MANUFACTURING PROCESS AND PERFORMANCE EVALUATION OF THERMAL INSULATION COATINGS

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Degree of Master of Engineering

Department of Mechanical Engineering

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Dissertation submitted in partial fulfillment of the requirements for the degree Master of Engineering.

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Declaration:

I declare hereby that the following research work is my research work and the dissertation content does not incorporate without previous acknowledgements any academic materials which are heretofore submitted for any degree, diploma or certificate course in another university, institution, or higher education college to the best of my acquaintance, as well as the belief it does not incorporate any other academic materials previously submitted, written, or issued by other individuals or higher educational institutions except where the acknowledgment is made within the chapters in the report. Correspondingly, I hereby grant a nonexclusive right to continue, replicate, or distribute to the University of Moratuwa my dissertation works, in entirety or in part in printed or electronic versions or other mediums.

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C. S. K. Ranasinghe

The above candidate has carried out research work for the Master / Dissertation under my supervision.

Signature of the Supervisor:

Name of the Supervisor: Dr. H. K. G. Punchihewa Date: 25th November 2022

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C. S. K. Ranasinghe.

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Abstract:

Manufacturing organizations are using a considerable amount of energy for their daily manufacturing operations and more than 60% of their total energy use is for thermal applications. Therefore, systems that use thermal energy as the main energy input for manufacturing operations continuously emit thermal energy to the environment, raising significant environmental, financial, human factors, and safety issues. Therefore, preventing the dissipation of thermal energy from manufacturing systems to their surroundings has become a priority in answering some of the most critical challenges. This could be done by improving energy efficiency and creating a safe workplace. However, due to the drawbacks of traditional insulation methods due to uneven hot surfaces and organizational rules and regulations on carcinogenic insulation materials, most organizations are moving toward environmentally friendly alternatives. Therefore, thermal insulation paints play an important role in substituting traditional insulations.

This research aims to develop a thermal insulation paint by changing the type of pigment to minimize the thermal conductivity of the final coating mixture. A two-factor factorial design was designed that considered pigment volume concentration (PVC) and additive percentage (Sodium polyacrylate) as variable factors and the thermal conductivity as the response variable. For each variable, nine different combinations of paint samples were considered at three different levels. In this experiment, tile body powder was selected as the pigment, polyvinyl acetate (PVA) as the binder and sodium polyacrylate (NaPA) as the dispersing agent, and the thermal conductivity of the final coating layer against the selected coating substrate was measured. Then a numerical relationship was developed between the thermal conductivity (K) of the final insulation coating layer and the percentage of the weight of the two factors. The results revealed that the pigment type is the most influential factor for the insulation properties or thermal conductivity. Hence, there is an opportunity to continue the same procedure to evaluate the insulation properties while changing pigment types, especially considering ceramic base materials.

Keywords: Pigment, Pigments volume concertation (PVC), Thermal Conductivity (K)

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1.0 INTRODUCTION

This chapter describes thermal energy applications in Sri Lankan manufacturing operations in various production processes and operations. It further represents the thermal energy loss in its surroundings and the issues that are rising on the production floor due to thermal energy dissipation. In addition, it discussed traditional insulation methods used in the manufacturing process to reduce thermal energy dissipation and the difficulties of using conventional insulation methods. In addition, it describes the ingredients of the coating manufacturing process and its importance for the final insulation properties of the coating film, as well as the manufacturing process of the thermal insulation coating. Finally, it expresses the research problem, its aim, and the objectives related to this thesis.

1.1 Background

Once Sri Lanka liberalized its economy, industrialization of the Sri Lankan economy was initiated very quickly after 1977 [01]. With these initiatives, new manufacturing organizations were built throughout the country and export processing zones were started while introducing thousands of manufacturing organizations. Therefore, the total energy consumption of manufacturing processes in the country has increased gradually over the last three decades [02].

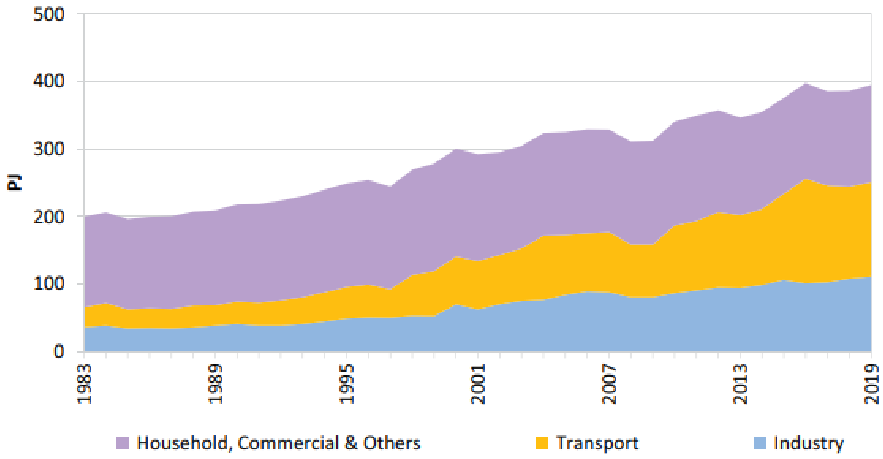


Figure 1.1: Positive trend for energy use for industrial applications [51].

The energy used for industrial applications converts different aspects of energy according to their process requirements such as thermal, mechanical, lighting, etc. Of these energy aspects, most industries use thermal energy for their manufacturing operations, and therefore thermal energy has become a common energy form in most manufacturing operations [03]. Most manufacturing systems frequently use thermal energy as a primary energy input during their operations; thermal energy plays a critical and crucial role in industries. Thermal energy generated through primary energy sources, which are located outside of manufacturing systems, is usually transferred to manufacturing systems for efficient manufacturing operations [04]. Heat transfer mechanisms are disciplines of thermal engineering that conclude the generation, application, or use of thermal energy, alteration, and exchange from one form to another between several physical systems. Thermal energy transmission methods are classified into thermal conduction, convection, radiation, and thermal energy through phase changes as latent heat [02]. Engineering processes also consider the transmission of mass of different product species, either under cold or in the hot state, to achieve thermal energy transformation. However, these mechanisms have special and distinct characteristics.

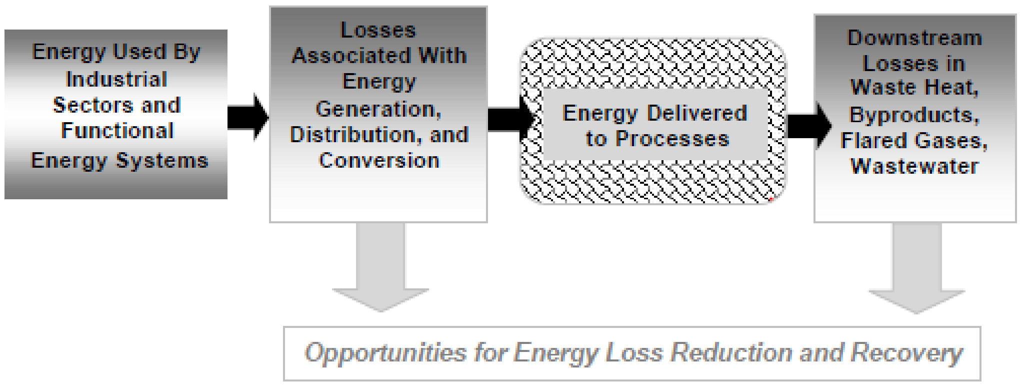


Figure 1.2: Energy use, loss and opportunities [52].

Thermal energy conduction, also called heat diffusion, is a direct microscopic exchange of the kinetic energy of the particles through their boundaries between two separate systems. When objects are at different temperatures from another body or its environment, the thermal energy flows from that object to another or its surroundings to become an equivalent temperature known as the thermal equilibrium position. As acknowledged in the second law of thermodynamics, spontaneous thermal energy transfer always occurs from a high-temperature region to another lower-temperature region [04].

Thermal energy convection occurs during the bulk flow of gas or liquid (fluid). During the bulk flow of the fluid, it carries thermal energy along with the matters in the fluid flow. The flow of gas or liquid may be continued by an external force or occasionally in gravitational fields. Furthermore, during the absorption of thermal energy, it causes the expansion of the particle and hence buoyancy forces affect its particle movement. The thermal expansion and particle transfer processes above are often termed "natural convection". During particle movements due to natural convection, it becomes a partial conduction process because the hot and cool particles touch together at the top layers after movement. Another way of convection heat transfer is "forced convection", which is made fluid flow through a pump, blower fan, or any other mechanism [04].

Thermal energy radiation takes place through a vacuum and any transparent medium, such as a solid, liquid, or gas. Radiation from thermal energy, transfers energy as electromagnetic waves, which are governed by the second law of thermodynamics.

During consideration of industrial applications, which use heating processes, process controls play a major role and a critical factor because a poorly optimized industrial process control system may quickly become more expensive in terms of loss of thermal energy to its surroundings and translating it into financial loss [02]. Thermal energy losses in the environment can inhibit the transference of hot fluids through the distribution piping, potentially damaging the quality of material within the pipelines.

In addition, it puts the safety of process workers at risk and the increase in the floor creates an unconditioned working environment, causing a reduction in the efficiency and effectiveness. To address the above issues, manufacturing systems have designed in the optimum temperature ranges and further managed by applying insulation methods. It uses conventional insulation materials, such as glass wool and rock wool materials, to achieve such objectives [04].

1.1.1 Heat transformation

Thermal energy can be defined as the 'total energy of all molecules within the object considered', and heat can be defined as the 'mount of energy transferred from one body to another due to the difference in the temperature of the objects'. Heat is a form of energy in transit and is also not a property of an object or a system. However, thermal energy transfer as heat occurs at the molecular levels as a result of temperature differences. The second law of thermodynamics gives this direction to thermodynamic processes [05].

As a result of the higher temperature of an object beyond its surrounding area, it continuously emits thermal energy to its surroundings. Because of the thermal energy dissipation, the temperature of the object decreases. When the temperature is equal to its surroundings, it stops the heat flow and is called 'thermal equilibrium' with its surroundings [04]. Therefore, the amount of thermal energy of a particular object or system will decide the temperature of the system (physical property) and the temperature difference between the object and its surroundings working as a thermal energy transfer driving force. Due to this temperature difference, thermal energy flows from a high-temperature point to a lower temperature point as thermal energy until the driving force gets zero or until the temperature becomes equal with its surrounding, which systems become thermal equilibrium with each other.

1.1.2 Thermal insulation

Manufacturing systems use a considerable amount of energy for the production process, and a significant percentage of the total energy used is thermal. Due to this, the machine parts, molds, tanks and distribution lines used for manufacturing operations always exist at temperatures higher than those surrounding [05]. According to the second law of thermodynamics, there is a temperature difference between such objects and their surroundings, the thermal energy flows from high to lower. Therefore, hot objects used for manufacturing operations under ambient environmental conditions continuously emit thermal energy to the surroundings during the process. Due to this phenomenon, thermal energy losses to the surroundings of manufacturing operations are generating more critical problems [05].

Thermal insulations are widely used to minimize thermal energy losses in manufacturing operations and in new high-rise buildings. The primary purpose of these thermal insulations is to decrease the entire heat transfer coefficient (K) by introducing lower thermal conductive materials. Thermal insulations, which are found in industrial operations and high-rise buildings, have become an essential requirement to achieve thermal comfort for operators and occupants. Thermal insulation can reduce unwanted thermal energy loss and excessive heat gain to its energy source [05]. Therefore, thermal insulation further reduces the thermal energy generation requirements of heating and cooling systems. However, there are no materials that can completely stop energy loss but can only be minimized up to some considerable level based on the performance of the insulation materials. These traditional insulation materials consist of lower thermal-conductive substrates and their physical geometry such as double panel windows. The insulation properties of these materials originated mainly from the insulation properties of air. It is a simple function that has a larger number of gas-filled air pockets to avoid bulk convection. In addition, the geometry of this material also plays a critical role, and, by increasing the width of the gas layer through the separate panels, it decreases the thermal conductivity of the final insulation layer. Glass wools are the most common traditional insulation material, used most frequently in the manufacturing process, generally available as pipe covers and insulation slabs [06].

1.1.3 Thermal energy loss issues

Thermal energy has become the most important energy type used for manufacturing operations. Of the total energy used for production operations, more than 60% is thermal energy. Therefore, the thermal energy applications and consumption points are spreading through the production plants, and the thermal energy is closer to the members who are in the operations. Because thermal energy-related operations are more common in production systems, they cannot completely stop thermal energy losses to their surroundings. Therefore, it generates more critical challengers in the production plant as follows [05, 06].

- ❖ Thermal energy dissipation increases the energy consumption of the operations and causes financial loss to the organization. Therefore, it increases the energy cost of the final product or service manufactured within organizations.

- ❖ It causes an energy crisis within the organization due to the loss of a significant percentage of thermal energy to its surroundings, and limits critical manufacturing operations.

- Affect the quality of the final products due to the inability to reach the critical temperature limitations or set points in the operations due to the loss of a significant portion of thermal energy to its surroundings.

- Limit the production process and plant expansions due to the limitation of existing energy sources through the loss of a significant portion as unusable.

- Unwanted and unnecessary heating surfaces cause severe burns and are harmful to operators in the manufacturing process. Due to the loss of thermal energy to the surrounding, the temperature of process environment has increased and it generates an uncomfortable working environment and reduce the efficiency of the human being in operations [06].

Due to the above difficulties in the manufacturing systems, the hot surfaces that are heated by thermal energy are always insulated with traditional insulation methods such as rock wool or glass wool.

1.2 Problem formulation

Manufacturing systems, which are using thermal energy for their operations, insulate their hot surfaces with traditional insulation materials such as glass wool or rock wool. However, due to operational requirements, physical shapes of the hot surfaces, properties of the hot surface materials, and some organizational rules and regulations, it is not possible to use traditional insulation materials for thermal insulation. Because of that, there are hot, naked surfaces in the manufacturing systems that continuously emit thermal energy to their surroundings. Figure 1.6 represents actual uninsulated hot surfaces and their temperature distribution or temperature profile in manufacturing organizations such as furnace doors, boiler back end doors, steam distribution lines, mold parts, etc which are actual thermal images from the PDM department of selected tire manufacturing organizations.

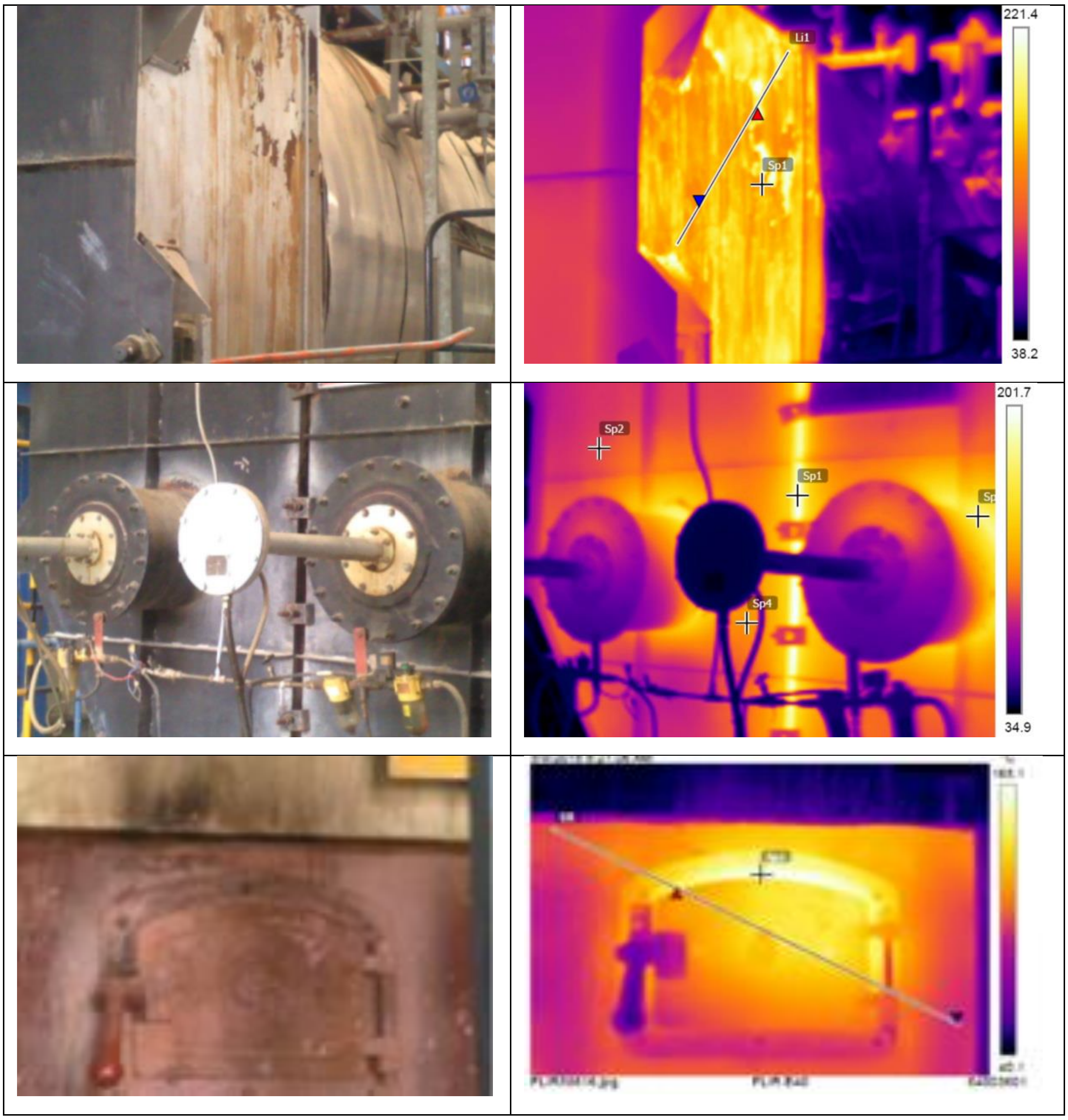


Figure 1.3: Uninsulated hot surfaces in the manufacturing organizations.
Source: PDM department thermal image gallery.

Furthermore, there is a finding that glass wool materials are carcinogenic, and more organizations' safety divisions are not further approving such materials for insulation purposes. Because of that, in modern manufacturing systems, there is a growing trend for alternative materials for thermal insulation, and thermal insulation coatings have become one of them to prevent thermal energy losses to the surroundings. Therefore, there is an opportunity to develop a new thermal insulation coating, to prevent thermal energy losses from the hot surfaces in the manufacturing systems to their surroundings. According to the identified research gap, there is a requirement and opportunity for 'Thermal insulation coating manufacturing process & performance evaluations' to minimize energy dissipation from hot surfaces to its surroundings.

1.3 Problem identification

Manufacturing systems and their operations are using a significant amount of thermal energy for manufacturing processes. Because of that, the machines and the system consist of several hot surfaces at temperatures higher than the atmosphere. As a result of the temperature difference between the components of the system and their surroundings, thermal energy is continuously emitting from high-temperature components to the surroundings at a lower temperature. This loss of thermal energy generates critical issues within manufacturing systems. It becomes directly a major component that affects the cost of the final product, which is manufactured in an organization as energy cost. Furthermore, it creates an uncomfortable environment within the manufacturing environment by reducing the efficiency of the process operators and lowering the efficiency of the production system.

The energy crisis that is developing all over the world always forces them to minimize their energy consumption by improving the energy efficiency of their manufacturing systems to achieve a lower manufacturing cost of their final product to compete in the modern competitive market. During energy conservation and improvement of the efficiency of manufacturing systems, thermal insulation plays the most important role because a higher percentage of the energy used for manufacturing systems is using as thermal energy. With these influences, traditional insulation methods, which are covered with glass wool or rock wool are the most common insulation methods that can be seen in most manufacturing systems.

However, due to some special cases in some manufacturing operations like uneven shapes of the hot surfaces, safety and environmental rules and regulations of the organizations (glass wools have been identified as a carcinogenic material, and many organizations have prohibited the use of the materials, and further in the food processing organization do not allow these insulation materials) it does not insulate the hot surfaces with the traditional insulation materials. However, with the existing trend in energy management and energy conservation, most organizations are focused on thermal insulation coatings. Several types of research have been conducted on the development and performance evaluation of thermal insulation coatings, but only a few have been conducted for commercial use. Therefore, there is an opportunity and a research gap in the development and evaluation of thermal insulation coatings. Therefore the research is conducted on the “Manufacturing process & performance evaluation of thermal insulation coatings” to minimize the thermal energy loss from hot surfaces to its surroundings.

1.4 Aim

This research aims to evaluate the performance of thermal insulation coatings to reduce thermal energy loss to their surroundings and to analyze the insulation properties against the compositions of the substrate raw materials.

1.5 Objectives

During the research, by selecting a lower thermal conductive filler material, develop a new thermal insulation coating. Then, check the thermal insulation properties of the final coating samples against their substrate compositions. Therefore, the following objectives are addressed during the research.

- To identify significant coating manufacturing ingredients, that affect the thermal conductivity of the final coating layer.

- To determine the insulation characteristics of the coating layer with respect to the ingredients.

- To develop a numerical relationship between the (temperature gradient) thermal conductivity (K) of the final insulation coating layer and its ingredient quantities.

1.6 Summary

This chapter describes the application of thermal energy in the manufacturing process and the challenges to the use of traditional insulation methods and the issues arising from thermal energy dissipation in manufacturing systems. In addition, it has identified an opportunity for new requirements for thermal insulation applications to prevent heat dissipation into its surroundings. The development of thermal insulation coatings has been identified as a new opportunity in thermal process applications to prevent heat dissipation from hot surfaces. Therefore, the Introduction discusses the coating manufacturing process and the influence of its ingredients or substrate on the final properties (thermal conductivity). Then formulate the research problem, aim, and objectives of the thesis. Then define the research methodology and how to formulate the decisions as to the outcome of the research, and then review the literature under the Prisma approach. Then the experiments will be formulated, conducted, and the test results will be reported. The conclusion is included in the discussion chapter, together with the improvement points and future opportunities.

2.0 LITERATURE REVIEW

The literature review collects relevant literature through research articles through research journals, database searches, and other related internet resources. A systematic selection process (through the PRISMA approach) selects the most appropriate literature that is necessary for the study. The following figure represents the 'Prisma approach' which is used to examine the literature collected from research journals and other databases.

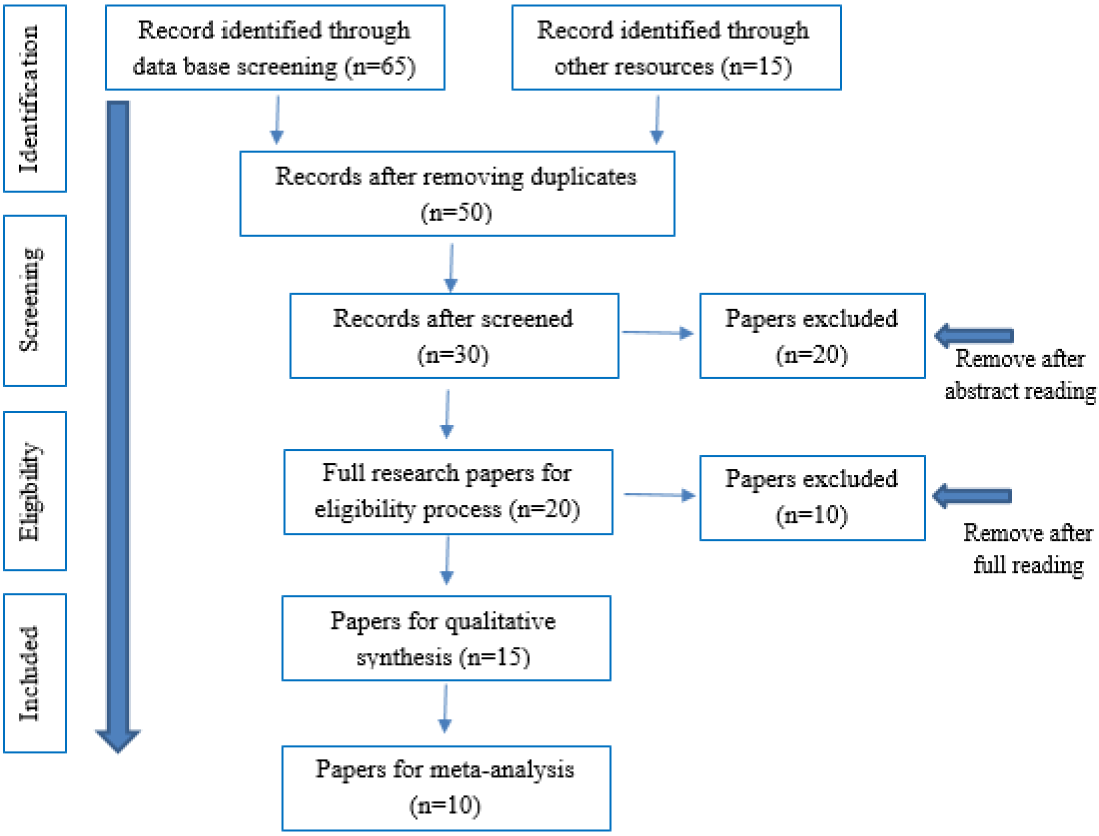


Figure 2.1: Prisma approach in the literature review [53].

2.1 Paint manufacturing

Paint can be introduced as a fluid material in general, and it is applied on selected surfaces as a thin film. After the drying and curing process, it forms a solid, colorful, protective, decorative, and purposeful thin coating film. Averill Paint Cooperation, in New York in 1868, filled the first patent for the paint invention. The first commercial production was started in 1880 by Sherwin-Williams Cooperation, including varnishes, dyes, and enamels [06]. The development of new artificially formulated synthetic coating resins and the industrial manufacturing of an extensive range of solvents for industrial paint and the discovery of unique pigments are the main reasons that have significantly affected the latest developments in the coating industry. However, in the modern world, there is an opportunity for the development of environmentally friendly coating applications such as low solvent coatings, solvent-free powder coatings, extraordinary low energy curable coatings, as well as water-based paint products beyond the traditional organic solvent-based coatings [06].

However, during the last two decades, increasing interest and developing trends in water-borne paints can be observed, and the increasing interest and growing trend on water-borne paints are due to extremely tough rules and regulations on the emission of high volatile organic compounds (VOCs) during industrial coating manufacturing operations. Water-based paint used for general purposes in day-to-day household applications is mainly a mixture of polymeric synthetic latex binders (resin) with pigments and various additives [07]. Binders are an indispensable character in paint, and they act as final coating film binding agent, having a maximum impact on the coating properties such as abrasion resistance, gloss, toughness, and flexibility. Acrylic polymers induced from acrylic acid as well as copolymers, which are widely used as polymeric coating binders in the manufacturing of water-based coating due to their brilliant flexible film-forming properties at lower temperatures, superior film elasticity, and good stability against UV radiation [07].

Pigment or fillers are a discontinuous phase, and they provide additional or enhanced properties to the final coating film. Titanium dioxide (TiO_2) is the most commonly used pigment type in the industrial coating manufacturing process, while providing a white color and a space-holding effect as a filler. Today, this traditional pigment, titanium dioxide (TiO_2) is replaced with calcium carbonate ($CaCO_3$) in the development of new coatings because calcium carbonate ($CaCO_3$) comprises more than 4.5% of the earth's crust and is also spread throughout the biosphere. After the $CaCO_3$ quarrying, milling is the next essential processing step in the manufacture of high-quality natural products, generally known as ground calcium carbonate (GCC). Ground calcium carbonate is a new trend in the coating industry to reduce the manufacturing cost of water-based coating without significant damage to the quality and properties of the film [08].

Pigment volume concentration (PVC) is an essential and significant parameter in the paint formulation. The pigment volume concentration is the percentage of pigment in the coating mixture concerning the total solid weight or volume without solvent.

$$\text{Pigment Volume Concentration (PVC)} = \frac{\text{Pigment Volume}}{(\text{Pigment + Polymer Volume})}$$

When considering a particular coating mixture, the pigment volume concentration has defined a maximum value, which is known as critical pigment volume concentration (CPVC), expressed as just enough binder volume to wet the entire pigment particles. Beyond this transition limit of a pigment–binder volume, the paint film properties deviate quickly to the worse [09]. In coating manufacturing CPVC is the most important and priority requirement because a perfect coating film can only be obtained below the CPVC. The value of CPVC is greatly dependent on the change of coating properties such as the mechanical properties of the coating film, the permeability of water and gas, etc. [10]. The advantages of critical pigment volume concentration of a particular pigment binder system may depend on several characteristics of the final coating mixture. The most critical parameter is the application of water or solvent-based binders. According to the general polymer particulate morphology, in the water-borne coating binders, the CPVC value for the polymeric latex binders will be lower than that of the solvent-borne binders. The larger particle size, as well as the surface functionalities and bonding abilities of the particle, also further affect the CPVC of the polymeric binder coating mixture [10].

2.2 Thermal insulation coatings

Most manufacturing systems such as petroleum processing plants, chemical manufacturing systems, and tire and glove manufacturing plants use a significant amount of thermal energy as the primary energy aspect of operations. Hence, prevention of heat dissipation has become a top priority requirement because it creates critical financial and safety issues. Due to that, there is a growing trend in the use of thermal insulation coatings in such industries.

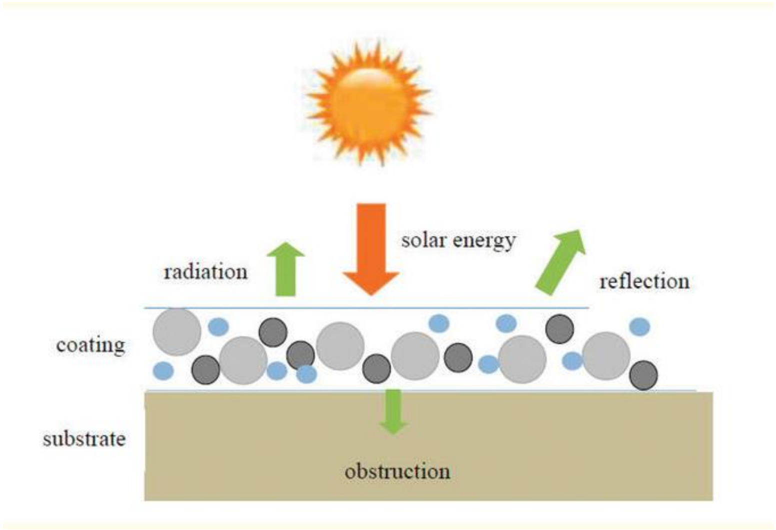


Figure 2.2: Thermal insulation methods applied in insulation coatings [54].

Thermal insulation coating can be classified into three main subgroups based on its thermal insulation mechanism as follows [10].

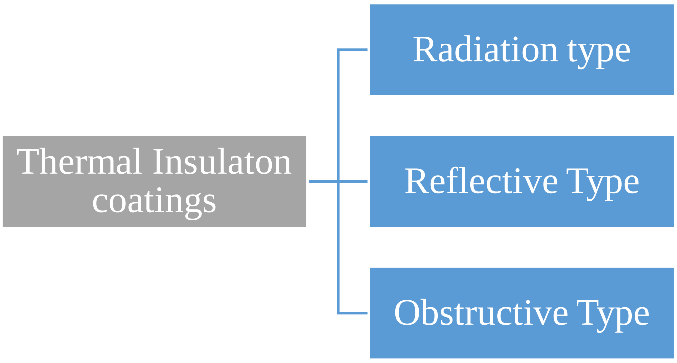


Figure 2.3: Thermal insulation coating types.

2.2.1 Radiation type insulation coating

When exposed to thermal energy, any objects begin to radiate thermal energy simultaneously. If the object absorbs more thermal energy from the outside, its temperature increases and similarly releases more radiation into the external environment, leading to a decrease in the temperature of the object. During this process, the radiation phenomenon occurs as invisible infrared light with longer wavelengths as a result of molecular-atomic energy interchanges

[09]. Theoretically, thermal energy radiation takes place in any object; while any object radiates thermal energy into its external environment, the exterior environment radiates at the same time back to the object. Although two phenomena occur at the same time, when the temperature is higher than its external surroundings, the resulting radiation takes place in its exterior environment [11].

Radiative-type thermal energy insulation paints are an exceptional invention through the addition of special coating fillers that can transform more absorbed thermal energy into its intermolecular vibration or its kinetic energy. Hence, absorbed thermal energy, as an atomic kinetic energy, can ultimately be transmitted to its exterior space through thermal radiation. Through this phenomenon, the substrate, which is covered by a thermal radiation coating film, can radiate more thermal energy to its exterior space, absorbing energy from the outside. Because of that, the radiative thermal insulation coating films, which are applied on particular substrates, can thermally insulate the object up to a considerable level. This insulation mechanism, which is found in radiative coatings, minimizes energy transfer through the insulation coating [11].

According to the above discussion, radiative coating fillers exhibit brilliant thermal radiation capabilities when the object's outer atmospheres work as a 'window'. Due to this, to achieve higher emissivity for applied coating film, fillers should have robust absorption properties in the range of 8 μm to 13 μm. Studies on radiative-type insulation coatings show that the addition of a small amount of far-infrared coating fillers into the insulation coating mixture can significantly improve the infrared thermal radiation capability of the final insulation coating film. Typically, Fe_2O_3, FeO, Cr_2O_3, ZrO_2, MnO_2, TiO_2, SiO2 and Al_2O_3 are far-infrared coating fillers with higher emissivity, which are traditionally used for radiative-type coating manufacturing [11].

2.2.2 Reflective type insulation coating

Reflective-type thermal insulation coatings can reflect more percentage of thermal energy that comes to their surface rather than resist or absorption. It can evaluate reflective efficiency through the Total Solar Reflectance (TSR), which is defined as the ratio of solar energy reflected by the surface to exposed quantity of thermal energy [12]. If the TSR value is 75%, that 75% of total energy from solar radiation is reflected by the coated substrate and only 25%

absorbs. Theoretically, any coating material can reflect solar radiation during the selection of fillers while manufacturing the reflective insulation coating. It should be concentrated in the 200 to 2500 nm range because solar radiation is mainly focused in the 200 to 2500 nm range (400 to 720 for the visible spectrum and 720 to 2500 for the early infrared spectrum) [12]. When the coating has higher reflectivity, it improves the thermal insulation ability of the final coating film when compared to traditional general thermal insulation resources.

Usually, the color, which is visible in the final insulation coatings, will decide the color of its filler material, and the color determines the reflection and absorption properties of the final coating layer. White coating fillers usually reflect the entire visible light spectrum from 400 nm to 720 nm, and black coating fillers return only 650 to 700 nm, while TSR for white is 95% and 5% for black. For example, Titanium dioxide is usually used as a white filler to reflect 95% of solar radiation, and carbon black reflects only 4% of the solar radiation. Concerning the other color wavelength, the reflection and absorption properties also vary between the white and black from 4% to 95% of TSR [13].

According to the above discussion, the addition of reflective coating filler during the manufacture of insulation coatings is an effective method to improve the thermal insulation properties. On such occasions, the selection of higher-thoughtful fillers in both visual and near-infrared spectrums is the most effective filler selection to achieve higher efficiency in thermal insulation. In this effective filler selection, metal oxide, fly ash globules, hollow glass beads, as well as ceramic beads with greater thermal reflectivity are commonly used as functional fillers for reflective-type insulation coating.

In the reflective type insulation paints, the reflective property is mainly induced by the surface properties of the final film, and the thickness of the coating film does not influence the thermal reflective properties or its performance. Generally, reflective thermal insulation coatings have an optimal film thickness for better insulation properties. When the film thickness is lower than its optimal thickness, the insulation properties will be lower than its expected efficiency because a significant amount of energy will penetrate the film due to its thinner properties. In thermal insulation, functional fillers can directly reflect thermal energy to their first medium without absorption and radiation [13]. Therefore, reflective thermal insulation indicates higher performance beyond the other coating type.

2.2.3 Obstructive type thermal insulation coatings

Obstructive type thermal insulation paints have a passive thermal insulation method that applies to heat transfer through particular fillers. However, the coating system always consists of its primary substrate of resin, pigment, additives, filler, and solvent. In obstructive thermal insulation, coating affects the thermal conductivity of the filler material and other substrates, which are essential to decide the heat resistance performance of the coating film. All substrates must be rich in thermal insulation properties; thermal insulation fractional filler should have excellent insulation performance to achieve a quality insulation coating layer [14]. Generally, the thermal conductivity of fractional filters is less than 0.06 W/mK which is relatively poor compared to air (0.26 W/mK). Most thermal insulation fractional fillers are ingredients consisting of hollow structures such as asbestos fibers, Inorganic Silicate based material, sepiolite, closed-laid perlite, etc. In the obstructive thermal insulation coating, closely packed hollow particles form a layer of air that acts as a thermal barrier to the thermal energy flow and blocks the "thermal bridge" [14].

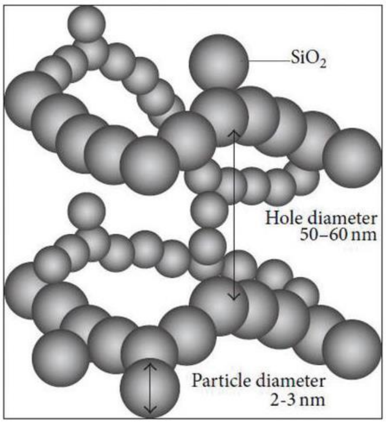


Figure 2.4: Thermal bridge in obstructive type coatings [54].

In practical applications, the thickness of the coating film always affects the performance of the insulation effect and the thicker film gives the best performance, which can vary from 5 µm to 20 µm. Although a thicker film is required to achieve better performance, several problems are encountered, such as weaker impact resistance, higher moisture absorption, evident dry shrinkage, etc. The condition will be relatively diverse if the hollow structure of the filler material is close to the open glass bide, ceramic bids, hollow porous silica ceramics, etc. Research shows that coating film with a hollow structure indicates excellent thermal energy insulation properties when the sizes are close to the nanoscale. Because of this hollow structure, it minimizes the thermal convection and thermal conduction properties of molecular vibration because bulk density and hole diameters are appropriately smaller [15].

2.3 Chemical composition

When considering the composition of basic paints, four main components can be identified as pigment, binder, solvent, and additives. However, the coating types in some manufacturing processes may not include some of these coating components. For example, varnishes do not contain pigment and the solid coating does not contain any solvents. Additionally, different additives are incorporated during their coating manufacturing process to enhance the dispersion properties of other coating components and facilitate application, which is the use of the coating and the preservation of the coating mixture [19].

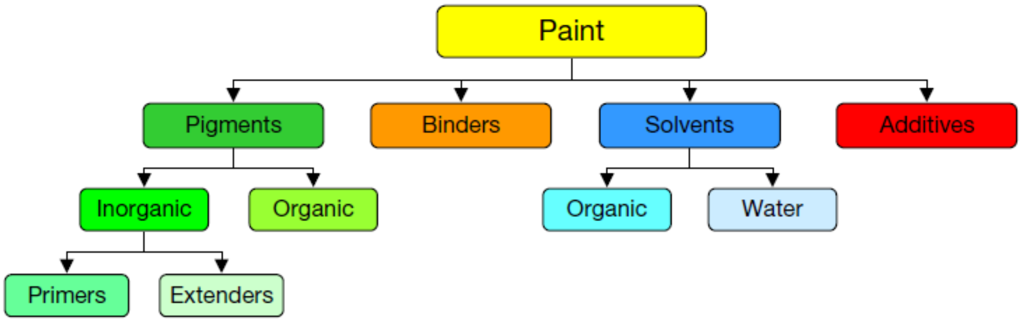


Figure 2.5: Main components of coating formulations [55].

2.3.1 Pigments

Pigments are non-dissolve fine solid particles dispersed in the binder and actual coloring material or substance of any coating. Generally, a pigment consists of bodies in contradiction to its visual color, which usually providing the special coating's color, gloss, and opacity of the special coating. Pigments are usually minerals of organic origin that are naturally or artificially modified. Pigments are insoluble particles used to import physical and chemical properties to the coating of wet or dry film. Generally, pigment can be classified as follows [19].

- ❖ Organic pigments
- ❖ Inorganic pigments
- ❖ Functional pigments
- ❖ Special effect pigments

In addition to thermal insulation coating pigments, a collection of extenders is used in the insulation coating formulation process. Extenders consist of lower hiding power, and those products are more economical than the traditional coating pigment; these products are used as fillers, and they decide the final properties of the coating, such as improving the hardener behavior of the coating matrix and it minimizes the coat of the final product. The most common extenders are silicates, borates, carbonates, phosphorus, sulfates, and Alumina [20].

2.3.2 Binders

Binders are the second essential component in the manufacturing of industrial coatings, which holds the pigment particle together with all other ingredients through their binding properties. With all elements within the layer, the binder forms a coating with protective properties [20]. When the correct ratio in the manufacturing coatings, significant properties, such as appearance and durability can be enhanced and maintained. Binders can also be further recognized as resins. By mixing with the coating solvent, they are generally referred to as the vehicle and catalyst of the coating layer. Binder is the only component that must be evenly mixed throughout the coating mixture, and everything meshes with each other. Generally, there are two ways to mix binders during coating manufacturing. They can be liquefied in the solution or transferred as a dispersion of small elements into the mixture. [21].

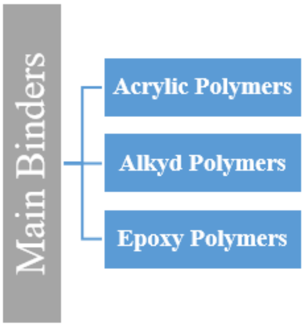


Figure 2.6: Main coating binder types.

Depending on the application of the coating and the expected properties of the paints, one particular resin is selected during coating manufacturing. Property variations can be summarized as follows as per the different binders that are used for coating manufacturing. Table 2.1 represents the properties of resin used to manufacture coatings.

Table 2.1: Properties of Resin.

Resin	Description	Properties of the resin
Acrylic polymers	Made up of acrylic acid and consists of a cross-linked system enriched by the use of additives [22].	Adapt quickly to environmental changes Pigments are more dispensable Resistance to heat, chemicals, and solvents Stable in adverse weather condition
Alkyd polymers	Esters-based polymers, which originate from the fatty acid or oil base.	Flexibility Hardens in the air. Easy in applications
Epoxy polymers	It consists of the active prepolymers, which include epoxide clusters. Consist of cross-link system and co-reactance. It is the most widely used binder or resin in coating applications [22].	Strongest mechanical assets Long self-life High heat & chemical resistance Lower shrinkage rate during hardening Strong adhesion properties Resistance to impact

2.3.3 Solvents

In coatings, solvents dissolve or disperse all the components (Pigments, Resin & additives) used for coating formulation, and it makes coatings eventual consistency for the application. Once coatings are applied, the solvents evaporate remaining a homogeneous phase of the resin, figment with other additives to make a paint film [22]. Therefore, the main task of the solvent is to act as a liquefying agent for coatings to allow easy application. These liquefying agents generally take from the water or other organic or inorganic solvents and according to the solvent source, the coatings are classified as ‘water-based’ or “solvent-based”. Due to strict rules and regulations on the discharge of volatile organic compounds in the coating industry, there is a growing trend in water-based coatings in the present context [22].

2.3.4 Water-based coatings

The coatings, which use water as their solvent, can be defined as water-borne or water-based coatings or paints. More regulations on volatile organic compounds (VOC) and research outcomes on carcinogenic properties of some common organic and inorganic coating solvents create a recurring trend in water-borne coatings. Water-based coatings make up more than 75% of household applications with fewer odors [22].

When working in a confined space with poor ventilation conditions, the solvent vapors generated through the evaporation of solvent-base coating applications can be uncomfortable for the workers or hazardous to their health. For this season, many projects such as fuel storage tanks, underground tunnels and storage cyclones use water-based coatings to reduce the concentration of flammable vapors within the confined space, and it is an essential OSHAS requirement in confined space safety measures [23]. The environmental impact is another common influence that is caused by the introduction of water-based coatings to reduce the emission of significant amounts of volatile compounds or VOCs. Most national governments regulate volatile organic compounds by limiting the amount of emission allowed at a particular time span.

2.3.5 Solvent-based coatings

Generally, solvent-based coatings are liquefying agents that evaporate through a chemical reaction with atmospheric oxygen. Hence, moving air streams in the surrounding atmosphere will help the solvent-based coatings speed up the curing process. The main advantage of these coatings over water-based coatings is lower susceptibility to environmental factors such as weather conditions, temperature, and air humidity during the coating cure phase [24]. Water-based coatings present a significant challenge during the surface preparation phase of the coating application. Water is a critical component in the corrosion phenomenon, and in industrial coating applications, water will contact the metal surfaces coating, getting curing. Because of that, spot rusting can begin to occur during the application of water-based coatings. Therefore, water base coatings must be formulated so that all water drains out of the coating film before corrosion occurs. Here is the main consideration in solvent-borne coatings [24].

2.3.6 Additives

Additives are lower-level ingredients that provide additional specific properties to the coatings such as mildew, abrasion resistance, deforming properties, and good flowing and leveling properties. Beyond the above properties, some layers can work as antifungal and algae resistance more durable, and rapid drying because coating manufacturers add different additives in the coating manufacturing process. Additives are unique components used in the coating manufacturing process and in small quantities to increase additional characteristics and qualities [24].

Table 2.2: Additives & their application.

Stage of Use	Expected Outcomes
Coating Production	Dispersing & Wetting additives Antistatic & Degassing additives [25].
Packing Stability	Rheological modifiers & anti-settling additives pH control Moisture Scavengers Preservatives & biocides
Application	Rheological modifiers to sag control and brush ability Form control Active surface modifiers to overcome film defects
Film Formation	Catalysts & photo-initiators Driers

2.4 Manufacturing of water-based coatings

Water-borne paints such as blends are generally prepared in two steps. In the preliminary step, the coating mill base prepared by dispersing the coating pigments and selected dispersing agents in the distilled water. Then in the second phase, the pre-pared mill base mixing with a selected binder or resin (Latex) at pH 9, and then the final coating mixture was obtained [26].

Initially, all ingredients need to be weighed according to the final batch size and the decided pigment volume concentration of the blend. In the first step of obtaining the mill base, additives used as dispersion agent is mixed with distilled water (Approximately 50 ml) and agitated using a high-speed stirrer under lower shear at 350 RPM for 15 minutes. Then the pigments are slowly added to the mixture and stirrer speed is increased up to 1300 RPM. After the addition of all pigments, the final mixture needs to stir at the same speed for another 30 minutes [27].

After that, in the second phase, the initially obtained mill base mix with preselected and weighted particular resin at pH 9 to receive the final paint mixture under the 1300 RPM stirrer speed. After adding all the resin or binder, the mixture needs to stir for another 30 minutes under same RPM. Then the final mix is stored at 25 ^{0}C – 30 ^{0}C at 50% relative humidity for 24 hours prior to use without stirring [27].

2.5 Measuring of coating thickness

The thickness is an important property that plays a significant role when considering the quality and insulation properties of a coating film. The measurement of coating thickness can be done with different instruments via different technologies. The issue is determining the best measurement method for a given coating thickness measurement depending on the coating type, substrate material, coating thickness range, etc. There are two main coating thickness measuring technologies to measure the thickness of the film, which is applied on the particular substrate [28].

2.5.1 Wet film thickness

Wet film thickness (WFT) is a measurement of the thickness of the applied paint coating before it is dries. WFT is measured with the WFT gauge (Figure 2.8) and provides quick, inexpensive, and easy results immediately after application. They can be used in a wide range, from thin coil coating to thick protective coatings for virtually any substrate. The WFT is measured by the applicators just after the application of the coating before the significant solvent evaporates for the correct thickness achievements. Multiple readings should be taken throughout the application process to ensure that the WFT is consistent on all areas of the coated surface. Therefore, WFT gauges are used by applicators rather than by inspectors [23]. The thickness is an important property that plays an important role when considering the quality and insulation properties of a coating film.

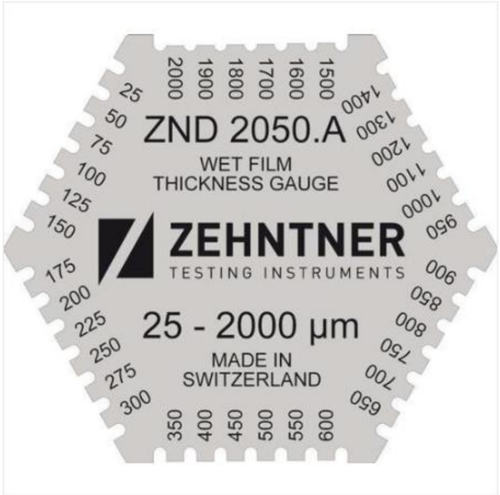


Figure 2.7: Wet film thickness gauge [56].

2.5.2 Dry film thickness

Dry film thickness (DFT) measuring gauges are used using different measuring technologies such as magnetic, eddy current, and ultrasonic measurement using non-destructive methods. Among the above technologies, magnetic film thickness measuring gauges are most commonly used to measure the non-magnetic coating on metal substrates. Magnetic meters use two principles, magnetic pull-off force or electromagnetic induction capacity, during film thickness measurement [28].

Magnetic pull-off thickness gauges contain a permanent magnet, a calibrated coil spring, and a graduated linear scale. The attraction between the permanent magnet and painted steel pulls two components together, and the coating between the two components will disturb the pull-off magnetic force. When the thickness of the coating increases, the full off energy reduces, and the thinner layer has a stronger magnetic attraction [29].

The magnetic induction method determines the thickness of the non-magnetic film over ferrous substrates and magnetic film thickness over non-metal substrates. The thickness gauge probe is placed on the part perpendicularly to the coated surface, which is needed to measure and then measure the linear distance between the probe tip and the ferrous base substrate.

There are two coils known as primary and secondary, and the primary coils inside the probe generate an oscillating magnetic field. When the probe is placed on the coating substrate, which is required to measure the thickness, the magnetic flux density of this field is varying as per the coating thickness. The magnetic inductance change is measured through the secondary coil and sent to the microprocessor to calculate the thickness of the coating [29].

Eddy-current coating thickness measuring gauges will determine the coating thickness of nonconductive coatings on conductive substrates or conductive layers on non-conductive substrates. It is similar to the induction method and consists of the same probe types. One coil has been connected to the high-frequency oscillator to generate a high-frequency field. Eddy currents are induced on the conductive substrate when the area is brought near the metallic substrate. The impedance change of the probe coil analysis and converted to the coating thickness [29].

Figure 2.8: Dry film thickness gauge [57].

The ultrasonic thickness gauge consists of an ultrasonic transducer probe, which generates pulses and sends them to the measured object through the coating film. The vibration from the probe reaches the substrate interface, returns again to probe and it analysis, and calculates the coating thickness.

2.6 Measuring surface temperature

Surface temperature can be measured using different measurement methods and technologies. Of these, thermal imaging is the most common method used to monitor surface temperature. Every object with a body temperature above absolute zero (0 Kelvin= -273.16 ^{0}C) radiates infrared radiation. The human eyes cannot sense these IR waves because they are in the blind region at these wavelengths. In a thermal imaging camera, the detector is sensitive to infrared radiation, and on the radiation intensity of IR radiation it determines the surface temperature of the object and further makes the image on its display visible to the human eye. This process refers to thermal imaging or thermography [30].

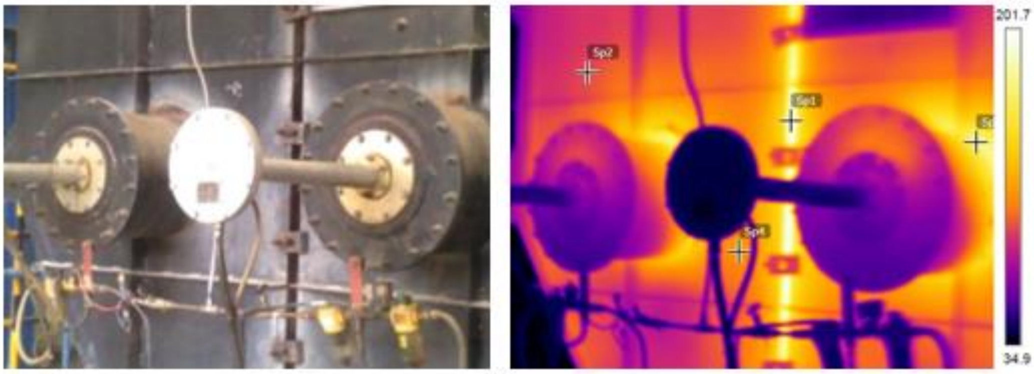


Figure 2.9: Thermal imaging of the hot surface.

Source: PDM department, Camso Loadstar, Tire manufacturing organization.

2.7 Factors affecting thermal insulation properties of coatings

The thermal insulation capabilities or properties of a coating can be developed through three main parameters, such as radiation, block, and reflectance. All three properties induce mainly in a particular coating through an alternation of the filler and the pigmenting material types, which are used in the manufacturing of coating. The most important coating properties of a thermal insulation paints are the thermo-physical properties, which are thermal conductivity, thermal expansion coefficient, and abrasion resistance, which are decided by the microstructure of the coating [41]. In a radiative-type insulation coating, radiation properties of the final coating layer are developed by adding radiative-type coating fillers, which can convert absorbed energy into molecular vibration. Then, the kinetic energy of the molecular vibrations can eventually be transmitted to the external surface in the form of thermal radiation. Fe_2O_3, MnO_2, Al_2O_3, Cr_2O_3 and La_2O_3 are the general thermal radiation functional fillers, which are used for radiative type thermal insulation coatings [42].

The thermal insulation properties of reflective-type thermal insulation coatings are induced through the reflect more thermal energy rather than absorption and it is expressed through Total Solar Reflectance (TSR), which is the mean, the ratio of reflection against exposed amount. These coating fillers give the exact color to the coating with greater reflectivity and reflect more thermal energy into the first medium without absorbing. Metal oxide, hollow glass bids, ceramic bids and fly ash bids are generally used as reflective-type functional fillers, and CoAl blue and MnSbTi brown are the most effective reflective-type functional fillers, which are used to enhance thermal insulation properties [43].

Table 2.3: Properties of the final coating layer and effecting parameters.

Coating properties	**Parameters affecting coating properties**
Thermal Conductivity	The thermal conductivity of the final coating layer depends on the insulation properties of the raw materials (pigment and fillers) which are used during the manufacturing of the coating. Generally, materials with hollow microspheres such as ceramic hollow spheres, inorganic silicate-based functional fillers, asbestos fibers, expanded perlite, sepiolite, and closed-cell perlite materials indicate the highest insulation properties in thermal insulation coating manufacturing. In the final coating layer, the tightly packed hollow spheres form a layer of gas that acts as a barrier to the heat while blocking the thermal bridge [44, 45].
Thermal Expansion Coefficient	The thermal insulation coefficient of the final coating layer applied on the particular substrate depends on its raw material properties and for proper bonding to the substrate, it should be close to the thermal coefficient of the painted substrate [46].

Reflectivity	The coating surface can reflect thermal energy rather than absorption or resistance. Typically, the reflectivity measure via TSR. The higher reflectivity of the coating means better thermal insulation properties. The first principle for selecting reflective filler for thermal insulation coating is higher reflectivity. According to the color of the coating fillers, the reflectivity will vary between white and black from maximum to minimum. Generally, metal oxide, fly ash beads, ceramic beads, and hollow glass beads with relatively higher reflectivity are selected as functional fillers during reflective coating manufacturing and not only the color but also the structure of the coating fillers decided the thermal insulation performance of the final coating film [47, 48, 49].
Emissivity	When the thermal energy is exposed to the coated substrate, the special fillers convert the absorbed energy into molecular vibration and transmit it back to the first medium as thermal radiation. When the emissivity coefficient (ε) is higher, more energy converts to molecular vibration and transmits back. Studies have shown that adding a small amount of far-infrared coating fillers to the coating mixture can greatly improve the infrared radiation capability of the film. Usually, La_2O_3, Cr_2O_3, SiO_2, and TiO_2 with high emissivity are regularly used as functional thermal radiation fillers [49].
Abrasion Resistance	The resistance of coating refers to the ability to resist wear due to corrosion or impact, permitting comprehensive protection to the coated substrate. Abrasion resistance is not a unique property of a coating and is correlated to other thermo-physical parameters as well. It is functionally associated with elastic properties and cohesive forces. The different factors that govern the abrasion resistance of the coating are toughness, hardness, elasticity, flexibility, cohesiveness, tensile strength, and pigment volume concentration [42, 48].

Opacity / Hiding power	Opacity is the term most commonly applied to explain the ability of paint to obliterate the color variance of a substrate. The opacity of a paint film depends on the ability of the pigment to both scatter & absorb light. The scattering of light is dependent on the pigment's refractive index; the higher the refractive index, the greater the light scattering and hence the better the opacity. Titanium dioxide, the general white pigment used in coatings absorbs a very small amount of light with a relatively higher refractive index and, for this reason, it is most commonly practiced in coatings to immerse excellent opacity [43, 50].
Density	The most common property of pigments, which are used in the manufacturing process.
Film formation ability	The ability of the binder to bind all materials in the coating mixture together.

The details shown in the above table clearly illustrate that the thermal insulation properties of coatings are immersing through the three main parameters as obstruction, reflectivity, and radiation. All three of the above parameters induce a particular coating through the selection of pigments and relevant fillers. Therefore, material selection in coating manufacturing is deciding the properties of the final coating layer and type of insulation coating as obstructive, reflection, and radiative types. During the manufacturing of an obstructive type thermal insulation coating, the pigment and filler material should have enough thermal insulation properties or lower thermal conductivity. In the same way as the resin should be strong enough to withstand higher temperatures that are applied on a particular hot surface. So, during the manufacture of thermal insulation coatings, it should initially be selected according to the final coating properties and insulation method as obstructive, radiative and reflective [48, 50].

2.8 Material selection for coating manufacturing

Thermal insulation coatings should have higher insulation performance when applied to a substrate. For that, the coating material should have lower thermal conductivity for better performance as an obstructive type insulation coating. Therefore, during selection of all substrates for the coating manufacturing, it should be a top priority to the insulation properties of the final coating rather than the color of the coating [31].

2.8.1 Pigment

Although pigment gives a particular color to the coating and it is obtained from the final coating layer after curing, in an obstructive-type insulation coating thermal conductivity is the most important property beyond the color. Therefore, during the selection of the pigment for the obstructive thermal insulation coating, it is vital to consider the thermal conductivity (K). Therefore, selecting lower thermal conductive materials, such as ceramic hollow bids, silica bids, or clay, is the ability to enhance the best insulation properties in the final coating layer. Therefore, in this experiment, a fine clay base powder (tile body power) was selected as the pigment because it is rich with lower thermal insulation properties and does not consider the color of the coating [32].

2.8.2 Tile body powder

Ceramic tiles are made of primary clay, silica sand, and water. Initially, a mixture of body power and other additives is pressed into the molds to form rectangular tiles. The wet tiles are baked in a kiln and the moisture is reduced to lower levels. In the Sri Lankan tile manufacturing process, the primary mixture of the body powder generally consists of feldspar. The powder substrate of the tile manufacturing consists of the following general formula.

Table 2.4: Weight percentage in tile body powder.

Component	**Weight %**
Ball Clay	28.0
Kaolin	10.0
Feldspar	57.0
Talc	1.0
Silica Sand	3.0

Source – Selected tile manufacturer of Sri Lanka.

2.8.3 Binder or resin

Binders are the binding agent in any coating, and they bind the pigment particles together to form the final paint film. Thus, the binder is the film-forming agent in any industrial coating. Generally, binders are too thick and, depending on the application and type of properties, become thin through the particular thinner. Binders impart properties such as flexibility, gloss, durability, heat, and toughness to the coating. Coating binders include synthetic and natural resins such as acrylics, vinyl acetate, alkyds, vinyl-acrylics, polyurethanes, polyesters, epoxy, or oils [33].

Further binders can be classified as thermoplastic or thermosetting according to the film formation mechanism. Thermoplastics involve simple evaporation of solvents to drying and a combination of pigment particles to form a thin coating film without any chemical reaction. The thermosetting mechanism involves chemical reactions among the binder or polymers to form the final coating film [34].

Paint binders are categorized into three major groups, acrylic, alkyd, and epoxy. Acrylic binders are made up of a cross-linked system enriched by the dispersing agents. The acrylic binders are resistant to chemicals, heat, solvents, and adverse weather conditions. Acrylics are generally formed by polymerization of acrylic acid monomers, and polyvinyl acetate (CH_2=CH-COO-CH_3) is the most performance binder in water-bone paints. In the water-borne coating industry, polyvinyl acetate (PVA) is the most performing binder and is widely used for latex paint to form an adherent coating film. PVA is generally included in acrylic acids [35].

Vinyl acetate is generally acetate esters of alcohol. Because vinyl alcohols are volatile when other acetaldehyde, the production of vinyl acetate has become more complex than that for the synthesis of other typical acetate esters. The primary industrial method of making vinyl acetate involves the reaction between ethylene and acetic acid with oxygen gas in the presence of a palladium catalyst [36]. The chemical reaction can be illustrated as follows.

$$2\,C_2H_4 + 2\,CH_3CO_2H + O_2 \longrightarrow 2\,CH_3CO_2CHCH_2 + 2\,H_2O$$

Then, the vinyl acetate undergoes free radical polymerization and generates the polyvinyl acetate as follows.

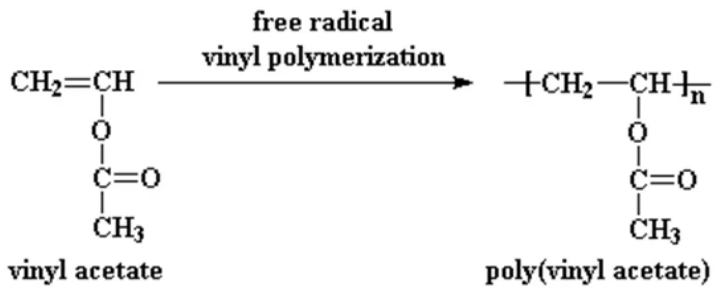


Figure 2.10: Vinyl acetate polymerization [58].

Polyvinyl acetate (PVA) is the most commonly used adhesive for water-borne coatings, pastes, and industrial glues. PVA offers remarkable gap-filling capabilities, and it may also be used as a resinous component of latex paint. PVA is used to laminate metal foils because of its thermosetting binding properties. Therefore, during the experiment, PVA was selected as the binder of the insulation coating manufacturing process [37].

2.8.4 Additives

Generally, additives are components that deliver specific properties to coatings, such as gloss, abrasion resistance, mildew resistance, and proper flowing and leveling properties on the substrate. Furthermore, during the manufacturing process, through the addition of special additives, the manufacturers added antifungal, more durable, algae resistance, and rapid drying properties to the coating. The additives are something special components added in small quantities to impart the most important additional properties and qualities to the coating layer. The use of the right additives in the right order and in the right proportion will improve the expected attributes as much as possible in the final coating layer [38].

The dispersing agent or dispersing additives in the coating industry properly spread the pigment, filler, and resin throughout the coating mixture, and without a dispersion agent, the coating mixture did not remain evenly. The demand for the pigment dispersing agent has also increased in modern coating binders. A wide range of dispersing agents have been developed over time. Current dispersing agent developments focus on more environmentally friendly, VOC-free, and solid products. Polymerization technology has developed highly effective copolymer additives with superior performance, such as sodium polyacrylate [39]. NaPA, also known as water lock, is generally, a sodium salt of acrylic acid with the chemical formula of [CH_2-CH-(CO_2Na) −]n, which is known as a super absorbent polymer (SAP) [39]. This super-absorbed polymer consists of the ability to absorb 100 to 1000 times its mass of water. NaPA is an anionic electrolyte with a negative charge carboxylic group in its main chain, which is developed through acrylates. The sodium in NaPA gives the super-water-absorbent property and separates into anionic electrolytes when dissolved in the water. This SAP consists of good mechanical properties such as mechanical stability, heat resistance, and vigorous hydration. So considering the above abilities, NaPA was selected as the dispersion agent to manufacture the heat insulation coating in this experiment [40].

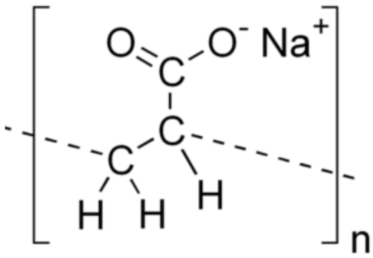


Figure 2.11: Sodium Polyacrylates (NaPA) [59].

3.0 METHODOLOGY

The research methodology systematically explains how its approach to achieving the research objectives. The initial step presents the identification of the research problem or identification of the research gap. The chapter discusses the actual examples of thermal energy dissipation in manufacturing organizations, and the issues related to thermal energy dissipation to its surroundings, as well as financial and other social issues that challenge manufacturing operations. Then it indicates the real examples in the production sections for uninsulated hot surfaces and why they are unable to use traditional insulation solicitations like rock wool or glass wool. Then define the aim and objective of the research.

The third chapter further describes the research methodology and how it reaches the research objectives. At the beginning, it gives a systematic approach to the identification of research problems, as well as an understanding of coating manufacturing and the significance of its ingredients. In addition, it describes the properties of the thermal insulation coating and how to improve its insulation properties.

Then, the ingredients for new coating formulation to decrease the thermal conductivity, such as pigments, binder, and additives, were identified. In the next step, define the independent factors that are used as two factors to determine the final thermal conductivity (K). Then the weight of the coating formulation ingredients was decided and manufacture the paint samples accordingly. Then conduct the performance evaluation and make decisions based on the result of the experiment.

Table 3.1: Research methodology

Research Methodology steps	
Step 01	Study of the coating manufacturing process ❖ Study the steps of the coating manufacturing process and identify the significance in each process steps of the manufacturing operation.
Step 02	Identify raw materials for paint manufacturing ❖ Identify the main ingredients for coating manufacturing such as pigment, binder, and additives to decrease the thermal conductivity of the final coating. ❖ Formulate the composition of the ingredients of each component considering the significantly lower thermal conductivity of the final coating layer.
Step 03	Design two-factor factorial design ❖ Identify the main two factors for the factorial design experiment. ❖ Design the experiments as per the requirement.
Step 04	Coating sample formulation ❖ Manufacturing of insulation coating samples as per the experiment design
Step 05	Painting of metal pieces & thickness measurements ❖ After 24 hr maturity time, paint 60 mm of pre-prepared metal pieces with prepared coating samples and remain 40 mm as is for reference. ❖ Check (WFT) during painting for even coating thickness and measure DFT after drying separately.
Step 06	Temperature gradient measuring and thermal conductivity calculation ❖ Painted metal pieces attached on a hot surface (on the boiler backend plate), remain for one hour for temperature stabilization and measure the temperature gradient against the insulation vs. non-insulation. ❖ Calculate the temperature gradient of the coating sample.
Step 07	Data Analysis ❖ Record the thermal conductivity of the samples against the two factors ❖ Conduct an ANOVA and Effect Model representation.
Step 08	Discussion ❖ Make a decision based on the experiment results.

3.1 Factorial design

Many experiments and research involve studying of the influences two or more factors. In such cases, factorial design is the most common well-organized research method, which can be followed for effective decision-making. Through a factorial design, the influences of all the factors in every complete trial and all replicates of combinations of all levels are deeply investigated. For example, consider factor A with the 'a'number of levels and factor B with the 'b'number of levels and then each replicates contain all the numbers of axb of treatment combinations. When all factors of research are pre-arranged within a relevant factorial design, they usually are expressed as crossed factors. The influence of a particular factor has defined as the variations of response or feedback, which occurs when changing the output of other selected factors. This is generally called the main effect of the selected factor because it refers to the primary interest factor in the considered research.

The following simple research will be considered as an example. The example research will consist of two factors, which are factor 'A' and factor 'B' as well as both factors consist of two levels which are known as 'Low' and 'High', denoted as A+, A- and B+, B-. The values of each factor at each level are as follows [04].

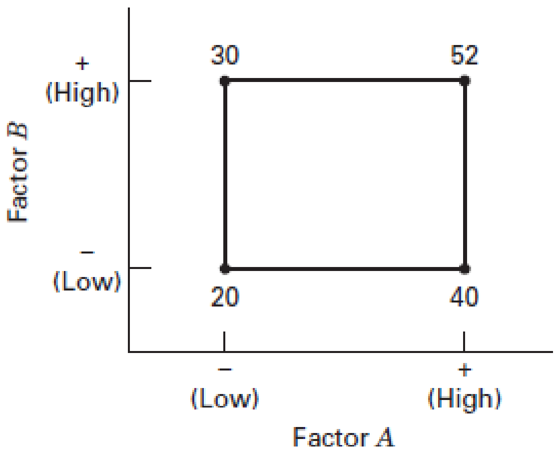


Figure 3.1: Example of a two-factor factorial design with two levels of each factor [60].

In factorial design experiments, each factor can be defined as a parameter as the 'main effect', which is expressed as the variance between the average response of factor 'A' at the higher level and the average response of factor ‘A’ at the lower level. For the above example, it can be indicated numerically as follows.

The main effect of factor ‘A’,

= [(40+52)/2] – [(20+30)/2]

= 21

The main effect of factor ‘B’,

= [(30+52)/2] – [(20+40)/2]

= 11

In some special experiments, it can be identified that there are changes in the response of a particular factor while other experiment factors. In such a case, it is expressed as there is an interaction among the testing factors. So, the two-factor factorial design experiments with interactions can be graphically illustrated below [04].

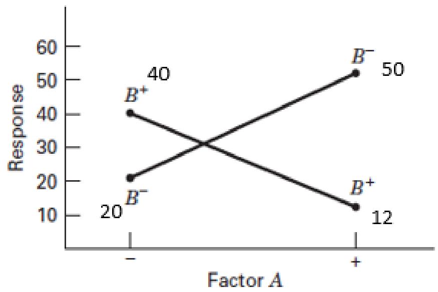


Figure 3.2: Two-factor factorial design with interaction [60].

In such cases, the effect of one factor (factor A) will depend on the value of the other factor (factor B). Therefore, during the expression of a particular factor (factor A), it is essential to consider the impact of the other factor (factor B). Therefore, the impact of a particular factor (factor A) at different levels of other experiment factors (factor B+ or B-) can be considered as follows.

Factor ‘A’ at the lower level of Factor ‘B’ or ‘B-’

= (50 - 20)

= 30

Factor ‘A’ at the higher level of Factor ‘B’ or “B^+”

= (12 – 40)

= -28

Because the response of factor ‘A’ depends on the selected level of factor ‘B’, it is expressed as there is an interaction between factor “A” and factor ‘B’. Magnitude of the interaction effect of factors described as the average of factor ‘A’ between the lower level of factor ‘B’ (B-) and high level of factor “B” (B+) as follows.

The interaction effect of Factor “A”,

= [(Factor A @ B^+) - (Factor A @ B^-)]/2

= [(-28) - (+30)] / 2

= -29

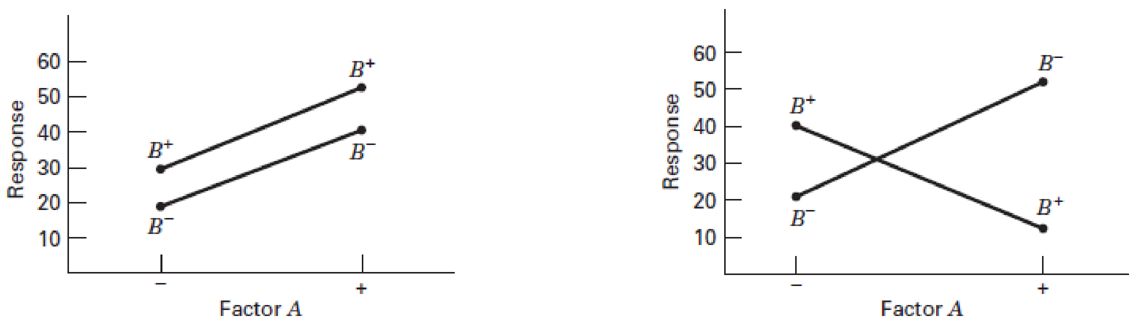


Figure 3.3: Factorial research examples without & with interaction [60].

There is an alternative way to illustrate the model of a two-factor factorial design interaction. Suppose that all design factors (factor “A” & factor ‘B’) are quantitative like Height, Length, Temperature, Current, Pressure, Weight, etc. Therefore, the **‘Regression Model’** demonstration of two-factor factorial research design can be used for such an experiment and can be normally written as follows.

$$y = \beta_0 + \ \beta_1 x_1 \ + \beta_2 x_2 + \beta_{12} x_1 x_2 + \ \varepsilon \tag{1}$$

y – Response

β – Parameters (values must be determined)

X_1 – Variables (factor A)

X_2 – Variables (factor B)

ε – Random Error

The β is the parameter that is needed to determine, and for the effect model, β values can be determined as flows. β_1 and β_2 are values corresponding to one-half of the main effect of factor ‘A’ and factor ‘B’ respectively. β_{12} is the half-value of interaction effect of the factor ‘A’ and factor ‘B’. The β_0 is defined as the average of all four responses to the factor ‘A’ & ‘B’.

For the above example, the main effect of factor A = 21, the main effect of factor B = 11, and the interaction effect of factor AB = 1. The four responses related to factor ‘A’ & ‘B’ are 20, 40, 30, and 52. So the β can be determined as follows.

β_1 = (main effect of A) / 2 = (21)/2 = 10.5

β_2 = (Main effect of B) / 2 = (11)/2 = 5.5

β_{12} = (Interaction of A & B)/ 2 = (1)/2 = 0.5

β_0 = (average of all four response) = (20+30+40+52)/4 = 35.5

$$y = \ \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \varepsilon \tag{2}$$

$$y = 35.5 + 10.5x_1 + 5.5x_2 + 0.5x_1 x_2$$

3.2 Research design

Thermal energy has been identified as one of the main sources of energy input used for most manufacturing operations. Therefore, hot surfaces are the most common picture within manufacturing systems. However, thermal energy is always released into the manufacturing environment through convection and thermal radiation, creating several critical issues within the manufacturing systems. Prevention of thermal dissipation has become a top priority requirement in manufacturing systems since a few decades back; to enhance energy efficiency and develop a comfortable safe working environment within the manufacturing systems, organizations have implemented different initiatives. Due to the above priorities, traditional insulation methods were applied in most manufacturing plants to minimize thermal radiation. But due to organizational regulations and difficulties in the application of traditional insulation methods, there are uninsulated hot surfaces in manufacturing systems. So, there is an opportunity for other insulation alternatives to minimize the thermal radiation from naked hot surfaces in the manufacturing systems. Therefore, the main objective of this study has become 'Manufacturing process and performance evaluation of thermal insulation coating'.

The insulation properties depend on the thermal conductivity (K) of the final coating. Therefore, thermal conductivity should be minimized as much as possible during the development of a new thermal insulation coating. The properties of an insulation coating or paint may determine the ingredients used for the coating formulation. Hence during the research, it was decided to use lower thermal conductive materials as filler (or pigment) of the coating, which most influenced the properties of the final coating layer. Change the percentage of filler material, changing the concentration of pigment volume (PVC) and additive percentage as variables, and check the thermal conductivity of each composition to develop optimal insulation properties of the coating. Therefore, the research may consider the pigment volume concentration and additive percentage as two factors and conduct the research as a two-factor factorial design at three level with two replicates to validate the results, and its designs as a three-level two factor (3^2) factorial design.

3.3 Factors identification for factorial design

The experiment continues as a two-factor factorial design with three levels, and the deciding factors are selected as the main factors, which are a test during the investigation.

Factor 01

Pigment volume concentration (PVC) of the coating. The pigment volume concentration has become a significant parameter in the coating formulation, which is expressed as the ratio of total pigment weight to the total solids weight in the coating mixture (pigment + resin) during paint formulation. It is tested at 30%, 40%, and 50% during the experiment.

Factor 02

The percentage of additives or dispersing agents in weight concerning the total sample weight without solvent, which is used for coating sample manufacturing. Normally, it is used below 2%. So it was tested at 0.5%, 1%, and 1.5% percentages during the experiment.

In each testing combination, two replicates are conducted to further verify the final results. The possible combinations and results of each replicate can be recorded in the following table.

Table 3.2: Research testing procedure for both factors of 'PVC' & 'additives percentage'

.

		Factor 'B' (Additives percentage)		
		30%	40%	50%
Factor 'A' (PVC)	30%	X	X	X
		X	X	X
	40%	X	X	X
		X	X	X
	50%	X	X	X
		X	X	X

The data collected from the experiments are analyzed and represented by two-factor factorial design concept (EFFECT MODEL) as follows. Then further analyze the research data with an ANOVA table.

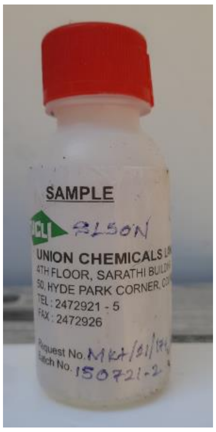
$$y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \epsilon_{ijk} \quad \begin{cases} i = 1,2, \dots \dots a \\ j = 1,2, \dots \dots b \\ k = 1,2, \dots \dots n \end{cases} \tag{3}$$

3.4 Raw materials selection for coating

The expected final properties of the coating (Temperature Gradient or Thermal Conductivity ‘K’) depend on the materials which are selected for the coating manufacturing. Therefore, on the basis of the lower thermal conductivity priority requirement, the following materials were selected as raw materials for the coating.

Table 3.3: Raw materials selected for the new coating.

Raw materials and properties	**Collected samples**
Pigments (fillers) - In the manufacturing of obstructive-type thermal insulation paints, coating pigments should have lower thermal conductivity properties. Therefore, tile body powder was selected as the pigment and the material was collected from a leading tile manufacturer in Sri Lanka. According to the physical appearance, it is a thin brown powder same as cement powder.	
Resin - resin acts as the bonding agent of coating and during the manufacturing of water-born coating acrylic polymers show maximum bonding properties, adding durability to the final coating film. So polyvinyl acetate (PVA) was selected as the resin and the material was collected from a leading chemical supplier in Sri Lanka. PVA is a white-colored semi-solid fluid just like natural latex	

Additives - In the coating manufacturing process, different additives are used to enhance the different properties and qualities of the final coating mixtures such as thickeners, emulsifiers, dispersants, pigment deformers, leveling agents, photostabilizers, and curing catalysts. These additives enhance the inherent properties of the resin. In this experiment, sodium polyacrylate (NaPA) was selected as the additive as a dispersing agent, and the material was selected from a leading chemical supplier in Sri Lanka.	
Solvent-The water base coating type was selected for the experiment, and distilled water was used as a solvent for the coating manufacturing.	

3.5 Design for data collection

According to the methodology in Chapter 03, two parameters were selected as factors for the two-factor factorial design, such as “pigment volume concentration” and “additives percentage”. The level of each factor was selected as follows, and nine coating samples with different combinations were manufactured for the experiment. Then, two metal pieces were painted from each coating sample, and the temperature gradient (thermal conductivity) was measured through the coating film.

Table 3.4: Selected factors and ratios

Factors	Level 01	Level 02	Level 03
Factor ‘A’ Pigment Volume Concentration (PVC)	30%	40%	50%
Factor ‘B’ Additive Percentage (NaPA)	0.5%	1.0%	1.5%

3.6 Performance evaluation

According to the predefined levels of the selected factors (PVC & additives percentage), calculate the pigment, resin, and additive quantities required for each coating sample. Then the coating samples were prepared according to the coating manufacturing process under the relevant parameters. After the coating maturity period, paint two metal pieces from each sample with a uniform coating thickness. Then following experiment procedure will be conducted to evaluate the performance of each coating sample through data collection, evaluation, and decision making.

- ❖ Prepare identical mild steel plate pieces for application of coating samples and performance evaluation. Cutting and cleaning of 18 Nos of mild steel plates with dimensions 100 mm x 100 mm x 3 mm. (Two metal pieces for one coating sample).

- ❖ Apply one coating sample (mixture) on two preprepared mild steel plate samples while checking WFT for uniform coating thickness (60 mm is painted with the coating sample and 40 mm remains as is without applying a coating for comparison of the temperature variation between insulation to non-insulation).

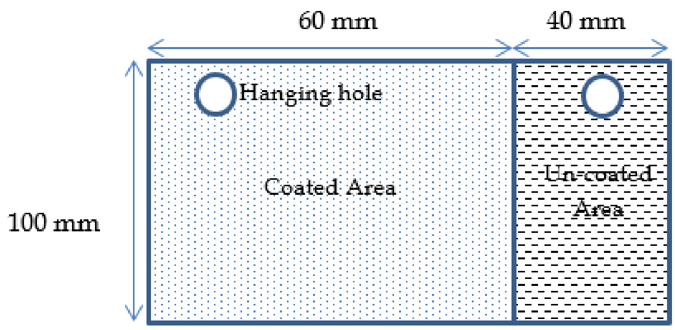


Figure 3.4: Sample mild steel plates coated with the insulation paint

- ❖ After curing and drying of the coating layers, measure the DFT (dry film thickness) of the coating layers, which is marked on each metal plate samples in black color.

- Then the metal plates attached on the hot surface (Boiler back-end exhaust emission chamber surface) through the hanging holes and remains for one hour for temperature stabilization.

- After one hour (after thermal equilibrium), measure the surface temperatures of marked coated and the temperature of the uncoated points as well as back end plate through the thermographic imager and evaluate the temperature variation.

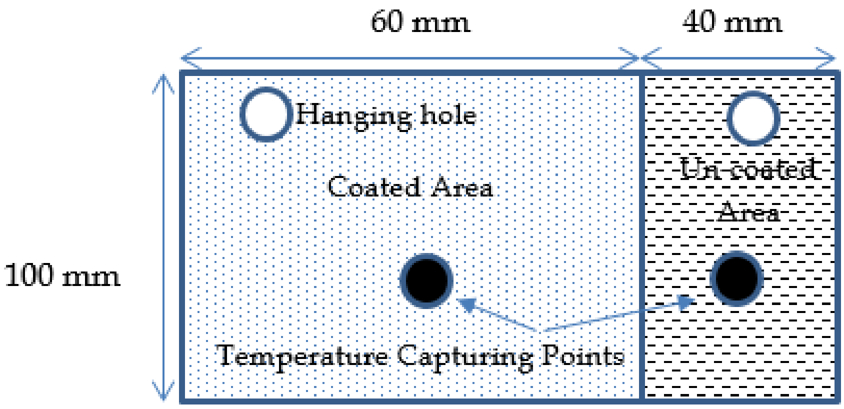


Figure 3.5: Painted plate sample with temperature monitoring points

Then conduct the same procedure for all 18 plate samples and record the results in the following format. After that, evaluate the results by using the effect model of the two-factor factorial design as well as an ANOVA table.

Table 3.5 Experiment result recording format

Test Number	WFT (Wet Film Thickness)	DFT (Dry Film Thickness)	Temperature Gradient	Thermal conductivity
01				
02				

3.7 Paint manufacturing & evaluation

- According to the following equations, initially relevant raw materials were weighted according to the predefined factor values to achieve the required pigment volume concentration (PVC) and additives percentage (Sodium poly acrylates - NaPA). Water is considered as the solvent, and each sample includes 50 ml of distilled water. The raw material weight combinations for the nine coating samples can be summarized as follows, and the table illustrates the weight of each ingredient of each coating sample that is relevant to the nine coating combinations.

$$Pigment\ Volume\ Concentration = {M_{TBP}}\Big/{[M_{TBP} + M_{PVA} + M_{NaPA}]} \quad (4)$$

$$Sodium\ Poly\ Acetate\ (NaPA)\ \% = {M_{NaPA}}\Big/{[M_{TBP} + M_{PVA} + M_{NaPA}]} \quad (5)$$

Table 3.6: Ingredient Weights for Paint Manufacturing

Sample Number	**Experiment Factors**		**Raw Material Weights**			
	Pigment Volume Concentration (PVC) %	Additives Percentage (NaPA) %	Tile body powder Weight (g)	Polyvinyl acetate weight (PVA) (g)	Sodium polyacrylate weight (g) (NaPA)	Distilled Water Weight (g)
Sample 01	30	0.5	60	139	1	50
Sample 02	30	1.0	60	138	2	50
Sample 03	30	1.5	60	137	3	50
Sample 04	40	0.5	80	119	1	50
Sample 05	40	1.0	80	118	2	50
Sample 06	40	1.5	80	117	3	50
Sample 07	50	0.5	100	99	1	50
Sample 08	50	1.0	100	98	2	50
Sample 09	50	1.5	100	97	3	50

- ❖ The mixing process was conducted using an in-house designed small-scale mixing unit operating at three different speeds at 600, 900, and 1200 rpm.

Figure 3.6: internally fabricated mixing unit used for coating mixing

- ❖ Initially, 50g of distilled water was measured and mixed with the additives (NaPA). Then the mixing continued for 15 minutes at 600 rpm.
- ❖ Then the tile body power (pigment) was added to the mixture and mixed at 1200 rpm for 30 minutes to get the mill base coating mixture.
- ❖ Finally, polyvinyl acetate (PVA) was added to the mixture as the binder and mixed for another 30 minutes at 1200 rpm to obtain the final coating mixture.
- ❖ After the 24 hours maturity period, coatings were applied to the pre-prepared metal plates for performance evaluation.

Figure 3.7: Manufactured Paint Samples

- After maturity period of coatings, the preprepared metal pieces (100 mm x 100 mm) were painted (60 mm length was painted and 40 mm length was retained as it is for temperature reference) and measured the DFT.

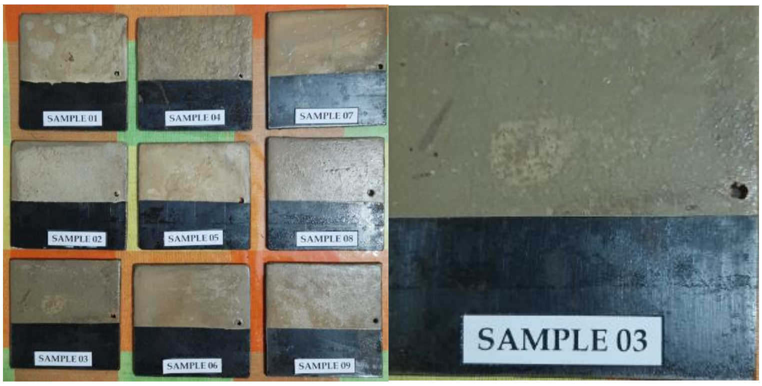


Figure 3.8 Painted Metal Pieces Samples

Figure 3.9: DFT Measuring of Samples

- Then determine the temperature variations against the insulated vs. uninsulated in each coating sample using painted mild steel pieces. Painted metal pieces were attached to the hot surface (boiler back plate) and remain for an hour to stabilize the temperature. Then measure the temperature of the black mark which is on the coated area and the temperature of the uncoated area of the metal pieces and the boilerplate temperature using a thermal imager (Model - FLIR E40 S/N – 64503601, resolution 0.1/1 ^{0}C, calibrate by ITI certificate No. SS 1800827)

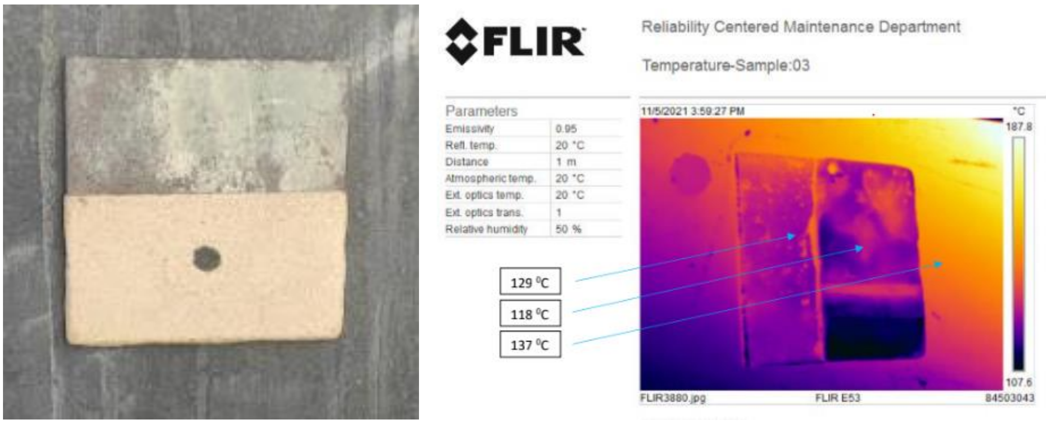


Figure 3.10: Thermographic imaging of coated plates

Figure 3.11: Temperature Measuring of Samples

- ❖ Based on the temperature difference and film thickness, the temperature gradient (thermal conductivity) of each coating sample is calculated and record the results.

4.0 DATA COLLECTION

According to the methodology in Chapter 03, nine coating samples were manufactured according to the predefined raw materials combinations. Then 18 metal pieces were coated with coating samples with two pieces of each sample. After curing, the thickness of the coating was measured on two points highlighted in black color. Then metal pieces were attached to the back-end chamber plate and the following temperatures were recorded.

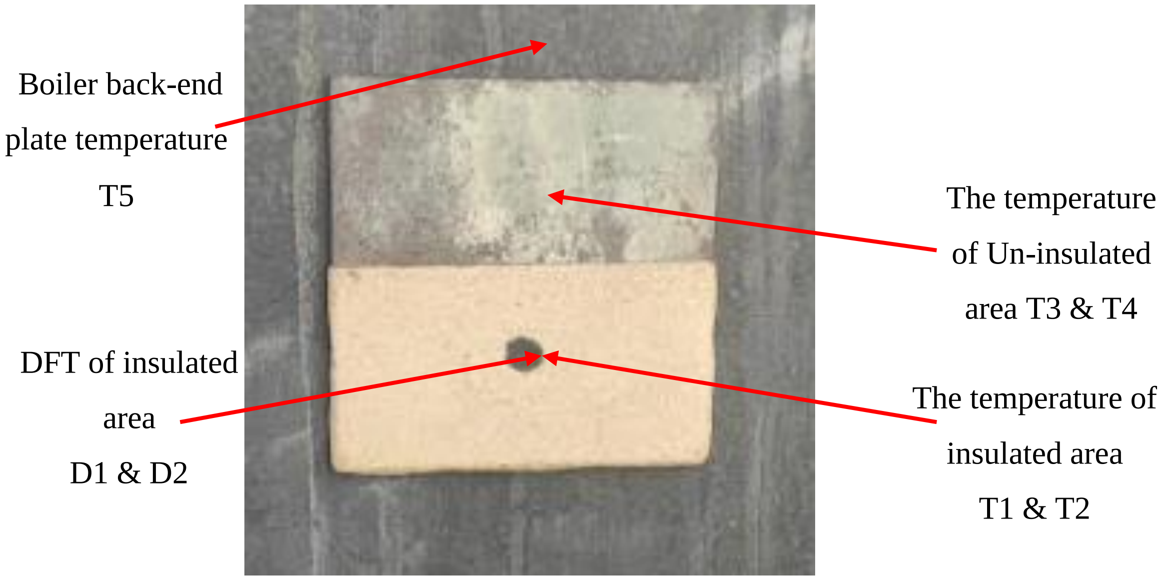


Figure 4.1: Temperature monitoring points of the metal plate during the experiment.

4.1 Experiment data

According to the 09 coating samples, 18 numbers of metal pieces were painted as two metal pieces from each coating sample. The results for the 18 replicates under these nine coating samples are recorded in the following Table 4.1. The temperature measurement points during temperature monitoring are shown in the figure above. Figure 4.1: indicates the measuring points during the temperature monitoring after being attached to the steam boiler back-end plate.

Table 4.1: DFT & Temperature measurements collected in each experiment replicate

Coating Sample Number	Metal Sample Number	DFT Reading 01 (D1)	DFT Reading 02 (D2)	Average DFT (D)	Coating surface temperature. 01	Coating surface temperature. 02	Average coating surface temp. (T)	Metal surface temp. 01 (T3)	Metal surface temp. 02 (T4)	Average metal surface temp. (T_0)	Temperature Difference (T_0-T)	Boiler back-end plate temp. (T5)
Sample 01	1	790	810	800	121.41	121.45	121.43	129.42	129.85	129.64	8.20	137.25
	2	865	855	860	120.87	120.72	120.80	129.64	128.95	129.30	8.50	137.56
Sample 02	3	920	930	925	119.55	119.75	119.65	129.25	129.25	129.25	9.60	138.28
	4	915	905	910	119.98	119.57	119.78	129.64	128.61	129.13	9.35	137.82
Sample 03	5	920	880	900	119.56	118.34	118.95	128.25	128.95	128.60	9.65	136.85
	6	880	900	890	120.04	119.18	119.61	129.20	128.92	129.06	9.45	138.26
Sample 04	7	1040	960	1000	116.85	117.82	117.34	128.52	128.65	128.59	11.25	138.54
	8	1140	960	1050	118.08	118.18	118.13	129.92	129.34	129.63	11.50	137.65
Sample 05	9	960	940	950	117.95	118.35	118.15	129.95	128.85	129.40	11.25	137.95
	10	1020	980	1000	117.39	117.12	117.26	128.95	129.45	129.20	11.95	137.25
Sample 06	11	890	910	900	119.10	117.80	118.45	129.35	129.84	129.60	11.15	137.29
	12	1050	1020	1035	117.70	118.31	118.01	128.86	129.85	129.36	11.35	137.95
Sample 07	13	1120	1080	1100	115.03	115.27	115.15	128.84	129.85	129.35	14.20	138.26
	14	1140	1100	1120	115.13	115.20	115.17	128.68	129.45	129.07	13.90	138.65
Sample 08	15	1030	1020	1025	114.74	114.70	114.72	129.95	128.48	129.22	14.50	137.25
	16	990	1010	1000	114.73	114.89	114.81	128.96	129.25	129.11	14.30	137.63
Sample 09	17	1030	970	1000	114.18	114.71	114.45	128.95	128.94	128.95	14.50	138.92
	18	1080	1020	1050	113.65	114.04	113.85	129.25	128.84	129.05	15.20	137.56

5.0 RESULTS

Through the processing of experimental data collected from the 18 testing replicates, the average thickness of the insulation coating, the temperature difference between the insulated area and the uninsulated area ($T_0 - T$), and the thermal conductivity (K) were calculated and recorded in the flow table.

Table 5.1: Result of the experiment

Pigment Volume Concentration (PVA)	Dispersion percentage (NaPA)	Sample Number	Dry Film Thickness (DFT) µm	Temperature Gradient through coating ^{0}C	Thermal conductivity (K) W/mK
30%	0.5%	Sample 01	800	8.20	0.0771
			860	8.50	0.0781
	1.0%	Sample 02	925	9.60	0.0761
			910	9.35	0.0769
	1.5%	Sample 03	900	9.65	0.0737
			890	9.45	0.0744
40%	0.5%	Sample 04	1000	11.25	0.0702
			1050	11.50	0.0721
	1.0%	Sample 05	950	11.25	0.0667
			1000	11.95	0.0661
	1.5%	Sample 06	900	11.15	0.0638
			1035	11.35	0.0720
50%	0.5%	Sample 07	1100	14.20	0.0612
			1120	13.90	0.0637
	1.0%	Sample 08	1025	14.50	0.0558
			1000	14.30	0.0552
	1.5%	Sample 09	1000	14.50	0.0545
			1050	15.20	0.0546

Although two separate experiments were conducted for each ingredient combination and take the results separately, the average thermal conductivity values of two replicate of the same coating combinations were considered for the final factorial design as follows.

Table 5.2: Results of Factorial Design

		Additives Percentage (NaPA) %		
		0.5	1.0	1.5
Pigment Volume Concentration	30	0.0776	0.0765	0.0741
	40	0.0712	0.0664	0.0679
	50	0.0625	0.0555	0.0546

The experiment has been designed to identify and evaluate the influence of two factors that are caused by the insulation properties of the coating layer. Therefore, the two-factor factorial design experiment methodology was used as an evaluation method, and an effect model is used to develop a numerical relationship between the factors as follows.

5.1 Effect model

There are several methods to represent two-factor factorial design experiments. The effect model is the most common application for the two-factor, three-level experiment and can be illustrated as follows.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \varepsilon \tag{1}$$

y – Response

β – Parameters (Values must be determined)

X_1 – Variables (Factor A)

X_2 – Variables (factor B)

ε - Random Error

The following summarized results, which were relevant to the nine coating sample combinations, were used for the representation of the effect model in the two-factor factorial experiment.

Table 5.3: Experiment results for factorial design

		Additives percentage		
Pigment volume concentration (PVC)		0.5	1.0	1.5
	30	0.0776	0.0765	0.0741
	40	0.0712	0.0664	0.0679
	50	0.0625	0.0555	0.0546

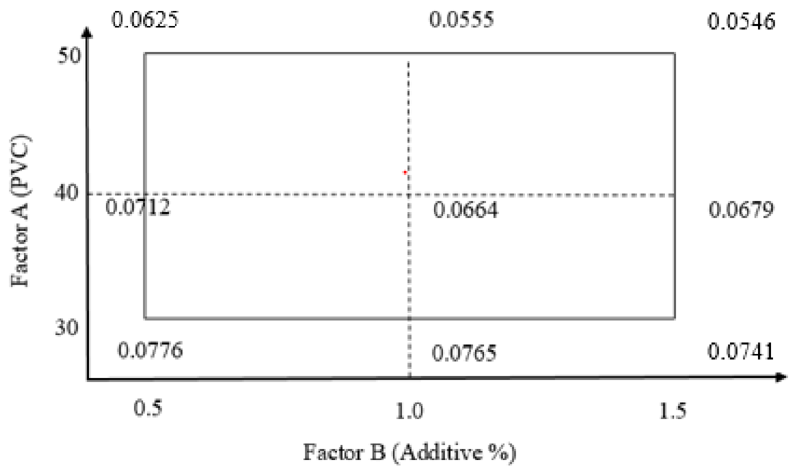


Figure 5.1: Graphical representation of thermal conductivity

β_1 = (main effect of factor A)/2

β_1 = [(0.0625+0.0555+0.0546)/3- (0.0776+0.0765+0.0741)/3]/ 2

β_1 = (0.0575- 0.0761)/2

$\beta_1 = -9.27\text{x } 10^{-3}$

β_2 = (Main effect of factor B) / 2

β_2 = [(0.0741+0.0679+0.0546)/3- (0.0776+0.0712+0.0625)/3]/ 2

β_2 = (0.0655 - 0.0704)/ 2

$\beta_2 = - 2.45 \times 10^{-3}$

β_{12} = {[(Effect of 'A' @ B^+) – (Effect of "A" @ B-)] / 2/2

β_{12} = [((0.0546-0.0741) – (0.0625-0.0776))/2]/2

$\beta_{12} = -1.10 \times 10^{-3}$

β_0 = Average of all responses

β_0 = (0.0776+0.0712+0.0625+0.0765+0.0664+0.0555+0.0741+0.0679+0.0546)/9

$\beta_0 = 0.0674$

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{12} X_1 X_2$$

$$y = 0.0674 - 9.27\times10^{-3} X_1 - 2.45\times10^{-3} X_2 - 1.10\times10^{-3} X_1 X_2$$

5.2 ANOVA

The results of the experiments can be summarized as follows. Then investigate the variation of the results within the group and between the groups which were collected from the 18 replicates of experiments through an ANOVA table.

Table 5.4: Result of the 18 experiments concerning the "pigment volume concentration" and the "additives percentage".

Factor A (PVC)	**Group**	**Factor B (Additives %)**		
		0.50	1.00	1.50
30	G1 (Exp. 1-6)	0.0771	0.0761	0.0737
		0.0781	0.0769	0.0744
40	G2 (Exp. 7-12)	0.0702	0.0667	0.0638
		0.0721	0.0661	0.0720
50	G3 (Exp. 13-18)	0.0612	0.0558	0.0545
		0.0637	0.0552	0.0546

Table 5.5: ANOVA table of the results

ANOVA: Two-Factor With Replication

SUMMARY	0.5	1	1.5	Total
30				
Count	2	2	2	6
Sum	0.155144	0.153007	0.148081	0.456232
Average	0.077572	0.076504	0.07404	0.076039
Variance	4.97E-07	2.95E-07	2.62E-07	2.83E-06
40				
Count	2	2	2	6
Sum	0.142353	0.13282	0.135806	0.410979
Average	0.071176	0.06641	0.067903	0.068497
Variance	1.82E-06	1.81E-07	3.42E-05	1.2E-05
50				
Count	2	2	2	6
Sum	0.124852	0.11109	0.109055	0.344997
Average	0.062426	0.055545	0.054528	0.057499
Variance	3.02E-06	1.8E-07	4.01E-09	1.54E-05
Total				
Count	6	6	6	
Sum	0.422348	0.396917	0.392942	
Average	0.070391	0.066153	0.06549	
Variance	4.73E-05	8.8E-05	8.65E-05	

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Factor A (PVC)	0.001043	2	0.000522	115.953	3.776185	4.256495
Factor B (NaPA %)	8.48E-05	2	4.24E-05	9.432244	0.006185	4.256495
Interaction	2.59E-05	4	6.47E-06	1.43923	0.297725	3.633089
Error	4.05E-05	9	4.5E-06			
Total	0.001194	17				

During the first six experiments (Experiments Nos. 01 to 06), the 'pigment volume concentration' was maintained at 30% and the 'additive percentages' were changed to 0.5%, 1.0%, and 1.5%. During this experiment, the variance within the groups was relatively low.

In the second group of experiments (Experiments Nos 07 to 12), the 'pigment volume concentration' was maintained at 40% and 'additive percentages' were changed to 0.5%, 1.0%, and 1.5%. In this experiment, the variance within the group was relatively low with respect to between the groups.

Finally, when considering the last six experiments (Experiments Nos 13 to 18), the 'pigment volume concentration' was maintained at 50% and 'additive percentages' were maintained at 0.5%, 1.0% and 1.5% and it also indicates relatively lower variance within the group. When considering all the results from the ANOVA table, it indicates a significantly higher variance between the groups. Further, the graphical representation of temperature gradients against the 'Pigment volume concentration' and 'Additives percentage' clearly indicates that there is no significant variation in the temperature gradient in changing of "additives percentage" when "Pigment volume concentration" is a constant value. But during the change in the quantity of pigments, the temperature gradient increases significantly.

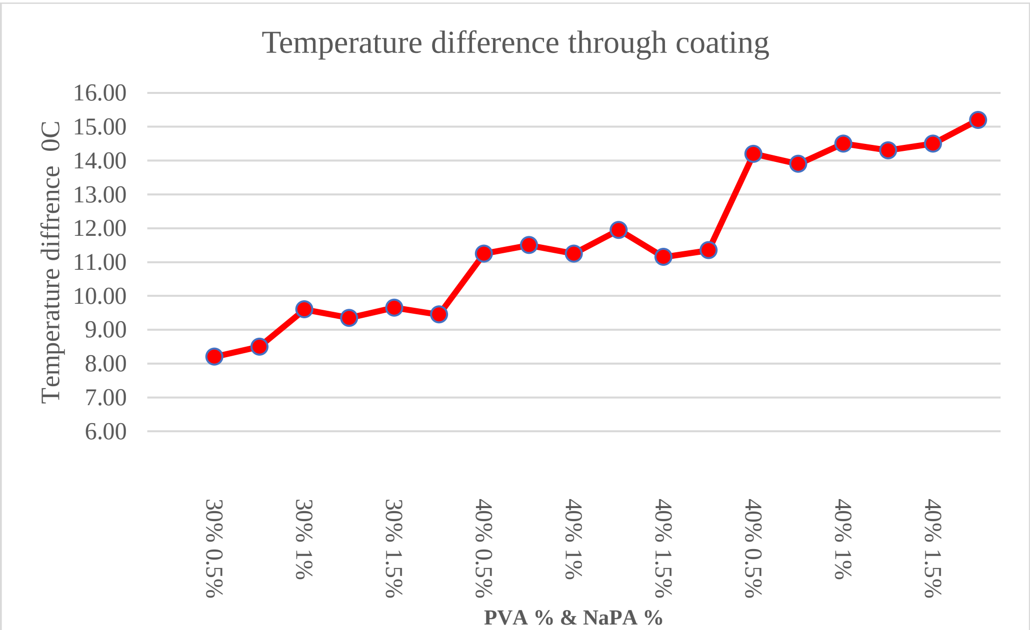


Figure 5.2: Temperature difference Vs PVC% & NaPA %

5.3 Key Findings

❖ According to problem identification and research design, a thermal insulation coating has been manufactured which can be applied up to 130 ^{0}C degrees (maximum surface temperature of the tested metal pieces) and it can reduce the surface temperature from 8 ^{0}C to 15 ^{0}C degrees under 800 µm to 1100 µm coating thickness.

❖ According to the results of the first six coating samples (pigment volume concentration at 30% and additive percentages at 0.5%, 1.0%, and 1.5%) the temperature difference between the insulation and un-insulation areas remains at a constant level although it changes the additive percentages. However, when the pigment volume concentration changes from 30% to 40%, it indicates a significant temperature difference between insulation and un-insulation sections of the coated metal pieces. Figure 6-1 illustrates the variation in temperature gradient & thermal conductivity (K) against the two independent variables of 'pigment volume concentration' and 'additives percentage'.

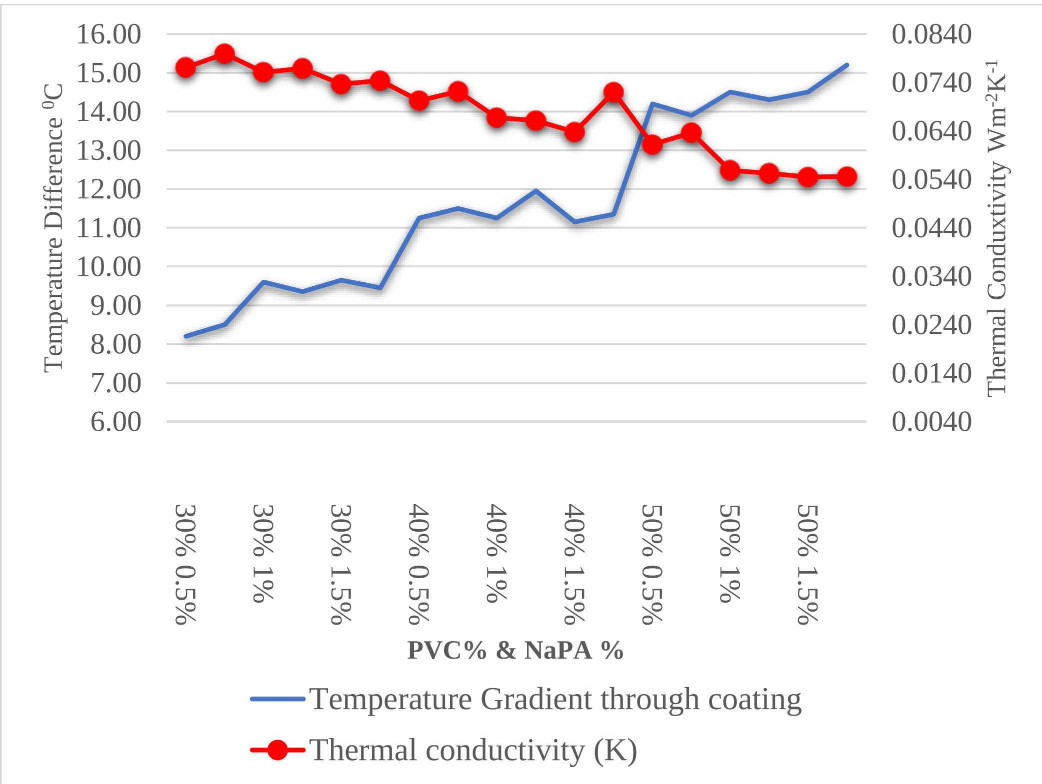


Figure 5.3: Temperature difference & thermal conductivity against PVC% & NaPA%.

- Using a two-factor factorial design effect model, a relationship between the thermal conductivity, PVC, and NaPA weight percentages has developed, and the numerical relationship is as follows.

$$y = 0.0674 - 9.27x10^{-3}X_1 - 2.45x10^{-3}X_2 - 1.10x10^{-3}X_1X_2$$

- According to the ANOVA table, the P values for factor A (pigment volume concentration) are 3.78 and factor B (additives percentage) is 0.01, and interaction between the factor A and factor B is 0.30. When considering 0.05 as the limit of the P value, factor A becomes a significant variable, and the interaction between factors A and B also becomes another significant variable. However, factor B (additives percentage) is not a significant variable for the final coating layer thermal conductivity. According to the graph in figure 5.3 it is further verified that during changing the pigment volume concentration from 30% to 40% temperature difference and the thermal conductivity changed significantly. But while pigment volume concentration maintains a constant level of 30% and changes the percentage of additives from 0.5% to 1.5%, there is no significant change in the output parameter or temperature difference and the thermal conductivity.

Table 5.6: ANOVA table for the experiment and the P-value of each factor.

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Factor A (PVC)	0.001043	2	0.000522	115.953	3.776185	4.256495
Factor B (NaPA %)	8.48E-05	2	4.24E-05	9.432244	0.006185	4.256495
Interaction	2.59E-05	4	6.47E-06	1.43923	0.297725	3.633089
Error	4.05E-05	9	4.5E-06			
Total	0.001194	17				

❖ Base on the results of the experiment data analysis, the following conclusions can be drawn.

Factor 01	Pigment volume concentration (PVC) is significantly influencing the thermal conductivity of the final insulation coating.	√
Factor 02	The additive percentage does not directly influence the thermal conductivity of the final insulation coating.	X

6.0 DISCUSSION AND CONCLUSION

The experimental results obtained through the two-factor factorial design clearly highlighted that the thermal conductivity of the final insulation coating depends on the pigment volume concentration. In addition, it further indicates that the percentage of additives has not become a significant factor for the thermal conductivity of the final coating layer.

During the manufacturing of an obstructive-type thermal insulation coating, the insulation properties of the final coating layers are obtained through the insulation properties of the raw materials, which are used for the manufacturing process. When considering the thermal insulation properties of raw materials, which are selected for coating manufacturing, tile body powder represents the maximum thermal insulation properties as a pigment. In any coating, the pigment is the material that forms the final coating layer and represents the properties of the pigment material. Because of that during the experiment, while the pigment quantity, pigment volume concentration is increased, and according to that, thermal conductivity is decreasing in the final coating layer. Therefore, the pigment volume concentration becomes a significant factor for the thermal insulation properties of the final insulation coating layer.

Additives are special materials, which are added in small quantities (lower 2% against weight percentage) to impart specific properties to the final coating layer. During this experiment, NaPA was used as an additive to improve the dispersing properties of the coating mixture. Hence, additives are unable to significantly affect the thermal insulation properties of the final coating layer and therefore have not become a significant factor for the final coating layer.

The binder is the material that binds all the materials together and forms the final coating layer of any coating. In this experiment, polyvinyl acetate is selected as a binder considering its higher binding properties and thermal, chemical, and water resistivity. PVA generally contains 10% - 30% solids, and the majority is water. During curing and drying of any coating, water is in the coating mixture is removed while the remaining solid particles. Therefore, during the experiment, if it increases the content of PVA while changing PVC it is unable to significantly influence the thermal conductivity of the final coating layer.

6.1 Limitations

During the research design, two main factors the variables, which are 'pigment volume concentration" and 'additives percentage'. Pigment volume concertation is the ratio between the pigment volume and total volume (Binder + pigment + additives). In this research design, the concentration of pigment volume has been considered as one factor, so it is unable to check the influence of the pigment and binder has not been checked separately. Hence, the effect of the binder cannot be evaluated separately, and it may cause to enable the evaluation of the effect of the most important factor, which depends on the binder volume of the coating.

The painted metal plate samples are tested on the hot boiler surface, which is at 130 ^{0}C degree temperature, and it is observed that no changes in the physical appearance and properties of the coating layers under the above-tested temperature. However, there is no data analysis for how the physical properties are acting in the final coating layers beyond the temperature of 130 $^{0C.}$ Therefore, there is a limitation for the product and it is not recommended to use beyond 130 ^{0}C temperature for insulation purposes.

6.2 Future work

During the above research work, tile body powder has selected as pigment and polyvinyl acetate (PVA) as a binder. The final coating has been tested at 130 ^{0}C degree temperature, and no data analysis has been performed on its physical behavior beyond the tested temperature. Therefore, there is an opportunity to design the same two-factor factorial design by changing the pigment type as well as the alternative binders for high-temperature thermal insulation applications.

The above research is conducted as a two-factor factorial design considering pigment volume concentration and additive percentage as experimental factors. Therefore, the effect of the pigment and binder has been considered as a single factor. Therefore, there is an opportunity to design a new experiment considering the percentages of pigment, binder, and additives as three factors and design a three-factor factorial design to evaluate the influence of the above factors separately.

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