

Table 4.3: Summary of the IAQ parameters at Sample A, B, C and D

Pollutant Type		TWA (7 hrs)	Std Dev	Max Con	Min Con	Exposure period ($p > p_{IPV}$)	Ambient conditions
CO_2 (ppm)	A (ave)	2015	132	2464	1279	1	428
	B (ave)	1270	144	1862	783	0.81	290
	C	1510	591	2464	660	0.77	330
	D	536	42	617	423	-	395
TVOCs (ppm)	A (ave)	0.07	0.01	0.12	0.02	-	0
	B (ave)	0.02	0.01	0.06	0	-	0
	C	0.01	0.01	0.06	0	-	0
	D	0	0	0	0	-	0
CO (ppm)	A (ave)	0	0	0	0	-	0
	B (ave)	0.27	0.09	0.53	0	-	0
	C	0	0	0	0	-	0
	D	0	0	0	0	-	0
NO_2 (ppm)	A (ave)	0.014	0.002	0.02	0.005	-	0.011
	B (ave)	0.023	0.003	0.032	0011	-	0.03
	C	0.012	0.003	0.018	0.005	-	0.008
	D	0.010	0.001	0.014	0.004	-	0.01
T(^{0}C) [RH%]	A (ave)	27.4 [63.5]	0.30	28.1 [59.9]	25.4 [61]	-	29.8- 30.1 [76.7- 78.5]
	B (ave)	25.6 [70.3]	0.55	28.8 [76.3]	21.9 [63.2]	-	27.3- 28.5 [76.2- 78.0]
	C	25.6 [63.7]	0.05	26.7 [69.3]	23.4 [57.8]	-	30.9- 31.2 [71.1-72.2]
	D	30.1 [86.2]	0.09	30.2 [86]	29.4 [84]	-	30.2- 31.6 [86.1- 87.2]

TWA- Time Weighted Average, **Std Dev**- Standard Deviation, **Max Con**- Maximum Concentration, **Min Con**- Minimum Concentration
$p > p_{IPV}$ -Probability of exposure period beyond the indoor permissible value (Note 01), **T**- Temperature, **RH**- Relative humidity
Note 01
Permissible exposure limits: CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

As per the summary in Table 4.3, it is apparent that the concentration of CO_2 is significantly higher in sample A, B and C irrespective of the paint application and the prevailing ventilation condition. Considering the sources of CO_2, high population density can be identified as the main source present in the indoor environment. It is observed that many of the buildings are not complying with the building regulations with respect to the population density during their operational period. Therefore, in all three samples, time weighted average of CO_2 over a 7 hour period is well above the ASHRAE guideline for the indoor CO_2 concentration and the average exposure period above the pertain guideline is 5.6 hours ($CO_{2\ TWA,\ A}$ = 2015 ppm, $p_{IPV,\ A}$= 1; $CO_{2\ TWA,\ B}$ = 1270 ppm, $p_{IPV,\ B}$= 0.81; $CO_{2\ TWA,\ C}$ = 1510 ppm, $p_{IPV,\ C}$= 0.77). However, the violation of the ASHRAE guideline could be directly linked with many of the SBS symptoms, as this guideline is defined based upon the human comfort and occupant odour with excess CO_2 exposure.

The analysis of TVOCs with respect to the sample A and B has illustrated that the concentration of TVOCs of sample A is comparatively high as a result of the emitted TVOCs from the wall paint, apart from the little contribution of TVOCs from the synthetic building material presence in the both locations. The time weighted average and maximum concentration of TVOCs of sample A and B are $TVOCs_{TWA,\ A}$ = 0.07 ppm , $TVOCs_{TWA,\ B}$ = 0.02 ppm and $TVOCs_{MAX,\ A}$ = 0.12 ppm , $TVOCs_{MAX,\ B}$ = 0.06 ppm respectively over a 7 hour working period. Comparison with the results of sample A and C, it has been evidenced that the TVOCs variation of sample C is much lesser than the values of the sample A due to the proper ventilation condition ($TVOCs_{TWA,\ C}$= 0.01 ppm). Although, the indoor TVOCs values are within the permissible exposure limit by OSHA (0.75 ppm), the occurrence of acute irritant symptoms of eye, nose, throat irritation as well as lower airway and pulmonary effects had been identified due to the low formaldehyde exposure (<0.05 ppm) possibly increasing the health risks of allergen sensitivities, chronic irritation, and cancer (Daisey, Angell, & Apte, 2003).

The concentration of CO and NO_2 were almost aligned with the ambient condition for all four samples, where the variation of CO in sample B was slightly above the surrounding conditions, though it is within the permissible indoor value ($CO_{TWA,\ B}$ = 0.27 ppm and $CO_{MAX,\ B}$ = 0.53 ppm). In sample A, B and C, temperature and RH were in the range of 22 ^{0}C- 29 ^{0}C and 58%- 76% with the air conditioning environment.

However, all the air quality parameters in sample D were very similar to the ambient condition without any accumulation of pollutants inside the building. The variation of temperature and RH in sample D was noted above the human desirable rage under the natural ventilation condition.

4.6 Relationship between sick building symptoms with indoor air pollutants

There are several literature, that outline the association between SBS symptoms and indoor air pollutants considering the exposure to an unacceptable concentration over a considerable time period. The summary of the finding of sick building symptoms with related pollutant types is illustrated in Table 4.4.

Table 4.4: Summary of symptoms with related pollutant type

Pollutant Type	SBS symptoms	Exposure levels	References
CO_2	Sore throat, Dry throat, Stuffy nose, Runny nose, Sinus congestion, Eye itching, Dry eye, Eye irritation, Chest tightness, Wheezing, Headache, Fatigue, Drowsiness, Tiredness, Dizziness, Dry cough at night, Upper respiratory symptoms, Lower respiratory symptoms, Neuroendocrine system related symptoms (Cough, Neck pain, Shoulder pain, Back pain)	Both short-term and long-term exposure	(Apte et al. 2000; Apte and Erdmann 2002; Erdmann et al. 2002; Sulaiman and Mohamed 2011; Tsai et al. 2012; Jung et al. 2014; Lu et al. 2015)
TVOCs	Sensory irritations {Eye irritation (Eye dryness) , Nose irritation, Throat irritation, Skin irritations (Skin dryness), Weak inflammatory irritation in eyes, nose, air ways and skin, Ear related symptoms} Odour, Headache, Fatigue, Dizziness, Tiredness, Difficulty concentrating, , Angry easily, Mucous membrane irritation Lower respiratory symptoms (Difficulty in breathing) Upper respiratory symptoms (Stuffy nose, Sneezing, Dry throat)	Short-term exposure	(Norback et al. 1990; Berglund et al. 1997; Apte and Erdmann 2002; Daisey et al. 2003; Takigawa et al. 2004; Sulaiman and Mohamed 2011; Chang et al. 2015; Lu et al. 2015)
	Pulmonary effects, Musculoskeletal effects, Neurological effects, Asthma, Respiratory irritations or congestion, Neurotoxic, Organotoxic and Carcinogenic effects, Allergen sensitivities Chronic symptoms (Headache, Tiredness, Sensation of getting a cold, Nausea, Eye irritation/ Swollen eyelids) Symptoms related to Chest, Central nervous system, Autonomic system and Digestive system	Long-term exposure	(Norback et al. 1990; Berglund et al. 1997; Daisey et al. 2003; Takigawa et al. 2004; Chang et al. 2015)
CO	Headache, Dizziness, Fatigue, Nausea, Lethargy, Tachycardia, Convulsions, Respiratory arrest, Lower respiratory symptoms, Cardiorespiratory complaints, Cardiopulmonary events, including death	Short-term exposure	(Cobb and Etzel 1991; Samet 1993; Alberts 1994; Chen et al. 2007; Goldstein 2008; Syazwan , Juliana et al. 2009; Sulaiman and Mohamed 2011)
	Cardiopulmonary events, Cardiovascular events, Diabetes mellitus, Atherosclerotic disease, including death	Long-term exposure	(Cobb and Etzel 1991; Chen et al. 2007)

Pollutant Type	SBS symptoms	Exposure levels	References
Particulate matter (Respirable/ PM_{10})	Cardiovascular diseases	Short-term exposure	(Pope and Dockery 2006)
	Mucosal symptoms {Eye irritation, Swollen eyelids, Nasal catarrh, Nasal obstruction, Dryness in throat, Sore throat, or irritating cough} Headache, Nausea, Sensation of getting a cold or tiredness, Dermal symptoms (Facial and hand rash, Itching, Eczema), Allergen sensitivities, Nasal patency, Dry cough at night, Respiratory illness, Asthma symptoms, Cardiovascular diseases, Cardiopulmonary health, Diabetes mellitus	Long-term exposure	(Brunekreef and Holgate 2002; Pope and Dockery 2006; Brook et al. 2010; Simoni et al. 2010; Puett et al. 2011; Zhang et al. 2014)
NO_2	Respiratory tract infections, Catastrophic injury to humans, including death due to high intensity, confined space exposure	Short-term exposure	(Chen et al. 2007)
Temperature and RH	Fatigue, Headache, Difficulty in thinking, Sensation of dryness	Short-term exposure	(Fang et al. 2004)
Dampness	Ocular symptoms, Respiratory symptoms, Facial dermal symptoms, Headache, Tiredness	Long-term exposure	(Engvall et al. 2001)
Biological contaminants (Bacteria, Fungus, Pollen, Viruses, Molds, Insects and Bird droppings)	Headache, Fever, Chills, Cough, Chest tightness, Eye irritation, Muscle aches, Allergic sensitivities, Infectious diseases	Short-term and long-term exposure	(Daisey et al. 2003; Joshi 2008; Sulaiman and Mohamed 2011; Chang et al. 2015)
	Blocked nose, Dry throat, Dry skin, Allergen sensitivities	Short-term exposure	(Daisey et al. 2003; Chang et al. 2015)

A relationship between measured IAQ parameters and symptoms obtained from the QS was established by considering the available facts in Table 4.4. The outcome of this study is graphically present in Figure 4.68 to 4.71 where the percentage of the existence of the symptom of the respondents exceeding 10% was considered for the analysis.

Legend

- Symptoms related to CO_2
- Symptoms related to TVOCs
- Symptoms related to CO
- Symptoms related to Temperature

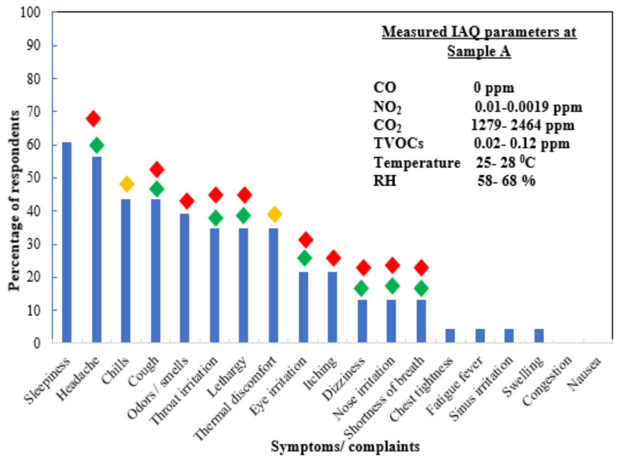


Figure 4.68: Relationship between IAQ parameters and SBS symptoms- Sample A

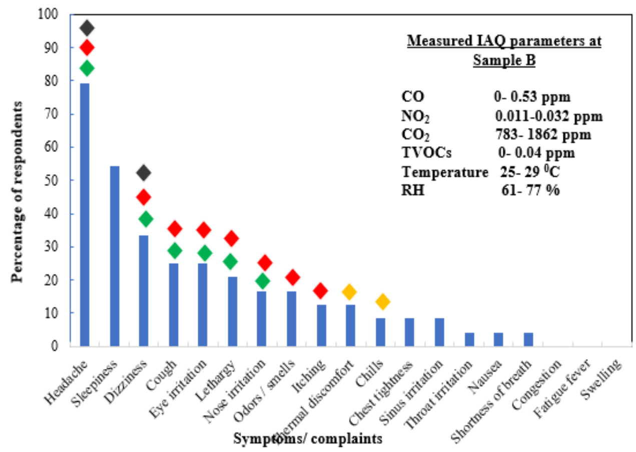


Figure 4.69: Relationship between IAQ parameters and SBS symptoms- Sample B

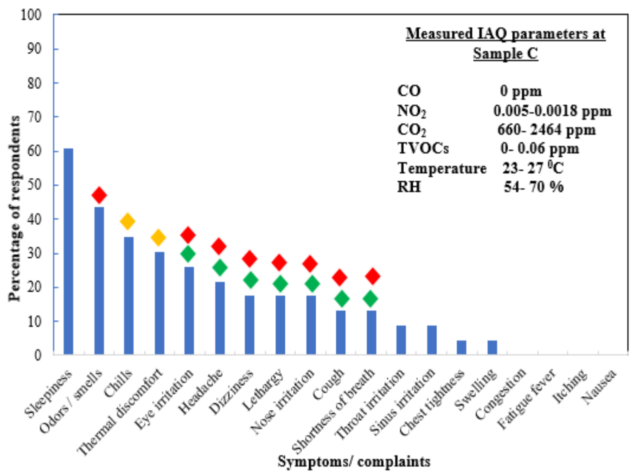


Figure 4.70: Relationship between IAQ parameters and SBS symptoms- Sample C

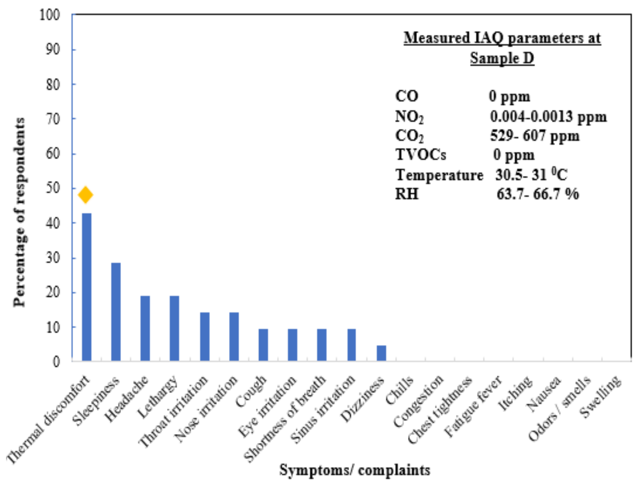


Figure 4.71: Relationship between IAQ parameters and SBS symptoms- Sample D

Considering the major pollutant type of CO_2 in sample A, B and C with the results of questionnaire survey and Table 4.4, it was able to justify the occurrence of headache, lethargy and cough due to the CO_2 exposure exceeding the permissible indoor limit defined by ASHRAE. Sensory irritation of eye, nose and throat irritation is also common for these three samples due to the exposure of CO_2 as well as the TVOCs concentration above the ambient condition. As the concentration of TVOCs in sample A is relatively high regarding to the sample B and C, many of the symptoms related to the TVOCs has been conspicuously appeared from the sample A, such as odour/smell and itching. The most frequently followed symptom of dizziness in sample B can be related due to the measured CO concentration beyond the ambience as it is only specific to the particular sample. Although the measured IAQ parameters including the temperature were not sufficient to express the prevalence of chills among the respondents of sample A and C, it could be linked with the occupational exposure to the biological contamination.

However, Sample D has reported thermal discomfort as the symptom which is experiencing the occupants repeatedly due to the undesirable temperature (31 ^{0}C) under the natural ventilation condition. Apart from that, throat and nose irritation are also associated with the higher indoor temperature resulting the sensation of dryness of the inhabitant. However, the other symptoms of sleepiness and lethargy described in sample D could be due to some other suspected pollutants/sources other than the measured IAQ parameters, i.e. visual discomfort, and the presence of microbes etc.

Table 4.5 represents the possible relationship matrix of SBS symptoms, IAQ parameters and respondent's perception about the symptom occurrence.

Table 4.5: Relationship matrix of SBS symptoms, IAQ parameters and respondent's perception about symptom occurrence

Covariate	Sample A				Sample B				Sample C				Sample D			
	CO_2	TVOCs	CO	T/RH	CO_2	TVOCs	CO	T/RH	CO_2	TVOCs	CO	T/RH	CO_2	TVOCs	CO	T/RH
Sleepiness																
Headache	+++	+++		+	+++	+++	+		+	+						+
Thermal discomfort				+				+				+				+++
Lethargy	+	+			+	+			+	+						
Odour/smell		+++				+				+++						
Cough	+++	+++			+	+			+	+						
Chills																
Eye irritation	+	+			+	+			+	+						
Throat irritation	+	+														+
Dizziness	+	+			+	+	+		+	+						
Nose irritation	+	+			+	+			+	+						+
Itching		+				+										
Sinus irritation																
Shortness of breath	+	+							+	+						
Respondent's perception about symptom occurrence																
Indoor environment	96 %				83 %				92 %				67 %			
Persistent	0 %				17 %				8 %				14 %			
Other	4 %				0 %				0 %				19 %			
Respondent's perception about the time of the symptom existence																
Just after the exposure	5 %				10 %				18 %				41 %			
While inside the room	96 %				90 %				91 %				53 %			
Persist for some time	9 %				35 %				0 %							

T – Temperature *RH- Relative Humidity* *+ Responses above 10%* *+++ Responses above 40%*

4.7 Impact of ventilation condition on IAQ: Based on questionnaire survey

The results obtained in Sample A, B, C and D were also considered during the evaluation of the ventilation condition on IAQ. The outcome of the QS was considered to witness occupant comfort with indoor environments under different ventilation conditions. Further to that, Sample E has been selected where the improved air-conditioned system was used with the proper supply of fresh air to the indoors, in order to investigate about the IAQ with all possible circumstances concerning the mode of the ventilation system. Although the IAQ measurements were conducted at this location, QS was not allowed to carry out due to the ethical concerns and policies related to the particular premises. Thus, the recorded data were used to compare the IAQ in five selected places. IAQ measurements were taken in four different activity spaces of Sample E and they are namely E_1, E_2, E_3 and E_4.

The obtained results are presented in Figure 4.72 to 4.77 in location E_1, Figure 4.78 to 4.83 in location E_2, Figure 4.84 to 4.89 in location E_3 and Figure 4.90 to 4.95 in location E_4 of Sample E.

<u>Location E_1</u>

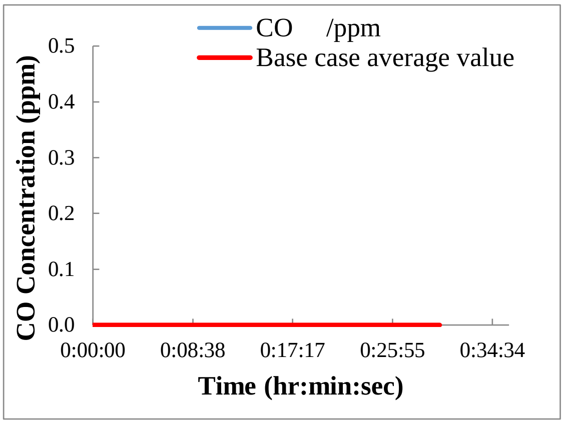


Figure 4.72: CO variation- Sample E (Location E_1)

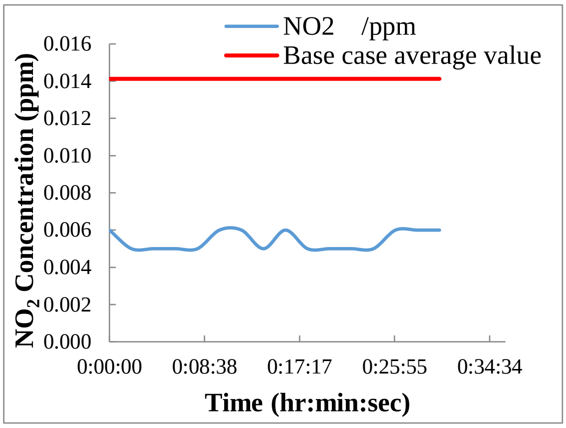


Figure 4.73: NO_2 variation- Sample E (Location E_1)

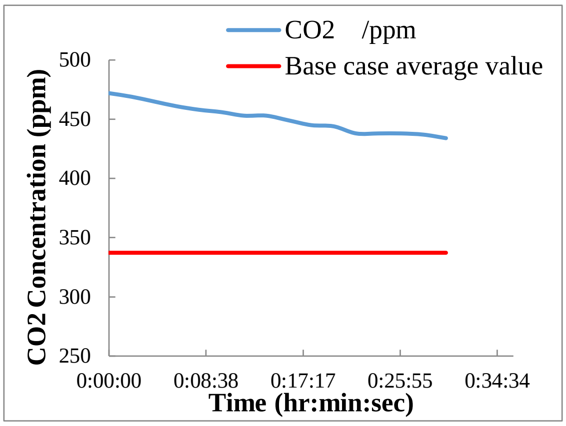


Figure 4.74: CO_2 variation- Sample E (Location E_1)

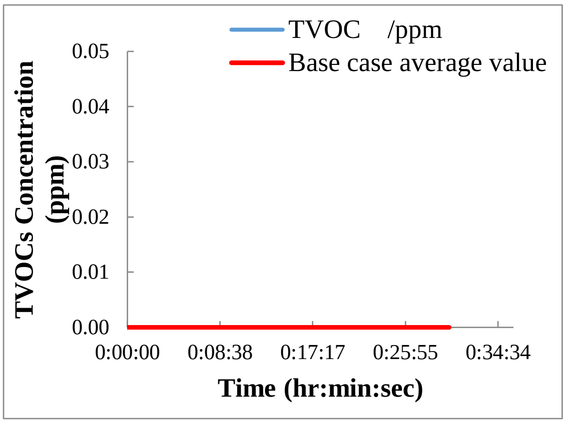


Figure 4.75: TVOCs variation- Sample E (Location E_1)

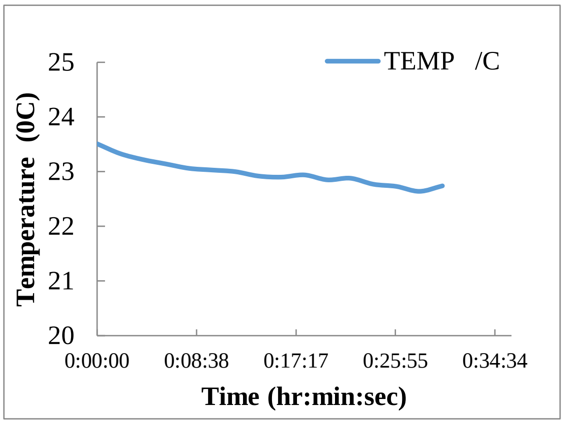


Figure 4.76: Temperature variation- Sample E (Location E_1)

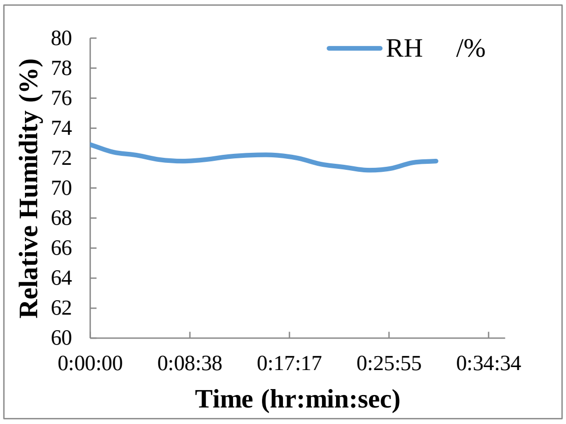


Figure 4.77: RH variation- Sample E (Location E_1)

Location E_2

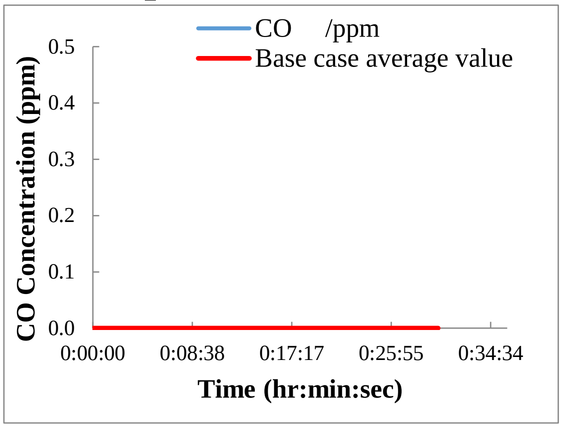


Figure 4.78: CO variation- Sample E (Location E_2)

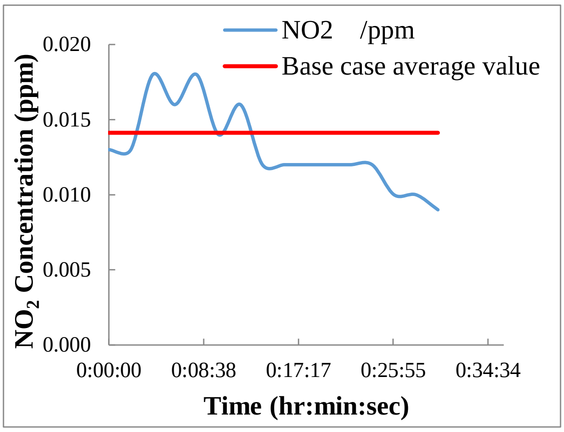


Figure 4.79: NO_2 variation- Sample E (Location E_2)

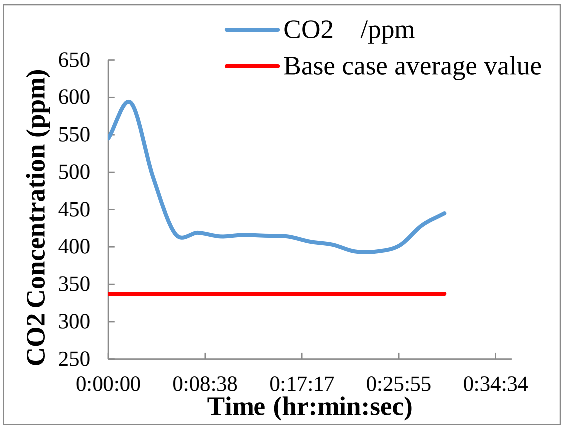


Figure 4.80: CO_2 variation- Sample E (Location E_2)

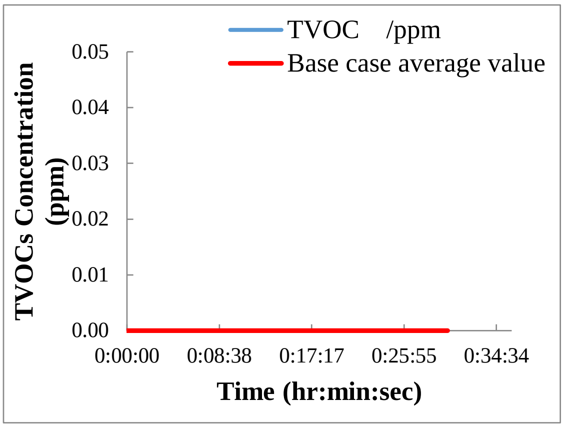


Figure 4.81: TVOCs variation- Sample E (Location E_2)

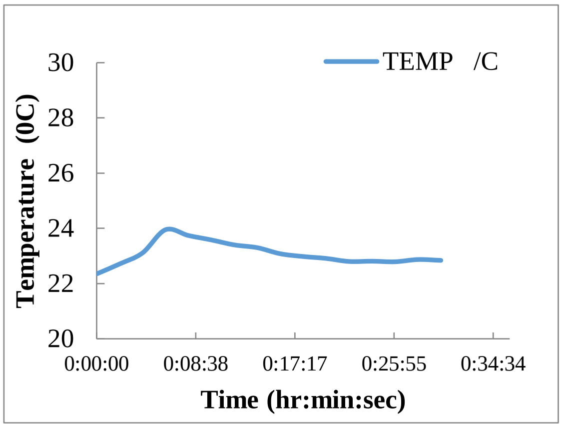


Figure 4.82: Temperature variation- Sample E (Location E_2)

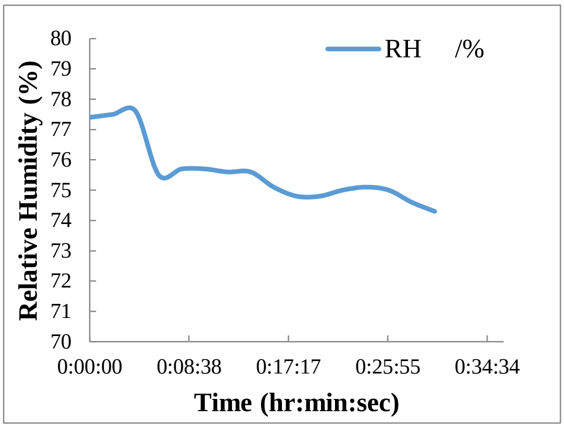


Figure 4.83: RH variation- Sample E (Location E_2)

Location E_3

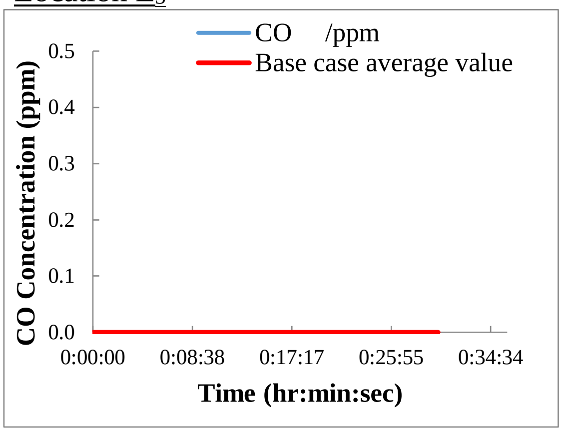


Figure 4.84: CO variation- Sample E (Location E_3)

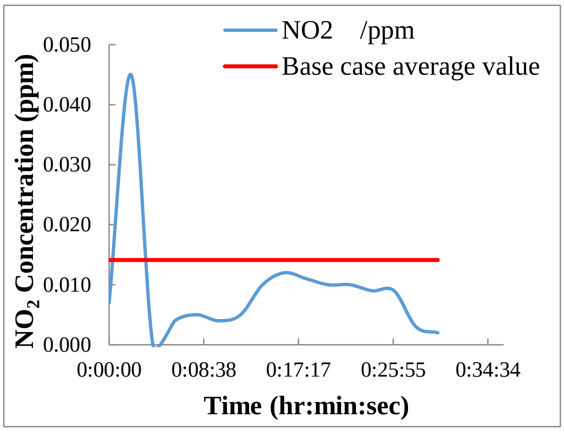


Figure 4.85: NO_2 variation- Sample E (Location E_3)

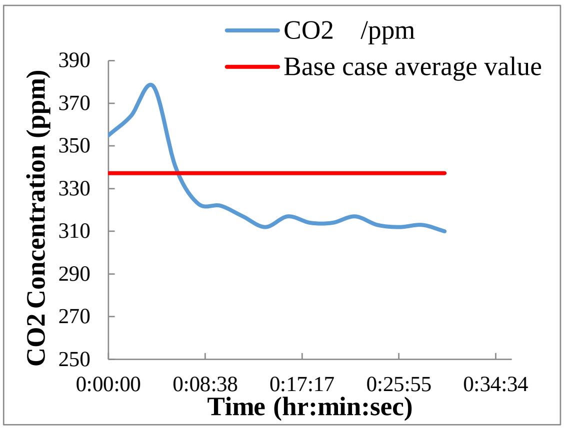


Figure 4.86: CO_2 variation- Sample E (Location E_3)

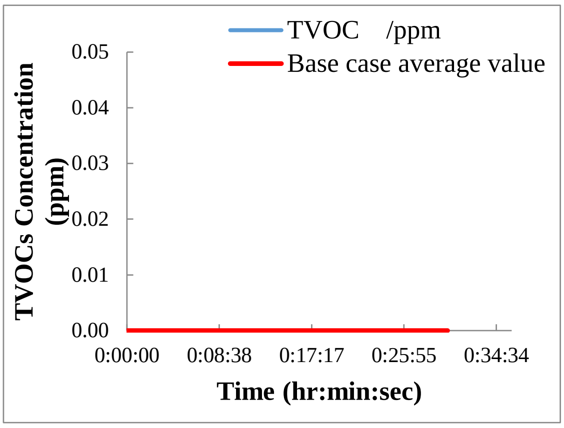


Figure 4.87: TVOCs variation- Sample E (Location E_3)

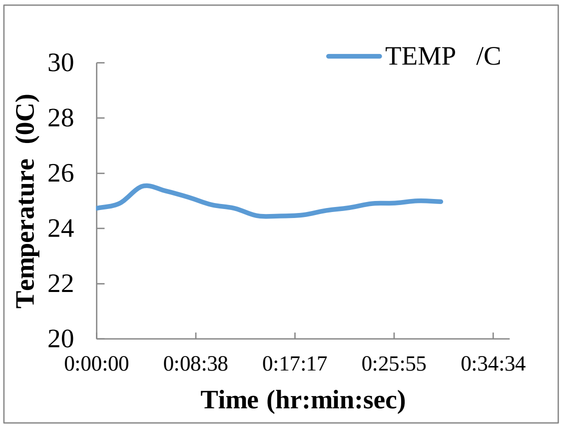


Figure 4.88: Temperature variation- Sample E (Location E_3)

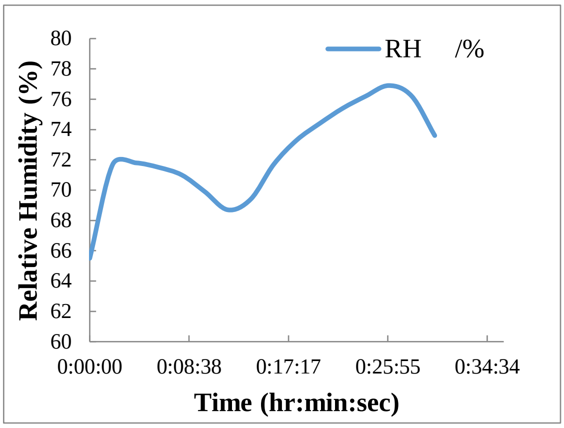


Figure 4.89: RH variation- Sample E (Location E_3)

<u>Location E_4</u>

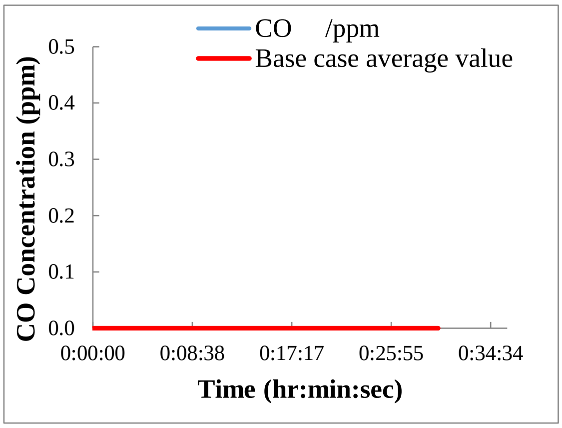


Figure 4.90: CO variation- Sample E (Location E_4)

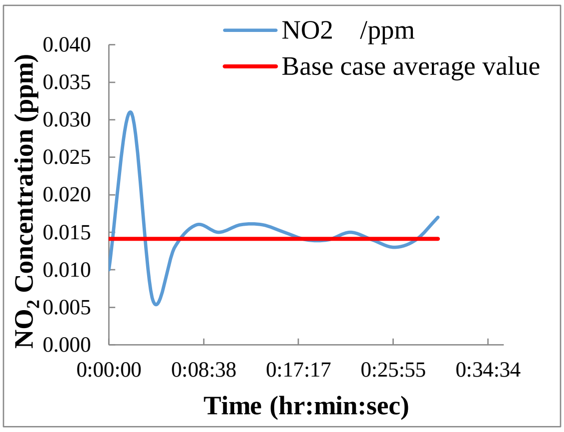


Figure 4.91: NO_2 variation- Sample E (Location E_4)

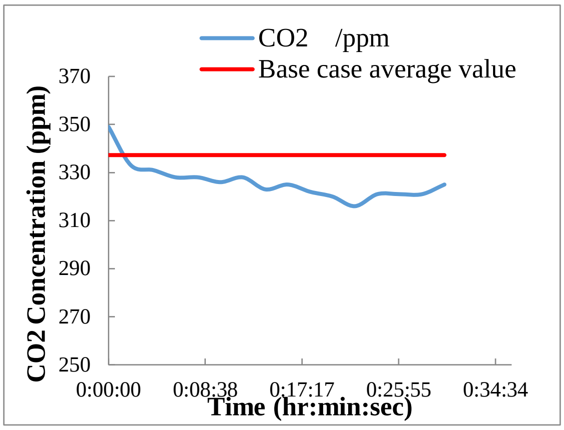


Figure 4.92: CO_2 variation- Sample E (Location E_4)

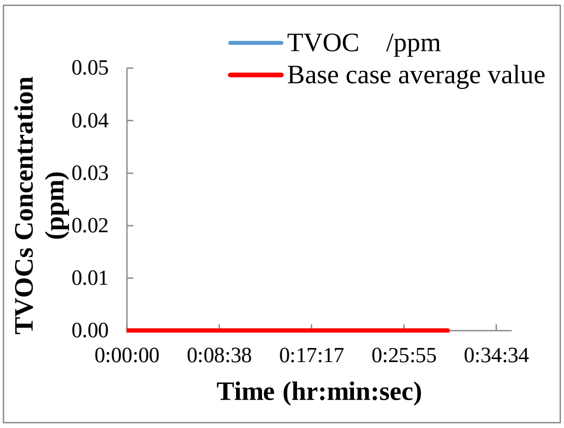


Figure 4.93: TVOCs variation- Sample E (Location E_4)

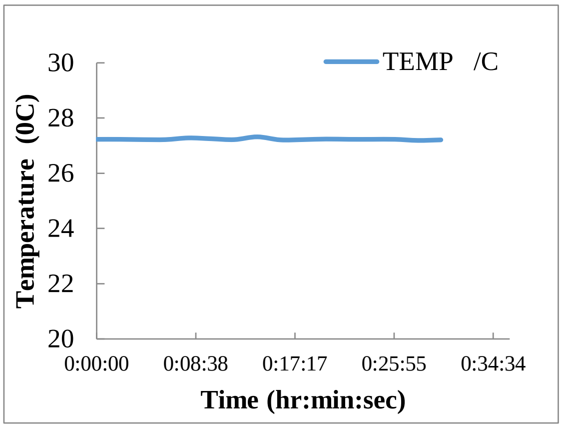


Figure 4.94: Temperature variation- Sample E (Location E_4)

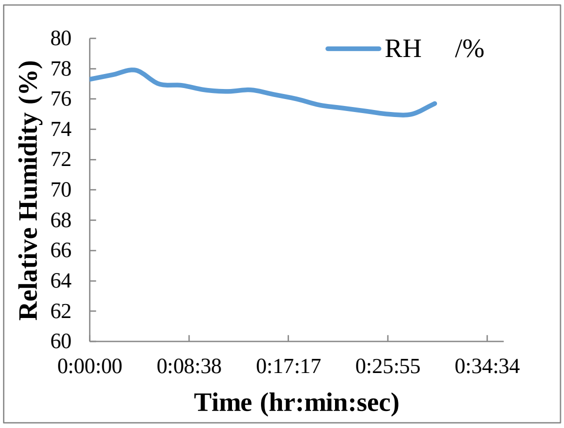


Figure 4.95: RH variation- Sample E (Location E_4)

As illustrated in Figure 4.72 to 4.95, all the IAQ parameters in Sample E are very similar to the surrounding condition. The summary of the results is presented in Table 4.6.

Table 4.6: Summary of IAQ at Sample E

Pollutant Type		TWA (0.5 hrs)	Std Dev	Max Con	Min Con	Exposure period ($p > p_{IPV}$)	Ambient conditions
CO_2 (ppm)	E (ave)	385	31	448	385	-	375
TVOCs (ppm)	E (ave)	0	0	0	0	-	0
CO (ppm)	E (ave)	0	0	0	0	-	0
NO_2 (ppm)	E (ave)	0.011	0.001	0.025	0.005	-	0.011
T(^{0}C) [RH%]	E (ave)	24.5 [74.0]	0.04	25.1 [76.3]	24.2 [71.5]	-	29.8- 30.1 [76.7- 78.5]

TWA- Time Weighted Average, **Std Dev**- Standard Deviation, **Max Con**- Maximum Concentration, **Min Con**- Minimum Concentration
$p > p_{IPV}$ -Probability of exposure period beyond the indoor permissible value (Note 01), **T**- Temperature, **RH**- Relative humidity
Note 01
Permissible exposure limits: CO- 9 ppm (USEPA), NO_2 – 0.053 ppm (USEPA), CO_2- 1000 ppm (ASHRAE), TVOCs- 0.75 ppm (OSHA) and $PM_{2.5}$- 0.025 mg/m^3 (WHO)

As illustrated in figures of sections 4.5 and 4.7, the timely variation of CO, NO_2, CO_2, TVOCs, temperature and relative humidity were measured in all five sample locations. However, the concentration of TVOCs and CO_2 were considered during the discussion as their values are above the ambient condition or the permissible indoor values defined by different organizations.

According to the variation of TVOCs at Sample A (Refer Figure 4.96 and Figure 4.97), it is observed that the concentration of TVOCs at location A_1 was dispersing with time up to the 0.05 ppm over a period of one hour and after that its concentration was stagnated with very little or no dispersion rate during the entire experiment including the location A_2 and A_3. Regarding the TVOCs variation in Sample B, it is identified that the average concentration of TVOCs was 0.03 ppm in all five locations and there is not any noticeable dispersion in the pollutants' concentration throughout the measurements. Thus, there is an almost constant value of TVOCs with time at Sample B, which is very much similar to the results obtained in Sample A as well.

However, the TVOCs variation of Sample C has a different pattern as presented in Figure 4.97. Although, there is some considerable amount of initial concentration of TVOCs at this location due to the painted area and other sources, it is found that the rapid dispersion of the concentration with time due to the provision of proper ventilation conditions. During the comparison of Sample A and C, where the environmental and test conditions were similar to each other, except the ventilation condition, it has been identified that the emitted TVOCs were diluted rapidly due to the proper ventilation condition prevail at Sample C.

Further to that, the impact of ventilation on IAQ is merely exhibited by the almost constant concentration of TVOCs in Sample A and B, where the ventilation condition was insufficient due to the poor maintenance in the air conditioner. However, Sample D and E have the IAQ parameters similar to the surrounding conditions by emphasizing the importance of ventilation conditions for the betterment of the indoor environment.

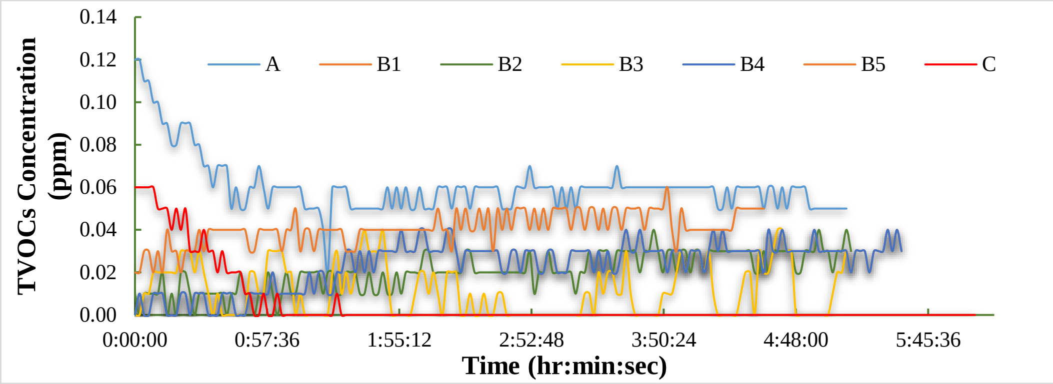


Figure 4.96: TVOCs variation with time at Sample A, B and C

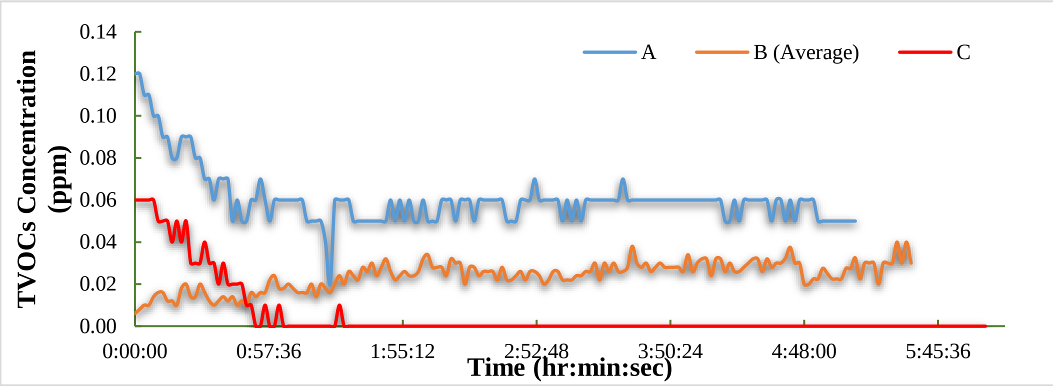


Figure 4.97: TVOCs variation with time at Sample A, B (average) and C

The level of CO_2 has exceeded the indoor permissible value which is 1000 ppm defined by ASHRAE in all the locations of Sample A, B and C. As illustrated in the figures of CO_2 variation in the above three samples (Refer section 4.5), it has been noticed that the CO_2 concentration was drastically increased with time even with the proper ventilation condition at Sample C. However, as detailed in Table 4.1, the population density was quite high in Sample A, B and C with reference to the building regulations for office and educational buildings. Thus, the pollutant accumulation rate is higher than their dispersion rate in all three locations under the specific air exchange rates. As the corrective measurement, the improved HVAC system can be mentioned at the locations when the natural ventilation condition is not sufficient to challenge this matter under the existing building and environmental conditions.

The results obtained from the QS were also justified that the respondents experienced more comfort in Sample D with good quality of indoor air, whereas the majority of respondents in the other three samples (Sample A, B and C) complained about many symptoms related to the SBS. Thus, it can be proved that the occupant's responses were directly connected to the indoor environmental quality (IEQ) where the IEQ is greatly affected due to the ventilation system of a particular location. By considering all the above facts, it can be concluded that ventilation condition is a key factor to minimize the SBS to create a healthier built environment.

4.8 Summary

The questionnaire survey was conducted at four different locations with considering the criteria of ventilation condition and paint application. IAQ measurements were also recorded while the QS was ongoing. The obtained results of QS revealed that Sample D has the lowest percentage in the response of the symptoms/complains existence under the provision of proper ventilation condition, whereas Sample A is with the highest percentage in response for many symptoms/complains compared to the other samples, where the air conditioner with the poor maintenance was used with the presence of wall paint application. Sleepiness, headache, lethargy, and thermal discomfort are identified as the most common types of symptoms among all four groups. Further to that, there were some symptoms which are only specific to Sample A and C such as odour/smell, sensory irritations (eye, nose, and throat) and shortness of breath. Nevertheless, the available literature has evidence that many of these symptoms were existent due to the TVOCs concentration accumulated in indoor environments due to the wall paint (Wieslander, et al., 1994). Based on the comprehensive literature review, it was possible to build up a relationship between pollutant concentrations with symptoms related to SBS. This relationship further concluded that the existence of the symptom among the targeted group is certainly due to the indoor environmental quality with the occurrence of air polluting sources under different ventilation conditions.

Moreover, experiments on IAQ at selected locations with QS results have disclosed that the building ventilation condition plays a vital role in relation to the indoor environmental quality and it directly affects the occupant comfort as well.

CHAPTER 5: EXPERIMENTAL PROGRAMME AND A MATHEMATICAL MODEL ON POLLUTANTS CONCENTRATION DUE TO WALL PAINT

5.1 General

The emission from building materials and human practices could cause a significant impact on indoor air pollution and it is discussed in detail under Section 3.3. With the industrial revolution, people prefer to use synthetic building materials rather than conventional building materials considering some of the advantages such as durability, cost-effectiveness, better finish, and speed construction. However, most of the synthetic building materials could be the main source of indoor air pollution. This can include products like partition boards, carpets, paints, cleaning products, wallpapers, furnishers and air fresheners, etc. (Guo, Murray, Lee, & Wilkinson, 2004); (Katsoyiannis, Leva, & Kotzias, 2008); (Plaisance, Blondel, Desauziers, & Mocho, 2014); (Nazaroff & Weschler, 2004); (Huang, et al., 2012); (NØrgaard, Kudal, Kofoed-SØrensen, Koponen, & Wolkoff, 2014).

Based on the preliminary study on sources of IAP, wall paint has been identified as a major source of indoor air pollution by considering its toxicity and exposure period beyond the indoor permissible guidelines. The QS conducted on the occupant's comfort with the presence of wall paint has been concluded that the occurrence of sick building symptoms among the respondents due to the poor indoor air quality. The introduction of wall paint in Subsection 3.3.2 has been highlighted the emission of VOCs and heavy metals as a major environmental impact due to the wall paint application. As per the studies on health impacts from the air pollutants have emphasize that the short-term and long-term exposure to the VOCs could cause several illnesses as presented in Table 4.4. The presence of heavy metals in paint is also identified as harmful especially for children since its bioaccumulate inside the bodies. Moreover, inhalation of heavy metals could cause high blood pressure, brain and kidney damages, loss of memory or learning difficulties, miscarriages, decrease in sperm production, nausea, diarrhea and lung and skin cancers. Though some of the symptoms occur only at high concentration levels, World Health Organization illustrates that the immune, reproductive and cardiovascular systems can be affected by a relatively low level of exposure to lead; that is less than 10 µg/dl (Groot, 2009); (USEPA, 2015(b)).

The basic constituents of the paint are solvent, pigment, binder, and additives. The proportions of the above ingredients are formulated according to the proposed use of paint.

The solvent is used to achieve the desired viscosity of paint for a better application. The common types of solvent are water and organic solvent. During the drying process, the solvent evaporates into the atmosphere lasting the solid dry film on the surface.

Pigments are finely ground particles or powder, which impart the colour and opacity for the paint. They help to form the film layer with the substrate protection. The pigment can be organic or inorganic. The most common inorganic pigment is Titanium Dioxide, which is used to prepare the majority of white colour paints. Sometimes dyes are used instead of pigment or in combination with pigment to add colour to the paint.

The binder provides adhesion, integrity and toughness to the dry paint film while binding the pigments together. It is strongly influenced by gloss, durability, and flexibility of paint. Acrylic, alkyd, epoxy polymers are used as binders in modern paints, which may form a dry film on the substrate in a different manner (CIEC Promoting Science, 2015).

Additives are used in small quantities to achieve additional characteristics of paint. The purposes of using additives are;

- Improve the production and storing properties
- Reduce the drag of the paint
- Enhance the adhesion for special surfaces
- Provide waterproofing characteristics
- Make the paint flow on a surface

- Add texture to the paint
- Give pleasant odour in case of interior painting etc.

Generally, there are two types of paints, which are to be chosen by consumers. They are:

- Solvent-based paint
- Water-based paint

Subsection 5.1.1 and 5.1.2 explain the solvent-based and water-based paints respectively.

5.1.1 Solvent-based paint

Five decades ago, almost all the paints were solvent-based and sometimes it was referred to as “Oil-based” or “Alkyd” paints. As its name emphasises, solvent-based paint contains a significantly higher level of organic solvents than the water-based paint. The functions of these organic solvents are to bring some paint properties like application, drying process, and the formation of the durable and regular paint film. The compounds that are released to the atmosphere by these solvents during the drying process will cause a strong odour, which can easily be found in newly painted buildings. In addition, these organic solvents emit VOCs with the potential to affect the health and comfort of the occupants and painters (Jin, Sumin, Hyun, & Yong, 2011).

This paint contains water-insoluble polymers. Therefore, paint must be mixed with an organic solvent with required consistency before the application and the brushes and utensils used for the paint application should also be cleaned with some organic solvents. Solvent-based paint is more popular for the application of commercial buildings over several advantages of it compared to the other paint types; such as durability, gloss levels, better appearance and suitability of the paints for the places where moisture and humidity are most prominent. Generally, it is applied to the interior faces of wood, metal and the places, which are mostly in wet conditions in the design life. Likewise, it is used in all kinds of industrial applications, including maintenance coatings for steel and concrete.

Enamel painting is one of the oil-based products and it exhibits the aforementioned properties of paint as described above. Thus, it is used for the experiments in this research by considering its popularity among the consumers.

However, solvent-based paint is more harmful and toxic to humans and the environment due to the chemical formulation of the product. Moreover, its manufacturing plants produce a significant amount of hazardous waste and it is required to dispose of them properly (Durand, 2006). This is another disadvantage of using this paint, as the treatments of waste for the reduction of the quantity and minimization of waste generated during the production could cost high. Hence, all these facts were led to advances in the paint industry and water-based paint was introduced as a result of it.

5.1.2 Water-based paint

Water-based paint is typically referred to as waterborne acrylics and it is the result of advances in paint technology with the minimum impact on the environment. The introduction of water-based paint has improved the working and living conditions of painters and occupants respectively by reducing the TVOCs exposure (Simion, Ionita, Grigoras, Favier-Teodorescu, & Gavrila, 2015); (Wieslander, et al., 1994). It contains polymers which are emulsified in water; hence it is well known as emulsion paint among the general public. Usually, this paint type is used for the interior painting as it inherits the quality of super resistance to chalking and chipping due to its excellent adhesion to most of the substrates. Very little odour, quick-drying process, stable colour over time without yellowing and easy cleanup with water and soap are some of the advantages observed from this paint.

5.1.3 Effect of environmental and test conditions on emission from paints

A comprehensive literature review was carried out to find out the factors, which are affected by the emission from paints. Yang et al. (2011) have conducted numerical simulations to study the effect of environmental and test conditions such as air velocity, temperature, film thickness, and sample application time on TVOCs emissions from a “wet” coating material. The obtained results indicated that there is a significant impact from air velocity and sample application time on the initial stage of emissions (time < 1 hour). During this period higher velocities cause to emit the VOCs faster. But after that (time > 8 hours) internal diffusion begins to dominate over the air velocity.

The time is taken for the paint application usually takes several minutes or sometimes longer. The loss of TVOCs during the sample preparation and application leads to cause a higher concentration in the early stage. Therefore, application time should be kept as short as possible to obtain an accurate emission rate.

The effect of the substrate on TVOCs emission has been studied by Chang et al. (1997) and discovered that significant differences in emission patterns between the generated TVOCs from the non-absorptive substrate (such as stainless steel or aluminum plate) and absorptive substrate (such as gypsum board). The emission from painted stainless steel is 2 to 10 times higher than the painted gypsum board. According to this study, absorptive substrate emits TVOCs over a long period while the other for a short period. However, they suggested that the real substrate should be used for the evaluation of emissions in indoor environments.

Wet film thickness is another key factor affecting the emission rate. As mentioned in Yang et al. (2011) studies on emission from different film thickness, have been revealed that there is the effect on long term emission profile, although it does not influence on the early stage emission. Therefore, film thickness should be controlled in experiments in order to identify the impact of the other factors of emission.

The results from the experiments by Haghighat et al. (1998) and Wolkoff (1995) have shown that there is a significant effect of the temperature and relative humidity on the emission rate of TVOCs from the different building materials such as paint, varnish and carpet, etc. It was noted that the concentration of TVOCs is enhanced with the increase of temperature. Further, the above researches have illustrated that there is no direct or inversely proportional relationship between the relative humidity and the emission rate.

5.2 Details of the experimental programme

5.2.1 Introduction

There are three main categories of paint experiments, namely Exp 1, Exp 2 and Exp 3 which were carried out in this research. Exp 1 was done as a comparative study to quantify the effect of solvent-based and water-based paints on indoor air quality. The concentration of indoor air pollutants such as CO, NO_2, CO_2, TVOCs, $PM_{2.5}$, temperature and RH were measured due to the application of paints under controlled environment and test conditions. This experiment was conducted to identify the variation of pollutants' concentration with time under the minimum ventilation rate. The results obtained from the experiment were exploited to identify and observe the most significant indoor pollutants and their dispersion generated from the paint application.

Exp 2 was conducted with varying the distance from the source or painted area to figure out the one-dimensional spatial variation of pollutants, generated from both types of paints. The collected data was used to develop the relationship for the dispersion of TVOCs generated from the solvent-based paint, with time and distance collaborated with the Exp 1. The obtained outcome was validated by using field data collected in the near vicinity under the same environmental conditions. As mentioned in Subsection 5.1.3, the ventilation rate plays a major role in the dispersion of the pollutants. Thus, Exp 3 was performed by varying the ventilation condition inside the chamber II with the solvent-based paint application. The obtained results were validated using a computational fluid dynamic model generated from ANSYS-Fluent and it is discussed in detail under Chapter 06.

5.2.2 Test chamber

The studies took place in two test chambers (Figure 5.1 and Figure 5.2) which were created in the Department of Civil Engineering, University of Moratuwa, Sri Lanka. The dimensions and details of the openings are shown in Figure B1.

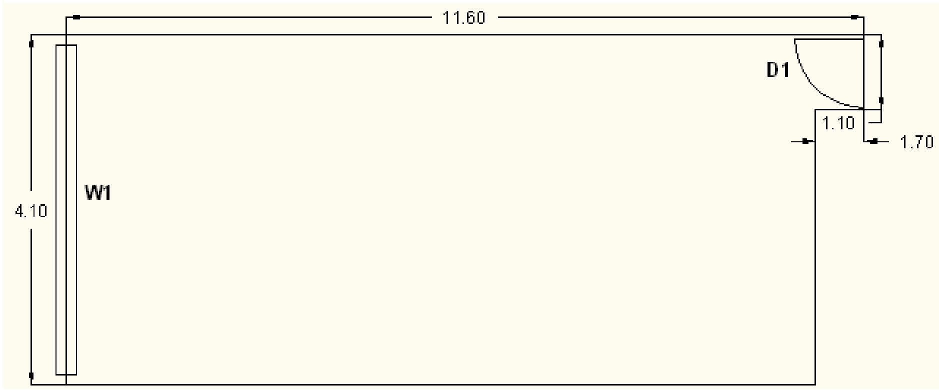


Figure 5.1: Plan view of the test chamber I (All the dimensions are in meters)

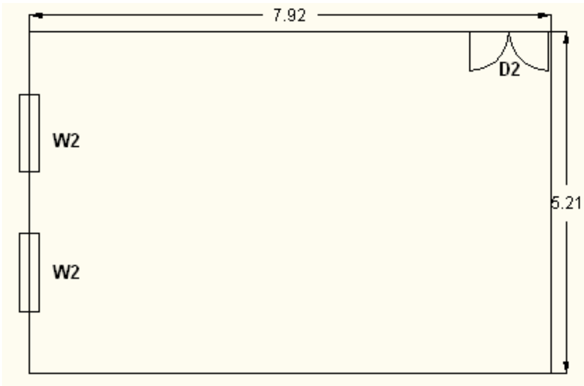


Figure 5.2: Plan view of the test chamber II (All the dimensions are in meters)

Factors that affect the pollutant transportation and distribution were thoroughly studied from the literature review and the following findings were identified to maintain control and environmental test conditions for this research. As per the Lin et al. the "Pollutant transportation and distribution depend in general upon the ventilation system, building geometry, pollutant source characteristics, and thermal/fluid boundary conditions such as flow rate, locations of supply outlets and return inlets, and diffuser characteristics. For a certain kind of building geometry and pollutant source, IAQ may be improved by increasing the ventilation rate" (Lin, Chow, Fong, Tsang, & Wang, 2005). The European Environmental Agency has also published about the influential factors on the dispersion of pollutants in the air as, meteorological conditions, the emission height, local and regional geographical features and the source characteristics which are similar to the given evidence of Lin et al. study

(European Environmental Agency, 2008). Thus, some of the above factors were kept constant during the entire research work in order to reduce the number of variables, which are affected on pollutant transportation as well as source emission (Refer Subsection 5.1.3).

The concept of identical geometry of the building was maintained by selecting rectangular formed test chambers with indistinguishable locations for the supply outlet and return inlets. Since the test chambers are part of a building that is 30 years old, there is no effect on IAQ from any other building materials. Further, there were no sink or source materials inside the test chamber such as fabric furniture and curtains etc which were identified as major sources of VOCs in the indoor environment (Wolkoff, 1995). Thus, the pollutants generated in the experiments can be entirely from the paint application.

During this research work, controlled environmental and test conditions were maintained based on the specific objectives of the experiments and which will mention separately under each experimental program. The same product type and colour (brilliant white) of paints were used with the help of skilled workers for the application during entire research experiments. The mixing proportions were maintained constant throughout the research which is three parts of paint with one part of turpentine for solvent-based paint, whereas in water-based paint, two parts of paint to one part of water. The laboratory experiments conducted on the densities of paint mixture were obtained **0.796** and **1.064** $g/cm^3$for the solvent-based and water-based paints respectively (Table A2).

5.2.3 Variation of pollutants' concentration with time due to the application of wall paints (Exp 1)

Exp 1 was conducted inside the test chamber I, which is shown in Figure 5.1. This study aims to measure and analyse the variation of indoor air pollutants concerning the dispersion time. In order to witness the maximum effect of the paint, the area was made fully enclosed with minimum ventilation. The Indoor Air Quality Monitor (IQM60 Environmental Monitor V5.0 – Figure 1.4) and Haz-Dust Particulate Air Monitor (Figure 1.5) was used to measure the concentration of the pollutants with time.

The instruments were mounted on the centre of the chamber at a height of 1 m from the ground level in order to simulate a seated person on a chair. As the base case, the measurements were taken prior to the application of paints with the two pieces of equipment on various causative agents, inside the test chamber. Table 5.1 shows the results of the base case from several trials throughout the experiments on paint.

Table 5.1: Concentration of causative agents inside the room (Before applying the paint)

Name	Concentration
CO (ppm)	0
CO_2 (ppm)	315~325
TVOCs (ppm)	0
NO_2 (ppm)	0.022~0.025
$PM_{2.5}$ (mg/m^3)	0.021~0.023
Temperature (^{0}C)	26~ 29.5
Relative Humidity (%)	76~78

As the layout of the test chamber, which is shown in Figure 5.3, one coat of solvent-based paint was applied only on the designated wall area (shaded area) and the instruments were operated continuously at the centre of the chamber until the pollutant concentration disperses to the ambient condition. The painted area was 80 m^2 as the height of the test chamber is 3.2m. The time taken for the paint application was 1hr 15min. During this period, there was one painter inside the test chamber.

The same test procedure was repeated for the water-based paint and the indoor air quality parameters were recorded with time.

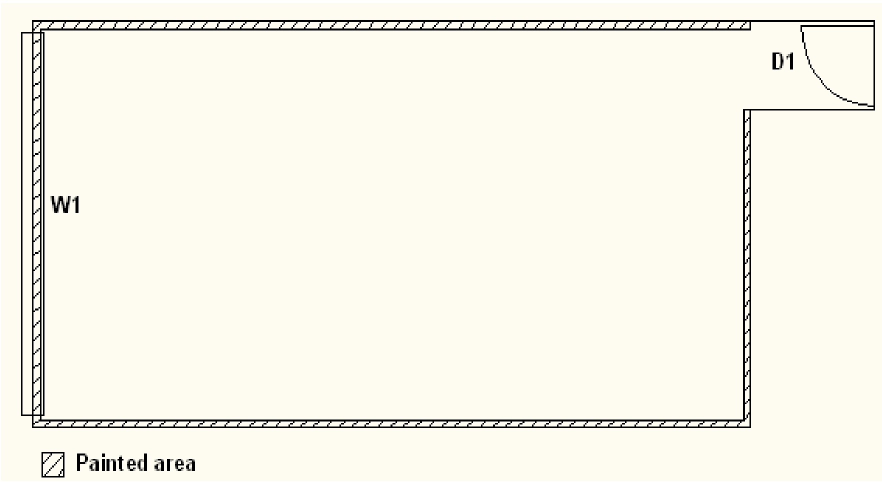


Figure 5.3: Plan view of the test chamber I during the Exp 1

5.2.4 Variation of pollutants' concentration with distance due to the application of wall paints (Exp 2)

Exp 2 was carried out by changing the position of the instruments from the source as shown in Figure 5.4. The specific objective of this experiment is to find out a relationship for pollutants dispersion with the distance due to the application of the wall paints. Similar environmental conditions were maintained for the Exp 2 like that for the Exp 1. One coat of solvent-based paint was applied to the sample wall area and the instruments were operated continuously at the 1m from the source until the pollutant concentration disperses to the ambient condition. The painted area was 4m^2 and its orientation is presented in Figure 5.5. The time taken for the paint application was 5min. The same test procedure was applied to the other locations such as 4m, 6m and 8m from the source with the fresh application of paint for each location.

This was repeated for the water-based paint and IAQ parameters were measured at different locations with time.

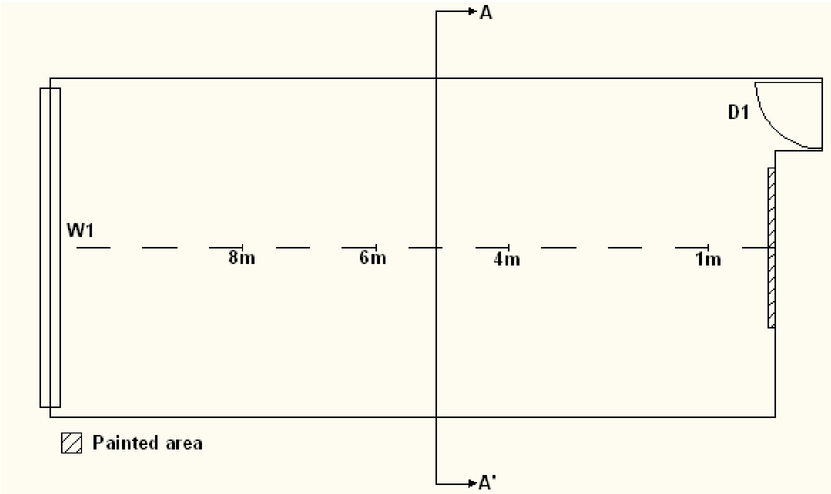


Figure 5.4: Plan view of the test chamber I during the Exp 2

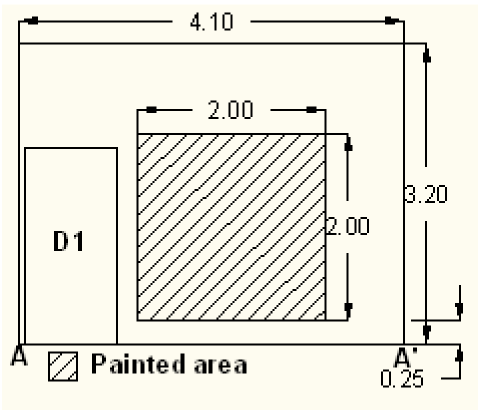


Figure 5.5: Orientation of the painted area during the Exp 2

5.3 Results and analysis

5.3.1 Results and analysis of Exp 1

The results obtained during the Exp 1 have shown different patterns of concentration with time.

Figure 5.6 and Figure 5.7 show the variation of TVOCs concentration with time due to the solvent-based and water-based paints. As illustrated in Figure 5.6, the concentration of TVOCs has drastically increased due to the solvent-based paint. Further, the maximum concentration of TVOCs is beyond the permissible indoor value

(0.75 ppm- OSHA) for a considerable period for both paints (Refer to Table 2.1). During this period, occupants are exposed to this adverse environmental condition, especially during the maintenance or the renovation period of a building.

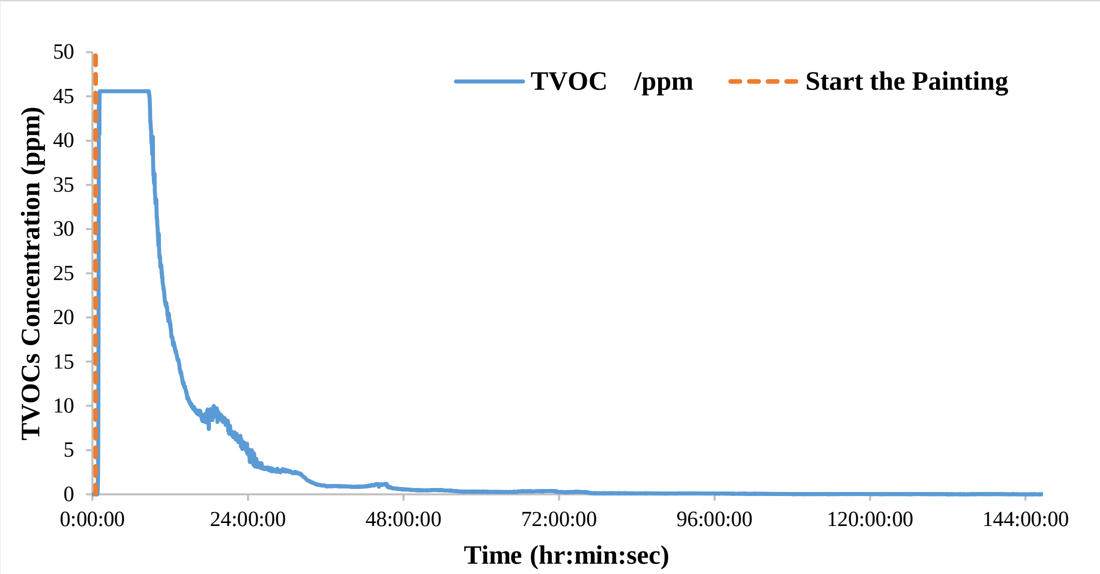


Figure 5.6: TVOCs variation with time- Solvent-based paint

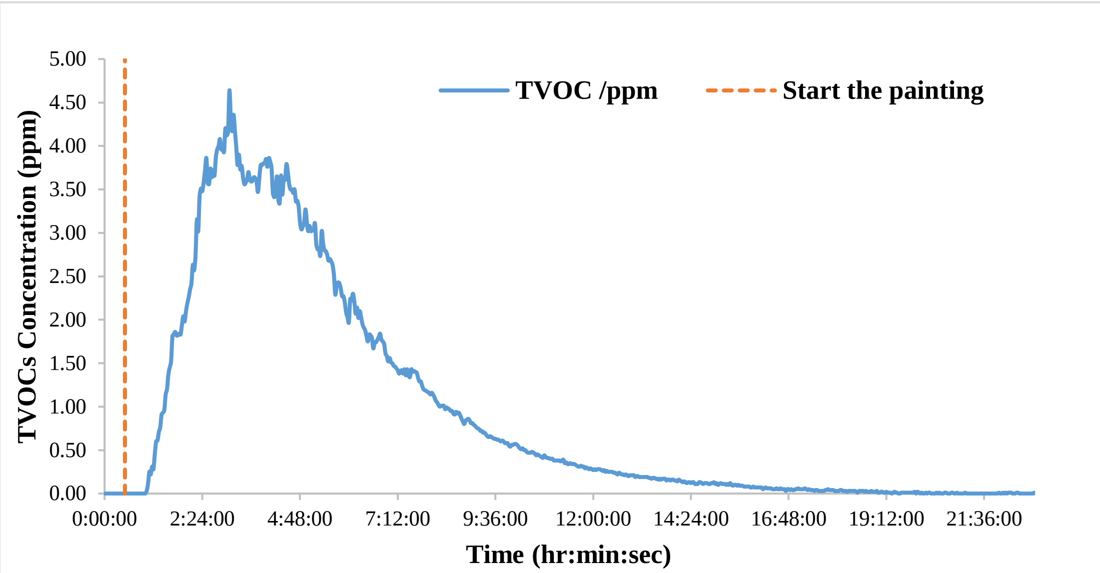


Figure 5.7: TVOCs variation with time- Water-based paint

Headspace Gas Chromatography (GC) technique was used to analyse the VOCs emitted from the paints under the room temperature. The Retention Index (RI) or retention time of a compound indicates where a compound will appear on a chromatography. Raw paint (before mixed with solvents), paint mixture of solvent-based and water-based paint and turpentine were tested; the obtained results for the above five samples are attached in Annex A. According to the Headspace GC analysis, the number of VOCs involved with the solvent-based paint production is enormous compared to the water-based paint (Refer to Table A3). Further to that, the solvent used to prepare the paint mixture for application is directly influenced by the VOCs emitted to the indoor environment. It has been clearly illustrated by tabularized data in Table A4 for the emitted VOCs from solvent-based paint mixture and turpentine.

In order to quantify the toxicity level of pollutants, the toxicity index parameter was introduced in Equation 5.1;

$$\textbf{\textit{Toxicity Index (TI)}} = \frac{\textit{Concentration of the pollutant}}{\textit{Permissible concentration for indoors}} \ldots\ldots \textbf{\textit{equation (5.1)}}$$

It was recorded TI of solvent-based and water-based paints as 61 and 6 respectively, with considering the maximum concentration of TVOCs generated from both paints under the ratio of 0.6139 for the painted area to chamber volume; referred the permissible value as 0.75 ppm. Moreover, time taken for the dispersion of TVOCs generated from solvent-based paint to the ambient condition was 6 days, whereas the water-based paint had taken only 21 hours. Therefore, the results have endorsed that the effect of solvent-based paint on indoor air quality is much more significant than that of water-based paint.

The summary of the results is presented in Table 5.2 with the maximum concentration and dispersion time for the TVOCs generated from both types of paints.

Table 5.2: Maximum concentration and dispersion time of the paints

Paint type	**Maximum concentration**	**Dispersion time to the ambient condition (0 ppm)**	**Dispersion time to the permissible indoor Value (0.75 ppm – OSHA) `**
Water-based	4.64 ppm	21 hr	9 hr 10 min
Solvent-based	45.58 ppm	140 hr	37 hr 14 min

CO concentration was also increased due to both paints and they are illustrated in Figure 5.8 and Figure 5.9. Compared to the water-based paint, solvent-based paint produced a higher concentration of CO inside the test chamber. Maximum concentrations of CO due to both types of paint were within the permissible indoor value defined by the USEPA (9 ppm- Refer Table 2.1).

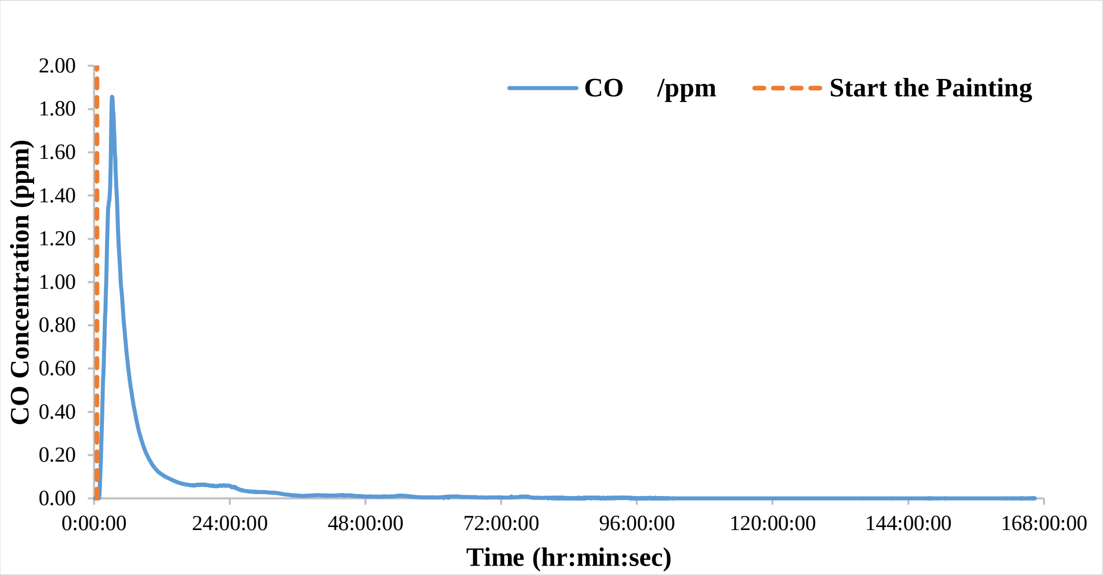


Figure 5.8: CO variation with time - Solvent-based paint

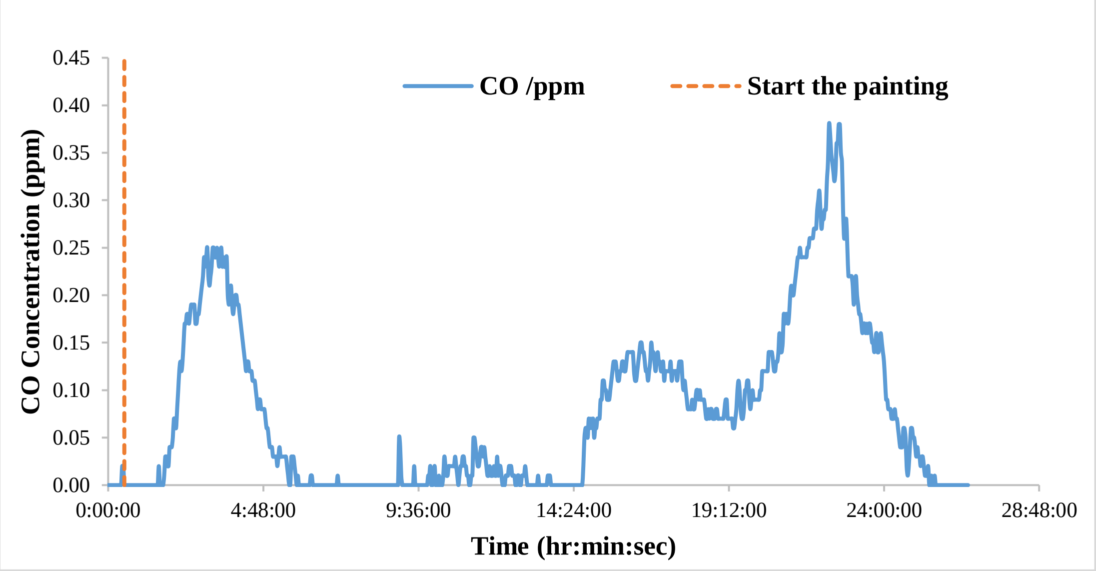


Figure 5.9: CO variation with time- Water-based paint

Figure 5.10 and Figure 5.11 indicate the NO_2 variation for solvent-based and water-based paints respectively. According to Figure 5.10, the concentration of NO_2 has increased drastically after the application of solvent-based paint, beyond the Secondary National Ambient Air Quality Standards of USEPA (0.053- Refer Table 2.1) and it was continued over a one day above the ambient condition. However, the NO_2 generation from the water-based paint was fairly low compared to the solvent-based paint.

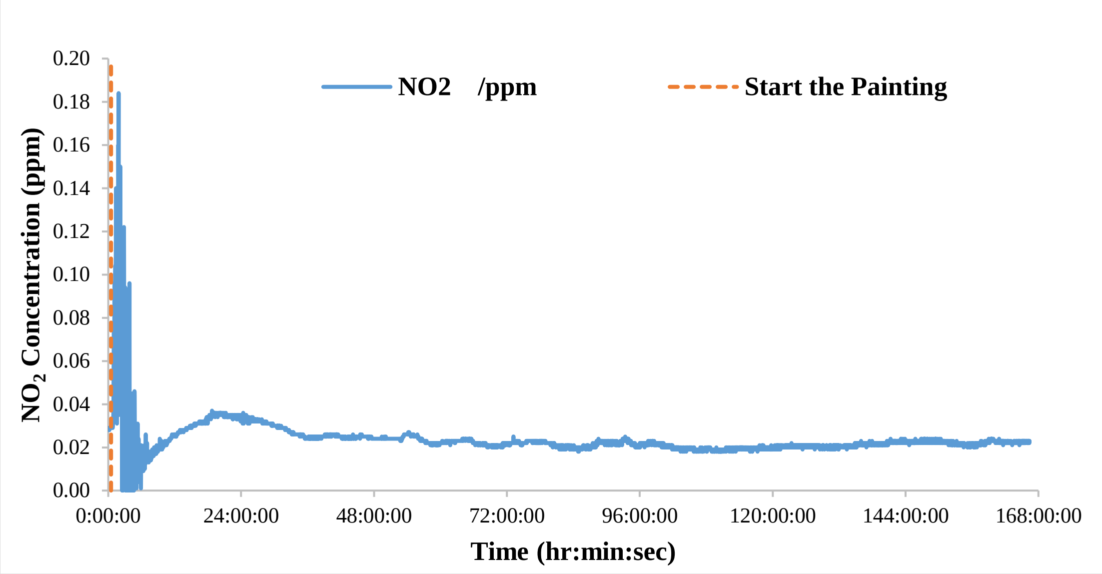


Figure 5.10: NO_2 variation with time - Solvent-based paint

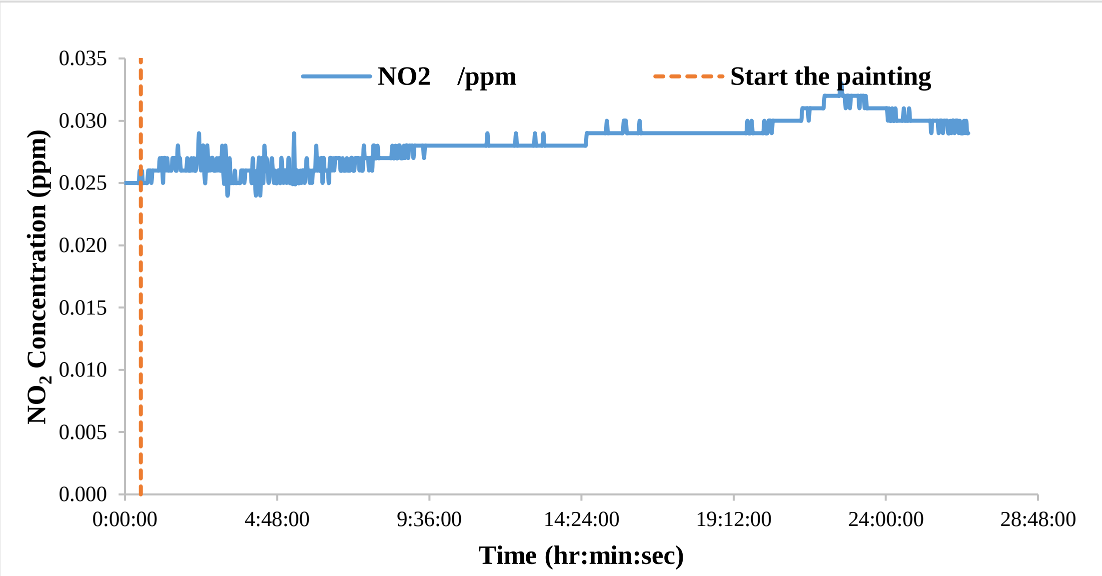


Figure 5.11: NO_2 variation with time- Water-based paint

VOCs, Nitrogen Oxide (NO_X) and CO have been called Ozone precursors since the formation of tropospheric Ozone which occurs when the above compounds react in the atmosphere with the presence of the sunlight. Tropospheric Ozone is known as "bad" ozone as it is affected by human health and vegetation since it is very much reactive. According to the study carried out on the health aspect of air pollution by the World Health Organization (b) (2003), it is revealed that ground-level ozone can harm the lungs and irritate the respiratory system. "In a mammoth analysis of data on 450,000 people in U.S. cities over an 18-year period, a team led by Michael Jerrett of the University of California, Berkeley, School of Public Health found that those who live in areas with high ozone levels, such as Houston or Los Angeles, have a more than 30% greater annual risk of dying from lung disease" (Jerrett, Ito, & Shi, 2009); (Chemical & Engineering News, 2009). Further, this indoor ozone could react with the VOCs and generate the polluting substances which may cause the Sick Building Syndrome (SBS) symptoms (Jones A. , 1999); (Groes, Pejtersen, & Valbjorn, 1996). Therefore, the generated pollutants of TVOCs, NO_2 and CO from paint applications are directly influenced by the formation of SBS.

According to Figure 5.12 and Figure 5.13, CO_2 concentration has also increased due to the solvent-based and water-based paints respectively. However, the maximum concentration values are within the permissible indoor value defined by the ASHRAE (1000 ppm- Refer Table 2.1). During the drying process of the paint, CO_2 is generated as it consumes some energy to evaporate the solvents and to achieve the desired viscosity to form the solid dry film on the wall. Therefore, water-based paint generates more CO_2 than solvent-based paint since the water must be evaporated using a force. However, there are some special paints (e.g. ceramic insulation paint) (Kawakami & Yamanaka, 2010) and mechanisms developed from modern technology to reduce the CO_2 emission during the drying process; such as Aqua-tech technology for water-based paint (Automotive Manufacturing Solutions, 2009).

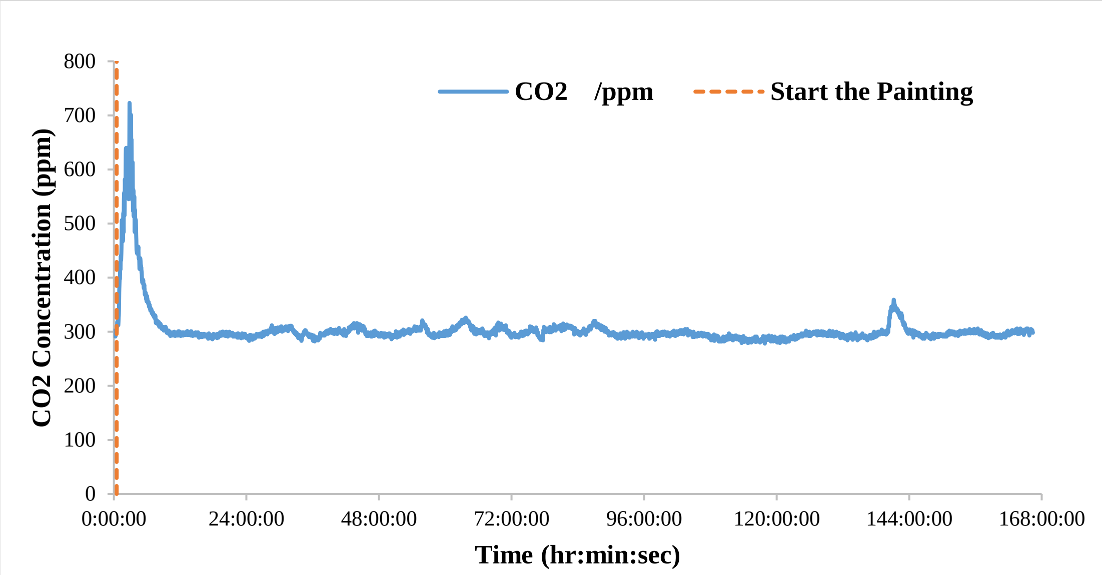


Figure 5.12: CO_2 variation with time - Solvent-based paint

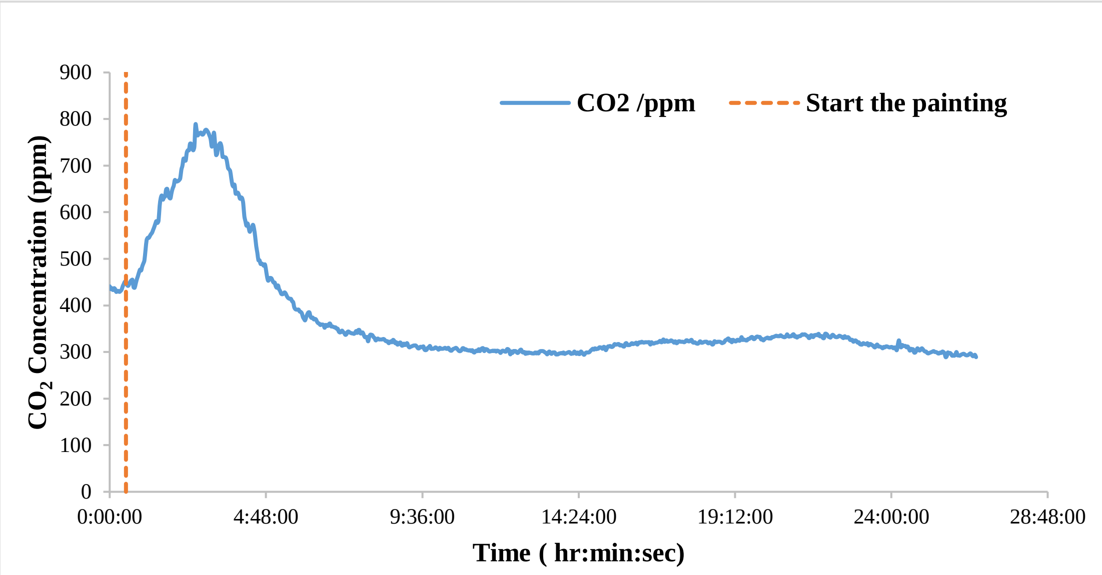


Figure 5.13: CO_2 variation with time- Water-based paint

Figure 5.14 and Figure 5.15 illustrate the timely variation of $PM_{2.5}$ concentration for solvent-based and water-based paint application. According to the figures, $PM_{2.5}$ concentration has increased due to both types of paint much more beyond the ambient average condition (0.021~0.023 mg/m^3) and the annual average value for Sri Lanka (0.025 mg/m^3) (Senevirathna, et al., 2011). Considering this experiment, the formation of the particulate matters could be identified as due to the emitted precursors from the paint application such as VOCs and NO_2, which are transformed through the atmospheric chemistry to particulate matters as secondary pollutants (Johns Hopkins Bloomberg School of Public Health, 2019); (Prienceton University, 1999).

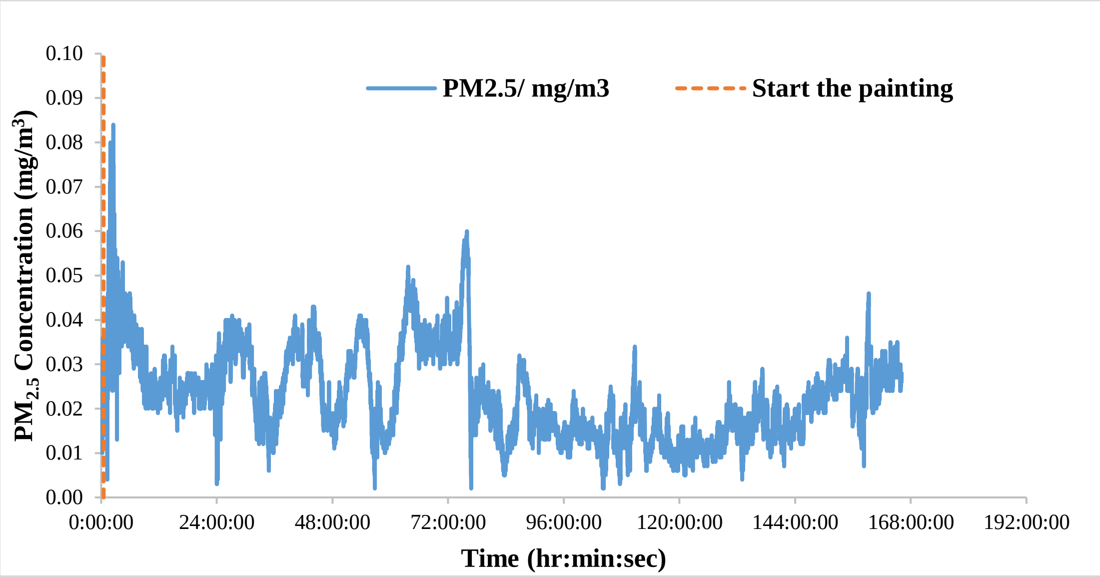


Figure 5.14: $PM_{2.5}$ variation with time- Solvent-based paint

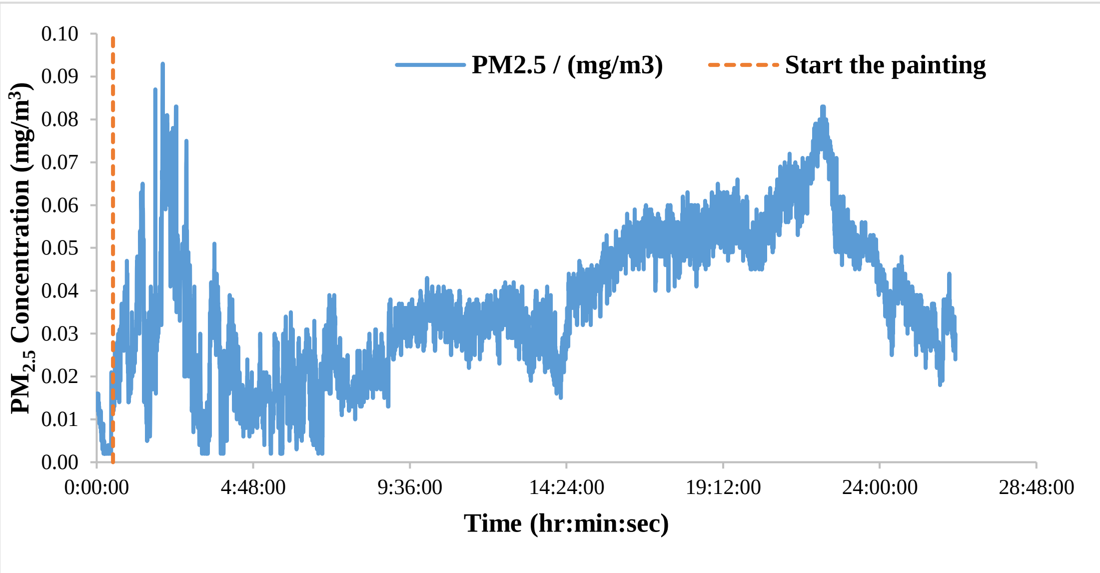


Figure 5.15: $PM_{2.5}$ variation with time- Water-based paint

Temperature and RH variations due to the paint application are presented in Figure B2 to Figure B5. As their diurnal variation of representation, there is no evidence to show the relationship for the temperature and RH variation with the paint application.

According to the results, the pollutant levels NO_2, CO, CO_2, and $PM_{2.5}$ have been affected with an increase due to both types of paint application, the most significant impact was made by the TVOCs concentration generated by the solvent-based paint. The variation of the temperature and RH did not show any difference with the paint application.

5.3.2 Results and analysis of Exp 2

As described in Subsection 5.2.4, Exp 2 was conducted in a test chamber under the same ventilation condition maintained in Exp 1. The most significant indoor pollutants from the paint application were able to find out from this experiment since the sample area was 4 m^2 (2m*2m) which is comparatively small from the real values. The dispersion behaviour of the pollutants generated from the solvent-based and water-based paint was exhibited dissimilar patterns with the distance from the source.

Timely variations of the TVOCs with the distance were presented in Figure 5.16 and Figure 5.17 for the solvent-based and water-based paints respectively. Considering the maximum concentration and the time taken for the dispersion of TVOCs, there was a significant effect on indoor air quality even from the sample area painted with solvent-based paint is compared to the water-based paint. Hence a detailed study has done on the dispersion of TVOCs generated from the solvent-based paint.

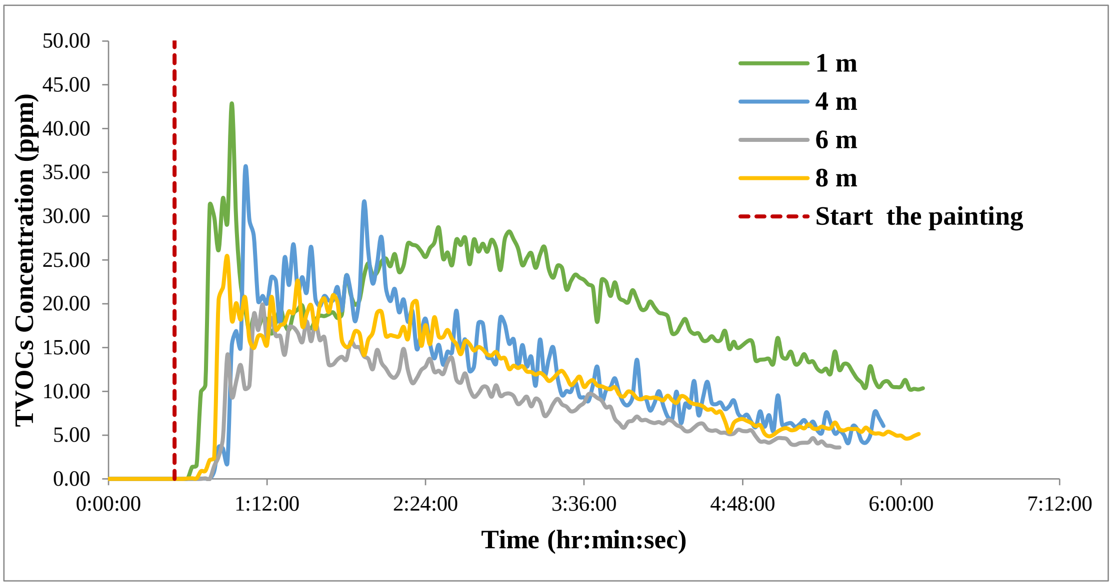


Figure 5.16: Timely variation of TVOCs with distances - Solvent-based paint

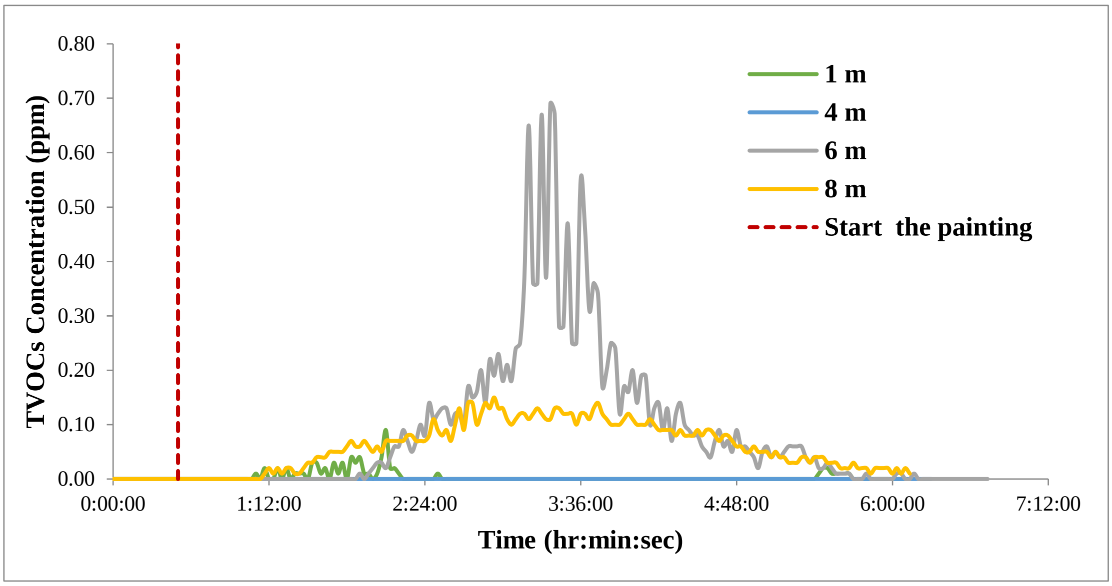


Figure 5.17: Timely variation of TVOCs with distances - Water-based paint

The maximum concentration of the TVOCs was occurred close to the source for the solvent-based paint, whereas, in water-based paint, it was at the centre of the chamber, which is 6m away from the source. Headspace GC analysis data were used to explain the above dispersion patterns using Table A3 and A4 about the ingredients of the solvent-based and water-based paint mixtures. As mentioned in Table A4, the number of VOCs caused by the paint application and their molecular weights is enormously high for solvent-based paint is compared to the water-based paint. Since the experiment was conducted under the minimum ventilation condition, pollutant transportation was mainly occurred due to the diffusion mechanism under the driving force of the thermal motion of molecules. Therefore, in solvent-based paint, pollutants were stacked close to the source as it produces numerous VOCs compared to the water-based paint and their mobility is low under the minimum ventilation condition with the high gravitational forces due to their molecular weights.

As in Figure 5.18, there was an irregular pattern of TVOCs variation with distance during the first one and half hours from the start of the painting, considering the different time taken for the pollutant transportation for the aforementioned locations. However, afterward there was a perfect pattern for the spatial variation of the TVOCs as presented in Figure 5.19; TVOCs concentration was decreased with the distance relative to the source area. According to the figure, TVOCs concentration was increased slightly near to the boundary of the test chamber due to the reflection of the pollutants after hitting on the walls. Spatial variation of the TVOCs concentration with time during the entire experiment is presented in Figure B6-i to B6-vii.

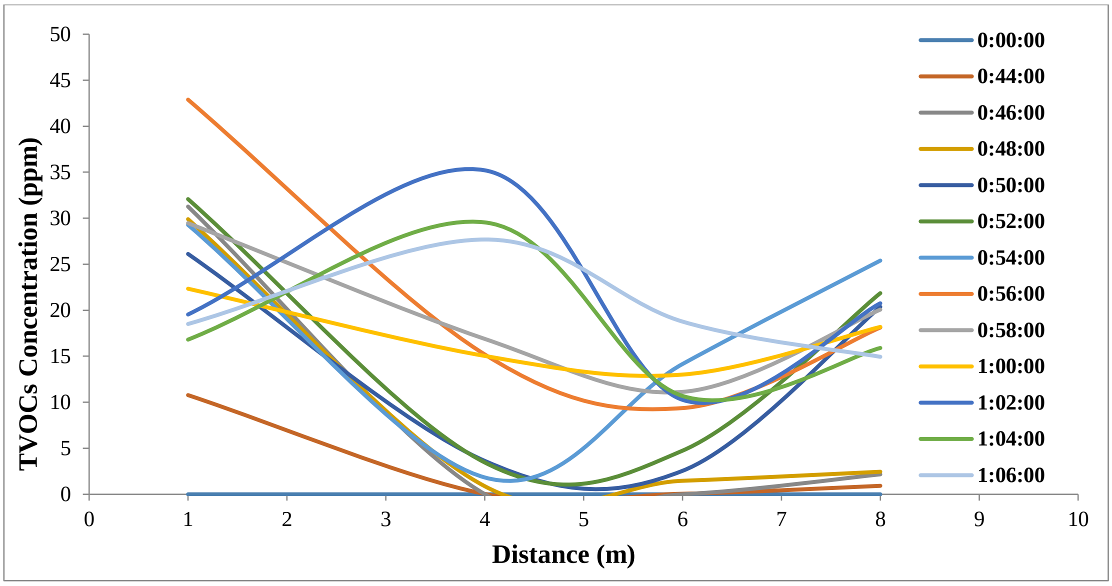


Figure 5.18: One dimensional spatial variation of TVOCs with time during the first hour - Solvent-based paint

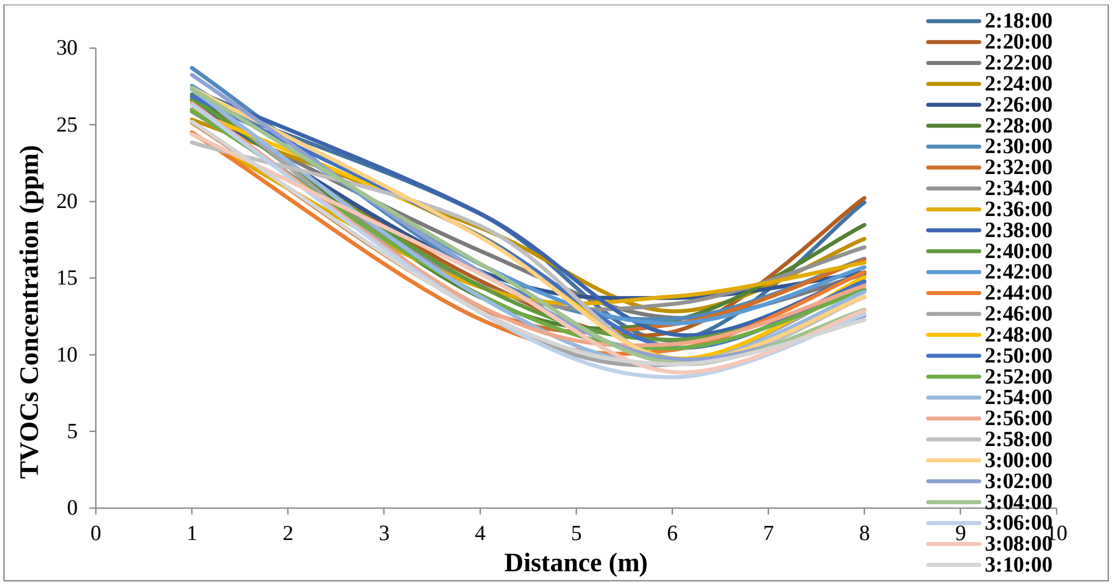


Figure 5.19: One-dimensional spatial variation of TVOCs with time - Solvent-based paint

Spatial variations of the other pollutants such as CO, NO_2, CO_2, $PM_{2.5}$, temperature and RH generated from the solvent-based and water-based paint application are presented in Figure B7 to Figure B18. According to the figures, the concentrations of the CO, NO_2 and $PM_{2.5}$ generated from the solvent-based paint is much more significant than the water-based paint. Similar to the results in Exp 1, the CO_2 emission during the drying process of the water-based paint is higher than the solvent-based paint. Temperature and RH did not show any variation due to the paint application.

According to the obtained results from Exp 1 and Exp 2, there are several pollutant generations and concentration variations due to the solvent-based and water-based paint application. Among them, TVOCs generated from the solvent-based paint exhibit the severe indoor air pollution with prolonged high concentration relative to the permissible indoor value. In low and middle-income countries, solvent-based paint is still at a considerable level of usage with considering some of the advantages as described in Subsection 5.1.1. Moreover, awareness to distinguish the effects of solvent-based paint and water-based paint on the occupants and painters is not at a satisfactory level. Therefore, further studies have conducted on the TVOCs generated from the solvent-based paint in order to create a healthier build environment.

5.4 Mathematical model for TVOCs dispersion from the solvent-based paint

The development of the mathematical model was carried out in terms of TVOCs variation with time and distance from the point of application. The results obtained from Exp 1 and Exp 2 which were conducted under the same environmental conditions were used for the analysis.

5.4.1 Mathematical models for TVOCs variation with time (Exp 1)

A mathematical model for the solvent-based paint dispersion was derived with the use of MATLAB software (MATLAB R2014a). The reason for the selection of this software over the other packages is depended on the size of the data set, time for the analysis and model verification with related statistical parameters. The "Time" and "TVOCs concentration" obtained from the experiment were used as the inputs for the MATLAB and the formulae indicated in the table are the outputs of the analysis.

Table 5.3: Mathematical models generated from MATLAB

Equation	Coefficients	Adjusted R^2 value	Sum of Square Error (SSE)	Root Mean Square Error (RMSE)
C(t) = a*exp(b*t) + c*exp(d*t)	a = 3206 b = -0.009692 c = 42.89 d = -0.001559	0.9949	590.5	0.4002
C(t) = a*exp(b*t)	a = 138.2 b = -0.002678	0.9645	4089	1.053
C(t) = a*t^b	a = 5.238e+07 b = -2.26	0.989	1266	0.5859
C(t) = a*t^b+c	a = 4.249e+07 b = -2.227 c = -0.09869	0.9892	1247	0.5815
C(t) = (a) / (t + b)	a = 4809 b = -401.6	0.9572	4933	1.156
C(t) = (a*t + b) / (t + c)	a = -1.382 b = 6919 c = -364.9	0.9878	1410	0.6184

As indicated in Table 5.3, the first form of equation (Exponential function with two terms) has been selected as the most suitable statistical model since it inherits the best fitting parameters as highest R^2 and lowest SSE and RMSE (R^2 = 0.9949, SSE = 590.5 and RMSE = 0.4002) for the experimental data with 95% confidence bounds. This model (equation 5.2) shows the relationship of TVOCs concentration with time.

$$C(t) = 3206\, e^{-0.00969t} + 42.89\, e^{-0.001559t} \ldots\ldots \textit{equation (5.2)}$$

Where C(**t**) = TVOCs concentration (ppm) as a function of time

t = Time relative to starting time of the paint application on a surface (min)

5.4.2 Statistical analysis using Chi-Square goodness-of-fit

The statistical hypothesis test called Chi-square goodness of fit (χ^2) was used to quantify the deviation of expected values from the statistical model with the observed values from the experimental data. The null hypothesis was made such that the experimental data follows the aforementioned distribution, which is shown in equation 5.2. The following formula was used to compute the value of the Chi-Square goodness-of-fit test.

$$\boldsymbol{\chi 2} = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

Where χ^2 =Pearson's cumulative test statistic

O_i= An observed the frequency

E_i= An expected frequency

k= Sample size

According to the Chi-squared test statistic with a degree of freedom of **k-1**,$\boldsymbol{\chi 2} < \boldsymbol{\chi 2_{k-1,\alpha}}$, the probability value ($\boldsymbol{\alpha}$) is 0 .99 **(**$\chi 2$ = 2239, $\chi 2_{k-1,\alpha}$ = 2522, k-1 = 2690) (Walker, 2015). Therefore, null hypotheses have been accepted.

5.4.3 Mathematical models for TVOCs variation with time and distance (Exp 1 and Exp 2)

In order to find out the relationship between the TVOCs concentration and distance, the data generated by changing the position of equipment from the source (Exp 2) was used. This set of data was collected under similar environmental conditions as that for the time variation (Exp 1), in the same test chamber. A similar form of equation 5.2 has been used for the data set which was generated from the Exp 2 and obtained the variation of the two coefficients (**a, c**) with the distance which are with the Euler's number (**e**). The obtained equations from MATLAB R2014a for TVOCs variation with time for the different locations are presented in equation 5.3 to equation 5.6.

Table 5.4: Mathematical models generated from MATLAB for the different locations

Location (Equation number)	**Coefficients**	**Adjusted R^2 value**	**Sum of Square Error (SSE)**	**Root Mean Square Error (RMSE)**
1m from the source (Equation 5.3)	a = 73.82 b = -0.009692 c = 13.15 d = -0.001559	0.965	123.4	1.05
4m from the source (Equation 5.4)	a = 35.94 b = -0.009692 c = 6.687 d = -0.001559	0.8444	308	1.673
6m from the source (Equation 5.5)	a = 21.6 b = -0.009692 c = 5.456 d = -0.001559	0.92	104	0.9509
8m from the source (Equation 5.6)	a = 38.63 b = -0.009692 c = 5.73 d = -0.001559	0.9758	42.96	0.5863

The relationships for the variation of the coefficient in the distance from the source are indicated in equations 5.7 and 5.8, which were obtained from Figure 5.20.

$$a(x) = 94.78\, e^{-0.24x} \quad (R^2 = 0.999) \text{ ....equation (5.7)}$$

$$c(x) = 15.13 e^{-0.18x} \quad (R^2 = 0.965) \text{ ....equation (5.8)}$$

Where **a(x) and c(x)** = **"a"** and **"c"** coefficients variation as a function of distance

x= Horizontal distance from the source (m)

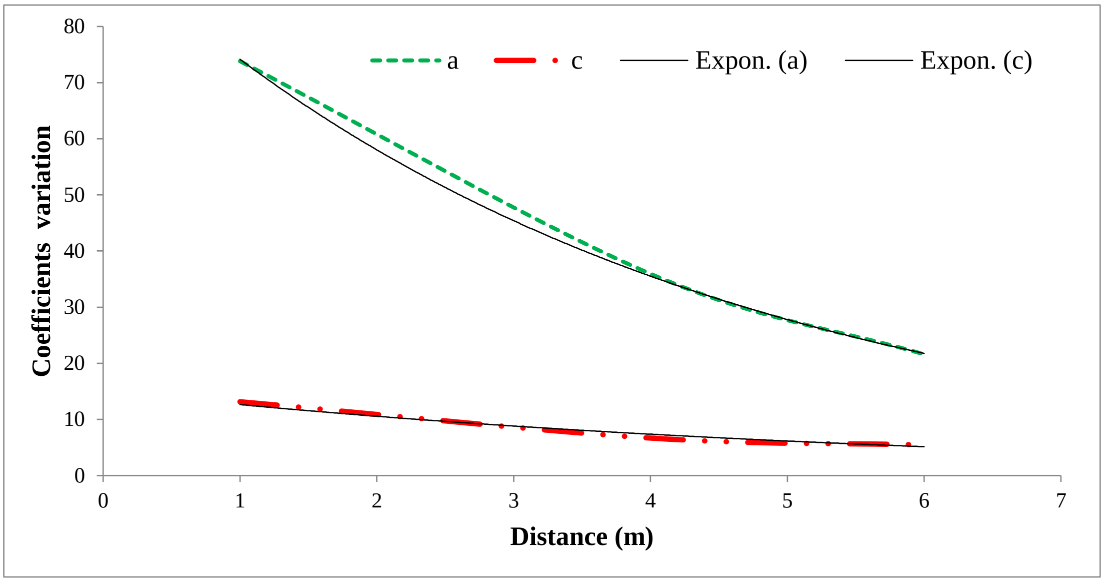


Figure 5.20: Coefficients (a, c) variation with the distance

The outcomes of the above experiments (Exp 1 and Exp 2) were used to derive a relationship for the TVOCs dispersion under the minimum ventilation condition. The obtained results in equation 5.2, 5.7 and 5.8 were considered during the analysis and TVOCs dispersion is presented in equation 5.9 as a function of time and distance from the painted area.

$$\mathbf{C(x,t) = 110.96\ e^{-(0.24x+0.00969t)} + 6.9\ e^{-(0.18x+0.001559t)})} \ldots\ldots\ \textit{equation (5.9)}$$

Where **C(x,t)** = TVOCs Concentration (ppm) as a function of distance and time

x= Horizontal distance from the source (m) {$\mathbf{x} \in \mathbb{R} \mid 0 < \mathbf{x} < \infty$; $\mathbf{x} \neq 0$, as the equation 5.9 represents the pollutant distribution in air from the source}

t = Time relative to starting time of the paint application on the surface (min) {$\mathbf{t} \in \mathbb{R} \mid 45 < \mathbf{t} < \infty$; Interval of "**t**" was defined considering the experimental data which explains the time taken for the pollutants' transportation from the source to the selected locations**}**

5.4.4 Impact of chamber volume on TVOCs dispersion using field data

The TVOCs dispersion generated from the solvent-based paint under the minimum ventilation condition is presented in equation 5.9 as a function of time and distance from the source. Field data were collected under the same environmental conditions of Exp 1 and Exp 2, with the use of the same product type and colour of paint in a different chamber (chamber III) in order to investigate the effect of chamber volume on TVOCs dispersion. One coat of solvent-based paint was applied to the shaded area in Figure 5.21 (16.988 m^2) and instruments were operated at the center of the chamber, which is 1.525 m horizontal distance from the painted wall. The time taken for the paint application was 20 min. The plan view of the chamber and door window details are presented in Figure 5.21 and Figure B1.

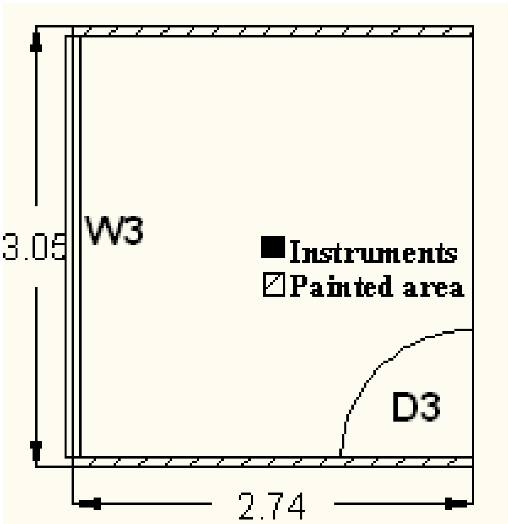


Figure 5.21: Plan view of the chamber III (All the dimensions are in meters)

Figure 5.22 represents the recorded data for the TVOCs variation with time for the solvent-based paint application on chamber III. As per the figure, dispersion of the TVOCs concentration was starting from the point "$\mathbf{a_o}$". Therefore, the graphical segment illustrated from "$\mathbf{a_o}$-$\mathbf{b_o}$" was considered during the analysis of the results.

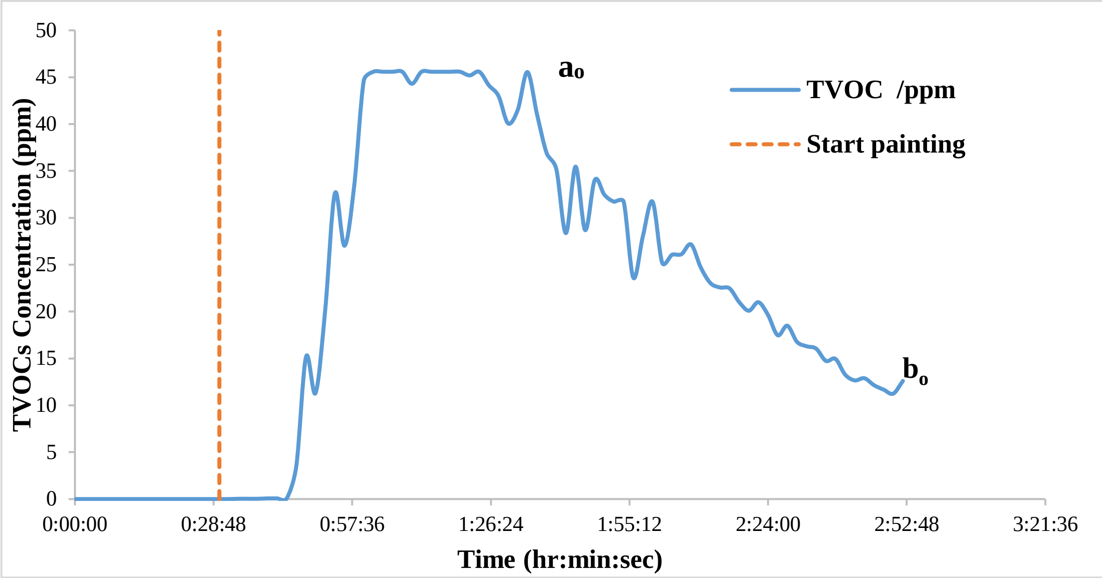


Figure 5.22: TVOCs variation with time inside the chamber III -Solvent-based paint

The comparison between the results of Exp 1 and Exp 2 with the field data, it was observed that the TVOCs concentration at a location is also depending on the chamber volume apart from the time and distance from the source. In order to generalize equation 5.9 for all types of chambers, it was re-derived with considering the TVOCs dispersion in a chamber size of unit volume. Thus, equation 5.10 explains the TVOCs dispersion as a function of time and distance for a unit volume of the chamber, where the definition of the symbols in equation 5.10 is the same as per in the equation 5.9.

$$C(x,t) = [85.35\, e^{-(0.24x+0.00969t)} + 5.31\, e^{-(0.18x+0.001559t)}]*10^{-2} \quad \text{........equation (5.10)}$$

Accordingly, the TVOCs dispersion can be presented as in equation 5.11 for the test chamber of any volume;

$$C(x,t) = V*[85.35\, e^{-(0.24x+0.00969t)} + 5.31\, e^{-(0.18x+0.001559t)}]*10^{-2} \quad \text{........equation (5.11)}$$

Where V= Volume of the test chamber (m^3)

However, the results of the mathematical model with the field data have been proven that the logarithmic scale of the volume is directly proportional to the TVOCs concentration with the best statistical parameters when it is compared to the equation in 5.11. Therefore, the following new form of equation (equation 5.12) can be suggested as the final outcome for the TVOCs dispersion over the analysis of the results of the paint application.

$$C(x,t) = \log V^* [52.5\, e^{-(0.24x+0.00969t)} + 3.3\, e^{-(0.18x+0.001559t)}] \quad \textit{equation (5.12)}$$

The result obtained from equation 5.12 is presented in Figure 5.23 with the field data related to the experiment carried out in chamber III. According to Figure 5.23, both data sets were very close enough and the gradient of the field data set is slightly higher than the results predicted from equation 5.12. Thus, the user will never receive a TVOCs flush out period which is lesser than the actual condition from the mathematical model. This situation could further ensure the healthier build environment for the occupants with the predictions from the equation derived in 5.12.

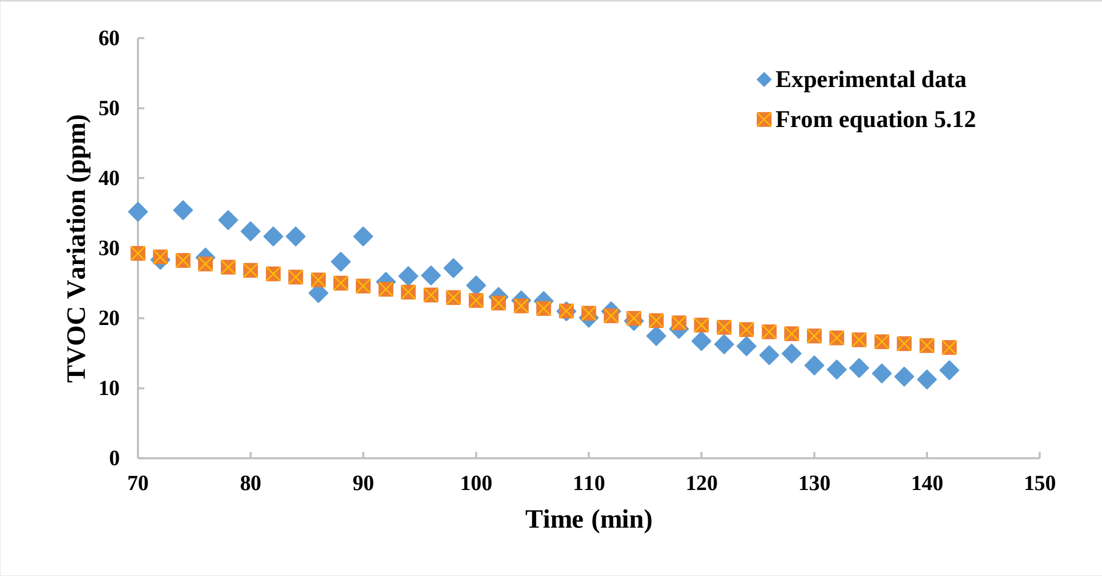


Figure 5.23: Comparison of the mathematical model for TVOCs dispersion with field data

5.4.5 TVOCs dispersion model validation using field data

The validation of the mathematical model in equation 5.12 was done using the field data which were collected in the test chamber II in Figure 5.2. The volume of the chamber is 147.2604 m^3 and the measurements were taken at 2.05m distance from the source area. Five different painted areas of 1m^2, 2 m^2, 3 m^2, 4 m^2 and 5 m^2 were tested with the fresh application of paint in each experiment. Field data were recorded in the same environments and test conditions which were maintained as for Exp 1 and Exp

2. One coat of paint was applied to the shaded area of the test chamber II with the same product type and colour of the paint. Figure 5.24 shows the plan view of the test chamber II during the experiments.

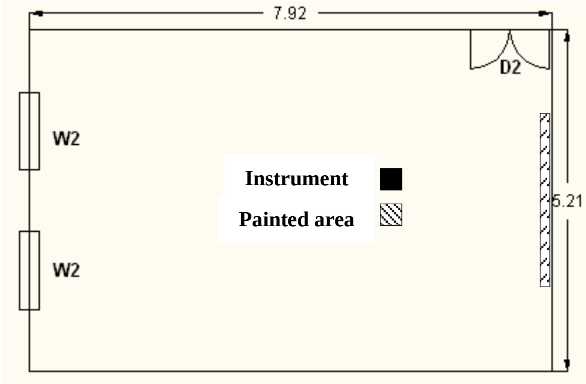


Figure 5.24: Plan view of the chamber II during the field data collection

The results obtained from equation 5.12 is presented with the experimental data related to the field measurements carried out in chamber II. According to the Figures, in 5.25 to 5.29, both data sets were very close enough except for the painted area of $1m^2$, where there is a minor deviation in the results from the mathematical model with experimental data during the initial hours of the dispersion curve. However, the prediction of the flush-out period from equation 5.12 is higher than in the existing scenario. Thus, equation 5.12 can be still used for the dispersion of TVOCs generated from relatively small areas.

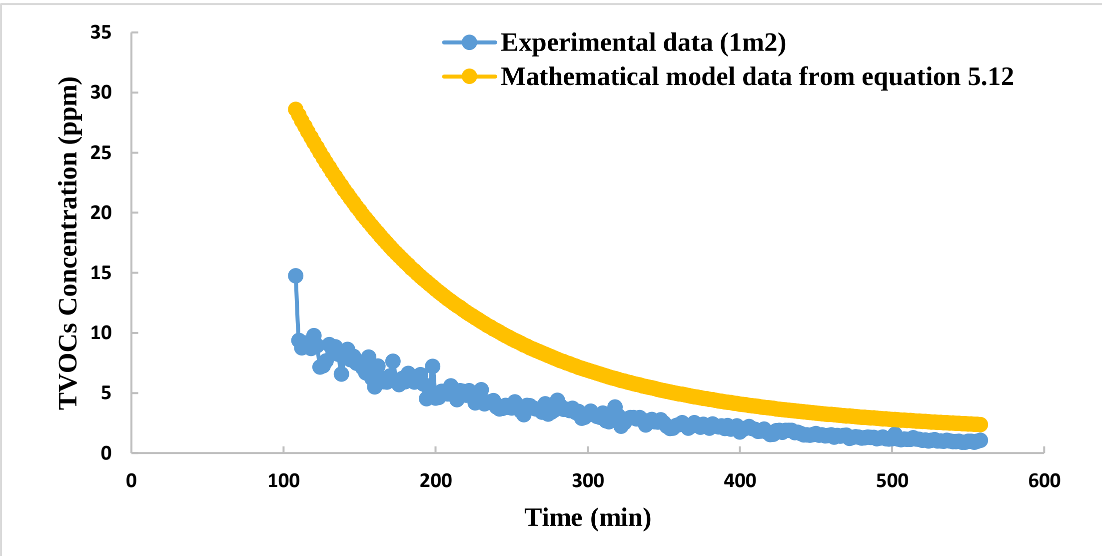


Figure 5.25: TVOCs dispersion model validation using field data- $1m^2$

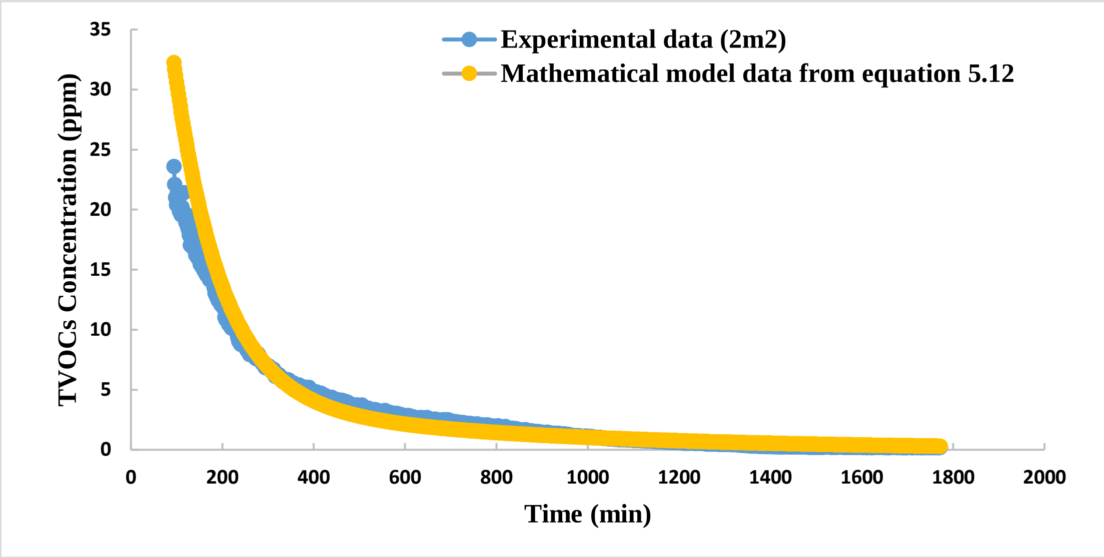


Figure 5.26: TVOCs dispersion model validation using field data- 2m^2

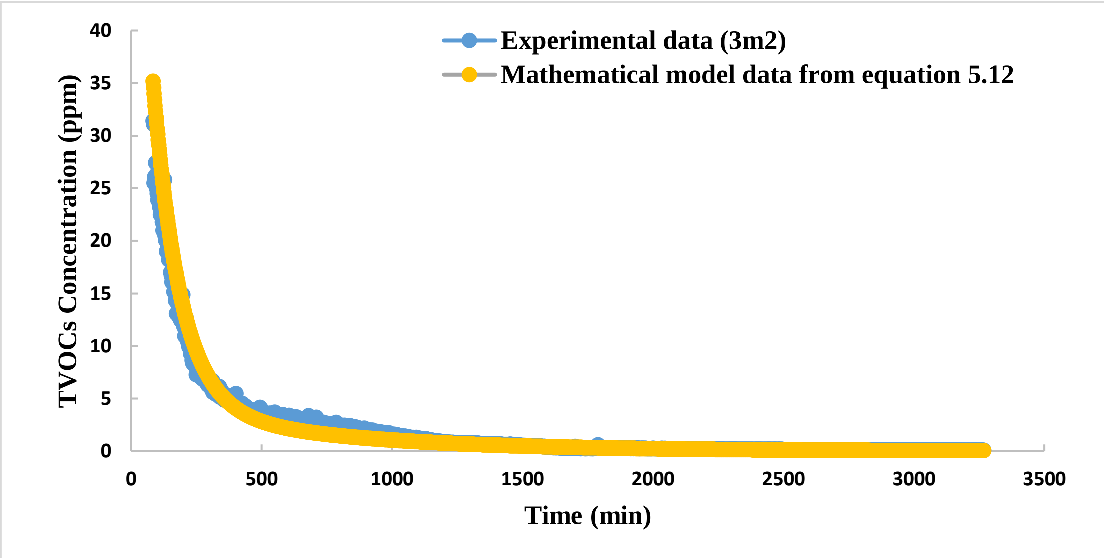


Figure 5.27: TVOCs dispersion model validation using field data- 3m^2

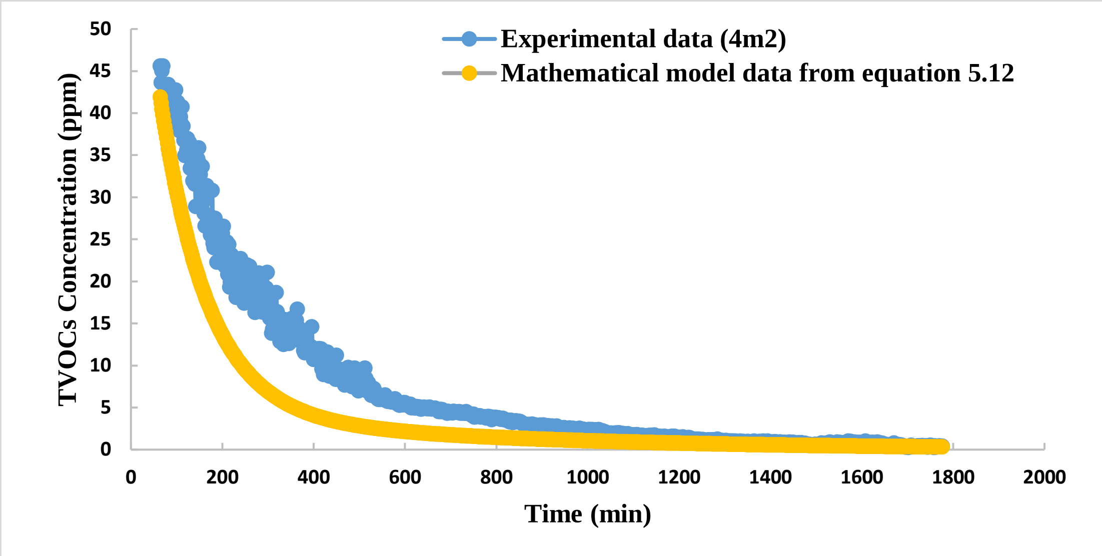


Figure 5.28: TVOCs dispersion model validation using field data- 4m^2

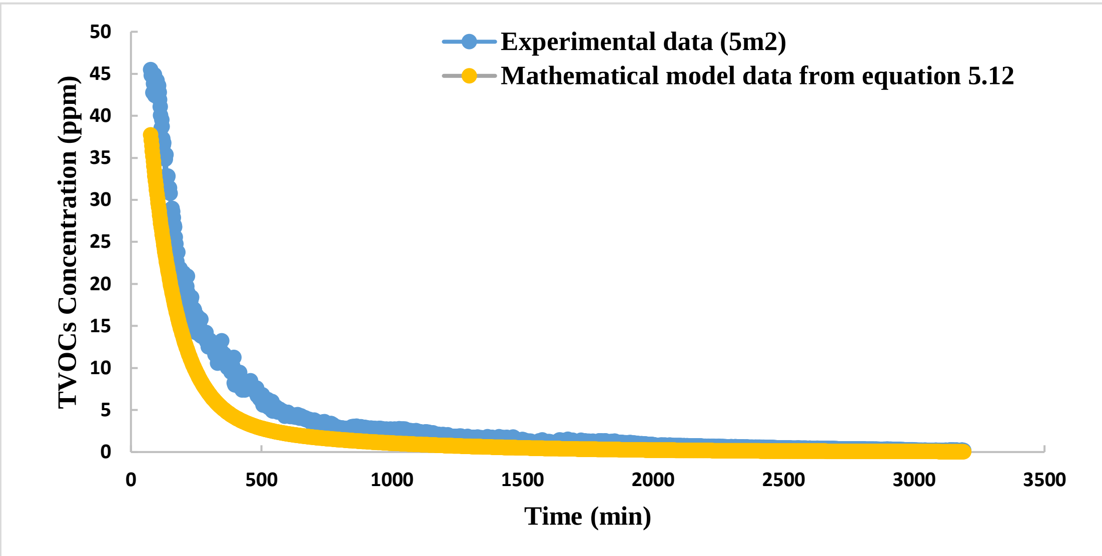


Figure 5.29: TVOCs dispersion model validation using field data- 5m^2

Table 5.5 illustrates the statistical parameters which were obtained for the above graphical representations in Figure 5.25 to 5.29 concerning the different painted areas. As per the table, R^2 values of the above five samples are very close to the “one”, where the minimum R^2 value is 0.9202 for the 4m^2 of the painted area. Further to that RMSE is also comparatively low considering the range of TVOCs concentration of the field data. Therefore, the TVOCs dispersion model in equation 5.12 can be validated from the field data as the proposed model will produce the results which are very much equal to the actual scenario.

Table 5.5: Statistical parameters of TVOCs dispersion model compared to the field measurements

Painted area	R^2 value	Adjusted R^2 value	Sum of Square Error (SSE)	Root Mean Square Error (RMSE)
1m²	0.946	0.9458	559.4	1.58
2m²	0.9712	0.9712	730.3	0.9335
3m²	0.9837	0.9837	561.7	0.5942
4m²	0.9202	0.9201	3393	1.992
5m²	0.9805	0.9805	764.3	0.7009

5.4.6 Applications of the mathematical model

The following applications have been identified from the developed model in Equation 5.12:

- To predict the building flush-out period of buildings under the minimum ventilation condition
- To determine the safe margin of distance from the painted surface for the occupancy during the building maintenance and renovation stages

Furthermore, the mathematical model for the TVOCs dispersion under minimum ventilation condition was used to calculate the flush-out period for the minimum area of any habitable space in residential buildings due to the wall paint application. Based on the building regulations of Sri Lanka, the minimum space inside a building shall be not less than 8 m^2 with a minimum width of 2.50 m clear between walls (Urban Development Authority, 2018). With reference to Equation 5.12, the building flush-out period is established as 30 hrs up to the indoor permissible value and 95.4 hrs or 4 days up to the ambient condition under the minimum ventilation condition.

5.5 Summary

The detailed experimental programme carried out in a test chamber I with solvent-based and water-based paints has shown a significant impact on IAQ with paint application. Among the generated pollutants, TVOCs from the solvent-based paint has been identified as the most prominent pollutant due to the wall paints. Therefore, further studies have been carried out on the emission of TVOCs from solvent-based paint and develop the mathematical model of exponential nature for the dispersion of TVOCs under the minimum ventilation condition. Thus, equation 5.12 represents the TVOCs dispersion model for solvent-based paint applications under the following conditions.

- Minimum ventilation condition as the entire closed indoor environment
- The rectangular shape of the chamber
- One coat solvent-based paint application with the mixture density of 0.796 g/cm^3 or 1:3 mixing proportion of solvent-based paint and turpentine
- Non-absorptive substrate
- Rate of sample application time is in the range of (0.8-1.0) min/m^2
- Average temperature and relative humidity are (26-29.5) ^{0}C and (76-78) %

The developed model can be used to predict the building flush-out period in new buildings. A safe distance of operation for the occupants from the painted area can also be worked out by the proposed model in the building maintenance and renovation stages. Based on the validated mathematical model in Equation 5.12, the building flush-out period for a minimum area of any habitable room in residential buildings is established as 4 days up to the ambient condition under the minimum ventilation condition.

Building related professionals can maintain a comfortable and healthy indoor environment using the proposed model with confidence.

Further studies on the dispersion of TVOCs generated from solvent-based paint for different ventilation rates are being carried out in Chapter 6 (Exp3) with the use of computational fluid dynamic analysis.

CHAPTER 6: EFFECT OF VENTILATION ON DISPERSION OF TVOCs – CASE STUDY WITH SOLVENT BASED PAINT

6.1 General

The consequences of the wall paint on IAQ have been directed to several advances in the paint technology to cater the consumer's requirements with better quality products. The paint contains low or no levels of VOC ingredients as one of the examples of innovation in paint technology. Moreover, 100% acrylic paint product with the durability, beauty and performance as traditional coatings is another achievement to minimise the indoor volatile compounds emitted from the paint application. Rules and regulations which are initiated from various organizations with the eco-labeling and ingredient limitation are also useful in order to regulate the paint companies or products; examples for such organizations are the United States green building council, Green Seal, Greenguard^{TM} Environmental Institute, Master Painters Institute (MPI), Scientific Certification Systems, etc. (USGBC, 2011); (Green Seal, 2016); (GREENGUARD Certification, 2016); (MPI, 2012); (SCS global services, 2016); (eurofins, 2016). However, it was observed that the majority of developing countries do not have any strong influence to initiate and maintain the aforementioned standards considering the consumer's health. Thus, the awareness of the general public is also substantially poor on the effect of their consumable products.

According to the previous chapter, experiments on water-based paint and solvent-based paint have been led to select the TVOCs from solvent-based paint as a major indoor air pollutant due to the paint application over the other type of pollutants. As a result, the mathematical model for TVOCs dispersion with time and distance from the source area was established for the minimum ventilation condition.

However, Lin et al. and Petrone et al. studies have illustrated that dispersal of air pollutants is affected by many factors such as meteorological conditions (wind speed, wind direction and atmospheric stability), building geometry, source characteristics and locations of supply outlets- return inlets, etc. (Lin, Chow, Fong, Tsang, & Wang, 2005); (Petrone, Balocco, & Cammarata, 2012). Therefore, the requirement of the

CFD model has emerged with the increase of the variables related to the pollutants' transportation. This chapter presents the details of the computational model which was carried out on solvent-based paint application under controlled environmental conditions to study the ventilation condition on pollutants' dispersion.

Computational modeling of IAQ is a modern tool that can be used by skilled personnel to reduce the risk of building failures due to unsatisfactory environmental performance. This technique can be applied to assist the building designs during the early concept design stage or the maintenance stage to create a desirable indoor environment for the inhabitants. In this analysis, IAQ models are used to describe the transportation and dispersion of air contaminants throughout the structure as a function of source characteristics, building geometry, air exchange rate and other parameters, etc. (Jones & Waters, 1993).

There are two modeling approaches for the indoor air environment which are;

- Macroscopic models
- Microscopic models

Macroscopic models are divided into two groups itself, namely single-zone and multi-zone models. Single zone models assume that the building can be considered as a single well-mixed zone. This is suitable for a single-story house with no partition and all internal doors and windows are opened. In multi-zone models, it is necessary to identify and describe all the zones of interest and link them between the zones and the outdoor air. The mass balance equation mentioned in equation 6.1 is used for the analysis purpose (Demokritou, 2016); (Shafie-Pour, Shrafi, & Tavakoli, 2009); (Blondeau, Tiffonnet, Allard, & Haghidhat, 2008).

$$C = [\,C_0 + \frac{G}{Q}\,] + [C_i - \frac{G}{Q} - C_0]\, e^{-\lambda t} \ldots\ldots \textit{equation (6.1)}$$

Where C = contaminant concentration inside the zone

C_0= outdoor contaminant concentration

G = generation rate of contaminant

Q = outdoor and exhaust airflow rate

C_i = initial contaminant concentration

λ = outdoor airflow to volume ratio

t = time

Microscopic models are based on the continuity, momentum and energy equations containing the spatial and time dependency of all indoor environment variables. It may have one, two and three dimensions depending on the flow problem and application to describe airflow and pollutant distribution in a ventilated room. As discussed in Section 2.7, CFD is a powerful instrument to simulate microscopic indoor air quality models as well (Ahmad, Farideh, Omid, & Ehyaei, 2016); (Jamriska, 2003); (Jreijiry, Husaunndee, Inard, & Villenave, 2016).

In this research, CFD analysis was done in order to propose the dispersion model for generating TVOCs from solvent-based paint application. ANSYS-Fluent was used for the computational analysis by considering its well-validated physical modelling capabilities to deliver fast, accurate results across the widest range of CFD and multi-physics applications. ANSYS-Fluent CFD solver is based on the finite volume method. Therefore, the domain is discretised into a cell-centred finite set of control volumes. General conservation equations for mass, momentum, energy, species, etc. are solved on this set of control volumes. The overview of CFD modelling is illustrated in Figure 6.1 (ANSYS, 2010 (a)).

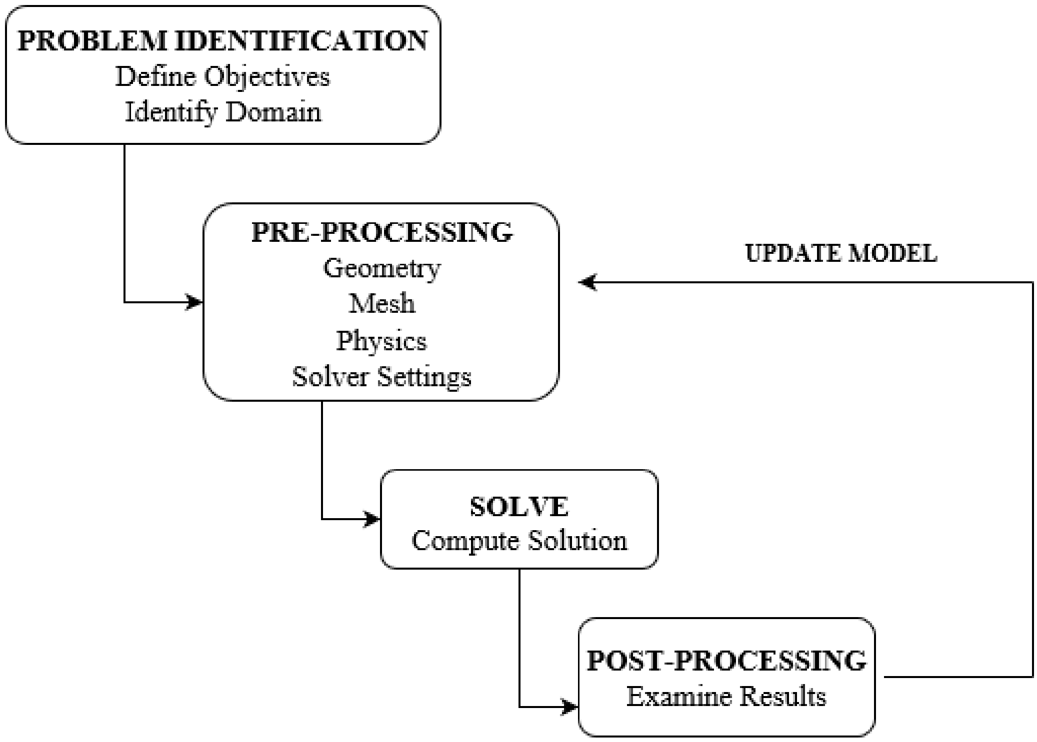


Figure 6.1: Overview of the CFD modelling

Each stage of computational analysis using ANSYS-Fluent software will be discussed in Section 6.3.

6.2 Details of the experimental program

6.2.1 Introduction

This study is named as Exp 3 and it was carried out with the use of experimental and computational data analysis. The main objective of Exp 3 is to develop a dispersion model for the TVOCs generated from solvent-based paint in different ventilation conditions. The study covered in this chapter is aimed at the following sub-objectives;

- Find out the variation of maximum concentration and dispersion time of TVOCs with different ventilation conditions
- Validate the CFD model using experimental data

The proposed model and recommendations from the study could be used by building related professionals such as building planners, designers and interior designers, etc. and occupants to mitigate the adverse indoor environmental conditions.

Experiments were done in a test chamber (test chamber II) which was created inside the Department of Civil Engineering, University of Moratuwa, Sri Lanka. The dimensions and the details of the chamber and openings are shown in Figures 6.2 and 6.3.

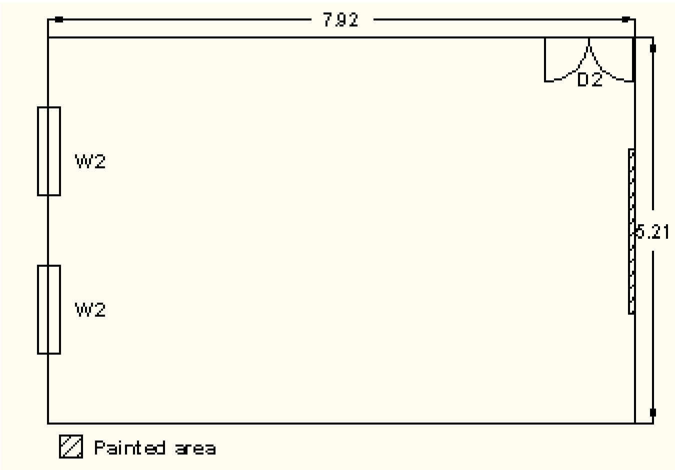


Figure 6.2: Plan view of the test chamber II (All the dimensions are in meters)

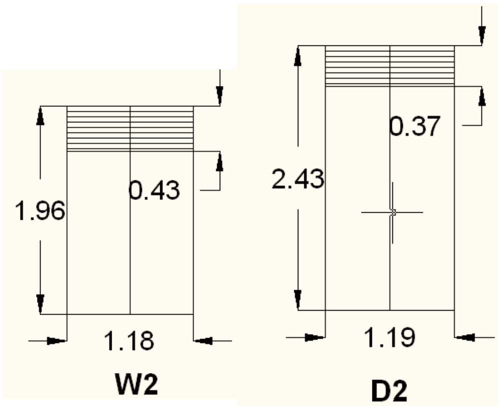


Figure 6.3: Dimensions and the details of the openings (All the dimensions are in meters)

The door (D_2) was closed during the experiments while the other four windows (W_2 was considered as two windows) were used to facilitate the different ventilation conditions for the experiment. Hence it was possible to maintain five different ventilation cases, including the enclosed chamber environment. The above five cases are listed below in Table 6.1.

Table 6.1: Ventilation conditions and their descriptions

Ventilation condition	Description
Case 01	All windows are closed
Case 02	One window is opened
Case 03	Two windows are opened
Case 04	Three windows are opened
Case 05	Four windows are opened

6.2.2 Environmental and test conditions with an experimental procedure

Experiments were carried out with controlled environmental and test conditions. Therefore, the following parameters such as paint density, painted area, wet film thickness, chamber geometry, source location, and reference point for measurements, etc. were kept constant during the entire research work.

The same product type and colour (brilliant white) of solvent-based paint were used for the entire experiments with the mix ratio of 1:4 of turpentine and paint. Thus, the density of the paint mixture was 0.8752 g/cm^3 in each case.

The painted area was 1.4884 m^2 (1.22 m*1.22m) and it is oriented perpendicular to the centre line (longitudinal) of the chamber. The treated gypsum board was used as a substrate for the paint application to simulate the wall for every fresh application in five different ventilation cases. Before the experiments, acrylic wall filler was applied to the gypsum board in order to moderate the absorptive capacity of the substrate and kept it for several weeks for the drying process. The test was done on the emission from the treated gypsum boards and found out no pollutants generated from it. Therefore, the generated pollutants from the experiments are entirely due to the paint application.

In many literatures, wet film thickness has been identified as a factor on the VOC emission from wet materials (Lee, Kwok, Guo, & Hung, 2003); (Yang X. , Chen, Zeng, Zhang, & Shaw, 2011). Therefore, it was fixed as 150 ± 5 μm with the use of skilled labour for the paint application. Details of the calculation of wet film thickness are presented in Table A6.

As mentioned in the previous chapter, Indoor Air Quality Monitor (IQM60 Environmental Monitor V5.0) was mounted on the centre of the chamber at a height of 1 m from the ground level in order to simulate a seated person on a chair. As the base case, the measurements were taken prior to the application of paint on various causative agents inside the test chamber. Table 6.2 shows the results of the base case from several trials throughout the experiments on paint.

Table 6.2: Concentration of causative agents inside the room (Before applying the paint)

Name	Concentration
CO (ppm)	0
CO_2 (ppm)	317~345
TVOCs (ppm)	0
NO_2 (ppm)	0.022~0.026
Temperature (^{0}C)	24~ 27.5
Relative Humidity (%)	77~79

Then, the painted gypsum board was immediately inserted into the chamber and the experiment was continued with case 01 ventilation condition until the pollutant concentrations disperse to the ambient condition. The details of measurement and calculation of the air exchange rate are presented in Subsection 6.2.3. The same test procedure was used for the other four ventilation conditions with the fresh application of paint on a newly treated gypsum board.

6.2.3 Air exchange rate

A Vane anemometer was used to measure the air exchange rate into the test chamber. The vanes were oriented at a right angle to the airflow at the center of a window. It detects the flow velocity of the air and expresses a reading in m/sec. The measurements taken at different intervals were averaged to calculate the air exchanges per hour through openings including windows and louvres. The volume of the test chamber is 147.2604 m^3 (floor to floor height 3.5687 m) and an area of one window and all louvres are 0.6525 m^2 and 0.372 m^2. The detailed calculation of the air exchange rate is presented in Table 6.3 (Atkinson, et al., 2009); (CHLOR, 2009).

Table 6.3: Detailed calculation of the air exchange rate into the test chamber

Ventilation condition	**Average air movement rate (m/s)**	**Air exchangeable area (m^2)**	**The volumetric flow rate of air (m^3/s)**	**The volume of the test chamber (m^3)**	**Air changes per hour (ACH-1/h)**
Case 01	0.0100	0.372 (0.372)	0.0037	147.2604	0.0909
Case 02	0.0533	1.0245 (0.6525*1+0.372)	0.0546	147.2604	1.3358
Case 03	0.0867	1.677 (0.6525*2+0.372)	0.1454	147.2604	3.5531
Case 04	0.1067	2.3295 (0.6525*3+0.372)	0.2486	147.2604	6.0745
Case 05	0.1167	2.982 (0.6525*4+0.372)	0.3480	147.2604	8.5049

6.2.4 Variation of TVOCs concentration with different ventilation conditions (Exp 3)

The results obtained during the experiment have shown different patterns of concentrations with time and ventilation conditions. A significant effect from the TVOCs generated from the solvent-based paint has been observed even under the maximum air exchange rate of 8.5 ACH maintained during the experiments.

6.2.5 Results and analysis of Exp 3

The recorded data for the TVOCs variation with different ventilation conditions are presented in Figure 6.4. The variation of maximum value and dispersion time to the ambient condition is discussed in order to quantify the ventilation effect on TVOCs dispersion. Chamber windows were closed during the nighttime of the experiment considering the safety requirement for the instrument used. Therefore, the dispersion curves obtained during the initial hours of experiment or before close the windows were considered in the analysis of case 02 – 05 (Figure 6.5).

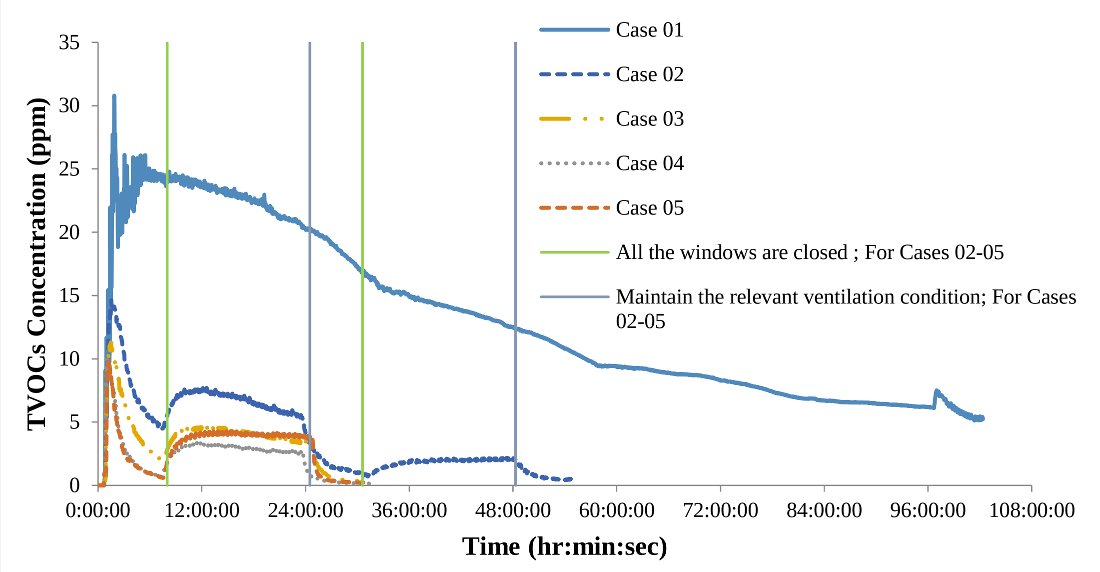


Figure 6.4: TVOCs variation with different ventilation conditions

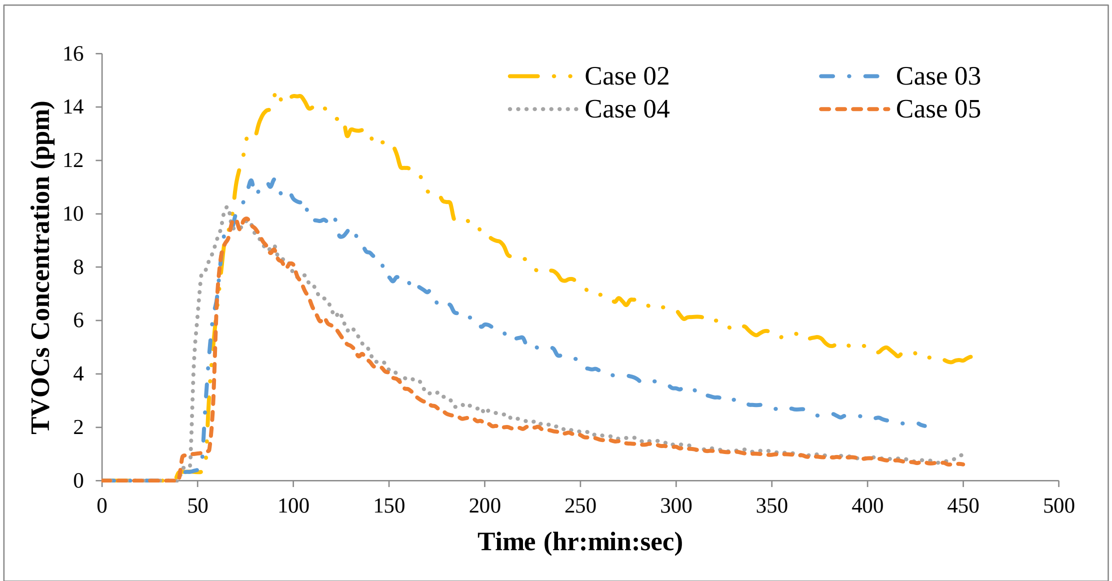


Figure 6.5: TVOCs variation during the initial hours of an experiment of case 02-05

Figure 6.5 is illustrated that there is a proper variation in the maximum concentration of TVOCs with different ventilation conditions. Thus, an empirical relationship was established as in Figure 6.6 for the maximum TVOCs concentration generated from the solvent-based paint under the natural ventilation conditions.

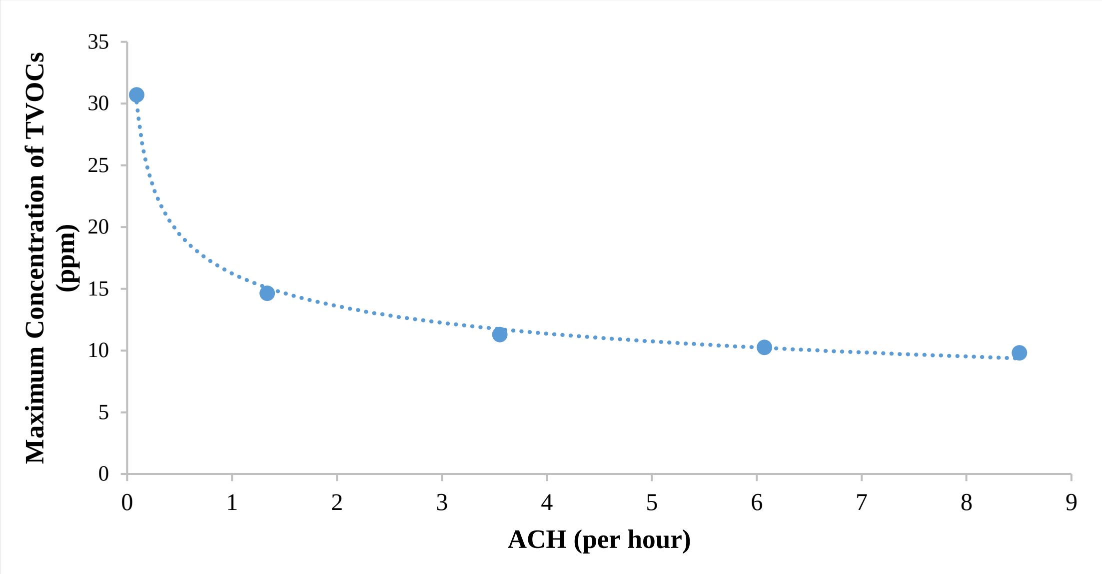


Figure 6.6: TVOCs max. concentration variation with ventilation conditions

The above graph in Figure 6.6 was plotted from the experimental data considering the best fitting parameters such as R^2 =0.9945 for the empirical equation 6.2 which is mentioned below. The following equation can be referenced in the upcoming researches to study the maximum possible TVOCs concentration which could expect in indoors with the known ventilation condition under the control of environmental and test conditions. Furthermore, the equation 6.2 can be used by building related professionals to consult the occupant and building planners and designers to mitigate the possible exposure period to the adverse indoor environment which is created during the building maintenance and construction period.

$$\text{Max. TVOCs concentration} = 16.249 * ACH^{-0.257} \quad \text{.........equation (6.2)}$$

The effect of ventilation condition on TVOCs dispersion time was quantified using the experimental data with the use of MATLAB R2014a analytical software. This software was used to generate the TVOCs dispersion curves for experimental data in Figure 6.5 until its concentration is dispersed up to the ambient condition. The obtained graphs are presented in Figures 6.7 and 6.8.

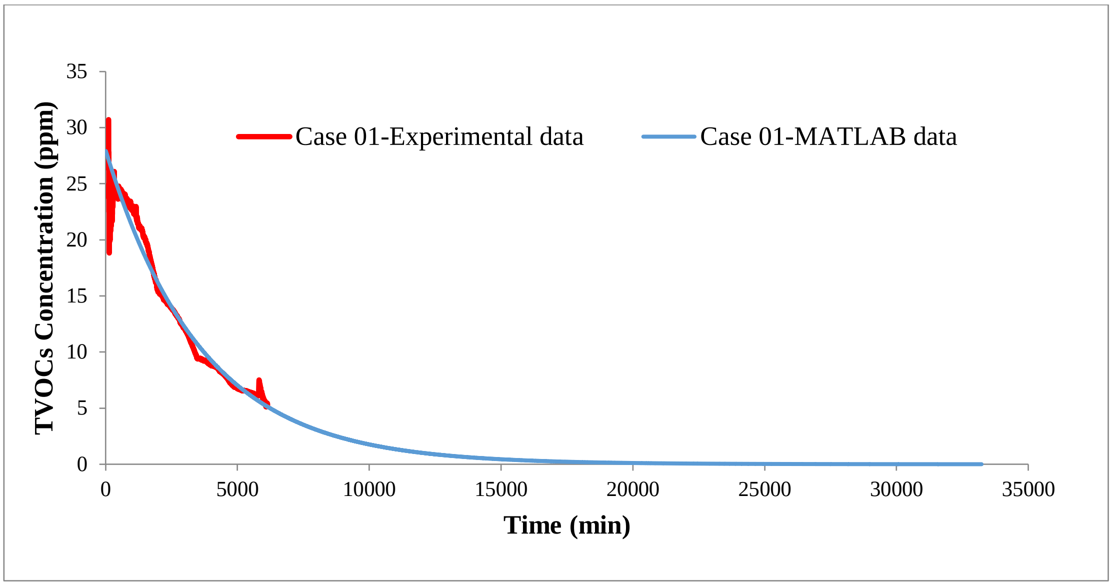


Figure 6.7: TVOCs variation curve obtained from MATLAB for experimental data- Case 01

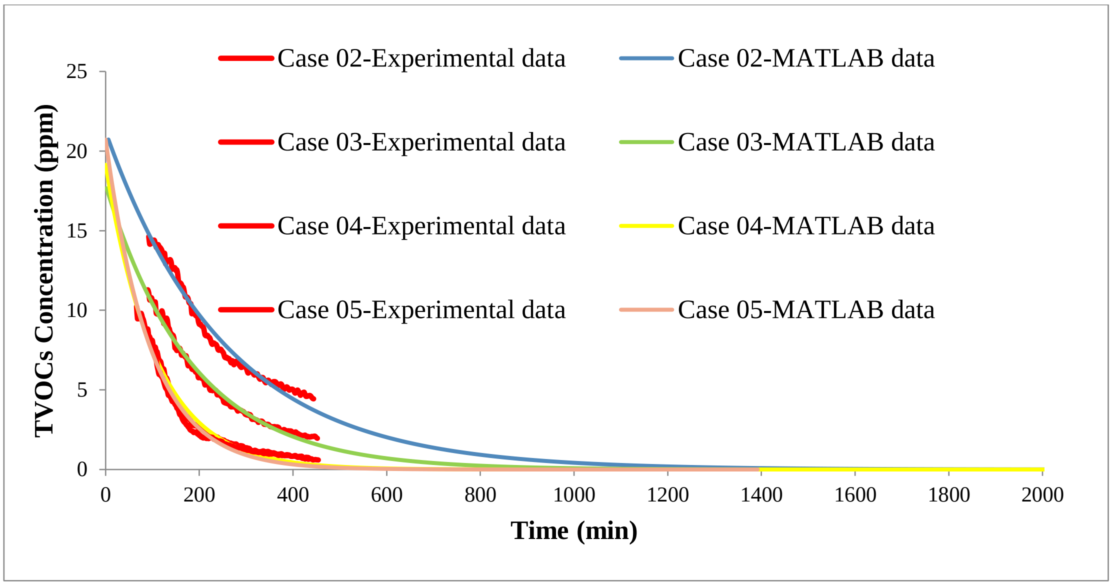


Figure 6.8: TVOCs variation curves obtained from MATLAB for experimental data- Case 02 - 05

The obtained equations from MATLAB for the experimental data were used for the upcoming analysis considering the goodness of fit parameters of them. All five equations are in the form of exponential function with two terms. Coefficient values and goodness of fit parameters are listed in Table 6.4.

Table 6.4: Goodness of fit parameters for MATLAB equations

Equation form: C(t) = a*exp(b*t) Where C(t) = TVOCs Concentration (ppm) as a function of time t = Time relative to the painted board insertion time (min)				
Ventilation condition	**Coefficients**	**R^2 value**	**Sum of Square Error (SSE)**	**Root Mean Square Error (RMSE)**
Case 01	a = 27.99 b = -0.00027636	0.9742	3103	1.015
Case 02	a = 21.22 b = - 0.0039138	0.976	41.89	0.4893
Case 03	a = 17.86 b = - 0.0053922	0.992	10.09	0.2367
Case 04	a = 19.14 b = -0.009366	0.9836	20.6	0.3346
Case 05	a = 20.72 b = -0.009366	0.9696	30.58	0.4033

As in Table 6.4, five equations inherit the highest R^2 and lowest SSE and RMSE values which are statistically proven the equations to represent the experimental data for the TVOCs dispersion.

Time taken for the pollutants' dispersion is the other criterion which can represent the occupational exposure to the adverse environmental conditions. As in Figure 6.4 and 6.5, TVOCs concentration was drastically increased above the permissible indoor value defined by OSHA (0.75 ppm) after the insertion of the painted gypsum board. Thus, the dispersion time for TVOCs is not a few hours, although with the ventilation conditions. The details of TVOCs dispersion time with the relevant ventilation condition are presented in Table 6.5.

Table 6.5: TVOCs dispersion time with ventilation condition

Ventilation condition	Average ventilation condition (1/h)	Dispersion time to the ambient condition (0 ppm)	Dispersion time to the permissible indoor value (0.75 ppm – OSHA)
Case 01	0.0909	520 hr 28 min	218 hr 40 min
Case 02	1.3358	35 hr 36 min	14 hr 16 min
Case 03	3.5531	25 hr 18 min	9 hr48 min
Case 04	6.0745	14 hr 42 min	5 hr 48 min
Case 05	8.5049	13 hr 20 min	5 hr 20 min

According to the building regulations of Sri Lanka, an unobstructed area of opening for natural lighting and ventilation should be provided as 1/7 of the floor area for all types of rooms, where the 50% of the windows should be operable. However, this regulation might not be used in the operational period as mentioned above due to the openings in the walls which are facing the occupied area. In Exp 3, the void/floor area ratio of the test chamber II is 1/5.5 (void and floor areas are 7.5173 m^2 and 41.2632 m^2 respectively) and the windows are facing the outdoor environment and the door is in the occupied area. Thus, the operable area is mostly limited to the area of windows including its louvers, which is greater than 50% of the openings as per the requirement. The cross ventilation also occurs across the door louvres.

Considering the details of dispersion time, it is observed that at least half of the day was taken for the dispersion of TVOCs generated even from the 4% of the painted area of the wall under the 8.5 ACH ventilation condition (wall area is 39.3397 m^2). As illustrated in Table 6.5, the TVOCs dispersion time was regularly varied with the ventilation rate as like the variation of maximum TVOCs concentration with the ventilation rate. Therefore, the interdependency of these three parameters was tested and the obtained relationships are illustrated in Figures 6.9 and 6.10 concerning the dispersion time taken to the ambient condition and the indoor permissible value defined by OSHA.

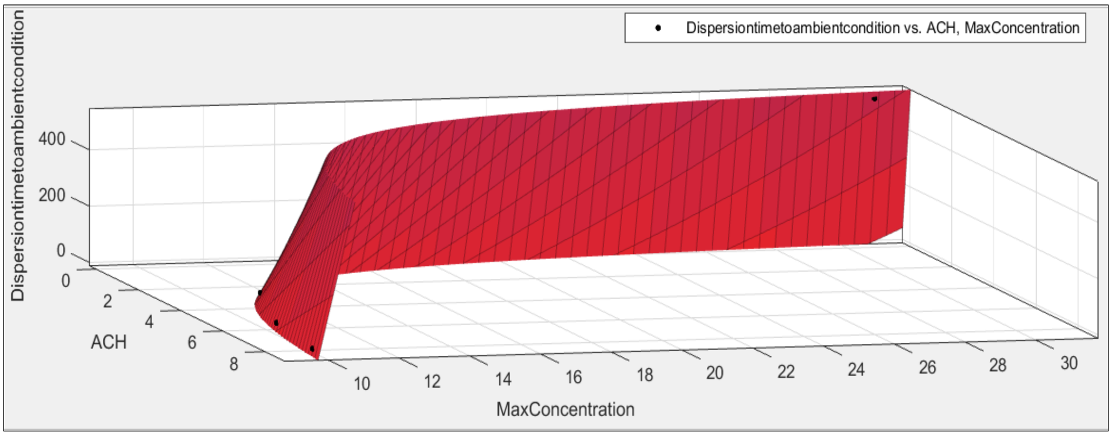


Figure 6.9: Variation of TVOCs dispersion time taken to the ambient condition (0 ppm) with TVOCs maximum concentration and air exchange rate (equation 6.3)

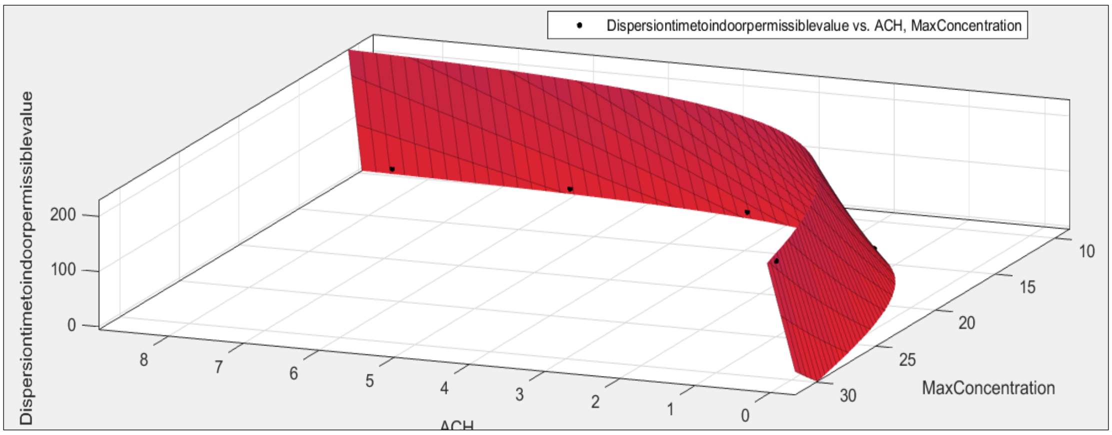


Figure 6.10: Variation of TVOCs dispersion time taken to the indoor permissible value (0.75ppm) with TVOCs maximum concentration and air exchange rate (equation 6.4)

The obtained mathematical equations for Figures 6.9 and 6.10 are presented in Table 6.6, in equations 6.3 and 6.4 respectively. As stated by the equations, the dispersion time of the TVOCs is linearly related to the air exchange rate, whereas the maximum TVOCs concentration follows the quadratic form of behavior with the dispersion time. Hence, the nonlinear behavior of the variables of maximum TVOCs concentration and ACH in equation 6.2 can be further concluded that from equation 6.3 and 6.4. The above relationships among the three parameters can be used in future researches related to the IAQ modeling with the presence of air polluting sources.

Table 6.6: Mathematical equations obtained from MATLAB for TVOCs dispersion time

Equation form: $DT_{ambient}$/ DT_{ipv} = $p_0 + p_1$*ACH + p_2* Cmax + p_3*ACH* C_{max} + p_4* C_{max} ^2 Where $DT_{ambient}$= Dispersion time taken to the ambient TVOCs condition (h) DT_{ipv}= Dispersion time taken to the TVOCs indoor permissible value (h) ACH =Average air exchange rate (1/h) C_{max}= Maximum TVOCs concentration (ppm)			
Equation number	**Coefficients**	**R^2 value**	**Sum of Square Error (SSE)**
Equation (6.3)	P_0 = -579.3 P_1= -503.1 P_2= -8.846 P_3= 57.9 P_4= 1.331	1	4.415e-24
Equation (6.4)	P_0 =-215.6 P_1= -193.1 P_2= -4.557 P_3= 22.22 P_4= 0.5617	1	8.01e-25

6.3 Computational Fluid Dynamic model for TVOCs dispersion under different ventilation condition

6.3.1 Introduction

ANSYS Fluent R15.0 software was used to simulate the IAQ models for the air circulation in Chamber II with the painted board under different ventilation conditions. The same environmental and test conditions in the Exp 3 were reproduced in the computational models by means of the ANSYS Fluent software and it will be discussed in Section 6.3.2. The 3D model views were generated from the SolidWorks 2012 for the five different ventilation conditions.

Governing equations in CFD comprise of three mathematical statements (Versteeg & Malalasekara, 2007). They are, the mass of fluid is conserved, the rate of change of momentum is equal the sum of the forces on a fluid particle (Newton's second law) and the rate of change of energy is equal to the sum of the rate of heat added to and the rate of work done on a fluid particle (first law of thermodynamics). The airflow will be considered at the macroscopic scale and the behavior of the fluid is discussed in terms of macroscopic properties such as velocity, pressure, density, specific gravity, viscosity and temperature, etc.

The objective of CFD simulation is to generate an IAQ model to predict the pollutant concentration due to the known behavior of a source under the different ventilation conditions. As mentioned in Section 2.7, this technique will provide several benefits to the user, where the reduction in the overall cost and time which are required for the experimentation can be highlighted. The outcome of the software can be proposed for the use of building related professionals or occupants after its validation from the experimental results.

The details of the pre-processing stage are discussed in Section 6.3.2.

6.3.2 Details on pre-processing stage

Pre-processing consists of the input of the flow problem for a CFD programme and successively transform this input data into a suitable form for the use of solver. The following are the stages to be addressed during the pre-processing (Refer Figure 6.1).

- Definition of the geometry of the region of interest
- Sub-division of the domain into a number of smaller and non-overlapping sub-domains
- Selection of physical and chemical phenomena that needed to be modelled
- Define the fluid properties
- Specification of the appropriate boundary conditions

The details of each stage are described below.

6.3.2.1 Geometry

SolidWorks 2012 was used to draw the Test Chamber II for the five different ventilation cases. Subsequently, the generated file was imported to the Geometry in ANSYS 15.0 workbench. The enclosure of the test chamber was designed to maintain the real condition of fluid-structure interaction. Heat transfer through the walls was neglected during the modelling. The model view of the ventilation case 05 is presented in Figure 6.11 and all other ventilation cases are in Figure B19 to B22.

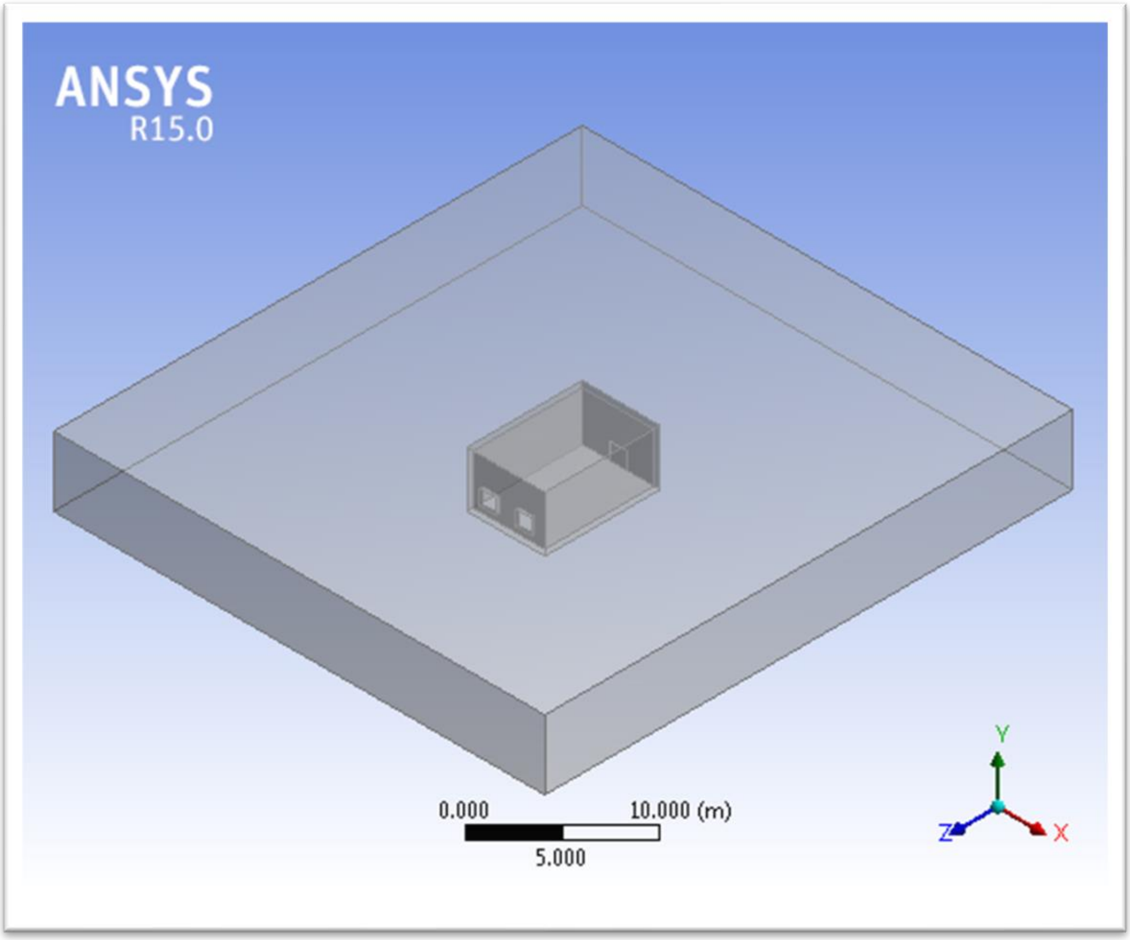


Figure 6.11: Model view of the ventilation case 05

6.3.2.2 Meshing of test chamber II and fluid body

In order to analyse the fluid flow, the domain was split into small volumes which are known as cells and the governing equations are applied on them and solved inside each of the sub-domain (finite volume method). The collection of all elements (cells) is called mesh or grid.

ANSYS provides several meshing methods as the domain is required to be divided into discrete cells to solve the equations at cell or nodal locations. Mesh can be generated automatically or manually. However, the efficiency, accuracy and quality of the results are absolutely dependent on the properties of the meshing method.

Considering all the meshing methods in ANSYS, the automated "CutCell" method was selected considering the following advantages such as; time taken for mesh generation, mesh quality and number of skewed elements in a mesh. This meshing method is capable of generating a large number of hexahedral elements with higher quality (ANSYS, 2010 (b)).

Meshing was done for the Test Chamber II and fluid body. The settings used for the "CutCell" mesh method is shown in Table 6.7 and 6.8.

Table 6.7: Details of "Mesh" with advanced size function property values

Property	Value
Physics Preference	CFD
Solver Preference	Fluent
Relevance	50
Use Advanced Size Function	On: Proximity and Curvature
Relevance Center	Fine
Smoothing	Medium
Curvature Normal Angle	1.0^0
Proximity Size Function Sources	Faces and Edges
Min Size	0.02 m
Proximity Min Size	0.01 m
Max Size	1.28 m
Growth Rate	1.1
Minimum Edge Length	0.225 m

Table 6.8: Details of Assembly Meshing

Property	Value
Method	CutCell
Feature Capture	Feature Angle
Feature Angle	0.0^0
Tessellation Refinement	Program Controlled
Intersection Feature Creation	Program Controlled

Inflation is useful for boundary layer resolution of structures. Properties of inflation were used as shown in Table 6.9.

Table 6.9: Inflation Properties

Property	Value
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Viewed Advanced Options	Yes
Collision Avoidance	Layer Compression
Fix the First Layer	No
Gap Factor	0.01
Maximum Height over Base	1
Growth Rate Type	Geometric
Maximum Angle	140.0^0
Fillet Ratio	1
Use Post Smoothing	Yes
Smoothing Iterations	5

6.3.2.3 Solver settings and boundary conditions used for simulation

- ***Solver type***

The generated flow from natural ventilation has a very low velocity. Thus, the flow is considered as incompressible. Pressure based solver was selected for the simulation as it is mainly designed to solve fluids with low velocities and incompressible fluids.

- ***Gravitational field used for simulations***

Gravitational acceleration of 9.81 ms^{-2} is specified in '–Y' direction. This is relative to the local coordinate system of the model.

- ***Models***

There are several models available in ANSYS Fluent. The selection of the models could be done considering the factors related to the output model. There are four types of models used for the simulation: namely Energy, Viscous, Species and Discrete Phase models.

(i) Energy model

Energy and momentum equations have to be solved for the fluid flow simulation. Thus, the energy equation has been activated.

(ii) Viscous model

- K-epsilon (2eqn) model

This model is widely used for turbulence simulations. It is a two equations model that includes two extra transport equations to represent the turbulent properties of the flow. Time taken for the computation and accuracy of the results are the factors to be considered during the selection of a model. The realizable k-epsilon (2 eqn) model was used for the simulation as it provides the acceptable, accurate results with utilizing the reasonable computing power.

- Near-wall treatment

Turbulent flow is significantly affected by the presence of walls. Thus, the details of the boundary layer should be captured accurately to acquire accurate results. Scalable wall functions are used to capture the features of the fluid flow near the walls of Test Chamber II. This function facilitates the log law in conjunction with the standard wall functions approach.

- Options- full buoyancy effects

This enables the inclusion of the buoyancy effect of viscous modelling. The simulation was performed for a buoyancy-driven ventilation since nonzero gravitational fields is used to model the non-isothermal flow. The generation of turbulent kinetic energy due to buoyancy is added to the epsilon equation and hence, the full buoyancy effect is used.

- Model constants

The model constants have been established to ensure that the model performs well for a certain flow. Based on the literature review, Energy Prandtl Number was taken as 0.85 during the calculation (Bonefacic, Wolf, & Frankovic, 2015).

(iii) Species model

- Species Transport

This enables the calculation of multi-species transport depending on the selection for reactions. “Diffusion Energy Source” was enabled since it includes the effect of enthalpy transport due to species diffusion in the energy equation.

- Mixture properties

This contains information about the mixture which is being modelled. Toluene-air has been considered as a mixture material for the emission from solvent-based paint application considering the literature on paint and results of gas chromatography (WHO, 2000 (b)); (USEPA, 2016(b)); (WISCONSIN Department of Health Services, 2015).

a) Density-incompressible ideal gas

The mixture was considered as incompressible ideal gas for the density calculation. As the air velocity of the flow is significantly low, the fluid flow remains incompressible and the density will be varied similar to an incompressible fluid following the ideal gas law.

b) Specific heat- mixing law

Composition-dependent specific heat capacity (Mixing Law) was selected for the model. Mixing Law computes the mixture’s specific heat capacity as a mass fraction average of the pure species heat capacities.

(iv) Discrete Phase Model (DPM)

This section includes the details related to the discrete phase particles by defining the source parameters such as particle type, size, velocity, emission behaviour, temperature and related parameters of physical models for individual particles. The detailed explanation is tabulated in Table 6.10.

Table 6.10: Details of "Discrete Phase Model"

Property	Value
Interaction	Interaction with continuous phase Update DPM sources every flow iteration
Particle Treatment	Unsteady particle tracking Track with a fluid flow time step

Table 6.11: Details of "Discrete Phase Model"- Continue

Property	Value
Injections	Injection type- Surface Particle type- Droplet Material-Toluene liquid Diameter distribution- Uniform Physical model • Drag law-Spherical • Breakup-Enable Breakup Parcel Release Method- Standard User defined functions (UDF) - The emission from the source was derived by using Equation 5.12 where the x was taken equal to the wet film thickness of the paint layer.
Tracking	Tracking parameters • Max. number of steps 50000 • Specify length scale 0.01 m
Physical Models	Stochastic Collisions Breakup
Numerics	Tracking option/ Accuracy Control/ Tolerance -1e-05 Maximum Refinement - 20
Parallel	Method -Hybrid

6.3.2.4 Cell zone conditions

The "Cell Zones Conditions" task page allows setting the type of a cell zone for the area which is considered for the modelling. There are two categories of zones in ANSYS Fluent which are namely fluids and solids zones. In this simulation, the enclosure of the test chamber was considered as a "fluid" cell zone since porous zones in ANSYS Fluent are treated as fluid zones.

6.3.2.5 Boundary conditions

The airflow from the outdoors is entered into the test chamber from the openings which were located opposite to the painted wall area. Different boundary conditions were applied depending on the location and the details of them are discussed below.

- ***Velocity inlet***

This boundary condition is active in the velocity inlet zone, which was applicable for walls with the openings. Flow velocity was measured using the Anemometer and the average velocity magnitude was 1.2 m/s. Turbulence intensity and viscosity ratio were considered as 5% and 2 (Lestinen, 2010). The static temperature of flow was recorded as 32 ^{0}C. Mass fractions of non-reacting multi-species of flow around the inlet zone are listed below.

Table 6.12: Mass fractions of non-reacting multispecies

Species name	Mass fraction
Toluene (C_7H_8)	0
Nitrogen (N_2)	0.751649
Oxygen (O_2)	0.227197
Carbon Dioxide (CO_2)	0.00045
Water Vapour (H_2O)	0.020704

The particle behaviour was reported as "escaped" when it encounters the boundary in question.

- ***Pressure outlet***

This boundary condition is applied for the zones which are with static pressure. Thus, the outer boundaries of the enclosure for the test chamber except for the surface with an opening and ground were considered as "Pressure outlets". The gauge pressure was 0 pa and backflow turbulent intensity and viscosity ratio were considered as 5% and 0.5. Flow temperature, the mass fraction of species and discrete phase boundary condition type were kept the same as the "Velocity inlet" zone.

- ***Type- wall***

The "Wall" type of boundary condition was selected for the simulation of the source area, fluid body walls and the ground surface of the enclosure of the test chamber. Wall motion is stationary with no-slip shear condition. Wall roughness height and constant were considered as 0 m and 0.5 for k-epsilon turbulent modelling (Natarajan & Hangan, 2009). Thermal boundary conditions at wall boundaries were defined as adiabatic; hence there was a zero-heat flux condition. The species boundary condition was taken as "Zero diffusive flux" by assuming zero gradient condition for all species at walls. The discrete phase model condition type was chosen as "reflect" at the wall boundaries and its behaviour was determined using the polynomial function.

6.3.2.6 Reference values

This task page allows setting the reference quantities used for computing normalized flow field variables such as force and momentum coefficients, Reynolds number and entropy, etc. The details of "Reference values" are listed in Table 6.13.

Table 6.13: Details of "Reference Values"

Property	Value
Area (m^2)	1
Density (kg/m^3)	1.138087
Length (m)	1
Pressure (Pa)	0
Temperature (^0C)	32
Velocity (m/s)	1.2
Viscosity (kg/m-s)	1.72e-05
Reference Zone	"Fluid body"

6.3.2.7 Solution methods

- ***Pressure-velocity coupling***

This contains settings for pressure-velocity coupling schemes. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was used since the steady-state problem is being solved iteratively.

- ***Spatial discretization***

This is used to control the spatial discretization of the convection terms in the solution equations.

(i) Gradient- least squares cell-based

Gradients are needed not for constructing values of a scalar at the cell faces, but also for computing secondary diffusion terms and velocity derivatives.

“CutCell” meshing algorithm is an unstructured meshing method. Compared to other methods presented by Fluent, “Least Squares Cell-Based” provides better accuracy in unstructured meshes and it is less computationally intensive. Besides, the solution is assumed to vary linearly in this method.

(ii) Pressure, momentum, turbulent kinetic energy

The selection of the options for the above parameter was done considering the accuracy of results and the time taken for the convergence.

6.3.2.8 Solution initialization

- Standard initialization

The defined values for flow variables were used to initiate the flow field. The details of “Initial Values” are listed in Table 6.14.

Table 6.14: Details of “Initial Values” for flow field

Property	Value
Gauge Pressure (pa)	0
X Velocity (m/s)	1.2
Y Velocity (m/s)	0
Z Velocity (m/s)	0
Turbulent Kinetic Energy	0.005400005
Toluene (C_7H_8)	0
Nitrogen (N_2)	0.751649
Oxygen (O_2)	0.227197
Carbon Dioxide (CO_2)	0.00045
Water Vapour (H_2O)	0.020704
Temperature (^{0}C)	32

After the pre-processing stage completion, the models were run for five different ventilation cases and obtained the timely variation of pollutant concentrations and velocities inside the test chamber.

6.4 Results and analysis of CFD models

The results obtained from ANSYS-Fluent computational simulation for TVOCs variation with time for different ventilation conditions have graphically represented in Figure 6.12 to 6.16. The figures interpret the TVOCs concentration at different times of the simulation.

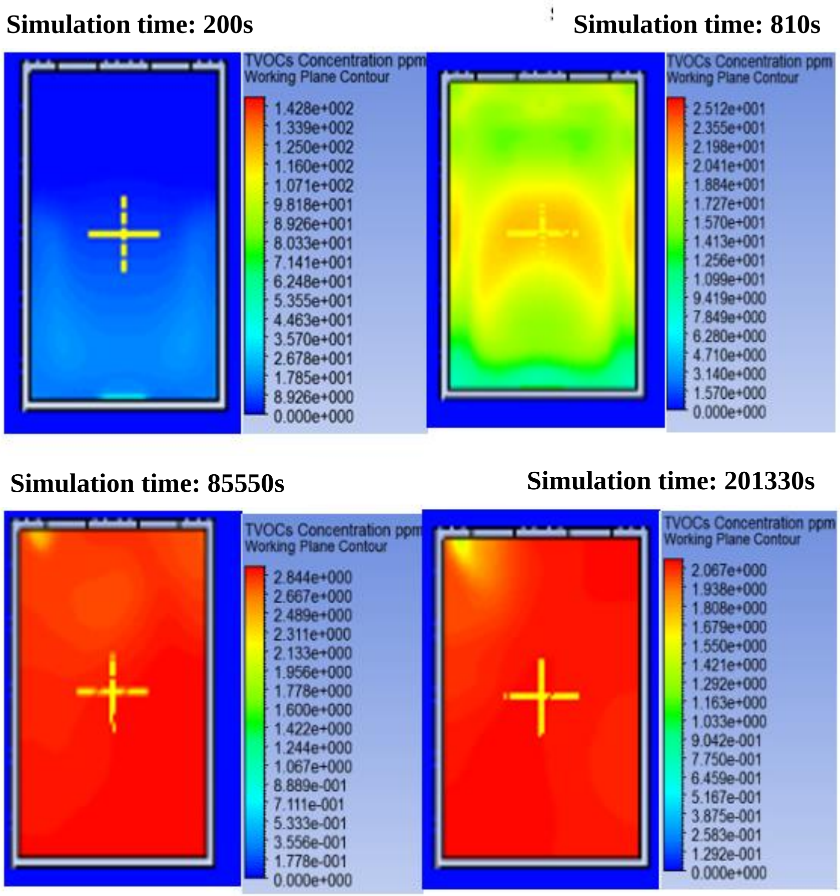


Figure 6.12: Graphical representation of the ANSYS-Fluent model data –Case 01

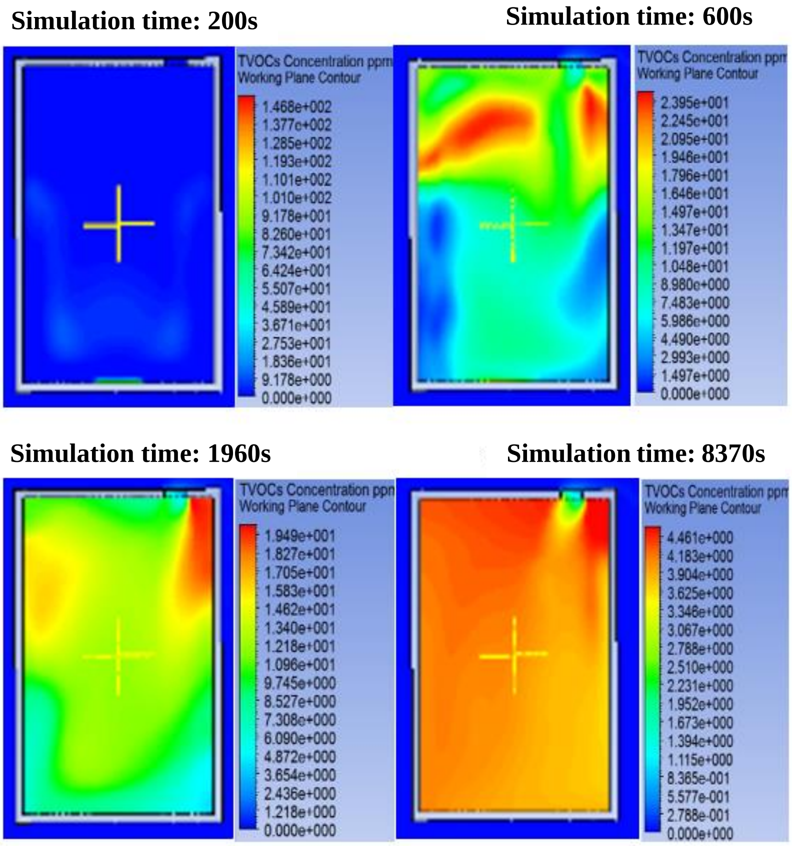


Figure 6.13: Graphical representation of the ANSYS-Fluent model data –Case 02

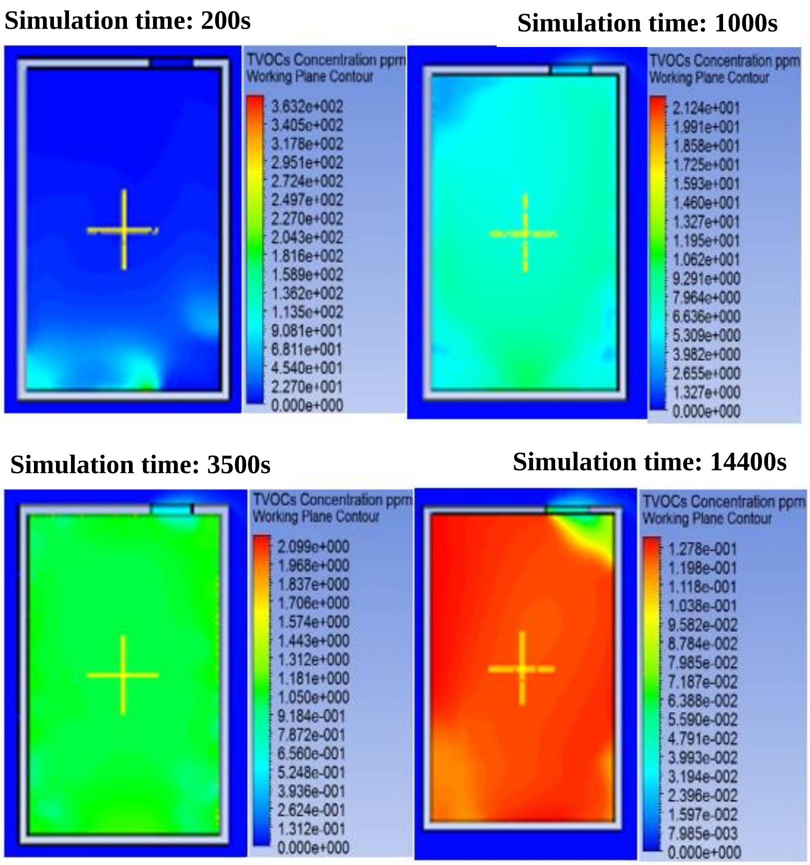


Figure 6.14: Graphical representation of the ANSYS-Fluent model data –Case 03

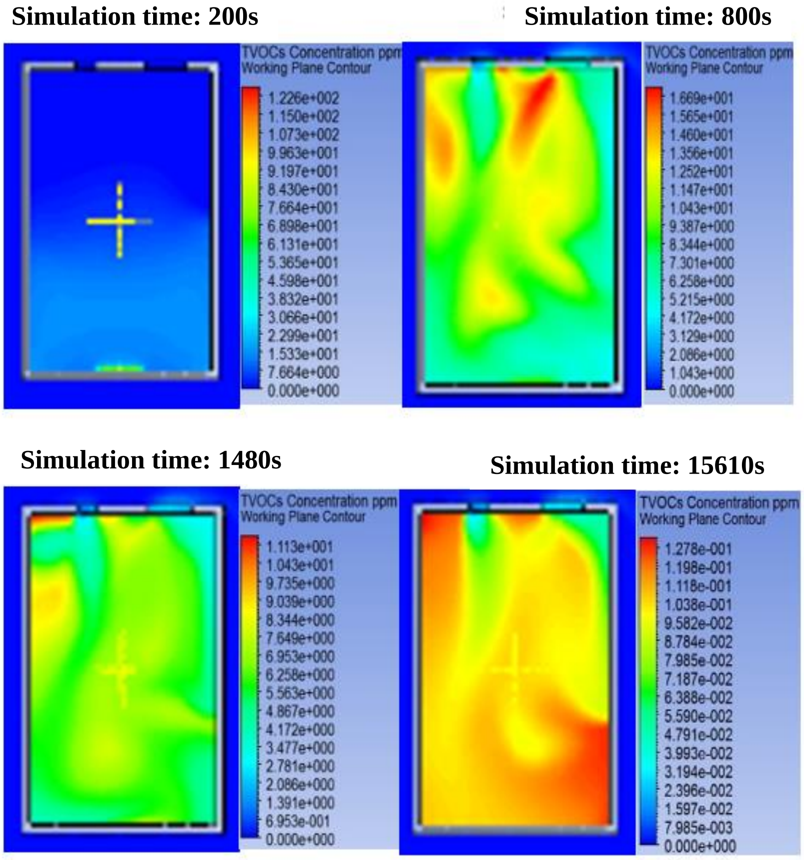


Figure 6.15: Graphical representation of the ANSYS-Fluent model data –Case 04

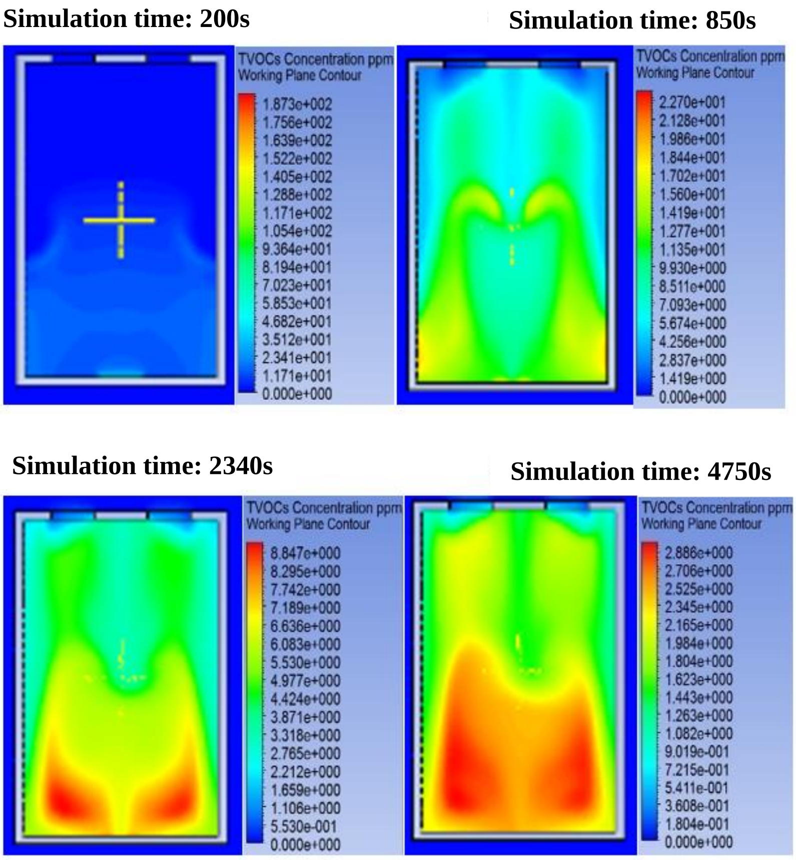


Figure 6.16: Graphical representation of the ANSYS-Fluent model data –Case 05

Entire simulation results for TVOCs dispersion until the atmospheric condition were exported to Excel 2013 as the above figures show only the TVOCs concentration for a single time slot. Figure 6.17 and 6.18 illustrate the results obtained from ANSYS-Fluent simulation models for TVOCs variation under different ventilation conditions. As the dispersion rate of TVOCs in Case 01 (Figure 6.17) is substantially low, the number of iterations of the model was limited to give a result of concentration above the atmospheric condition. Thus, the MATLAB 2014a software was used to extrapolate the results of Case 01 until the atmospheric condition. Figure 6.19 illustrates the graph prepared from MATLAB 2014a for the computational model data of TVOCs variation for Case 01 ventilation condition. It can be greatly proposed to refer the model generated from the MATLAB on behalf of the computational model data with considering the goodness of fit parameters of it. (R^2 = 0.9874, SSE =335.1 and RMSE =0.4942).

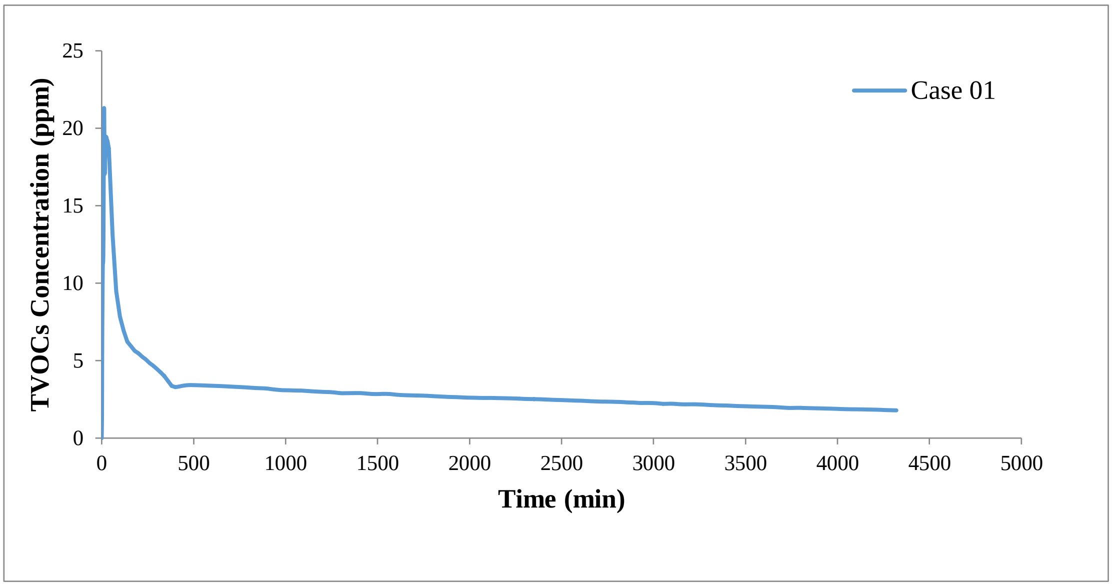


Figure 6.17: Computational simulation results representation of TVOCs variation -Case 01

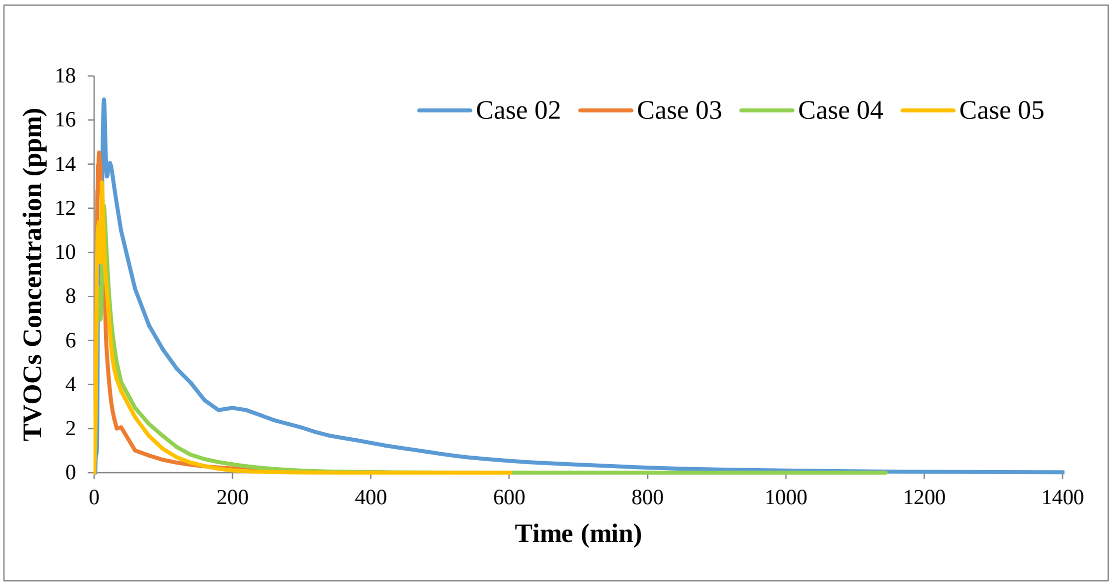


Figure 6.18: Computational simulation results representation of TVOCs variation -Case 02 -05

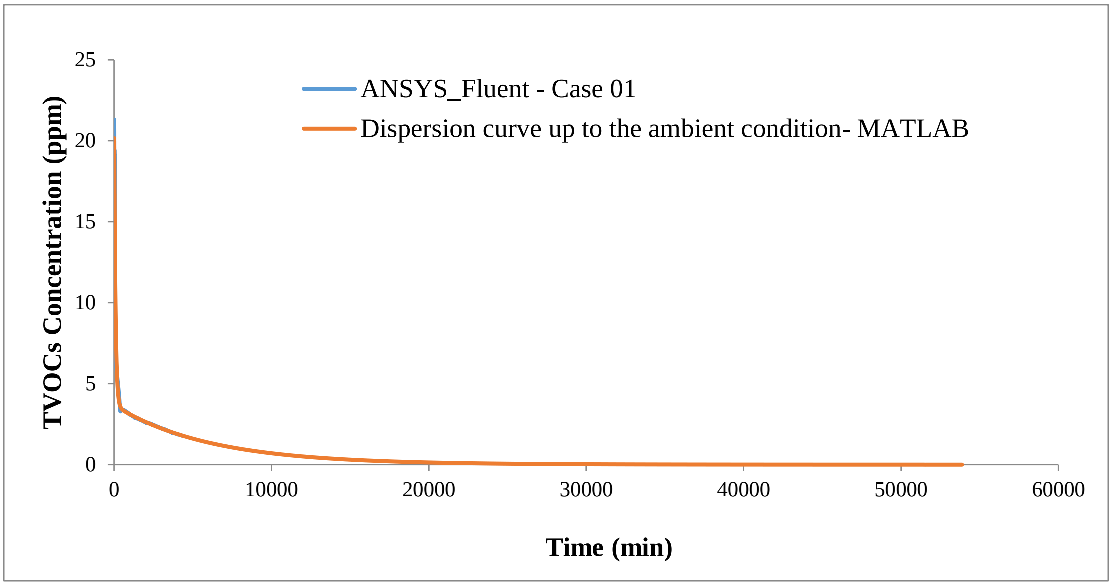


Figure 6.19: Computational simulation results representation of TVOCs variation until the atmospheric condition -Case 01

As mentioned in Subsection 6.3.1, the objective of the CFD modelling is to produce a computational model for the TVOCs dispersion generated from solvent-based paint under different ventilation conditions. The output from the ANSYS-Fluent software will be validated from the experimental results of Exp 3 which were obtained under the same environmental and test conditions. Therefore, the comparison of the computational and experimental data sets was done separately with respect to the ventilation condition and they are presented in Figure 6.20 to 6.24. Corresponding to the aforesaid figures, the same pattern of TVOCs variation was observed in all five ventilation conditions where the experimental curves are all above their respective computational simulation result. Further to that, the gradient of the computational model is much higher than that of the experimental results. However, the maximum concentration of both data sets is similar to each other.

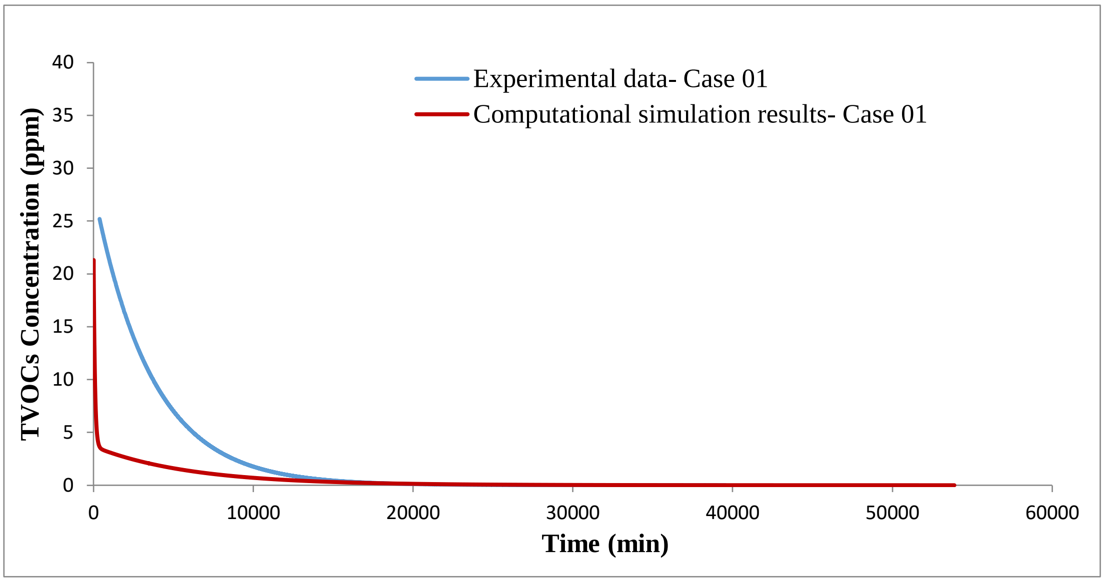


Figure 6.20: Comparison of ANSYS-Fluent data with Experimental data- Case 01

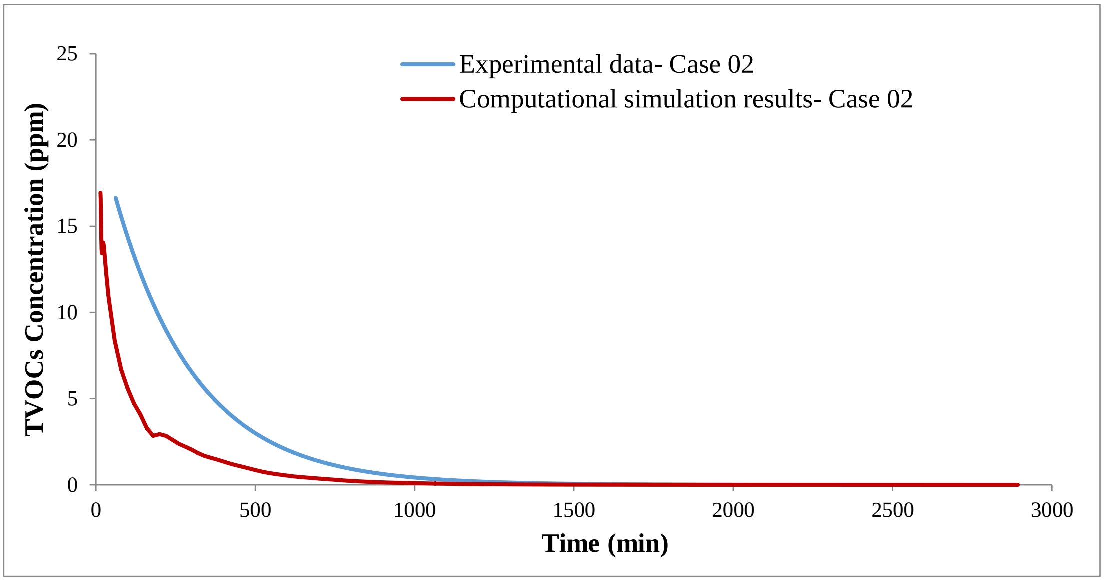


Figure 6.21: Comparison of ANSYS-Fluent data with Experimental data - Case 02

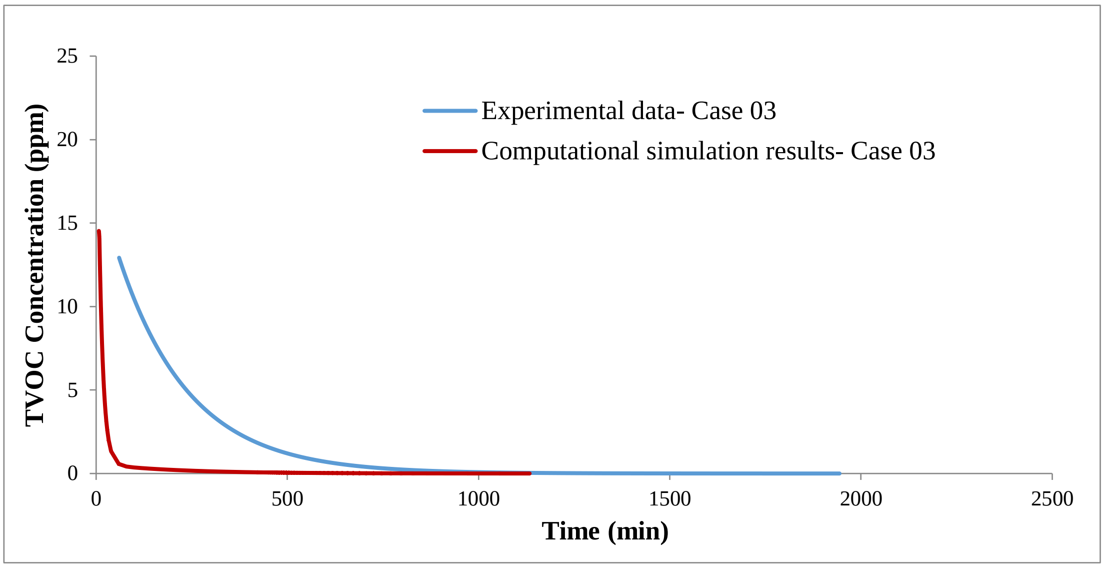


Figure 6.22: Comparison of ANSYS-Fluent data with Experimental data - Case 03

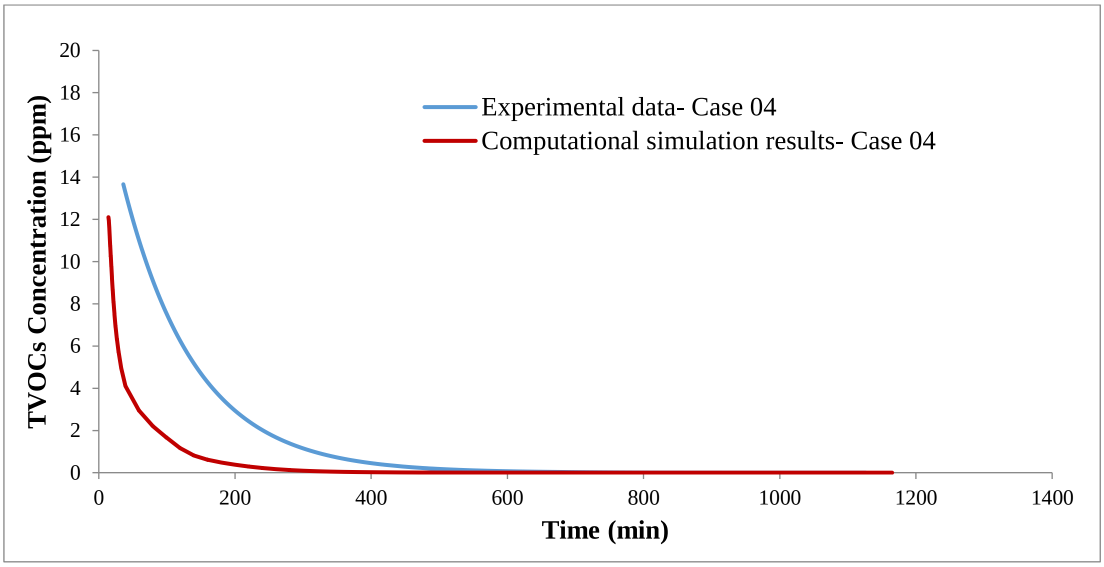


Figure 6.23: Comparison of ANSYS-Fluent data with Experimental data - Case 04

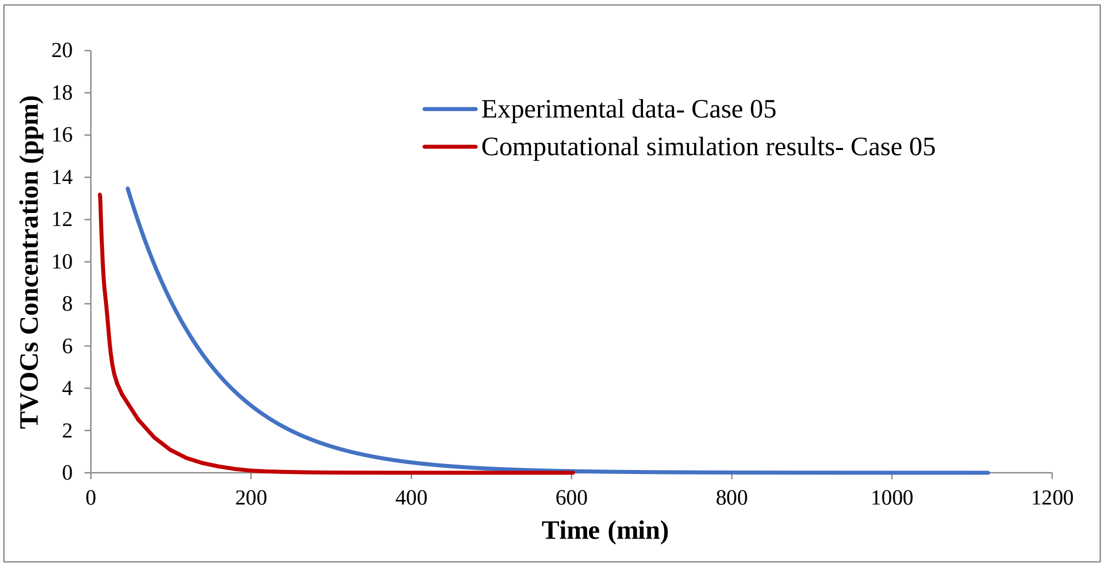


Figure 6.24: Comparison of ANSYS-Fluent data with Experimental data - Case 05

The summary of the graphical representation in Figure 6.20 to 6.24 is recorded in Table 6.15 and 6.16 for further analysis. The maximum concentration and dispersion time of TVOCs generated from solvent-based paint is discussed individually for Case 02-05 ventilation conditions and Case 01 will not be assessed herewith as the computational simulation was limited to the produce the TVOCs dispersion curve much above the ambient condition.

Table 6.15: Comparison of Computational Model with Experimental Data using the Maximum Concentration of TVOCs

Ventilation condition	Max. Concentration (ppm)		Time Taken to Reach the Max. Concentration (min)	
	Experimental results	ANSYS-Fluent results	Experimental results	ANSYS-Fluent results
Case 01	25.2	21.3	380 min	13.1 min
Case 02	16.65	16.94	62 min	14.2 min
Case 03	12.92	14.53	60 min	7.1 min
Case 04	13.66	12.10	36 min	14.2 min
Case 05	13.47	13.17	46 min	11.18 min

Table 6.16: Comparison of Computational Model with Experimental Data using the Time taken for the TVOCs Dispersion

Ventilation condition	Dispersion Time to the Ambient Condition (min) (0.001 ppm)		Dispersion Time to the Permissible Indoor Value (min)	
	Experimental results	ANSYS-Fluent results	Experimental results	ANSYS-Fluent results
Case 01	39558 (27.5 days)	53879 (37.4 days)	13120 (9.1 days)	9656 (6.7 days)
Case 02	2722 (1.9 days)	2491 (1.7 days)	854 (0.6 days)	541 (0.4 days)
Case 03	1944 (1.35 days)	1133 (0.8 days)	588 (0.4 days)	59 (0.04 days)
Case 04	1126 (0.8 days)	642 (0.4 days)	346 (0.2 days)	154 (0.1 days)
Case 05	1146 (0.8 days)	521 (0.4 days)	354 (0.2 days)	119 (0.08 days)

With reference to Table 6.15, the maximum concentration of TVOCs of the computational model is very much similar to the experimental results of Case 02- 05 ventilation conditions. However, the time taken to reach the maximum TVOCs concentration in computational model is less than the experimentation. Furthermore, the time taken for the TVOCs dispersion is also fairly low for the CFD model compare to that of experimental results (Refer Table 6.16). Therefore, it is clear that the diffusion rate of the computational model is very high compare to the actual scenario. Thus, the time is taken to reach the maximum concentration and dispersion time of TVOCs is significantly low in the computation model. However, the comparison between the ANSYS-Fluent dispersion curve until the ambient condition and experimental results up to the permissible indoor value was determined to recommend the ANSYS- Fluent model for a building with the provision of ventilation to evaluate the time for TVOCs dispersion until the atmospheric condition in order to ensure the public health.

Moreover, the generated computational model has to be refined by considering the following factors which were identified as the causes for the discrepancies in the above two models. They are;

- Diurnal variation of the wind pattern should be studied in detail and it has to be programmed into the ANSYS-Fluent software for the most precise results.

  During the CFD analysis, averaged air exchange rate was used by assuming that the wind speed is constant throughout the day. However, this assumption has made the high diffusion rate of TVOCs in the computer simulation compared to the experimental results.

- Source emission characteristics should be related to the prevailing ventilation condition of the indoor environment.

As mentioned in Subsection 6.3.2, the emission from the source was derived for the computational model by using the experimental results which are obtained under the minimum ventilation condition. Thus, the effect of air velocity on TVOCs emission from the wet coating is not considered during the computational analysis.

As described in Subsection 6.2.5, experiments were carried out in the test chamber which is complying with the building ventilation regulations in Sri Lanka. However, it is identified that even in the well designed and operated buildings, there can be some random activities that could contribute to indoor air pollution by violating the IAQ guidelines defined by several organizations. Thus, there is a requirement to define a building flush-out period by considering the indoor activities with the ventilation condition to overcome the exposure to an adverse environment and to minimize the SBS. The generated CFD model and the methodology can be recommended as a strategy that could be implemented by building-related professionals to enhance indoor environmental quality.

6.5 Summary

The detailed experimental programme was done inside the test chamber II to investigate the effect of ventilation on the dispersion of TVOCs generated from solvent-based paint. The two relationships of (equations 6.2, 6.3 and 6.4), the non-linear behaviour of max TVOCs concentration with ventilation condition and the interdependence of the TVOCs dispersion time, maximum TVOCs concentration and air exchange were derived using the experimental results.

The ANSYS-Fluent software was used to produce a computational model for the TVOCs dispersion under different ventilation conditions. After the comparison of the computational model with experimental data, the CFD model is proposed to estimate the dispersion time of TVOCs of a ventilated building until the atmospheric condition to ensure the occupants' health and safety. Further refinement of the CFD model is also discussed with future studies.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The research conducted on the "Influence of Indoor Environment on Sick Building Syndrome" has revealed that there is a severe impact on IAQ from the building materials and human practices used in modern buildings. The results have emphasised that there is an episodic pattern of IAQ problems even in the well-run buildings. However, the detailed experiments carried out on the wall paint under different ventilation conditions and computational fluid dynamic analysis have guided to introduce of several strategies to minimize the occurrence of sick building syndrome while ensuring the desirable indoors for the occupants.

Based on the objectives of the study following conclusions can be made with respect to the obtained results and analysis of the main sections:

<u>Preliminary study: Effect of building materials, adverse indoor environments and human practices on IAQ</u>

- TVOCs and $PM_{2.5}$ have been identified as the most critical causative agents which were emitted from many of the selected indoor air polluting sources (Refer Figure 7.1).
  - TVOCs- Air Freshener, Wall paint, Incense sticks, IAQ in hospital theatre and motor vehicle service centre
  - $PM_{2.5}$- Air Freshener, Wall paint, Incense sticks, IAQ in hospital theatre and motor vehicle service centre, Mosquito coil, Open waste burning and Environmental tobacco smoke

- A huge impact on IAP was caused by CO due to the human activities related to the partial combustion process (Refer Figure 7.1).
- In many places, the concentration of CO_2 is exceeded the PEL defined by ASHRAE due to the high population density during the operational period of the building.

- Wall paint has been selected as the most prominent indoor polluting source by considering its toxicity level and exposure period to adverse environmental conditions.

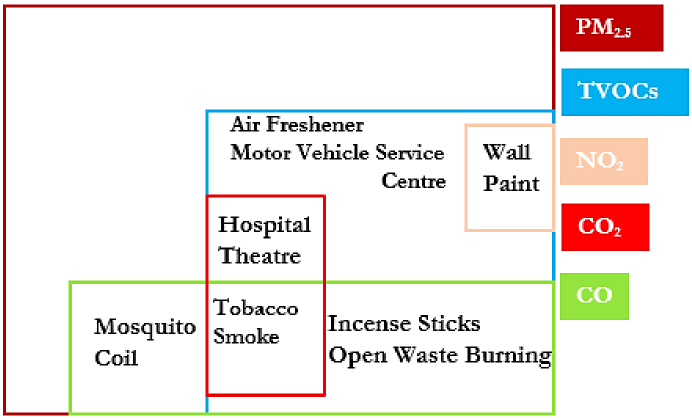


Figure 7.1: Most prominent indoor air polluting sources with causative agents

<u>**Preliminary study: Occupant comfort and IAQ related health impacts**</u>

- Sleepiness, headache, lethargy, and thermal discomfort are diagnosed as the most common type of symptoms related to the SBS (Refer Figure 7.2).
- Odour/smell, sensory irritations (eye, nose, and throat) and shortness of breath have been found as symptoms that are more specific to the newly painted spaces (Refer Figure 7.2).
- Many of the symptoms were occurred related to the time spent indoors. Thus, they have been identified as SBS symptoms.
- A relationship between pollutant concentration with SBS symptoms was further concluded that the existence of the symptom is certainly due to the indoor environmental quality with the occurrence of air polluting sources under different ventilation conditions.
- There is a considerable impact on IAQ from the wall paint even after one month of its application.
- Ventilation condition plays a vital role to minimize the impact of SBS.

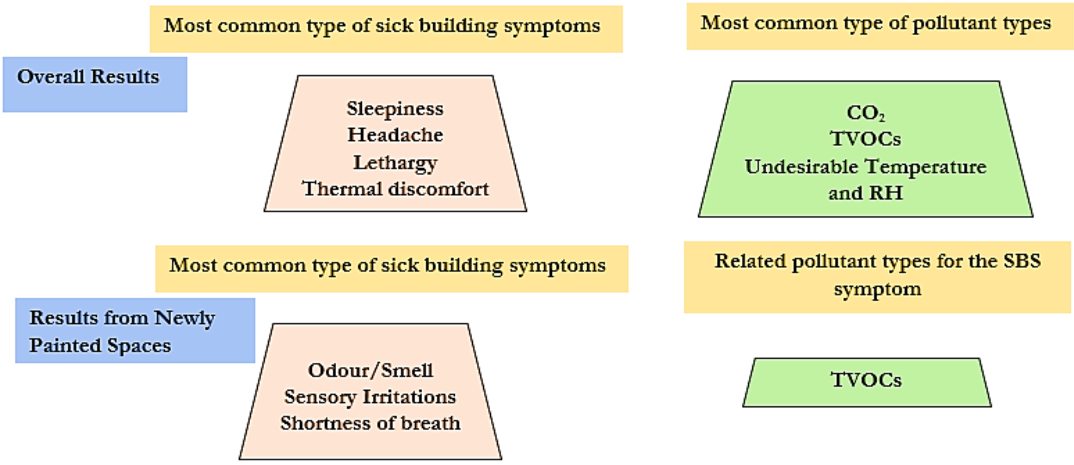


Figure 7.2: Relationship of the SBS symptoms with air pollutant types

<u>**The detailed study on solvent-based and water-based paint**</u>

- Application of solvent-based and water-based paint has shown a significant impact on IAP where the concentrations of TVOCs, $PM_{2.5}$, CO_2, NO_2 and CO were increased due to both types of wall paint.
- The highest concentration of TVOCs from solvent-based paint is occurred at close to the source, whereas the water-based paint is at the center of the chamber depending on the molecular weights of the emitted volatile organic compounds.
- Among the generated pollutants, TVOCs from solvent-based paint has been identified as the most prominent causative agent from wall paint application.
- A mathematical model of exponential nature (Equation 5.12) has been derived for the dispersion of TVOCs from Solvent-based paint under minimum ventilation conditions.
- Developed mathematical model (Equation 5.12) can be used to predict the building flush-out period of buildings under minimum ventilation conditions.
- A safe distance of operation for the occupants from the painted area can also be worked out by the proposed model (Equation 5.12) during the building maintenance and renovation stages.

- Based on Equation 5.12, building flush-out period for a minimum area of any habitable room in residential buildings is established as 30 hrs up to the indoor permissible value and 95.4 hrs or 4 days up to the ambient condition under the minimum ventilation condition.

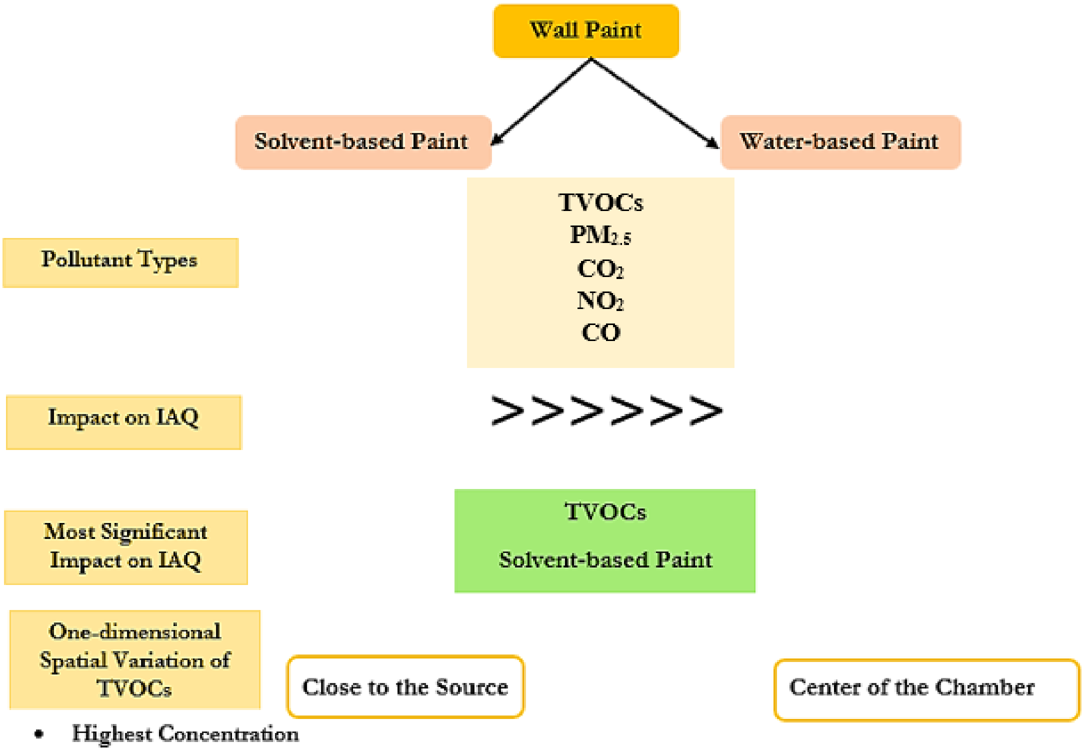


Figure 7.3: Summary of the experimental results of wall paint

<u>Experiments and CFD model for the TVOCs dispersion with different ventilation conditions</u>

- The non-linear behavior of maximum TVOCs variation has been identified with the ventilation condition.
- The interdependence of the dispersion time, max. TVOCs concentration and air exchange rates were found in Equation 6.3 and 6.4.
- The proposed ANSYS-Fluent model can be used to estimate the dispersion time of TVOCs until the atmospheric condition in order to ensure the occupant exposure concentration below the PEL. Building related professionals can obtain several advantages from this computational model as it could apply to find out the building flush-out period and desirable ventilation condition for pollutant dispersion.
- Building planners can maintain a comfortable and healthy indoor environment using the proposed model with confidence.

7.2 Recommendations

- The developed mathematical model in Equation 5.12 can be recommended to predict the
    - Building flush-out period for the wall paint application under the minimum ventilation condition
    - Safe margin of distance from the painted surface for occupancy during the building maintenance and renovation stages
- Based on the mathematical model in Equation 5.12, a minimum building flush-out period of 4 days can be recommended for any habitable building under minimum ventilation condition
- The proposed CFD model can be recommended to estimate the dispersion time of TVOCs of a ventilated building until the atmospheric condition in order to maintain a comfortable and healthy indoor environment. Moreover, the above generated model can be suggested to find out the ventilation requirement for the dispersion of TVOCs generated from the wall paint application.

- Further refinement of the CFD model is needed with future studies on the followings:
    - Diurnal variation of the wind pattern
    - Source emission characteristics with the ventilation condition of the indoor environment
- The empirical research findings of nonlinear behavior of maximum TVOCs variation with ventilation condition and relationship among the dispersion time, maximum TVOCs concentration and air exchange rate can be recommended to refer in future research studies.
- It is essential to educate about the possible causes of IAP with the health effects, through the best practices such as using the mass media, press conferences and the professionals related to the medical sector where they could reach the people and emphasize the gravity of the present situation as they are frequently encountered with the general public.

General Recommendations

a) Even after the recommended building flush out periods from mathematical and CFD models, it is advised to facilitate fresh air to the enclosed indoors every morning as a daily routine practice since there is a risk associated with the accumulated indoor pollutants over the nighttime.

b) Water-based products can be recommended for interior painting over solvent-based products by considering their emitted pollutants' concentration and the occupant exposure period to the adverse environment.

c) As the painters are the most vulnerable group due to the impact of the wall paint, it is recommended to mandate the safety precautions for them during the paint application.

d) Disclosure of all the ingredients of consumer products is highly required to enhance the public health and safety

e) It is suggested to install an improved air conditioning system where the population density is above the building regulations. Furthermore, it is recommended to consider the population density during the operational period for the calculation of the capacity of the air conditioner.

f) In order to minimize the observed adverse effect from the selected sources and human practices on IAP, the following strategies can be recommended as a suitable alternative solution for the consumer as well as the manufacture and related personnel.

Source of IAP	**Strategy to minimize the SBS**
Air Freshener	Water-based air fresheners and air freshener with the least harmful compounds can be introduced to the industry under green certification
	Use natural fragrances
Wall Paint	The paint contains low or no levels of VOCs ingredients
	Acrylic paint product
	Green certification of the paint products and ingredient limitation to ensure public health and environmental protection
Mosquito coil	Use of insecticide-treated nets such as pyrethroid treated nets at the recommended concentration for the personnel use
	Prevent and control the mosquito breeding places
Incense sticks/ Naphthalene balls	Use of alternative products such as smokeless incense sticks and natural fragrances under proper ventilation condition
Open waste burning	Dumpsites for the waste disposal with the proper waste management system
IAQ in hospital theatre	Improved air circulation system and installation of the air suction system to collect anesthetic gas or evaporated medication emanating from the surgical area
IAQ in motor vehicle service centre	The improved air circulation system
	In-plant IAQ monitoring stations with a well-designed HVAC system

7.3 Future Research

The following future works have been identified from this research study in order to improve the CFD model.

- Consider the diurnal variation of the wind pattern for the CFD analysis
- Investigate on the TVOCs emission from the wet coating under different ventilation conditions

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ANNEXES

ANNEX A: SUPPLEMENTARY TABLES

Table A0: Dimensions and the details of the openings (All the dimensions are in meters)

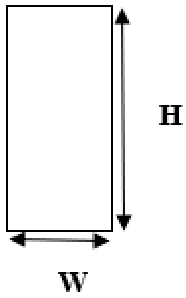
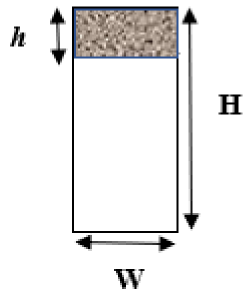
Type	Name	Size (W* H [h])	Description for all the openings
WINDOWS	*w1*	4.5* 1.1	
	w2	4.5* 1.4	
	w3	4.5* 1.25	
	w4	0.8* 1.96 [0.43]	
	w5	1.8* 2.3 [0.43]	
	W1	3.8* 1.5	
	W2	1.18* 1.96 [0.43]	
	W3	2.9* 2.13 [0.62]	
DOORS	*d1*	1.1* 2.1	
	d2	1.1* 2.2	
	d3	2* 2.5	
	d4	1* 2.3	
	d5	1* 2.3	
	d6	1.8* 2.4 [0.3]	
	d7	2.3* 2.6 [0.4]	
	d8	1.9* 2.6 [0.4]	
	D1	1.0* 2.1	
	D2	1.9* 2.43 [0.37]	
	D3	0.9* 2.0	

Table A1: Base case average values for the comparison of experimental results

Source	Causative agents						
	CO (ppm)	NO_2 (ppm)	CO_2 (ppm)	TVOC (ppm)	$PM_{2.5}$ (mg/m^3)	Temperature (^0C)	RH (%)
Air freshener							
• 20 ml	0	0	467	0	-	25.6- 26	44.5- 44.8
• 40 ml	0	0.005	410	0	0.012	27.1- 27.6	48.8- 50.7
Wall paint	0	0.014	327	0	0.009	29.9- 30.2	74.6- 75.4
Open Waste Burning							
• Dry leaves	0	0.0004	410	0	0.010	30- 30.4	75.8- 77
• Polythene	0	0.001	382	0	0.011	29.8- 30.1	76.7- 78.5
Hospital theatre	0	0.018	336	0	0.016	30.9- 31.2	71.1- 72.2
Vehicle service centre	**Note 01**						
Synthetic Building Materials	0	0.038	290	0	-	28.4- 29.2	74.5- 76.7
Environmental Tobacco Smoke							
• Smoking cigars	0	0	454	0	-	28.0- 29.9	51.5- 71.2
• Burning cigars	0	0.006	492	0	0.049	27.5- 30.2	55.4- 73.2
Mosquito coil	0	0	365	0	0.031	29.2- 29.4	77.8- 78.9
Naphthelene balls	0	0	378	0	-	28.4- 28.8	84.8- 85.6
Incense sticks	0	0.0002	159	0	0.008	27.2- 28.9	57.2- 78

Note 01: IAQ was measured outside the vehicle service centre for the base case scenario. However, the values are beyond the average ambient condition and the pollutants' concentration varied with time as per the activities which were carried out in the service area. Therefore, the base case scenario was not presented here since the air quality in the vicinity of a particular area was affected by its activities.

Table A2: Densities of water-based and solvent-based paint mixtures

Paint Type	Beaker Weight (g)	Beaker + Magnetic stir bar weight (g)	Beaker + Magnetic stir bar+ Paint mixture weight (g)	Mixture weight (g)	Mixture volume (ml)	Density of paint sample (g/ml)	Average density of paint (g/cm^3)
Water based paint (1:2)	102.10	108.65	205.40	96.75	90	1.075	**1.064**
	102.10	108.65	204.20	95.55	90	1.062	
	102.10	108.65	203.55	94.90	90	1.054	
Solvent based paint (1:3)	102.10	108.65	194.75	86.10	108	0.797	**0.796**
	102.10	108.65	196.05	87.40	108	0.809	
	102.10	108.65	193.20	84.55	108	0.783	

Table A3: Emitted VOCs from water-based and solvent-based paints

Emitted VOCs from the water-based paint	**Emitted VOCs from the solvent-based paint (Molecular weight- g/mol)**
Octasiloxane, 1,1,3,3,5,5,7,7,9,9,11,11,13,13,15,15-hexadecamethyl (577.23212)	Cyclononasiloxane, octadecamethyl (667.38546)
Cycloheptasiloxane, tetradecamethyl (519.07758)	Octasiloxane, 1,1,3,3,5,5,7,7,9,9,11,11,13,13,15,15-hexadecamethyl (577.23212)
Hexasiloxane, tetradecamethyl (458.99)	Heptasiloxane, hexadecamethyl (533.14722)
Cyclohexasiloxane, dodecamethyl (444.92364)	Cycloheptasiloxane, tetradecamethyl (519.07758)
Benzoic acid, 2,6-bis [(trimethylsilyl)oxy]-, trimethylsilyl ester (370.6635)	Cyclohexasiloxane, dodecamethyl (444.92364)
Benzoic acid, 2,4-bis [(trimethylsilyl)oxy]-, trimethylsilyl ester (282.4830)	Eicosane (282.5475)
Octane, 4-methyl (128.2551)	1-Trifluoroacetoxy-2-methylpentane (198.18283)
1-Hexene, 4,5-dimethyl (112.213)	Undecane (156.31)
Methylene Chloride (84.93)	Nonane, 2,6-dimethyl (156.3083)
1,3-Dihydro-5-(3-nitrophenyl)-2H-1,4-benzodiazepin-2-one	Decane (142.29)
	Heptane, 4-propyl (142.282)
	Octane, 2,6-dimethyl (142.2817)
	Nonane, 4-methyl (142.28168)
	Octane, 3,4-dimethyl (142.28168)
	Heptane, 2,4-dimethyl (128.2551)
	Nonane (128.2)

	Octane (114.23)
	Heptane, 2-methyl (114.22852)
	Ethylbenzene (106.165)
	Benzene, 1,3-dimethyl (106.1650)
	p-Xylene (106.16)
	Heptane (100.21)
	Hexane, 3-methyl (100.20194)
	Oxetane, 2-ethyl-3-methyl (100.15888)
	1-Hexene, 4-methyl (98.18606)
	Cyclohexane, methyl (98.18606)
	Pentane, 2-methyl (86.18)
	Methylene Chloride (84.93)
	1,2-Benzenediol, 4-(2-amino-1-hydroxyethyl)-,tetrakis (trimethylphenyl) derive., R

Table A4: Emitted VOCs from the water-based and solvent-based paint mixtures and Turpentine

Emitted VOCs from the water-based paint mixture (Molecular weight- g/mol)	Emitted VOCs from the solvent-based paint mixture (Molecular weight- g/mol)	Emitted VOCs from the solvent used to prepare the solvent-based paint mixture (Turpentine) (Molecular weight- g/mol)
Cyclononasiloxane, octadecamethyl (667.38546)	Cycloheptasiloxane, tetradecamethyl (519.07758)	Cycloheptasiloxane, tetradecamethyl (519.07758)
Cyclohexasiloxane, dodecamethyl (444.92364)	Hexasiloxane, tetrademethyl (458.993)	Cyclohexasiloxane, dodecamethyl (444.92)
3-Demethyl-3-ethylthiocolchicine (429.52918)	Cyclohexasiloxane, dodecamethyl (444.92364)	Oxalic acid, bis (6-ethyloct-3-yl) ester (370.56648)
Cyclopentasiloxane, decamethyl (370.7697)	Hexasiloxane, 1,1,3,3,5,5,7,7,9,9,11,11-dodecamethyl (430.940)	Methylene Chloride (359.46)
Acetic acid, [bis[(trimethylsilyl)oxy]phosphinyl]-,trimethylsilyl ester (356.575222)	Di-n-octyl phthalate (390.56)	Oxalic acid, 2-ethylhexyl nonyl ester (328.48674)

2-Chloro-4-(4-methoxyphenyl)-6-(4-nitrophenyl) pyrimidine (341.74848)	Silicic acid, diethyl bis (trimethylsilyl) ester (380.69984)	Octacosyl acetate (312.5304)
2-(Acetoxymethyl)-3-(methoxycarbonyl) biphenylene (282.29066)	2-Decanol, pentafluoropropionate (304.2967)	Dichloroacetic acid, tridecyl ester (311.28762)
2-[2-Thienyl]-4-acetyl quinoline (253.31894)	Eicosane, 10-methyl (296.5741)	Phytol (296.53)
2-Chloropropionamide (107.54)	2,4,6-Cycloheptatrien-1-one, 3,5-bis-trimethylsilyl (250.48418)	Heptadecane, 7-methyl (254.4943)
Cyclohexasiloxane, tetradecamethyl	1-Hexadecanol (242.44)	Pentadecane, 7-methyl (226.441)
1,3,5,7-Tetraethyl-1-ethylbutoxysiloxycyclotetrasiloxane	Hexadecen-1-ol, trans-9 (240.4247)	Hexadecane (224.43)
Benzonitrile, m-phenethyl	Nonane, 5-(2-methylpropyl) (184.36142)	Dodecane, 2,7,10-trimethyl (212.41458)
1,1,1,5,7,7,7-Heptamethyl-3, 3-bis(trimethylsiloxy) tetrasiloxane	Undecane, 4,6-dimethyl (184.3614)	Pentadecane (212.41)
1'H- Androst-16-eno [17,16-g]indol-3-ol, acetate (ester), (3.beta., 5.alpha)	Undecane, 2,6-dimethyl (184.3614)	Cyclopentane, decyl (210.3987)
Silane, [[4-[1,2-bis[(trimethylsilyl)oxy] ethyl]-1,2-phenylene] bis(oxy)]bis[trimethyl]	Dodecane, 4-methyl (184.36)	n-Tridecan-1-ol (200.36)
	Heptylcyclohexane (182.35)	Tetradecane (198.39)
	5-Phenylvaleric acid (178.23)	Tridecane, 2-methyl (198.39)
	Dodecane (170.33)	Tridecane, 4-methyl (198.39)
	Undecane, 5-methyl (170.33)	Dodecane, 3-methyl (184.36616)
	Decane, 4-methyl (156.31)	Undecane, 5,5-dimethyl (184.36142)
	n-Amylcyclohexane (154.29)	Undecane, 3,9-diemthyl (184.36142)
	Benzene, 1-methyl-4-(1-methylpropyl) (148.2447)	Undecane, 2,6-dimethyl (184.3614)
	Heptane, 3-ethyl-2-methyl (142.28)	Dodecane, 4-methyl (184.36)
	Decane (142.28)	Dodecane, 2-methyl (184.36)
	Nonane, 4-methyl (142.28)	Tridecane (184.36)
	Nonane, 3-methyl (142.28)	Decane, 3,8-dimethyl (170.3348)
	Octane, 3,6-dimethyl (142.28)	Undecane, 5-methyl (170.3348)

	Benzene, 4-ethyl-1, 2-dimethyl (134.22)	Undecane, 4-methyl (170.3348)
	Benzene, 1-isocyanato-3-methyl (133.15)	Undecane, 2-methyl (170.33484)
	Hexane, 2,3,5-trimethyl (128.26)	Decane, 3,8-dimethyl (170.3348)
	Heptane 3,3-dimethyl (128.26)	Decane, 3,7-dimethyl (170.3348)
	Nonane (128.26)	Nonane, 4-ethyl-5-methyl (170.3348)
	Octane, 3-methyl (128.26)	Dodecane (170.33)
	Octane, 2-methyl (128.26)	1,4-Diazabicyclo [2.2.2]octane-2-carboxylic acid, methyl ester (170.20896)
	Heptane, 2,3-dimethyl (128.26)	Cyclohexane, (4-methylpentyl) (168.31896)
	Octane, 2-methyl (128.26)	Ethane, 1,1,2,2-tetrachloro (167.85)
	Cyclohexane,propyl (126.24)	1-Penten-3-ol, 1-Phenyl (162.22826)
	Cis-1-Ethyl-3-methyl-cyclonexane (126.239)	Undecane (156.31)
	Benzene, 1-ethyl-2-methyl (120.19)	Decane, 2-methyl (156.31)
	Benzene, 1,3,5-trimethyl (120.19)	Decane, 3-methyl (156.31)
	Benzene, 1,2,3-trimethyl (120.19)	Decane, 5-methyl (156.3083)
	Heptane, 2-methyl (114.23)	Napthalene, 2,6-dimethyl (156.22368)
	Heptane, 3-methyl (114.23)	Napthalene, 1,6-dimethyl (156.22368)
	Octane (114.23)	Cyclopentane, hexyl (154.2924)
	Heptane, 2-methyl (114.23)	n-Amylcyclohexane (154.29)
	Cyclohexane, 1,2-dimethyl-, trans (112.21)	4-Butyl-cyclohexanone (154.24932)
	Cyclohexane, 1,4-dimethyl-, cis (112.21)	Benzene, pentamethyl (148.24)
	Cyclohexane, ethyl (112.21)	Benzene, (1,1-dimethylpropyl) (148.24)

	Ethylbenzene (106.17)	Benzene, 1-methyl-4-(2-methylpropyl) (148)
	Benzene, 1,3-dimethyl (106.17)	Benzene, 1-methyl-4-(1-methyl-2-propenyl) (146.2289)
	p-Xylene (106.17)	Octane, 3,3-dimethyl (142.282)
	Hexane, 3-methyl (100.2)	Nonane, 4-methyl (142.28)
	Heptane (100.2)	Nonane, 2-methyl (142.28)
	Oxirane, 2-methyl-3-propyl-, cis (100.1589)	Disiloxane, 1,1,3,3-tetramethyl (134.32)
	Furan, tetrahydro-2, 4-dimethyl-, cis (100.15888)	Benzene, 1-methyl-4-(1-methylethyl) (134.22)
	Cyclohexane, methyl (98.19)	Benzene, 1,2,4,5-tetramethyl (134.22)
	Toluene (92.14)	Benzene, 1-methyl-3-(1-methylethyl) (134.22)
	Pentane, 2-methyl (86.18)	Benzene, 2-ethyl-1, 4-dimethyl (134.2182)
	Hexane (86.18)	Heptane, 4-ethyl (128.26)
	Cyclopentane, methyl (84.16)	Nonane (128.26)
	Oxalic acid, 2-ethylhexyl tetradecyl ester	Octane, 2-methyl (128.26)
	Benzoic acid, 2-[6-(ethylamino)-2, 7-dimethyl-3H-xanthen-9-yl]-,ethyl ester	Octane, 3-methyl (128.26)
		Heptane, 2,6-dimethyl (128.26)
		Azulene (128.17)
		Cyclohexane, 1,1,3-trimethyl (126.24)
		1-Ethyl-4-methylcyclohexane (126.24)
		Benzene, 1-ethyl-2-methyl (120.19)
		Hexane, 3,3-dimethyl (114.23)
		Heptane, 2-methyl

		(114.23)
		Heptane, 3-methyl (114.23)
		Octane (114.23)
		Cyclohexane, ethyl (112.21)
		p-Xylene (106.17)
		Ethylbenzene (106.17)
		Heptane (100.2)
		Cyclohexane, methyl (98.19)
		2-Pentyn-1-ol (84.12)
		Furan, 2,3-dihydro-4-methyl (84.1164)
		Benzeneethanamine, N-(3-chloropropyl)-alpha-methyl
		4-Ethylbenzoic acid, 6-ethyl-3-octyl ester
		Benzeneproponoic acid, beta., 3,4-trimethyl-, methyl ester
		Oxalic acid, cyclohexylmethylisohexyl ester

Table A5: Details of the wet film thickness calculation

Case number	Gypsum board area (m^2)	Board weight before application of paint (g)	Board weight after application of paint (g)	Wet film thickness (µm) (Paint density- 0.8752 g/cm^3)
01	1.4884	2014.6	2204.5	145.78
02	1.4884	2552	2752	153.53
03	1.4884	2110.0	2299.9	145.78
04	1.4884	3762.0	3955.0	148.16
05	1.4884	3701	3894	148.16

ANNEX B: SUPPLEMENTARY FIGURES

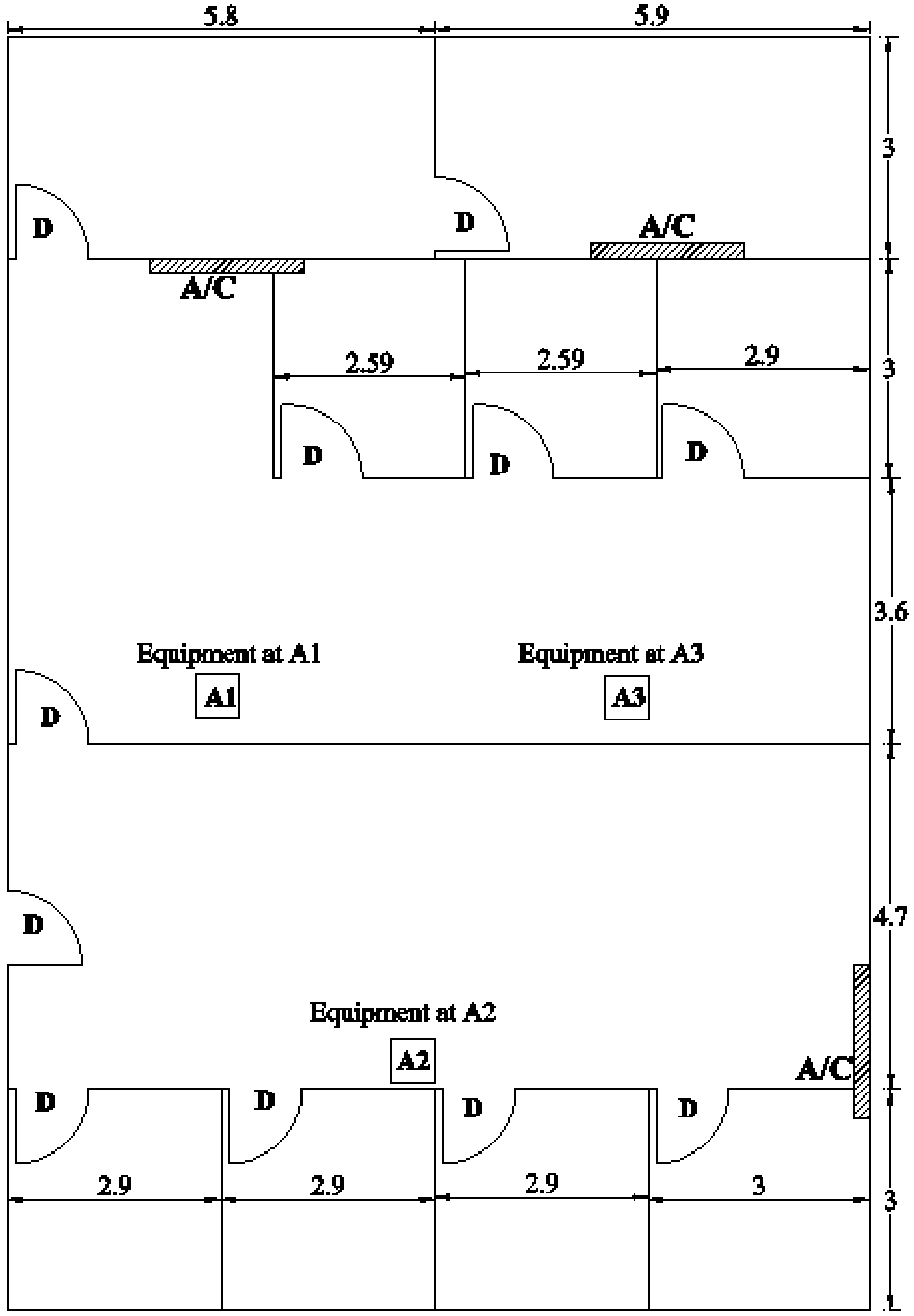


Figure B1- i: Plan view of the location used for the questionnaire survey and IAQ measurements of Sample A (All the dimensions are in meters)

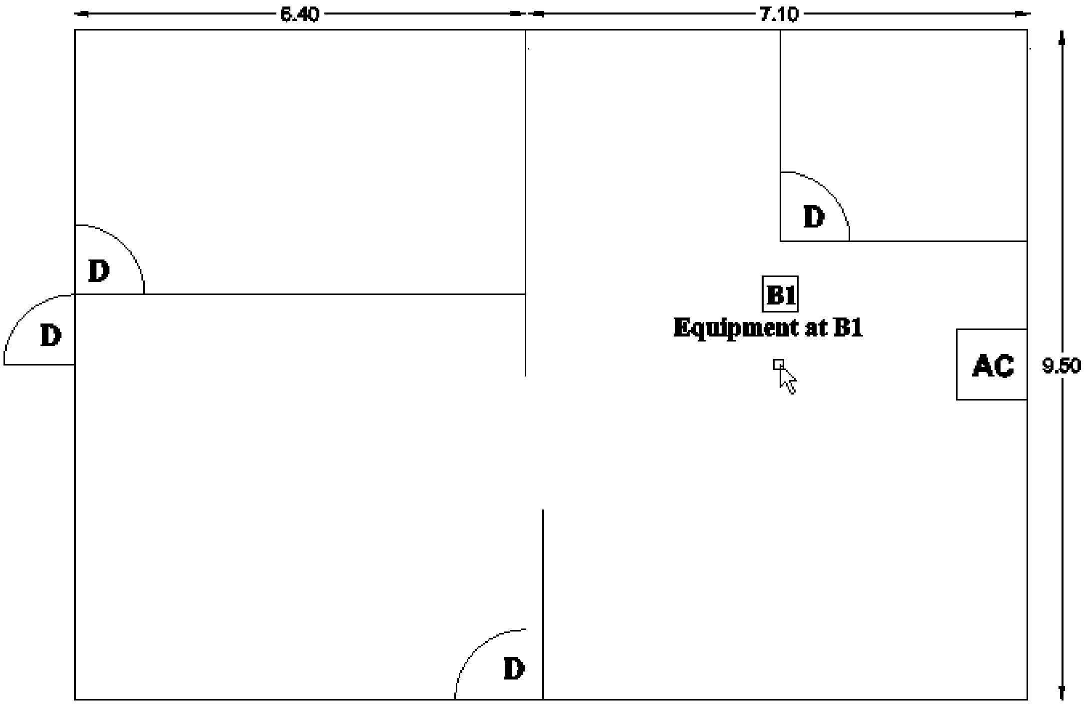


Figure B1- ii: Plan view of the location used for the questionnaire survey and IAQ measurements of Sample B1 (All the dimensions are in meters)

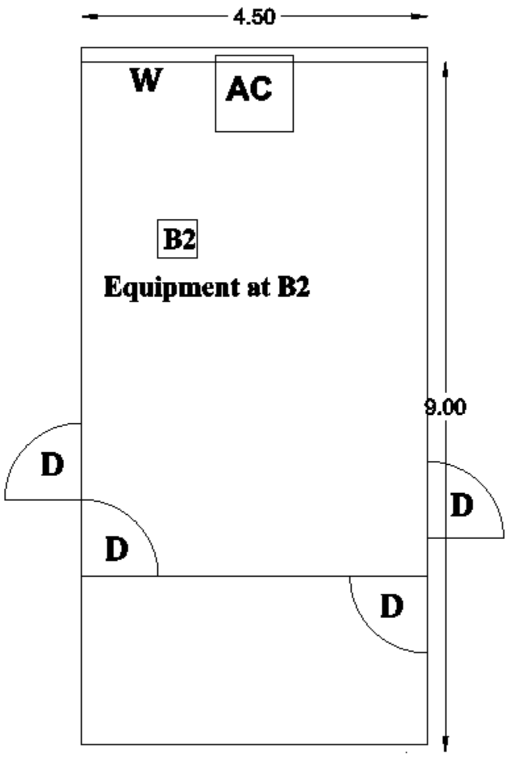


Figure B1- iii: Plan view of the location used for the questionnaire survey and IAQ measurements of Sample B2 (All the dimensions are in meters)

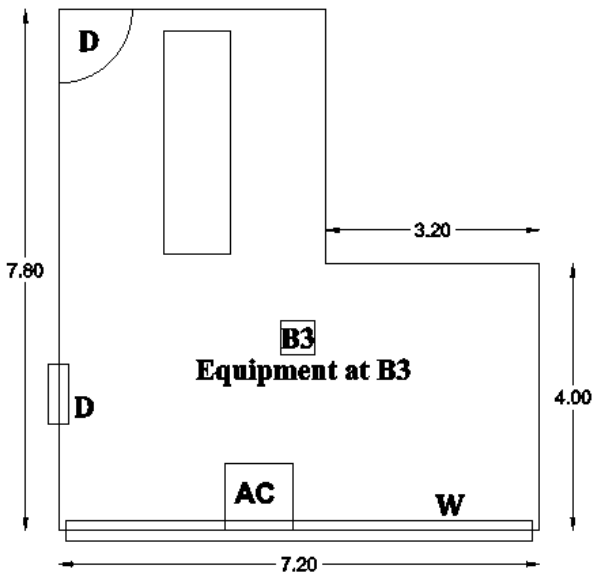


Figure B1- iv: Plan view of the location used for the questionnaire survey and IAQ measurements of Sample B3 (All the dimensions are in meters)

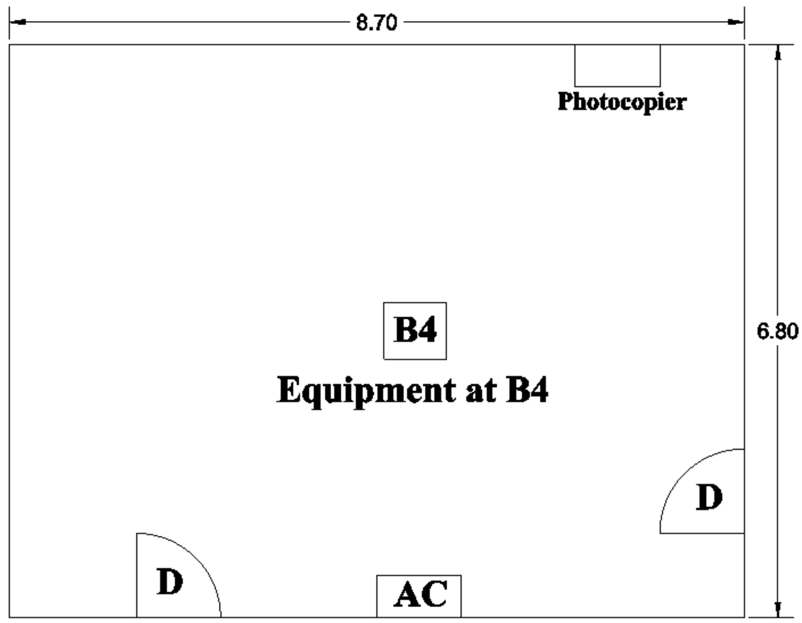


Figure B1- v: Plan view of the location used for the questionnaire survey and IAQ measurements of Sample B4 (All the dimensions are in meters)

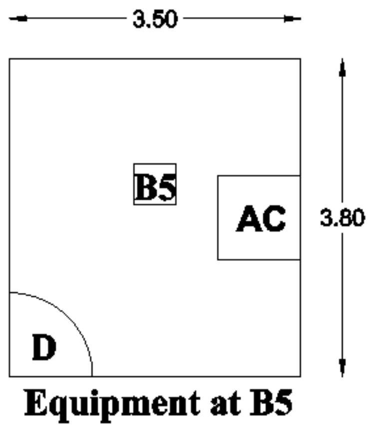


Figure B1- vi: Plan view of the location used for the questionnaire survey and IAQ measurements of Sample B5 (All the dimensions are in meters)

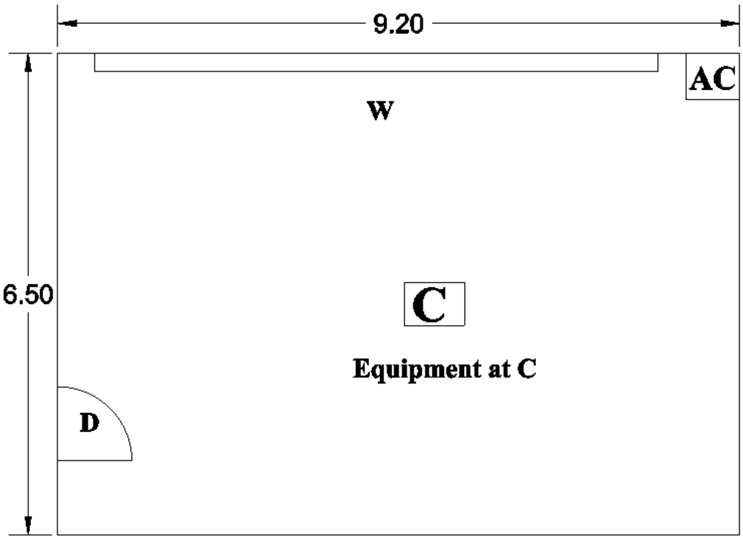


Figure B1- vii: Plan view of the location used for the questionnaire survey and IAQ measurements of Sample C (All the dimensions are in meters)

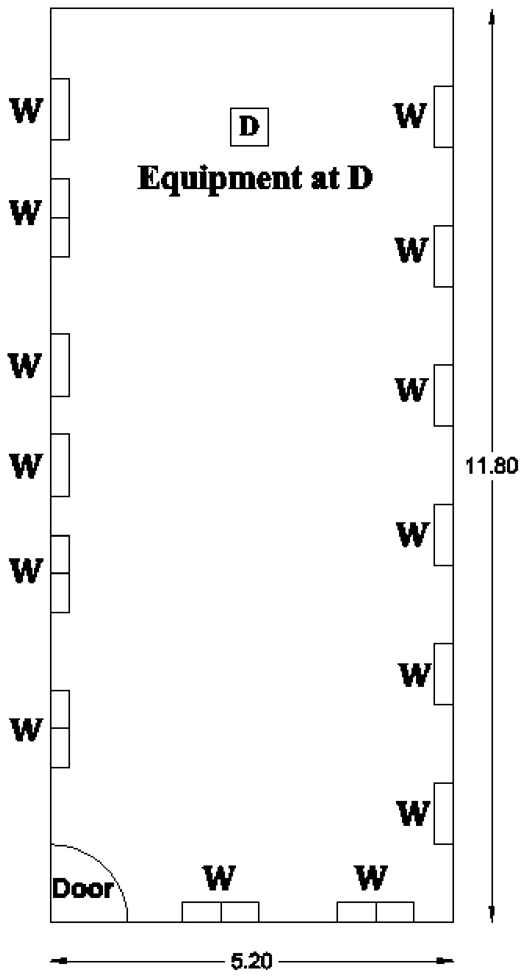


Figure B1- viii: Plan view of the location used for the questionnaire survey and IAQ measurements of Sample D (All the dimensions are in meters)

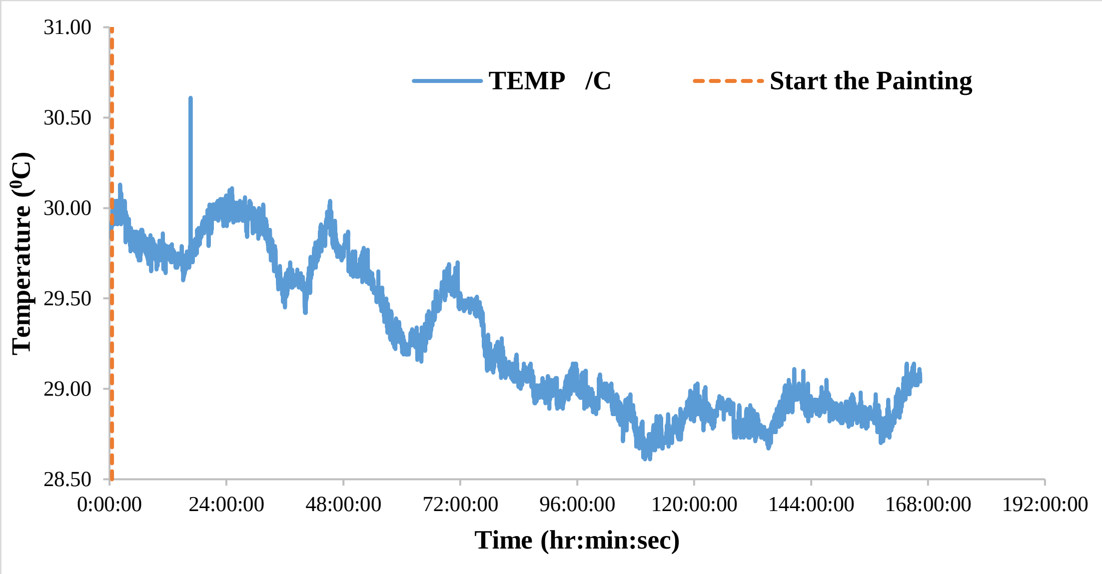


Figure B2: Temperature Variation with Time –Solvent based paint

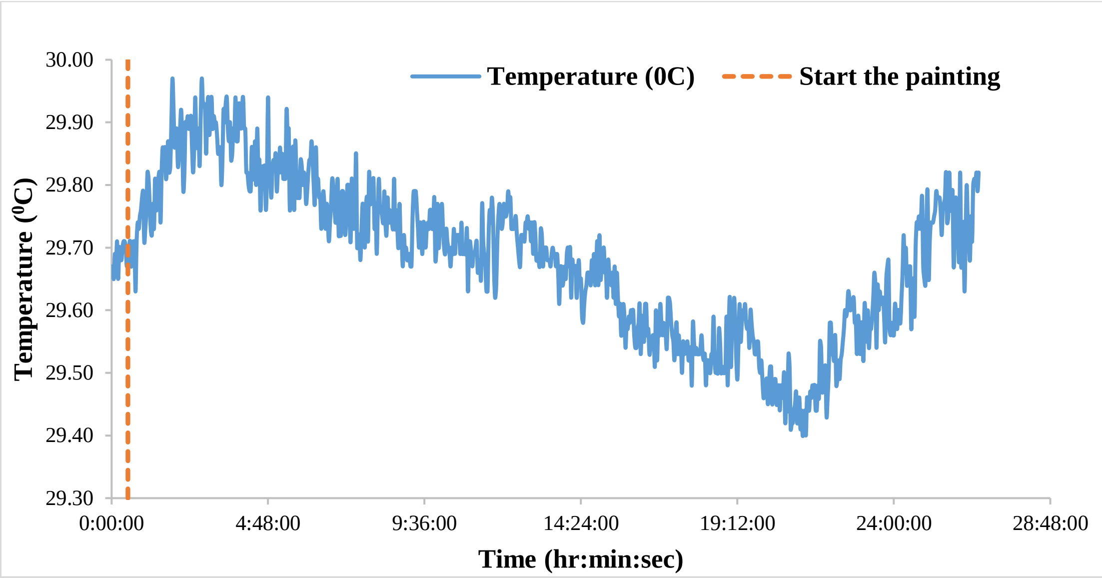


Figure B3: Temperature Variation with Time –Water based paint

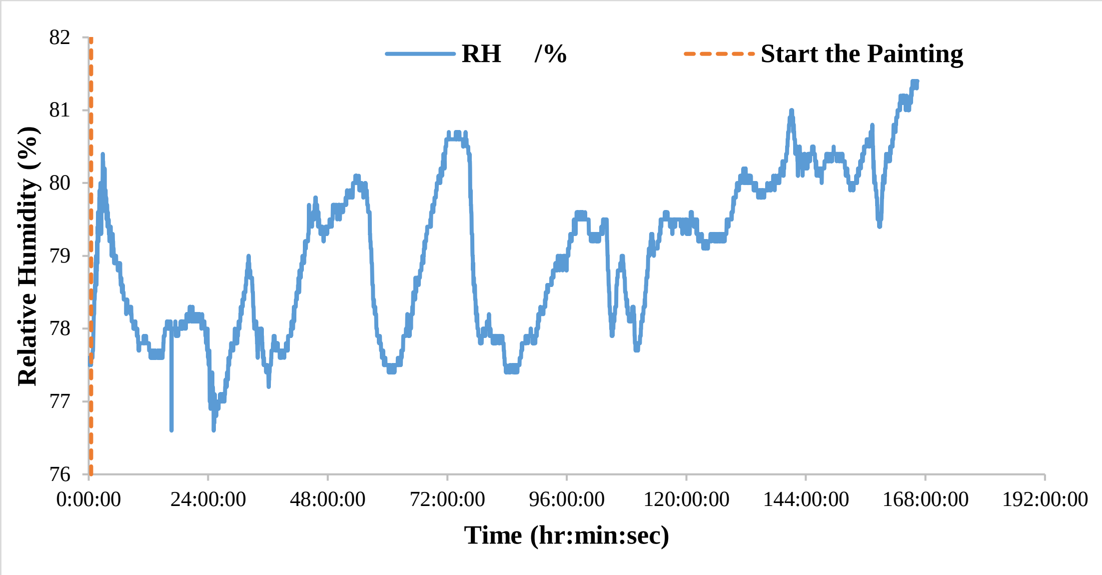


Figure B4: Relative Humidity Variation with Time - Solvent based paint

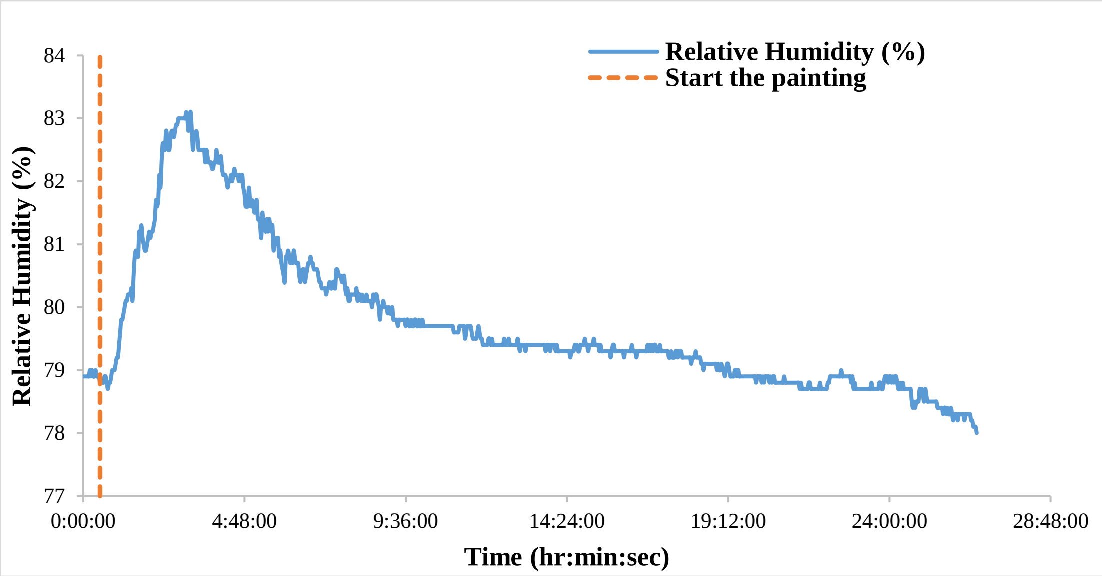


Figure B5: Relative Humidity Variation with Time - Water based paint

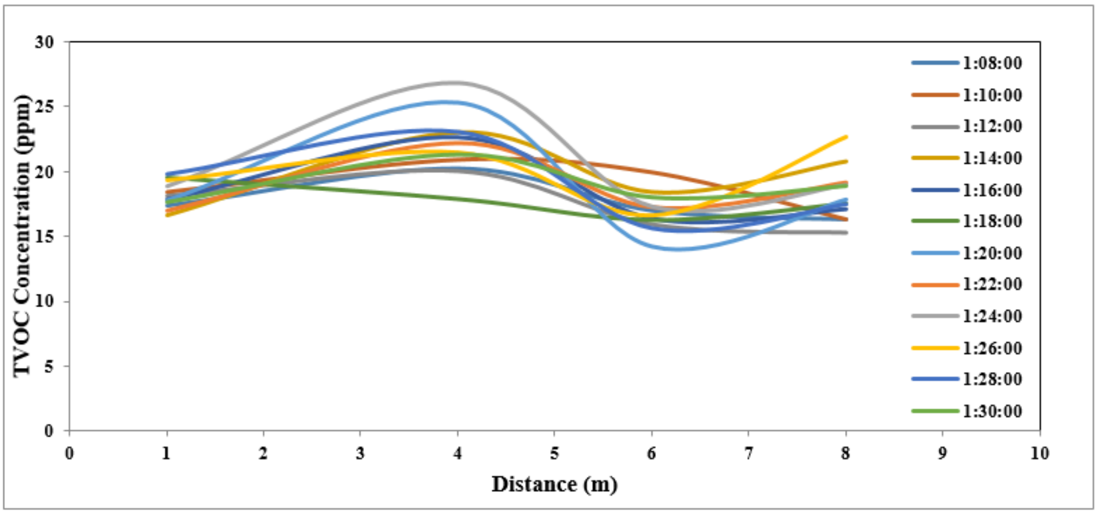


Figure B6-i: One dimensional spatial variation of TVOCs with time for entire experiment-Solvent based paint: 1 hr -1.30 hr period from painting

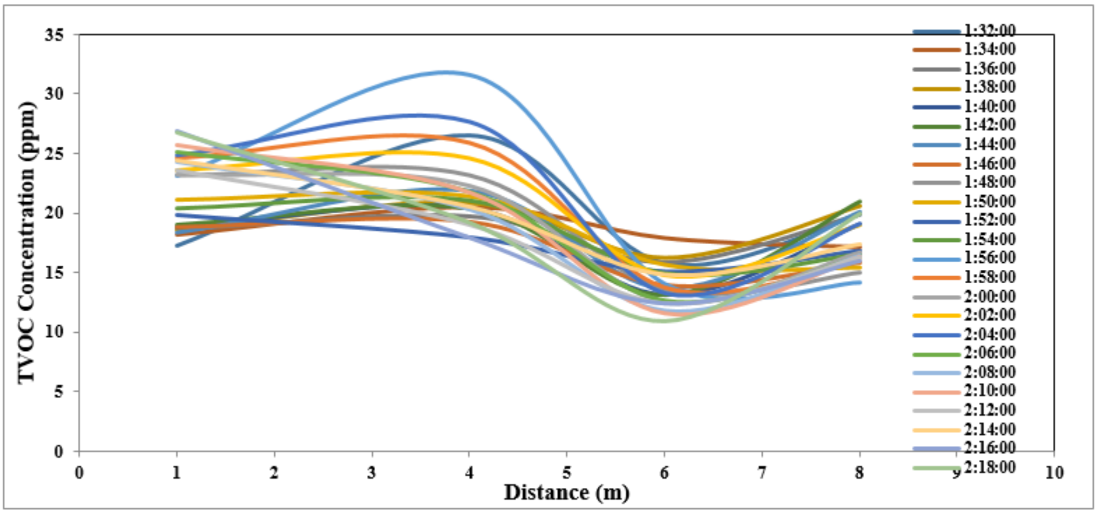


Figure B6-ii: One dimensional spatial variation of TVOCs with time for entire experiment-Solvent based paint: 1.30 hr- 2.20 hr period from painting

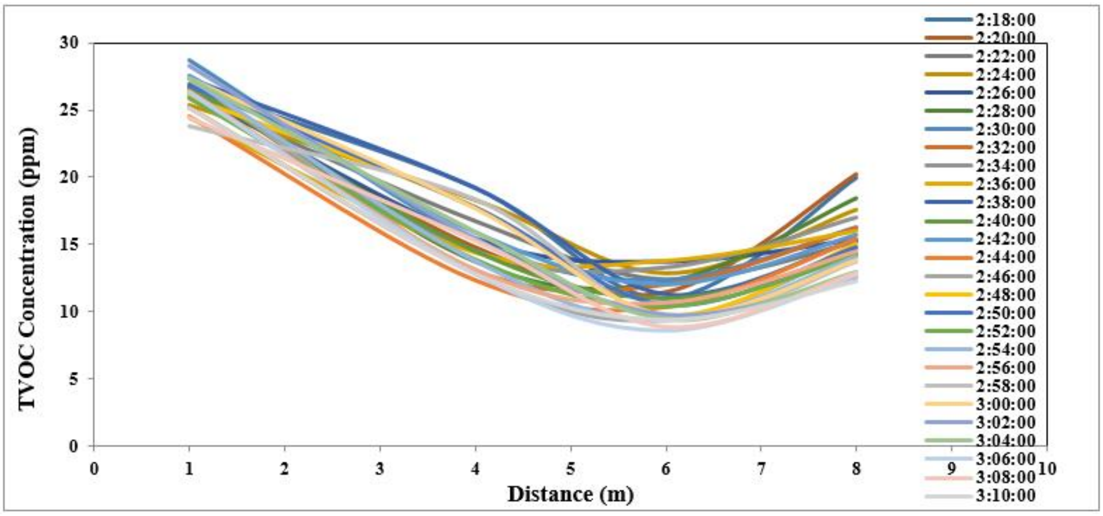


Figure B6-iii: One dimensional spatial variation of TVOCs with time for entire experiment-Solvent based paint: 2.20 hr -3.10 hr period from painting

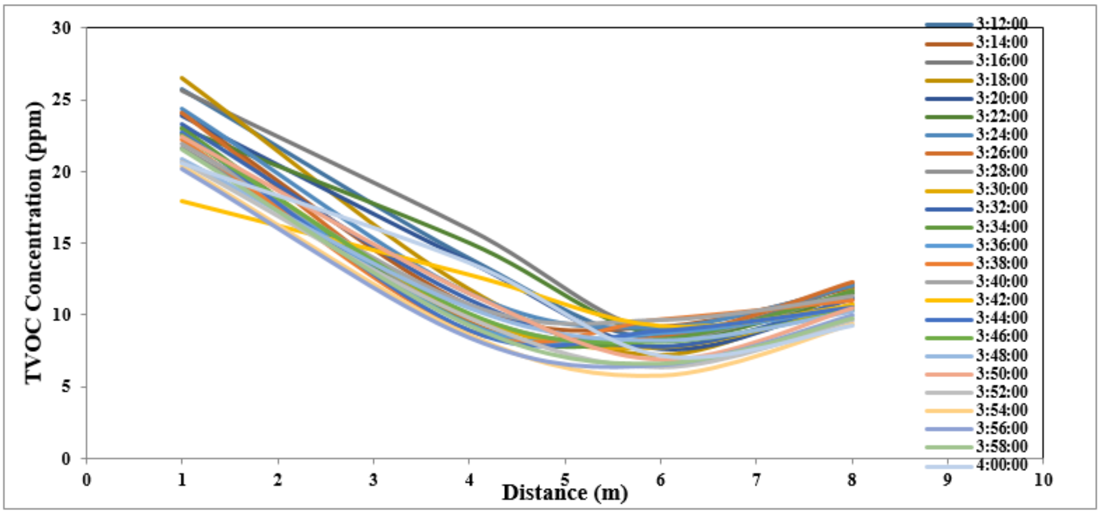


Figure B6-iv: One dimensional spatial variation of TVOCs with time for entire experiment-Solvent based paint: 3.10 hr- 4.00 hr period from painting

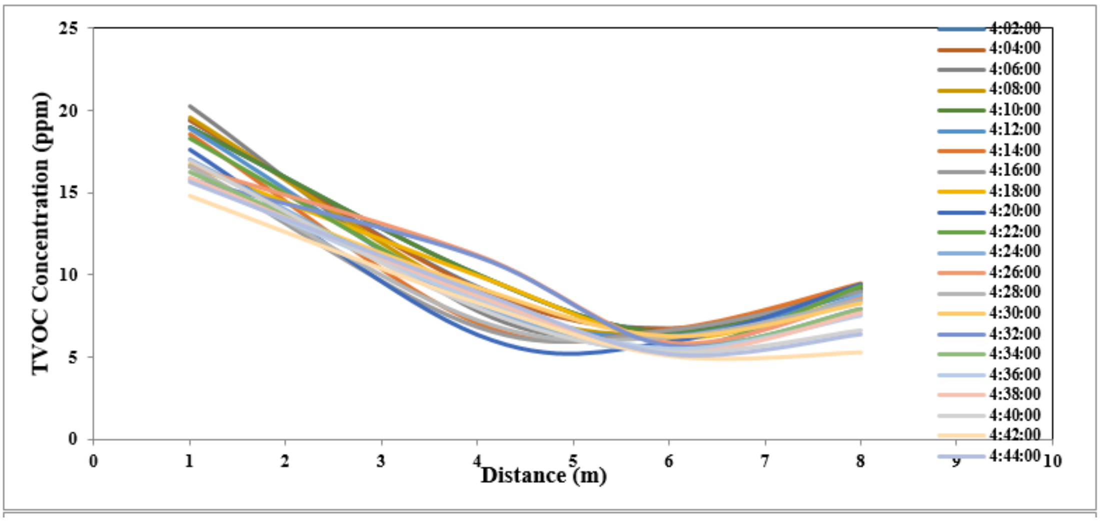


Figure B6-v: One dimensional spatial variation of TVOCs with time for entire experiment-Solvent based paint: 4.00 hr- 4.45 hr period from painting

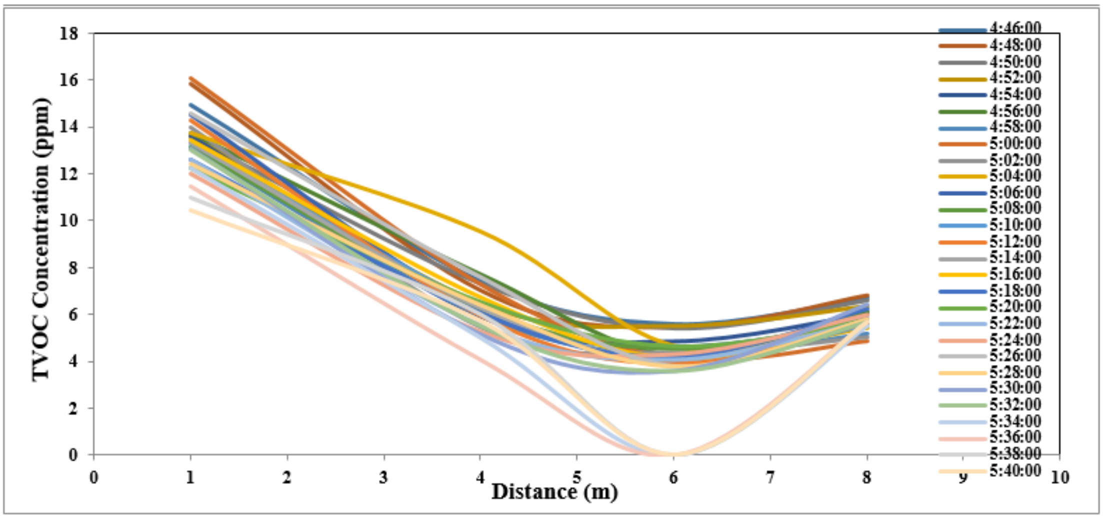


Figure B6-vi: One dimensional spatial variation of TVOCs with time for entire experiment-Solvent based paint: 4.45 hr -5.45 hr period from painting

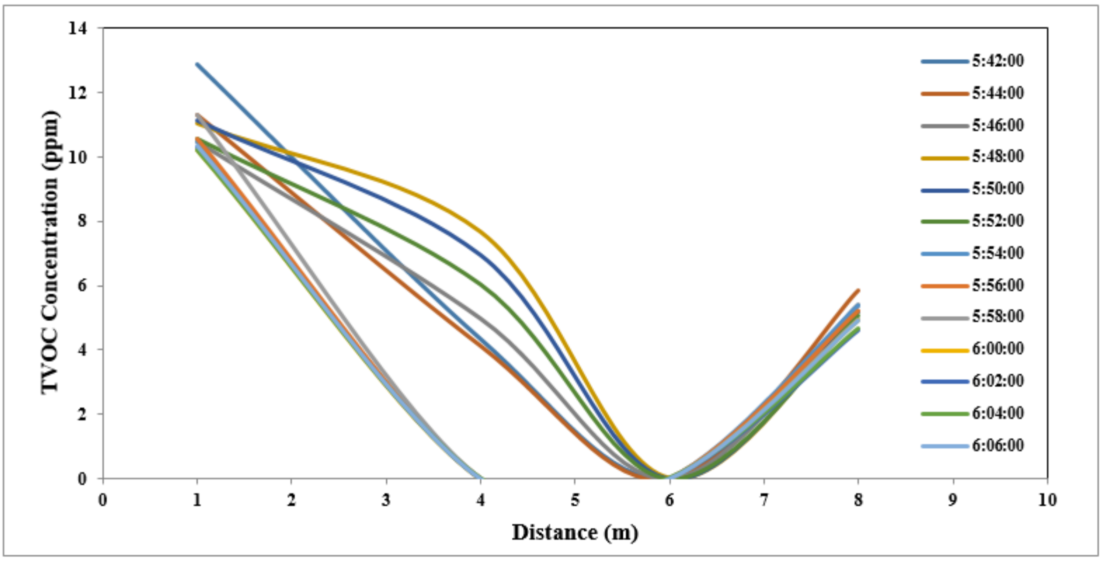


Figure B6-vii: One dimensional spatial variation of TVOCs with time for entire experiment-Solvent based paint: 5.45 hr-6.00 hr period from painting

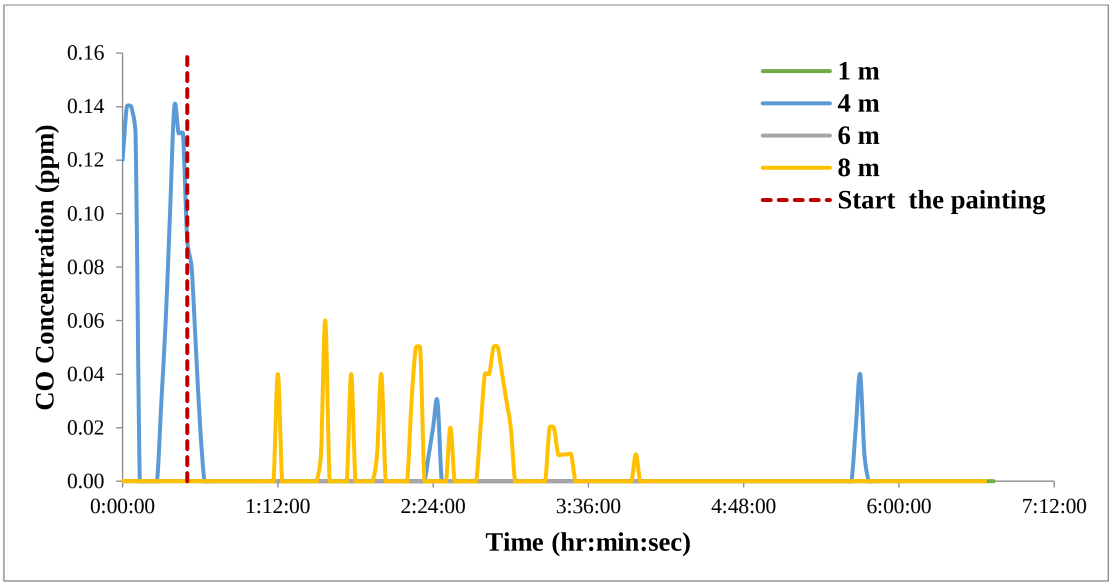


Figure B7: Timely variation of CO with distances - Solvent based paint

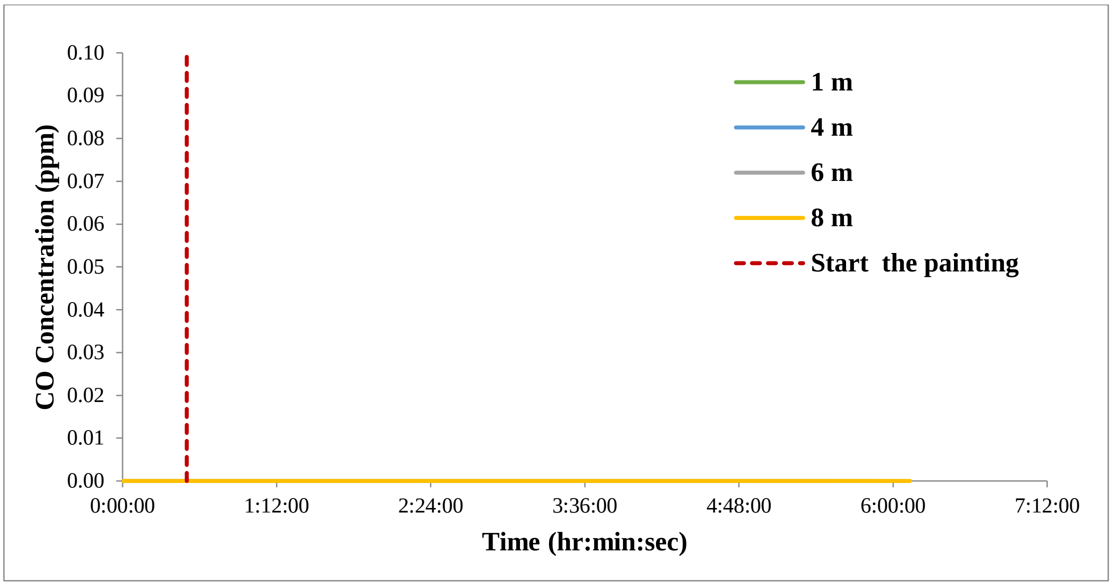


Figure B8: Timely variation of CO with distances - Water based paint

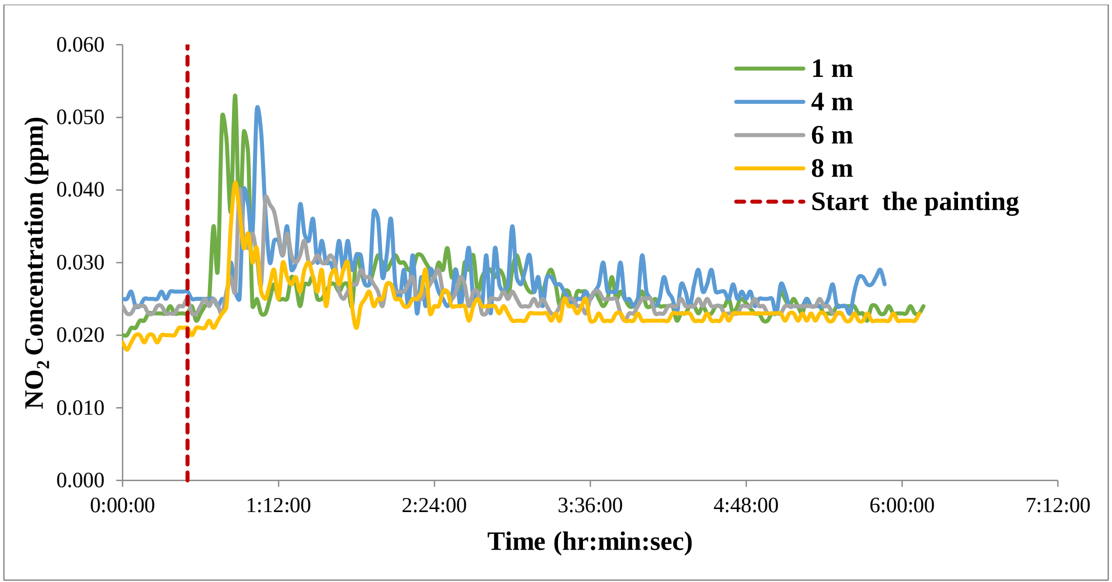


Figure B9: Timely variation of NO_2 with distances - Solvent based paint

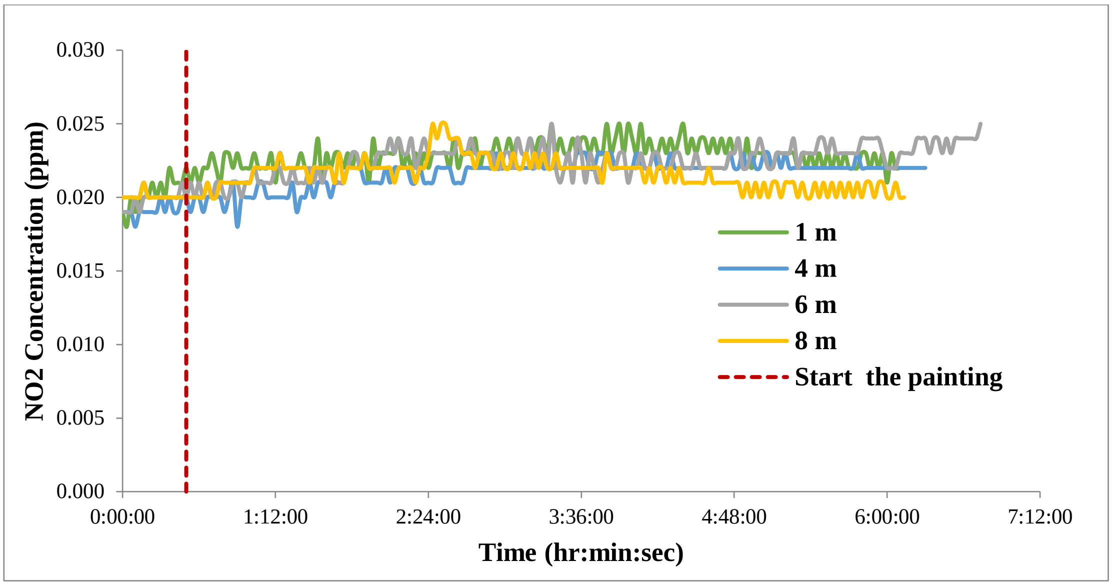


Figure B10: Timely variation of NO_2 with distances - Water based paint

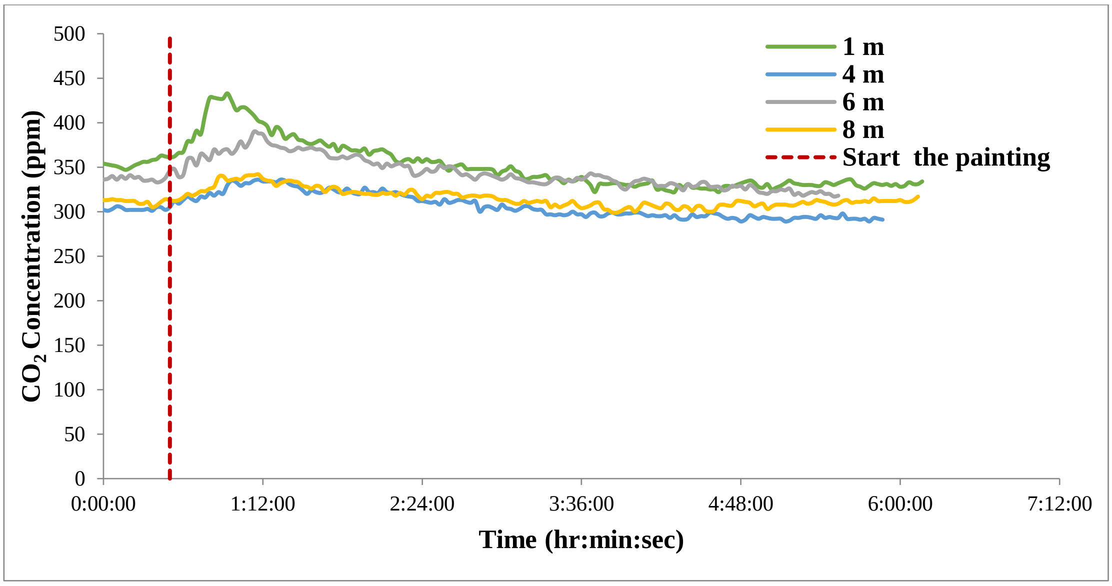


Figure B11: Timely variation of CO_2 with distances - Solvent based paint

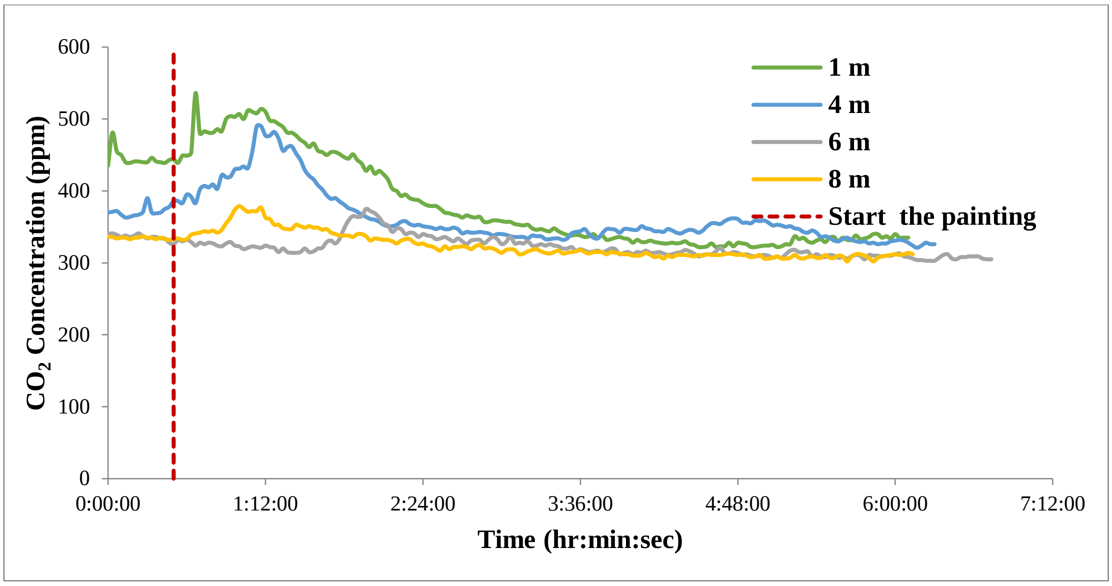


Figure B12: Timely variation of CO_2 with distances - Water based paint

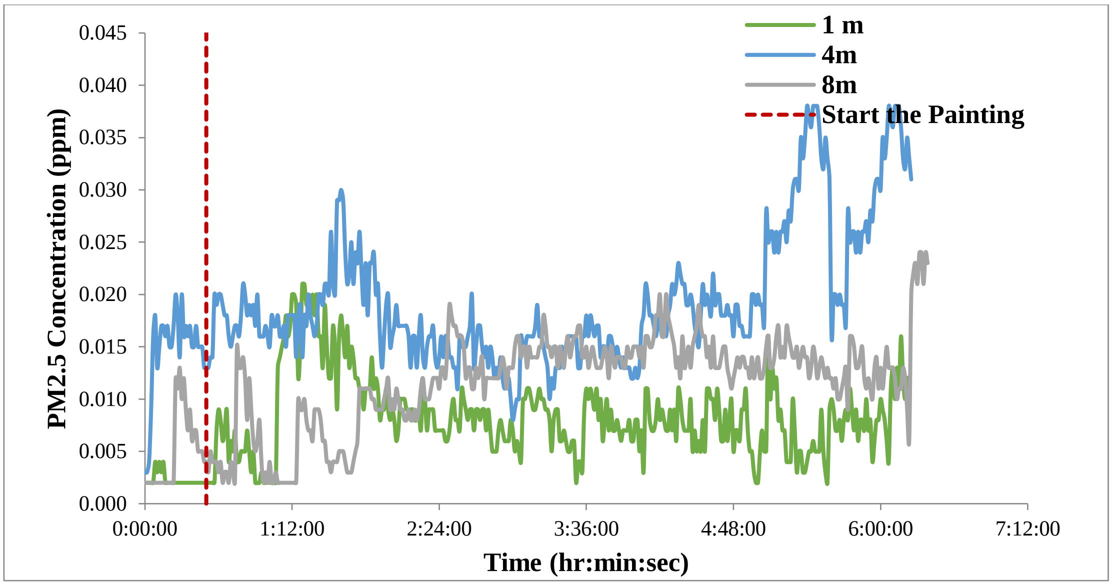


Figure B13: Timely variation of $PM_{2.5}$ with distances - Solvent based paint

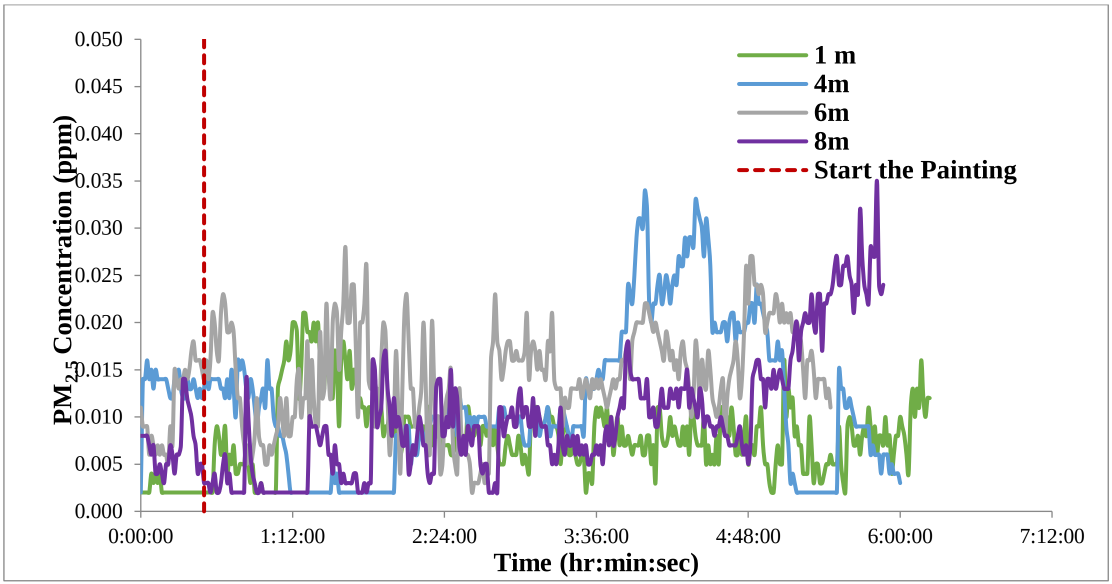


Figure B14: Timely variation of $PM_{2.5}$ with distances - Water based paint

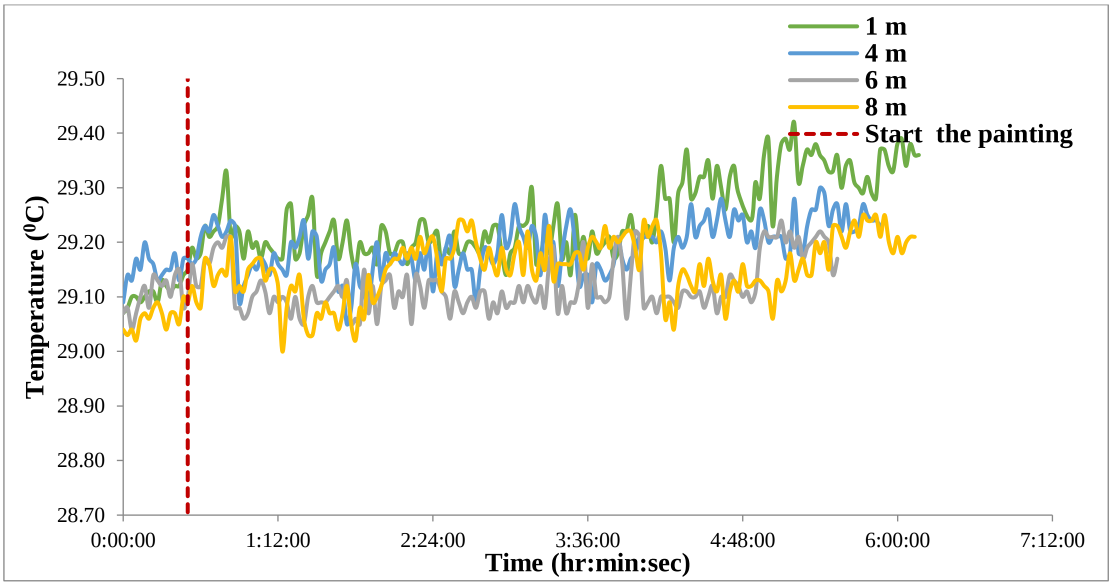


Figure B15: Timely variation of Temperature with distances - Solvent based paint

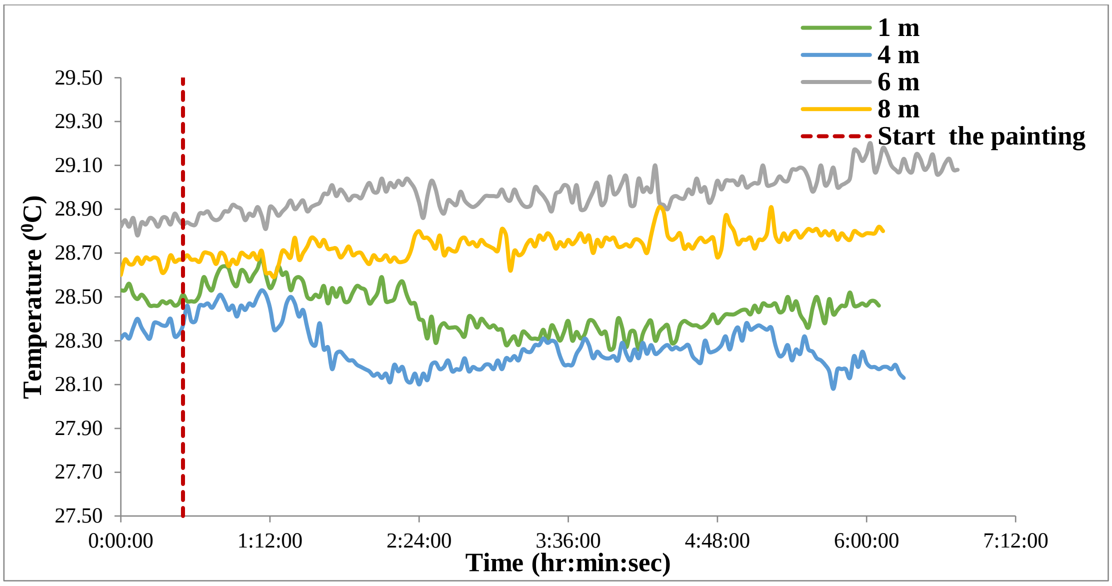


Figure B16: Timely variation of Temperature with distances - Water based paint

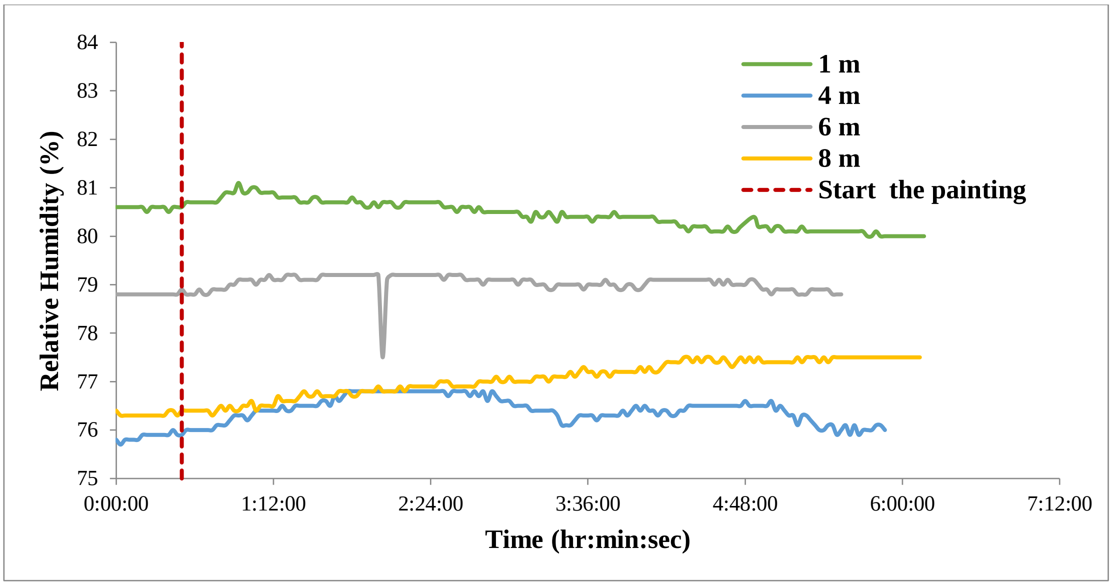


Figure B17: Timely variation of Relative Humidity with distances - Solvent based paint

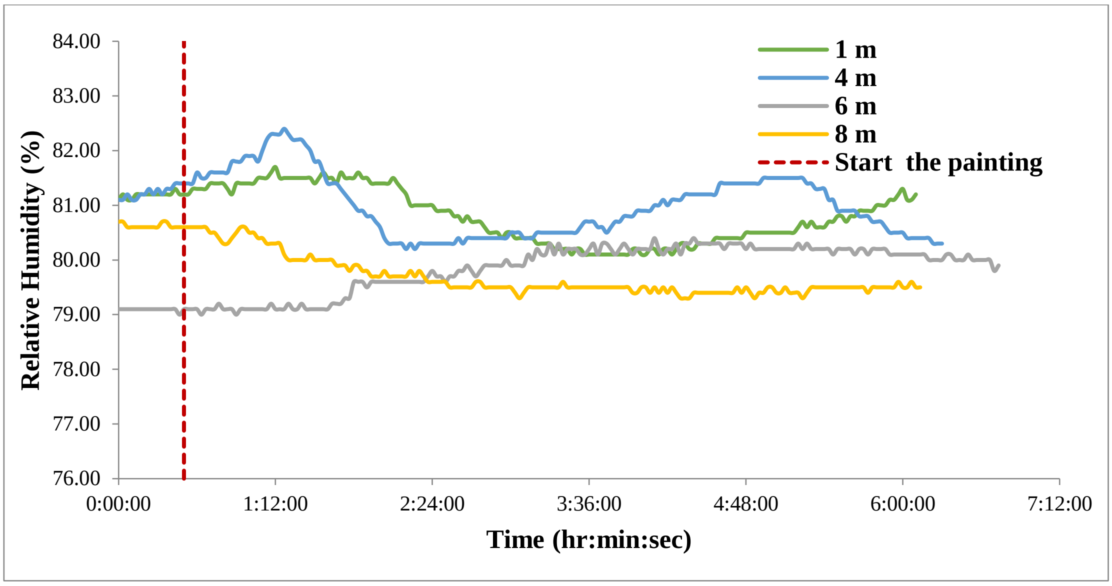


Figure B18: Timely variation of Relative Humidity with distances - Water based paint

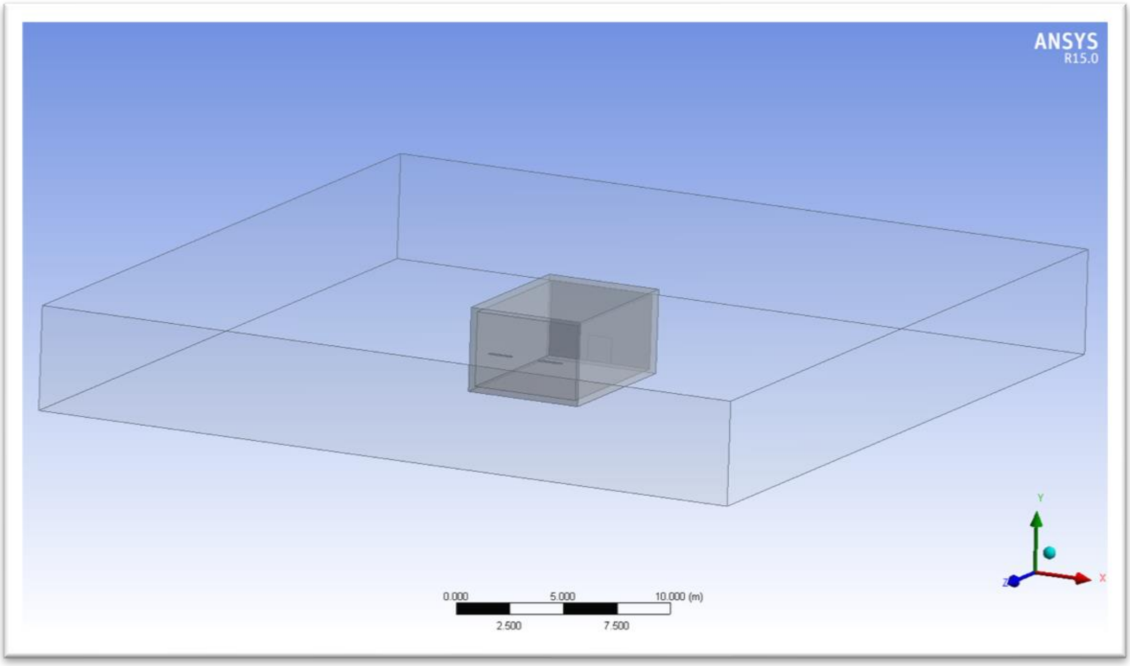


Figure B19: Model view of the ventilation case 01

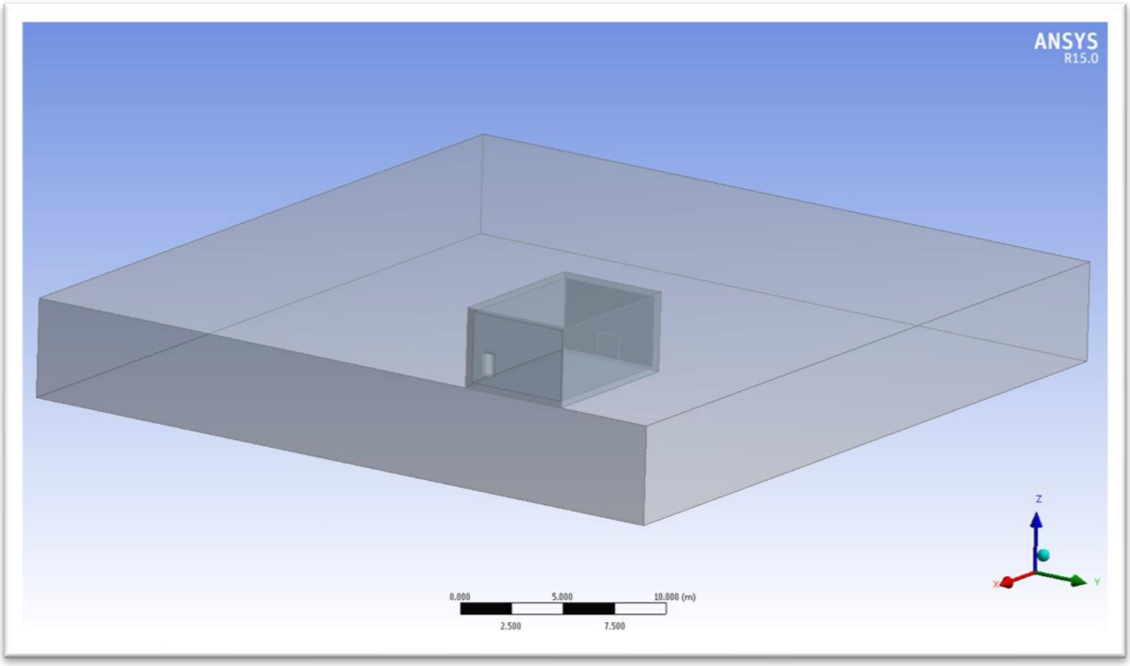


Figure B20: Model view of the ventilation case 02

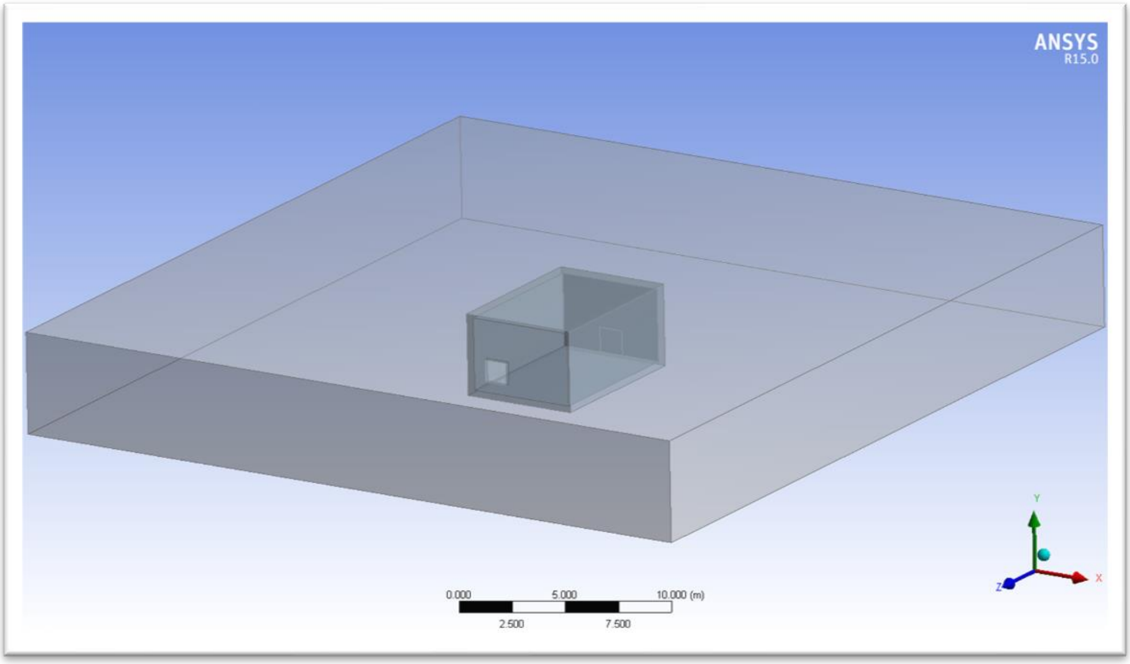


Figure B21: Model view of the ventilation case 03

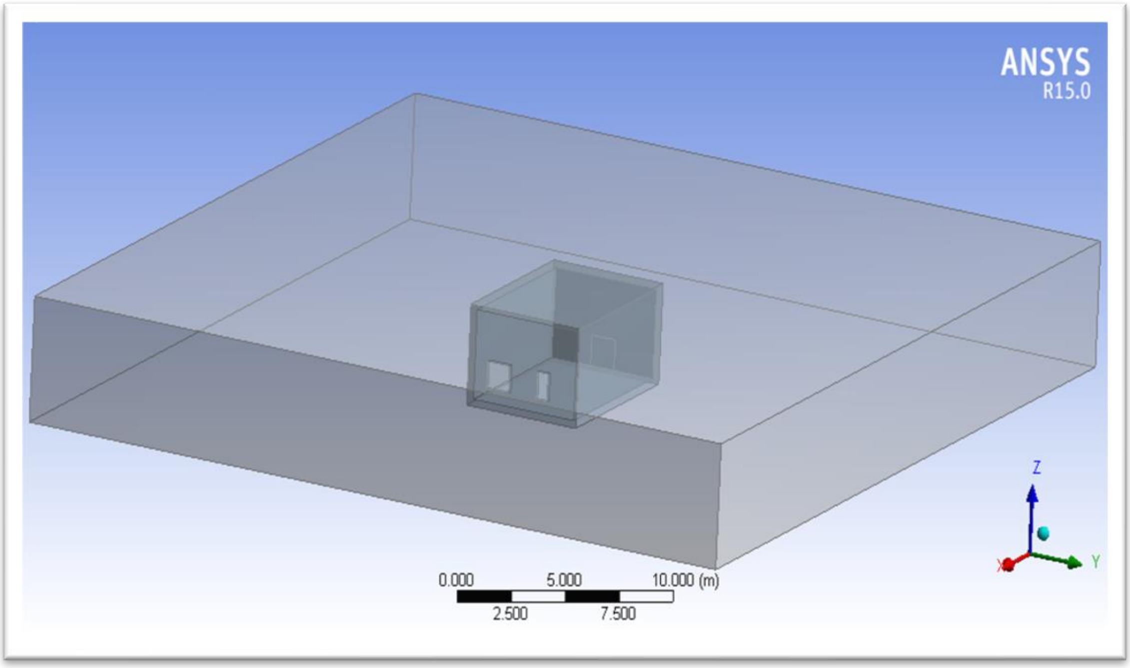


Figure B22: Model view of the ventilation case 04

ANNEX C: IAQ GUIDELINES FOR SELECTED POLLUTANTS

Table C1: Summary of the IAQ guidelines for selected pollutants

Pollutant Name	Guidelines (Permissible Exposure Limits)		Averaging Time [a]	Organization	Selected Criteria for the Guideline Definition [b]	Source
	ppm	mg/m^3				
Carbon Monoxide (CO)	9		TWA (8 hrs)	USEPA	To protect against the occurrence of carboxyhemoglobi-n levels in human blood associated with health effects of concern	USEPA, Primary National Ambient Air Quality Standards- health based and Review of National Ambient Air Quality Standards for Carbon Monoxide; Final Rule (USEPA, 2018 (a)) and (USEPA, 2011)
	35		TWA (1hr)			
		7	TWA (24 hrs)	WHO	Acute exposure related reduction of exercise tolerance and an increase in symptoms of ischemic heart disease (e.g. ST-segment changes)	WHO Guidelines for Indoor Air Quality: Selected Pollutants (WHO, 2010)
	9	10	TWA (8 hrs)			
		35	TWA (1 hr)			
	90	100	TWA (15 min)			
	50		TWA (8 hrs)	OSHA	Carboxyhemoglobi-n (COHb) measurements provided by medical professionals	OSHA Occupational Chemical Database (OSHA, 2018 (a))
	35	40	TWA (10 hrs)	NIOSH	Risk of cardiovascular effects	OSHA Occupational Chemical Database and NIOSH Recommendations for Occupational Safety and Health (OSHA, 2018 (a)) and (NIOSH, 1992)

a- **Type of exposure period (TWA-** Time Weighted Average. This refers to a concentration that a person has been exposed to average over some period, **C**- Ceiling, **STEL**- Short Term Exposure Limit, **REL**- Recommended Exposure Limit)

Note 01: -This is not a requirement of ASHRAE 62-1989. It can be considered as a target concentration level.

b- **Related health effects listed during the guideline's preparation (HE1**- Respiratory effects other than irritation- Cumulative lung damage, **HE2**- Irritation-Eyes, nose, throat, skin, **HE3**- Nervous system disturbances-Narcosis, **HE4**- Respiratory effects-Acute lung damage/edema or other, **HE5**- Asphyxiants, Anoxiants, **HE6**- Cancer- Currently regulated by OSHA as carcinogen, **HE7**- Respiratory effects other than irritation- Respiratory sensitization (asthma or other), **HE8**- Nervous system disturbances- Narcosis)

Pollutant Name	Guidelines (Permissible Exposure Limits)		Averaging Time [a]	Organization	Selected Criteria for the Guideline Definition [b]	Source
	ppm	mg/m^3				
Nitrogen Dioxide (NO_2)	0.1		TWA (1 hr)	USEPA	Public health protection, including the health of sensitive population such as asthmatics, children and elderly people	USEPA, Primary National Ambient Air Quality Standards-health-based (USEPA, 2018 (a))
	0.053		TWA (Annual)			
	0.053		TWA (Annual)	USEPA	Public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings	USEPA, Secondary National Ambient Air Quality Standards-welfare-based (USEPA, 2018 (b))
		0.2	TWA (1 hr)	WHO	Respiratory symptoms, bronchoconstriction, increased bronchial reactivity, airway inflammation and decreases in immune defence, leading to increased susceptibility to respiratory infection	WHO Guidelines for Indoor Air Quality: Selected Pollutants (WHO, 2010)
		0.04	TWA (Annual)			
	5	9	C	OSHA	Specific description is not given. Related health effects; HE1 and HE2	OSHA Occupational Chemical Database (OSHA, 2018 (b))
	1	1.8	STEL	NIOSH	Risk of respiratory and blood effects	OSHA Occupational Chemical Database (OSHA, 2018 (b)) and (NIOSH, 1992)
		0.10	TWA (Annual)	ASHRAE	To protect against adverse respiratory effects, average exposure for 1 year.	ANSI/ASHRAE Standard 62.1-2007, Ventilation for Acceptable Indoor Air Quality (ASHRAE, 2010)
		0.47	TWA (24 hrs)		24-hour average to prevent high exposures during use of combustion appliances such as space-heating devices and gas stoves.	

a- **Type of exposure period (TWA-** Time Weighted Average. This refers to a concentration that a person has been exposed to average over some period, **C-** Ceiling, **STEL-** Short Term Exposure Limit, **REL-** Recommended Exposure Limit)
Note 01: -This is not a requirement of ASHRAE 62-1989. It can be considered as a target concentration level.
b- **Related health effects listed during the guideline's preparation (HE1-** Respiratory effects other than irritation- Cumulative lung damage, **HE2-** Irritation-Eyes, nose, throat, skin, **HE3-** Nervous system disturbances-Narcosis, **HE4-** Respiratory effects-Acute lung damage/edema or other, **HE5-** Asphyxiants, Anoxiants, **HE6-** Cancer- Currently regulated by OSHA as carcinogen, **HE7-** Respiratory effects other than irritation- Respiratory sensitization (asthma or other), **HE8-** Nervous system disturbances- Narcosis)

Pollutant Name	Guidelines (Permissible Exposure Limits) ppm	mg/m^3	Averaging Time [a]	Organization	Selected Criteria for the Guideline Definition [b]	Source
Carbon Dioxide (CO_2)	1000	1800	**Note 01**	ASHRAE	Human comfort or occupant odours	ANSI/ASHRAE 62-1989 standard (ASHRAE, 1995)
	5000	9000	TWA (8 hrs)	OSHA	Specific description is not given. Related health effects; HE3, HE4 and HE5	OSHA Occupational Chemical Database (OSHA, 2018 (c))
	5000	9000	TWA (10 hrs)-REL	NIOSH	Risk of respiratory effects	OSHA Occupational Chemical Database (OSHA, 2018 (b)) and (NIOSH, 1992)
Formaldehyde (CH_2O)		0.1	TWA (30 min)	WHO	Health effect of nasal cancer	WHO Guidelines for Indoor Air Quality: Selected Pollutants (WHO, 2010)
	0.75		TWA (8 hrs)	OSHA	Specific description is not given. Related health effects; HE2, HE4, HE6 and HE7	OSHA Occupational Chemical Database (OSHA, 2018 (d))
	0.5 (Action level)					
	2		STEL			
	0.016		REL-TWA (10 hrs)	NIOSH	Risk of nasal cancer	OSHA Occupational Chemical Database (OSHA, 2018 (b)) and (NIOSH, 1992)
	0.1 (15 min)		REL-C			

a- Type of exposure period (TWA- Time Weighted Average. This refers to a concentration that a person has been exposed to average over some period, **C-** Ceiling, **STEL-** Short Term Exposure Limit, **REL-** Recommended Exposure Limit)

Note 01: -This is not a requirement of ASHRAE 62-1989. It can be considered as a target concentration level.

b- Related health effects listed during the guideline's preparation (HE1- Respiratory effects other than irritation- Cumulative lung damage, **HE2-** Irritation-Eyes, nose, throat, skin, **HE3-** Nervous system disturbances-Narcosis, **HE4-** Respiratory effects-Acute lung damage/edema or other, **HE5-** Asphyxiants, Anoxiants, **HE6-** Cancer- Currently regulated by OSHA as carcinogen, **HE7-** Respiratory effects other than irritation- Respiratory sensitization (asthma or other), **HE8-** Nervous system disturbances- Narcosis)

Pollutant Name	Guidelines (Permissible Exposure Limits)		Averaging Time [a]	Organization	Selected Criteria for the Guideline Definition [b]	Source
	ppm	mg/m³				
Particulate matter ($PM_{2.5}$)		0.035	TWA (24 hrs)	USEPA	Public health protection, including the health of sensitive population such as asthmatics, children and elderly people And Public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings	USEPA, Primary National Ambient Air Quality Standards-health-based and USEPA, Secondary National Ambient Air Quality Standards-welfare-based (USEPA, 2018 (a)) and (USEPA, 2018 (b))
		0.012	TWA (Annual)		Public health protection, including the health of sensitive population such as asthmatics, children and elderly people	USEPA, Primary National Ambient Air Quality Standards-health-based (USEPA, 2018 (a))
		0.015	TWA (Annual)		Public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings	USEPA, Secondary National Ambient Air Quality Standards-welfare-based (USEPA, 2018 (b))
		0.025	TWA (24 hrs)	WHO	Relationship between 24-hour and annual PM levels	WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide (WHO, 2005)
		0.010	TWA (Annual)		Lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to PM2.5.	

a- Type of exposure period (TWA- Time Weighted Average. This refers to a concentration that a person has been exposed to average over some period, **C**- Ceiling, **STEL**- Short Term Exposure Limit, **REL**- Recommended Exposure Limit)

Note 01: -This is not a requirement of ASHRAE 62-1989. It can be considered as a target concentration level.

b- Related health effects listed during the guideline's preparation (HE1- Respiratory effects other than irritation- Cumulative lung damage, **HE2**- Irritation-Eyes, nose, throat, skin, **HE3**- Nervous system disturbances-Narcosis, **HE4**- Respiratory effects-Acute lung damage/edema or other, **HE5**- Asphyxiants, Anoxiants, **HE6**- Cancer- Currently regulated by OSHA as carcinogen, **HE7**- Respiratory effects other than irritation- Respiratory sensitization (asthma or other), **HE8**- Nervous system disturbances- Narcosis)

Pollutant Name	Guidelines (Permissible Exposure Limits)		Averaging Time [a]	Organization	Selected Criteria for the Guideline Definition [b]	Source
	ppm	mg/m^3				
(PM_{10})		0.15	TWA (24 hrs)	USEPA	Public health protection, including the health of sensitive population such as asthmatics, children and elderly people And Public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings	USEPA, Primary National Ambient Air Quality Standards-health-based and USEPA, Secondary National Ambient Air Quality Standards-welfare-based (USEPA, 2018 (a)) and (USEPA, 2018 (b))
		0.05	TWA (24 hrs)	WHO	Relationship between 24-hour and annual PM levels	WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide (WHO, 2005)
		0.02	TWA (Annual)		Lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to PM2.5.	
Sulfur Dioxide (SO_2)	0.075		TWA (1 hr)	USEPA	Public health protection, including the health of sensitive population such as asthmatics, children and elderly people	USEPA, Primary National Ambient Air Quality Standards-health-based (USEPA, 2018 (a))
	0.5		TWA (3 hrs)		Public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings	USEPA, Secondary National Ambient Air Quality Standards-welfare-based (USEPA, 2018 (b))
		0.02	TWA (24 hrs)	WHO	Asthmatics indicate that a proportion experience changes in pulmonary function and respiratory symptoms	WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide
		0.5	TWA (10 min)			

a- Type of exposure period (TWA- Time Weighted Average. This refers to a concentration that a person has been exposed to average over some period, **C-** Ceiling, **STEL-** Short Term Exposure Limit, **REL-** Recommended Exposure Limit)

Note 01: -This is not a requirement of ASHRAE 62-1989. It can be considered as a target concentration level.

b- Related health effects listed during the guideline's preparation (HE1- Respiratory effects other than irritation- Cumulative lung damage, **HE2-** Irritation-Eyes, nose, throat, skin, **HE3-** Nervous system disturbances-Narcosis, **HE4-** Respiratory effects-Acute lung damage/edema or other, **HE5-** Asphyxiants, Anoxiants, **HE6-** Cancer- Currently regulated by OSHA as carcinogen, **HE7-** Respiratory effects other than irritation- Respiratory sensitization (asthma or other), **HE8-** Nervous system disturbances- Narcosis)

Pollutant Name	Guidelines (Permissible Exposure Limits)		Averaging Time [a]	Organization	Selected Criteria for the Guideline Definition [b]	Source
	ppm	mg/m^3				
	5	13	TWA (8 hrs)	OSHA	Specific description is not given. Related health effects; HE2	OSHA Occupational Chemical Database (OSHA, 2018 (e))
	2	5	REL-TWA (10 hrs)	NIOSH	Specific description is not given.	OSHA Occupational Chemical Database (OSHA, 2018 (e))
	5	13	REL-STEL			
Lead (Pb)		0.00015 (0.15 $\mu g/m^3$)	TWA-(3 months)	USEPA	Public health protection, including the health of sensitive population such as asthmatics, children and elderly people And Public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings	USEPA, Primary National Ambient Air Quality Standards-health-based and USEPA, Secondary National Ambient Air Quality Standards-welfare-based (USEPA, 2018 (a)) and (USEPA, 2018 (b))
		0.0005 (0.5 $\mu g/m^3$)	TWA (Annual)	WHO	Assuming that the upper limit of nonanthropogenic blood is 30 µg/l	Air Quality Guidelines for Europe (WHO, 2000 (a))
		0.05	TWA (8 hrs)	OSHA	Specific description is not given. Related health effects; HE2 and HE8	OSHA Occupational Chemical Database (OSHA, 2019)
		0.03 (Action Level)				
		0.05	REL-TWA (10 hrs)	NIOSH	Specific description is not given.	OSHA Occupational Chemical Database (OSHA, 2019)

a- **Type of exposure period (TWA-** Time Weighted Average. This refers to a concentration that a person has been exposed to average over some period, **C**- Ceiling, **STEL**- Short Term Exposure Limit, **REL**- Recommended Exposure Limit)

Note 01: -This is not a requirement of ASHRAE 62-1989. It can be considered as a target concentration level.

b- **Related health effects listed during the guideline's preparation (HE1**- Respiratory effects other than irritation- Cumulative lung damage, **HE2**- Irritation-Eyes, nose, throat, skin, **HE3**- Nervous system disturbances-Narcosis, **HE4**- Respiratory effects-Acute lung damage/edema or other, **HE5**- Asphyxiants, Anoxiants, **HE6**- Cancer- Currently regulated by OSHA as carcinogen, **HE7**- Respiratory effects other than irritation- Respiratory sensitization (asthma or other), **HE8**- Nervous system disturbances- Narcosis)

ANNEX D: QUESTIONNAIRE SURVEY TEMPLATE

Questionnaire Survey on Indoor Comfort Level

- Location : ....
- Date : ....
- Time : ....

1. Personal details of the occupant

1.1 Age group : ☐ Below 20 ☐ 20-30 ☐ 30-40 ☐ 40-50 ☐ 50-60 ☐ Above 60

1.2 Gender : Male ☐ Female ☐

1.3 Occupation: ....

2. Complaints / Symptoms

2.1 Any of the following symptoms experienced inside the room? (Please tick the boxes which indicate your Complaints / Symptoms)

Chills	☐	Lethargy	☐
Cough	☐	Nausea	☐
Congestion	☐	Nose irritation	☐
Chest tightness	☐	Odors / smells	☐
Dizziness	☐	Shortness of breath	☐
Eye irritation	☐	Sinus irritation	☐
Fatigue fever	☐	Sleepiness	☐
Headache	☐	Swelling	☐
Itching	☐	Thermal discomfort	☐
Throat irritation	☐		

2.2 Do you usually have any of the symptoms mentioned in **2.1** as a persistent health condition or could it be due to the indoor environment?

Persistent ☐ Indoor environment ☐

Figure D1: Questionnaire survey template- page 01

2.3 If you are having persistent health conditions please specify them :

………

………

2.4 In your opinion, do you suspect any other pollutant sources?

………

2.4.1 If "yes", please specify :

………

………

2.5 What is the time of the day when you feel the above mentioned discomfort?

- Just after the exposure ☐
- While inside the room ☐
- Persist for sometime ☐

2.6 How long does it last?

- Hours :
- Days :

2.7 Any other comments:

………

………

………

Figure D2: Questionnaire survey template- page 02