Environmental Impact of Liquified Natural Gas Fire Accident Emissions

G.K.S.N. Gangodawila, K.R.A.M.T. Menike, and M.Y. Gunasekera

1 Introduction

Liquefied Natural Gas (LNG), which mainly consists of methane, is produced through the process of cryogenically cooling natural gas. This versatile energy source is extensively used for generating electricity and providing clean-burning fuel for heating in residential and commercial settings.

There are two primary ways an LNG spill can ignite which are by a pool fire and by a vapor cloud explosion. A pool fire occurs when ignition happens early, sustaining the fire through the liquid pool. On the other hand, if LNG forms a vapor cloud before ignition, it can lead to a vapor cloud explosion. In the case of an LNG spill near an ignition source, the risk of immediate ignition and combustion above the spilled LNG is high, resulting in a pool fire [1]. Unconfined LNG pools can rapidly expand, especially upon contact with water, leading to fires that burn at very high temperatures and are resistant to conventional extinguishing methods [1]. These fires continue until the LNG is entirely consumed, and the thermal radiation from such fires poses severe risks to individuals and property even at considerable distances [1].

If LNG spills and does not ignite immediately, a vapor cloud may form and drift away from the spill site, influenced by prevailing winds [1]. If this vapor cloud encounters an ignition source while within the flammable gas to air ratio, it can ignite, causing a vapor cloud fire [1]. Such fires are generally smaller and less intense than pool fires because only a part of the cloud is in a combustible state [1].

LNG fires release a variety of emissions, including thermal and gaseous emissions like CO_2, CO, NO_2, SO_2, N_2O, and particulate matter. While specific dispersion studies have been conducted for pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2), and methane (CH_4), a comprehensive study covering all emissions has yet to be undertaken.

This research aims to develop a methodology for assessing the environmental impacts caused by emissions from LNG fires. The sub objectives include developing fire accident scenarios, modelling the dispersion of emissions from LNG fires, and assessing the environmental impacts of emissions resulting from accidental LNG releases.

Several studies have investigated the dispersion of LNG vapours, particularly in the context of FLNG (Floating Liquefied Natural Gas) facilities [2]. The quantification of radiant heat emissions from LNG fires were studied through controlled testing environments simulating large scale fire conditions [3], [4]. These experimental studies have provided valuable insights into combustion rates, radiant heat emissions, emissive power, and smoke production [3]. In addition to experimental investigations, research has focused on developing dynamic simulations to model LNG fires within established LNG facilities [4]. However, these studies did not comprehensively address the emission and dispersion of combustion products. The dispersion of emissions from LNG fires, focusing particularly on nitrogen dioxide (NO_2) and carbon monoxide (CO) has been explored by Baalisampang et al., who utilized model facility layouts incorporating various process equipment to simulate LNG spill scenarios [5]. They have done a detailed analysis of emission dispersion, specifically focusing on NO_2 and CO releases from the LNG fire [5]. Other research has employed Computational Fluid Dynamics (CFD) using the FLACS code to model the dispersion of hazardous contaminants, including CO, NO_2, and methane (CH_4), following an LNG fire on an offshore platform [6].

Further work by Baalisampang et al. applied Computational Fluid Dynamics (CFD), particularly using the Fire Dynamics Simulator (FDS), to assess fire consequences within FLNG facilities, evaluating fire impacts through two main aspects which are human and asset impact criteria [7]. While existing research has made significant progress in modelling the dispersion of emissions from LNG fires, primarily focusing on pollutants like methane (CH_4), carbon monoxide (CO), and nitrogen dioxide (NO_2), a notable gap exists regarding other gaseous emissions commonly associated with LNG fires [5], [6]. The limited scope of investigated emissions necessitates comprehensive studies encompassing a wider range of pollutants for a more holistic understanding of the environmental consequences [5], [6]. Moreover, although research has extensively assessed LNG fire impacts based on human and asset criteria, a significant knowledge gap exists regarding the environmental impacts of such incidents [7]. The ecological repercussions and effects on the surrounding environment have not received sufficient attention in current literature. This critical gap highlights the need for future studies that delve into the environmental implications of LNG fires

2 Experimental Section

2.1 Materials

Computational tools and software are utilized for modelling and analysis rather than physical materials in this study. The ALOHA software was used to simulate vapor dispersions, estimate chemical concentrate zones and visualize threat zones associated with LNG fire scenarios.

Microsoft Excel was utilized to perform emission quantification and subsequently calculate the environmental impacts such as global warming impact, acidification impact, human toxicity impact and photochemical smog formation impact.

2.2 Methods

2.2.1 Release Scenario

In this study, a release scenario is developed which involves an LNG storage tank and accidental release of Liquefied Natural Gas (LNG) within a purely hypothetical manufacturing facility in Gampaha District since there are currently no LNG facilities in Sri Lanka. The LNG is assumed to be stored in a vertical cylindrical tank with a volume of 400 cubic meters. The tank dimensions are specified as a height of 7.05 meters and a diameter of 8.5 meters.

LNG is assumed to be comprised solely of methane and is maintained at atmospheric pressure and below atmospheric temperature. Structural damage is assumed to occur, leading to rupture of storage tank. This rupture results in the rapid vaporization of the LNG, forming a methane vapor cloud. The volume of vaporized LNG is calculated to be 260,000 cubic meters. An ignition source near the release is considered to trigger a flash fire.

This scenario allows the study of emissions from LNG fires and the dispersion of these emissions. Furthermore, this scenario facilitates an environmental impact assessment, providing insights into the potential hazards associated with LNG storage.

Release consequence cases and emission quantification.

Under the developed release scenario, different cases can be studied to analyse the combustion of LNG vapor and its resulting emissions. For this research, three specific cases are considered. In case 1, it is assumed that all the LNG undergoes complete combustion, resulting in the formation of carbon dioxide. The reaction for complete combustion is shown in Eq. (1).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \text{Eq. (1)}$$

Under complete combustion with sufficient oxygen, the primary emission can be identified as carbon dioxide

In case 2, the LNG undergoes incomplete combustion due to insufficient oxygen supply. The emissions include carbon monoxide (CO), carbon dioxide (CO_2), and unburnt methane (CH_4). The reactions for incomplete combustion are shown in Eq. (2) an Eq. (3).

$$2CH_4 + 3O_2 \rightarrow 2CO + 4H_2O \qquad \text{Eq. (2)}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \text{Eq. (3)}$$

The primary emissions are CO, CO_2, and unburnt methane highlighting the inefficiency of the combustion process.

In case 3, high temperature reaction of nitrogen with oxygen is considered along with complete combustion. adiabatic flame temperature of methane is 1960°C, which is a significantly high temperature [8]. At such elevated temperatures, nitrogen (N_2) in the air reacts with oxygen (O_2), leading to the formation of nitrogen oxides (NO_x), specifically nitric oxide (NO) and nitrogen dioxide (NO_2), in addition to carbon dioxide (CO_2) [9]. The reactions for this case are as follows.

$$N_2 + O_2 \rightarrow 2NO \qquad \text{Eq. (4)}$$

$$2NO + O_2 \rightarrow 2NO_2 \qquad \text{Eq. (5)}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \text{Eq. (6)}$$

These three cases provide a comprehensive framework for analysing the emissions and environmental impacts of LNG combustion under different conditions. For each case, the emissions are quantified based on the stoichiometric equations.

2.3 Dispersion modelling using ALOHA Software

Dispersion modelling of accidental LNG releases is performed using ALOHA software. ALOHA is a widely used tool for estimating the downwind spread of hazardous chemical vapours. Three release scenarios are analysed, assuming a storage tank located at a manufacturing facility in the Gampaha district. In this area, wind speed varies significantly throughout the year, with the highest average wind speed observed in June [10]. For modelling the worst-case scenario, the peak conditions are considered. The meteorological conditions include an air temperature of 28.33°C and a westerly wind blowing at a speed of 21.4 kilometres per hour, measured at a height of 10 meters above the ground [10]. The source emission height is set to correspond with the tank height [10].

ALOHA is used to define threat zones based on concentration thresholds for CO_2, CO, CH_4, NO, and NO_2. These zones represent areas surrounding the release point where chemical concentrations pose potential health and safety risks. ALOHA visualizes these zones as colour coded regions extending downwind from the release, with each colour signifying a distinct hazard level. The Red Threat Zone indicates severe, life-threatening hazards, the Orange Threat Zone signifies areas with significant health risks causing temporary or irreversible effects, and the Yellow Threat Zone highlights regions with mild, transient health effects.

Concentration thresholds for CO_2 are established based on guidelines set by the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA). The yellow zone ranged from 5,000 to 15,000 ppm, the orange zone ranged from 15,000 to 40,000 ppm, and the red zone signified concentrations exceeding 40,000 ppm, which corresponds to the Immediately Dangerous to Life or Health (IDLH) value [11], [12]

Acute Exposure Guideline Levels (AEGLs) published by the U.S. Environmental Protection Agency (EPA) are used to determine threat zones for CO and NO_2. For CO, the red zone (AEGL-3) corresponds to a concentration of 330 ppm, while the orange zone (AEGL-2) represents a concentration of 83 ppm. NO_2 threat zones are defined as red zone (AEGL-3) at 20 ppm, orange zone (AEGL-2) at 12 ppm, and yellow zone (AEGL-1) at 0.5 ppm [13], [14].

Protective Action Criteria (PAC) values serve as the basis for defining CH_4 and NO threat zones. The PAC-3 concentration of 400,000 ppm defines the red zone for CH_4, with the orange zone ranging from 230,000 ppm to 65,000 ppm (PAC-2) and the yellow zone includes concentrations below 65,000 ppm (PAC-1). Similarly, PAC values are used for NO, with the red zone set at 20 ppm (PAC-3), the orange zone at 12 ppm (PAC-2), and the yellow zone at 0.5 ppm (PAC-1)[15] .

2.4 Environmental Impact Assessment

This study evaluates the potential environmental impacts associated with the release of emissions, including CO_2, CO, CH_4, NO, and NO_2. The assessment focuses on four key environmental impacts including global warming, photochemical smog formation, acidification, and human toxicity.

Emissions of CO_2, CH_4, and CO contribute to global warming. Global Warming Potential (GWP) is a metric used to compare the ability of different gasses to trap heat relative to CO_2 over a chosen period. Equation (7) illustrates a common method for calculating global warming impact, where 'i' represents a specific greenhouse gas (GHG), and 'm' denotes its emission quantity. This methodology, established by the Intergovernmental Panel on Climate Change (IPCC), allows for a standardized comparison of the warming impact of different greenhouse gases [16].

$$Global\ warming\ impact_i = m_i * GWP_i \qquad \text{Eq. (7)}$$

Global warming potential for greenhouse gasses CO_2, CO, CH_4, NO_x is 1, 21, 2 and 310 kg CO_2-eq/kg respectively [16].

NO and NO_2 can react with other pollutants in the presence of sunlight to form photochemical smog. Photochemical Ozone Creation Potential (POCP) is a metric used to assess the potential of a pollutant to contribute to smog formation. Equation 8 illustrates a common method for calculating POCP, where i represents a specific pollutant, and 'm' denotes its emission quantity [16].

$$Photochemical\ smog\ formation\ impact_i = m_i * POCP_i \qquad \text{Eq. (8)}$$

Photochemical ozone creation potential for CH_4 and NO_x are 0.006 and 0.028 kg C_2H_4-eq/kg respectively [16].

NO_2 and NO emissions can contribute to acidification. Acidification Potential (AP) is a metric used to compare the potential of different pollutants to contribute to acidification, with sulphur dioxide (SO_2) used as the reference gas. Equation 9 illustrates a common method for calculating acidification impact, where 'i' represents a specific acidic gas, and 'm' denotes its emission quantity[16] .

$$Acidification\ impact_i = m_i * AP_i \qquad \text{Eq. (9)}$$

Acidification potential for NO_x is 0.7 kg SO_2 -eq/kg respectively [16].

CO and NO emissions can pose human health risks through inhalation. Human Toxicity Potential (HTP) is a metric used to assess the potential health impacts of pollutants. Equation 10 illustrates a common method for calculating human toxicity impact, where 'i' represents a specific gas, ‘m’ denotes its emission quantity[16] .

$$Human\ toxicity\ impact_i = m_i * HTP_{1,4-C6H4Cl2-eq} \qquad \text{Eq. (10)}$$

CO and NO emissions can pose human health risks through inhalation. Human toxicity potential of NO_x and CO are 1.2 kg 1,4-$C_6H_4C_{12}$ -eq/kg and 0.012 kg 1,4-$C_6H_4C_{12}$ -eq/kg respectively.

Using ALOHA software, the concentration and dispersion of emitted gases such as CO_2, CO, CH_4, NO and NO_2 were modelled, and threat zones were visualized in red, orange and yellow based on AEGL and PAC safety limits. Using these dispersed concentration data the environmental impacts including global warming impact, photochemical smog formation impact, acidification impact, and human toxicity impact were quantitatively calculated.

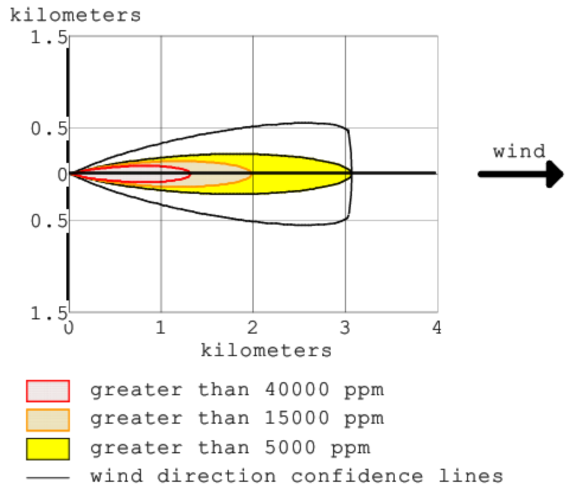

Figure 1. Threat zone plot for CO_2 in case 1.

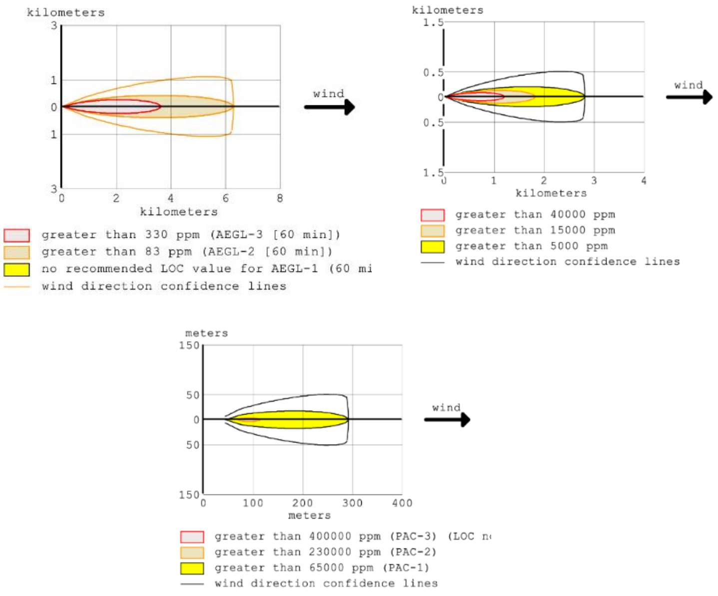

Figure 2. Threat Zone plots for Case 2; (a) CO, (b) CO_2, (c) CH_4

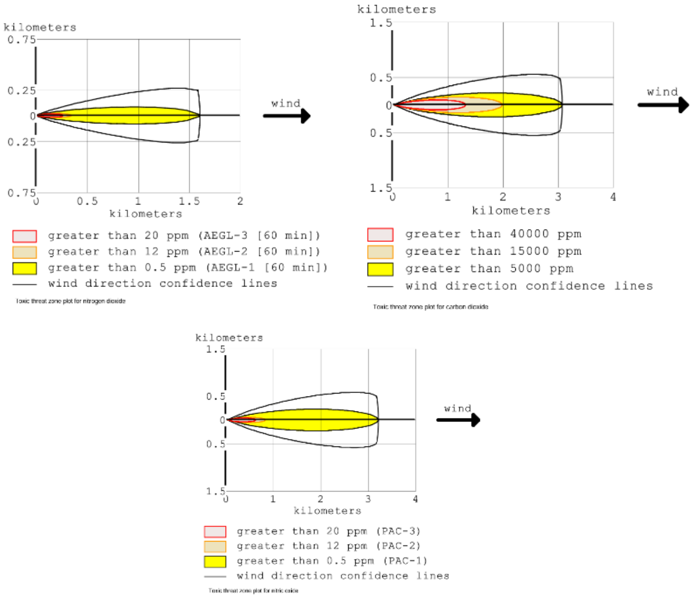

Figure 3. Threat Zone plots for Case 3; (a) NO_2, (b) CO_2, (c) NO

3 Results and Discussion

3.1 Case 1

This case simulates an LNG flash fire event, specifically focusing on the complete combustion of the released LNG gas. Nitrogen in the air reaction with oxygen is not considered under this case. For simplification, the modelling neglects other potential products of incomplete combustion, such as soot and volatile organic compounds (VOCs). The quantification of gas emission was conducted to gain a comprehensive understanding of the resultant gasses from the simulated LNG fire event. This data is essential for dispersion modelling and impact assessment. While the amount of LNG gas burnt is 260,000 m^3, the released CO_2 emission quantity is 461662.63kg. Dispersion of the CO_2 gas emissions for this case and associated threat zones are shown in Fig 1. In this case, CO_2 contributes to global warming. Therefore, the Global warming impact calculated using equation (7) is 461662.63 kg CO_2-eq.

3.2 Case 2

This case focused on the incomplete combustion of the released LNG gas. In this scenario, it is assumed that 80% of the total released gas undergoes complete combustion, 10% undergoes incomplete combustion, and the remaining 10% of the LNG does not combust at all, resulting in the release of unburnt methane (CH_4) directly into the atmosphere. For simplification, the modelling neglects other potential products of incomplete combustion, such as soot and volatile organic compounds (VOCs).

For the LNG storage tank containing 400 m^3 of LNG, the quantified emission results of CH_4, CO_2 and CO gases are 16787.73 kg, 369330.10kg and 29378.53 kg respectively. In this case, emissions of CO_2, CH_4, and CO contribute to global warming, and the global warming potential results are 369330.10, 352542.33, and 58757.06 kg CO_2 equivalence respectively. The total global warming impact is 780629.49 kg CO_2-eq. In this case, emissions of CO contribute to Human Toxicity. Total Human Toxicity Impact is 352.54 kg 1,4-$C_6H_4Cl_2$ equivalence.

3.3 Case 3

At elevated temperatures, nitrogen in the air reacts with oxygen to form nitric oxide and nitrogen dioxide [17]. In this case, it is assumed that the Nitrogen in the air reacts with oxygen. Due to the high temperatures resulting from LNG fires, the reaction favours the formation of NO over NO_2 [17]. Therefore, it is assumed that the formation of NO and NO_2 occurs in a ratio of 90% to 10%, respectively. For every 1 cubic meter of released LNG vapor combusted, 0.15 grams of NO_x are produced [17]. It is also assumed that all the LNG is completely combusted, forming CO_2. The quantified emissions of CO_2, NO and NO_2 are 461662.63 kg, 35.10kg and 3.90kg respectively.

The dispersion plots and threat zones generated using ALOHA for NO, NO_2, and CO_2 gases are indicated in Fig 3. From these gaseous emissions, the global warming potential impact, human toxicity impact, acidification impact and photochemical smog formation impact are 473752.6 kg CO_2 equivalence, 46.8 kg 1,4-$C_6H_4Cl_2$ equivalence,27.3 kg SO_2 equivalence, and 1.092 kg C_2H_4 equivalence respectively.

3.4 Discussion

The global warming impact of different combustion scenarios for liquefied natural gas (LNG) are examined by using three cases.

In Case 1, a Complete combustion of LNG represents an ideal scenario, resulting solely in CO_2 emissions. The total Global warming impact is directly calculated based on the released CO_2 mass translating to 461662.63 kg CO_2-eq. This scenario serves as a baseline for comparison with incomplete combustion cases.

In Case 2, Incomplete combustion introduces additional GHGs beyond CO_2, including methane (CH_4) and carbon monoxide (CO). While CO_2 emissions are lower than in the case 1, the presence of CH_4 significantly elevates the total Global warming impact. Even though the released mass of CH_4 is lower than CO_2, greater warming potential per unit mass of CH_4 makes it the dominant contributor to the increased impact in Case 2.

Case 3 scenario broadens the assessment by incorporating nitrogen oxides (NO_x), specifically NO and NO_2, alongside CO_2. While NO_x does not directly contribute to the global warming impact calculation, they indirectly influence atmospheric processes like ozone formation, which acts as a greenhouse gas. Despite their lower emission quantity compared to CO_2 and CH_4, the combined impact of NO_x increases the total Global warming impact in this case. This finding highlights the importance of considering a broader range of pollutants beyond traditional GHGs for a more comprehensive understanding of climate change impact.

According to the analysed cases, a significant increase in Global warming impact is observed when considering incomplete combustion (Case 2) compared to complete combustion (Case 1). The presence of CH_4, with its higher global warming potential, significantly elevates the overall warming impact.

The human toxicity impact is observed in both case 2 and case 3 due to the formation of CO, NO, and NO_2 gases. Case 2 exhibits the highest human toxicity impact, quantified at 352.54 kg equivalence of $C_6H_4Cl_2$. In case 3, there are two toxic gases present, which are NO and NO_2, in contrast to case 2, where only CO is present. Despite the higher human toxicity potential of NO_x

compared to CO, the significant quantity of CO emissions in case 2 results in a substantial human toxicity impact. Thus, while CO has a lower HTP, its higher emission mass in case 2 leads to the highest overall human toxicity impact.

The acidification impact is caused only in case 3, where NO_x emissions are present. This impact is quantified as 27.3 kg of SO_2 equivalence. While the acidification potentials of both NO and NO_2 are equal, the greater quantity of NO results in the highest acidification impact among these emissions.

Similarly, the photochemical smog formation impact is only observed in case 3, due to NO_x emissions. This impact is quantified as 1.092 kg of C_2H_4 equivalence. Despite the photochemical smog formation potentials of both NO and NO_2 being equal, the higher amount of NO leads to a greater impact of photochemical smog formation from these two emissions.

4 Conclusions

This research has comprehensively explored the environmental impacts of emissions resulting from accidental fires of LNG by developing fire accident scenarios, modelling emission dispersion using ALOHA software, and assessing the environmental impacts. This study focuses on three specific cases of LNG combustion which are complete combustion, incomplete combustion, and high-temperature reactions with nitrogen, providing a detailed analysis of emissions and their impacts.

The first scenario simulated ideal combustion, resulting solely in carbon dioxide (CO_2), a major greenhouse gas, and established a baseline for comparison. The second scenario, representing incomplete combustion, revealed a more concerning situation. While CO_2 emissions were lower, the presence of unburnt methane, a potent greenhouse gas, significantly increased global warming impact and introduced human toxicity impact through carbon monoxide emissions. The third scenario incorporated the effect of high temperatures on nitrogen in the air, leading to the formation of nitrogen oxides (NO_x) alongside CO_2. While the global warming impact was lower than the incomplete combustion scenario, NO_x emissions introduced additional environmental concerns such as acidification, smog formation, and human toxicity impact.

The findings show the critical need to prevent accidental LNG fires in LNG storage and handling as harmful environmental impacts are involved. Future research should focus on expanding the scope of emission studies to include a wider range of pollutants and their impacts on the environment.

Declaration of Competing Interest

The authors declare no competing interests.

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Keywords

LNG, ALOHA software, dispersion modelling, environmental impacts

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