Experimental Investigation on Droplet Evaporation and Leidenfrost Phenomenon

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Of

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DECLARATION:

We, students of Mechanical Engineering Department, Military Institute of Science & Technology (MIST), Mirpur Cantt, Dhaka, hereby declare that the presented paper is the consequence of the accomplishment of the project and thesis on "**Experimental Investigation on Droplet Evaporation and Leidenfrost Phenomenon**" under the supervision of Dr. Aloke Kumar Mozumder, Professor, Mechanical Engineering Department, Bangladesh University of Engineering & Technology (BUET), Dhaka.

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ABSTRACT:

This experiment presents a detailed and thorough parametric study of the Leidenfrost point which serves as the boundary of the transition and film boiling regimes. The evaporation time in film boiling region of a sessile drop of liquid on a hot metallic surface has been analyzed in the present study. The time of evaporation for the droplet on the hot metallic surface was measured.

With the time-temperature plot of these experimental data, the Leidenfrost phenomena has been clarified and explained. In the boiling curve for liquid, just after the transition boiling region and before the film boiling region, the heat transfer approaches its minimum value. The corresponding temperature of this minimum value was termed as the Leidenfrost temperature and the phenomenon is known as Leidenfrost phenomena. Sessile drop of four different liquids namely Distilled Water, Acetone, Methanol and Ethanol having diameters 1.5mm, 2.25mm, 4.5mm were used to conduct the experiment for a wide range of solid surface temperatures of 50-350^{0}C. Three solid surfaces namely Brass, Aluminum and Mild Steel were used to conduct the experiment.

The graph we plotted by placing evaporation time of liquids against surface temperature of metal blocks is exactly the opposite to the conventional boiling curve. The temperature at which time required for evaporation is maximum is called the Leidenfrost point.

These variations in Liquid types, Diameter of drops and Metals have been done to present a clear statement that the Leidenfrost temperature range does not change. The only change obtained from varying liquid, diameter and metal is the time of evaporation.

So for all the metal blocks and test liquids of different diameters used in our experiment, Leidenfrost temperature is within the range 170-210^{0}C. This concludes to the fact that Leidenfrost point does not change for any parameter.

CHAPTER 1

INTRODUCTION

1.1 Introduction

When a liquid drop falls upon a hot solid surface, an insulating vapor layer is immediately formed between the droplet and hot surface which results in decrease of heat transfer compared to the case of direct contact. Many studies of the Leidenfrost phenomenon have already been appeared in the literature. This phenomenon was first investigated by Johann Gottlob Leidenfrost**[1]** in 1756 and is named the Leidenfrost phenomenon in honor of him. The temperature at that point is known as Leidenfrost temperature and the corresponding evaporation time is known as Leidenfrost time. The droplet evaporation process after impinging on a solid wall near Leidenfrost point was theoretically analyzed by Heng and Zhou (2007)**[2]**. A correlation for predicting evaporation lifetime was obtained based on the theoretical analysis and experimental results. Gottfried et al. (1966)**[3]** analyzed evaporation time data for small droplet of five ordinary liquids and proposed an analytical model which was in fair agreement with the data. The model postulates that heat is transferred to the droplet by conduction from the plate below the droplet through the supporting vapor film and by radiation from the plate; mass is removed by diffusion from the outer surface and by evaporation from the lower surface.

Michiyoshi and Makino (1978)**[4]** investigated the heat-transfer characteristics for evaporation of droplet of pure water placed on smooth surfaces of copper, brass, carbon steel and stainless steel at temperature ranging from 80-450°C. They correlated the heat transfer with temperature. A numerical investigation for the evaporation process of n-heptane and water droplets impinging onto a hot substrate was conducted by Nikolopoulos et al. (2007) **[5]**. The evaporation rates of droplets of n-heptane and water were also investigated by Elyssa and Black (2004) **[6]** which showed that the trends in the wetted diameter, height and contact angle for water were fundamentally different from heptane.Literature reveals that according to the definition of Leidenfrost temperature, it varies approximately from 600-800°C for pool boiling. In the present study, for sessile drop evaporation, the value of this temperature has been tried to found out. Among all of the experimental conditions, the Leidenfrost temperature varies from 175-200°C which is much smaller than the value of pool boiling. It is not an easy task to explain this difference unless the mechanism of Leidenfrost phenomena is completely understood. Among several causes, vapor pressure might be one of them. In the case of pool boiling, a liquid column exists over the vapor layer which might increase the vapor pressure (and ultimately the boiling curve shifts to the right) and increase the temperature for minimum heat flux (Leidenfrost temperature). On the other hand, for a sessile drop evaporation, the weight of the drop let is very much negligible compared to a liquid column which is not capable to produce any extra pressure on the vapor layer, this relatively lower pressure consequences the Leidenfrost temperature to become smaller. To obtain more insight into the phenomenon an investigation has been carried out concerning sessile drop evaporation.

Nguyen and Avedisian**[7]** presented a numerical solution for the problem of film evaporation of a liquid droplet on a horizontal surface. They assumed the horizontal surface having a constant 3surface temperature which was considered to be isolated from the ambience. There are manyother scientists and researchers who conducted experiment on this phenomenon **[8-10].** Yao andCai**[11]** studied the dynamics of water drops impacting at small angles on hot surfaces. The Experiments were conducted using a monosize droplet stream and a rotating disk. When the impact angle was decreased, the Leidenfrost temperature was found to be reduced. Correlations were established for the description of this behavior. Nagai and Nishio**[12]** studied Leidenfrost temperature on a very smooth surface. The Leidenfrost temperature was measured on single crystal and metal plates. The maximum surface roughness of the former was 0.03 μm, and that of the latter was 1.25 μm. Results of the experiment showed that the Leidenfrost temperatures on these two surfaces did not differ from each other as long as the surfaces were the same in wettability and thermal conductivity (or thermal diffusivity).

In the present study, an analytical model will be proposed for the prediction of sessile drop evaporation time at Leidenfrost temperature on hot solid surface. The model will be verified with some experimental data. In the proposed model, conduction and radiation heat transfer along with mass diffusion have been successfully included. It was roughly observed in the experiment that for small droplet diameter, the liquid droplet usually flattens on the hot metal surface having a thin vapor cushion beneath it. In the proposed model, it is considered that the liquid droplet on the heated surface to have an almost cylindrical shape with a very little height.

The vapor layer thickness is considered to be uniform during the entire vaporization process and the vertical velocity of the vapor leaving the bottom surface of the droplet has been considered to be uniform. Heat is assumed to be transferred at the bottom surface of the liquid by conduction and radiation. The side surface is assumed to get the heat energy by radiation only. Mass diffusion is also considered from side surface of droplet in the analysis. This study experimentally investigates the evaporation of sessile drop for three different heated surfaces of Aluminum, brass and mild steel with a combination of four different liquids as methanol, ethanol, water and acetone.

1.2 Objectives:

1. To determine Leidenfost temperature of different liquids on different metal blocks of different properties with respect to boiling point, latent heat of vaporization, thermal conductivity, density, etc.
2. To find the required evaporation time of different liquids by varying size of drops, type of metal and finally temperature.
3. To obtain graphs by plotting temperature vs. evaporation time for different combinations of liquids of different sized drops and metals.

CHAPTER 2

LITERATURE REVIEW

2.1 Leidenfrost Effect

The Leidenfrost effect is a physical phenomenon in which a liquid, in near contact with a mass significantly hotter than the liquid's boiling point, produces an insulating vapor layer keeping that liquid from boiling rapidly. Due to this 'repulsive force,' the droplet hovers over the surface rather than making physical contact with it. This is most commonly seen when cooking; one sprinkles drops of water in a pan to gauge its temperature: if the pan's temperature is at or above the Leidenfrost point, the water skitters across the pan and takes longer to evaporate than in a pan below the temperature of the Leidenfrost point (but still above boiling temperature). The effect is also responsible for the ability of liquid nitrogen to skitter across floors. It has also been used in some potentially dangerous demonstrations, such as dipping a wet finger in molten lead or blowing out a mouthful of liquid nitrogen, both enacted without injury to the demonstrator. The latter is potentially lethal, particularly should one accidentally swallow the liquid nitrogen. It is named after Johann GottlobLeidenfrost **[1]**, who discussed it in A Tract About Some Qualities of Common Water in 1756.

The Leidenfrost effect can be seen as drops of water are sprinkled onto a pan at various times as it heats up. Initially, as the temperature of the pan is just below 100 °C (212 °F), the water flattens out and slowly evaporates, or if the temperature of the pan is well below 100 °C (212 °F), the water stays liquid. As the temperature of the pan goes above 100 °C (212 °F), the water droplets hiss when touching the pan and these droplets evaporate quickly. Later, as the temperature exceeds the Leidenfrost point, the Leidenfrost effect comes into play. On contact with the pan, the water droplets bunch up into small balls of water and skitter around, lasting much longer than when the temperature of the pan was lower. This effect works until a much higher temperature causes any further drops of water to evaporate too quickly to cause this effect. This is because at temperatures above the Leidenfrost point, the bottom part of the water droplet vaporizes immediately on contact with the hot plate. The resulting gas suspends the rest of the water droplet just above it, preventing any further direct contact between the liquid water and the hot plate. As steam has much poorer thermal conductivity, further heat transfer between the pan and the droplet is slowed down dramatically. This also results in the drop being able to skid around the pan on the layer of gas just under it.

The temperature at which the Leidenfrost effect begins to occur is not easy to predict. Even if the volume of the drop of liquid stays the same, the Leidenfrost point may be quite different, with a complicated dependence on the properties of the surface, as well as any impurities in the liquid.
Some research has been conducted into a theoretical model of the system, but it is quite complicate. As a very rough estimate, the Leidenfrost point for a drop of water on a frying pan might occur at 193 °C (379 °F).

The Leidenfrost effect was also described by the eminent Victorian steam boiler designer, Sir William Fairbairn**[13]**, in reference to its effect on massively reducing heat transfer from a hot iron surface to water, such as within a boiler. In a pair of lectures on boiler design, he cited the work of Pierre Hippolyte Boutigny (1798-1884) **[14]** in studying this. A drop of water that was vaporized almost immediately at 168 °C (334 °F) persisted for 152 seconds at 202 °C (396 °F).
Lower temperatures in a boiler firebox might evaporate water more quickly as a result; compare Mpemba effect. An alternative approach was to increase the temperature beyond the Leidenfrost point. Fairbairn **[13]** considered this too, and may have been contemplating the flash steam boiler, but considered the technical aspects insurmountable for the time.
The Leidenfrost point may also be taken to be the temperature for which the hovering droplet lasts longest.
It has been demonstrated that it is possible to stabilize the Leidenfrost vapor layer of water by exploiting super hydrophobic surfaces. In this case, once the vapor layer is established, cooling never collapses the layer, and no nucleate boiling occurs; the layer instead slowly relaxes until the surface is cooled

2.2 <u>Leidenfrost Point</u>

Fig 2.1 A water droplet experiencing Leidenfrost effect on a hot stove plate

The Leidenfrost point signifies the onset of stable film boiling. It represents the point on the boiling curve where the heat flux is at the minimum and the surface is completely covered by a vapor blanket. Heat transfer from the surface to the liquid occurs by conduction and radiation through the vapor. In 1756, Leidenfrost observed that water droplets supported by the vapor film slowly evaporate as they move about on the hot surface. As the surface temperature is increased, radiation through the vapor film becomes more significant and the heat flux increases with increasing excess temperature.

2.3 Leidenfrost's Experiment:

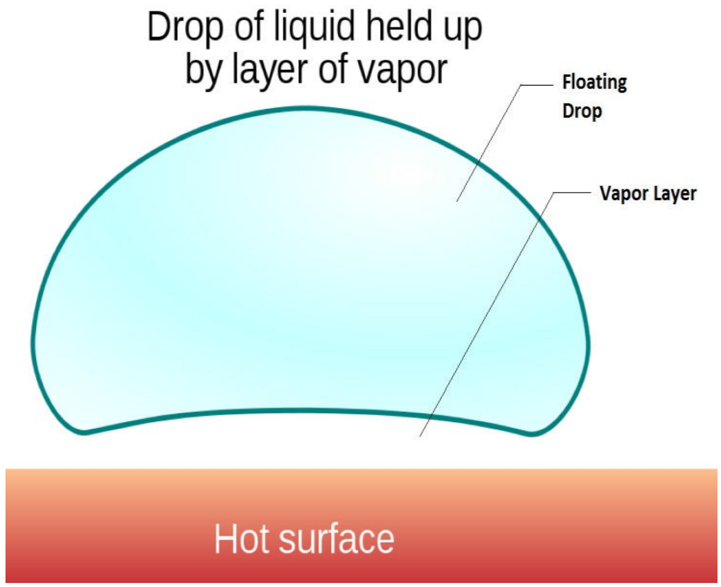


Figure 2.2 A Leidenfrost drop in cross section

Leidenfrost conducted his experiments with an iron spoon that was heated red-hot in a fireplace. After placing a drop of water into the spoon, he timed its duration by the swings of a pendulum. He noted that the drop seemed to suck the light and heat from the spoon, leaving a spot duller than the rest of the spoon. The first drop deposited in the spoon lasted 30 s while the next drop lasted only 10 s. Additional drops lasted only a few seconds.

Leidenfrost misunderstood his demonstrations because he did not realize that the longer-lasting drops were actually boiling. When the temperature of the plate is less than the Leidenfrost point, the water spreads over the plate and rapidly conducts energy from it, resulting in complete vaporization within seconds.

When the temperature is at or above the Leidenfrost point, the bottom surface of a drop deposited on the plate almost immediately vaporizes. The gas pressure from this vapor layer prevents the rest of the drop from touching the plate (Fig. 4). The layer thus protects and supports the drop for the next minute or so. The layer is constantly replenished as additional water vaporizes from the bottom surface of the drop because of energy radiated and conducted through the layer from the plate. Although the layer is less than 0.1 mm thick near its outer boundary and only about 0.2mm thick at its center, it dramatically slows the vaporization of the drop.

2.4 Stability of Leidenfrost Phenomenon:

In 1756, Leidenfrost observed that water drops skittered on a sufficiently hot skillet, owing to levitation by an evaporative vapor film. Such films are stable only when the hot surface is above a critical temperature, and are a central phenomenon in boiling. In this so-called

Leidenfrost regime, the low thermal conductivity of the vapor layer inhibits heat transfer between the hot surface and the liquid. When the temperature of the cooling surface drops below the critical temperature, the vapor film collapses and the system enters a nucleate-boiling regime, which can result in vapor explosions that are particularly detrimental in certain contexts, such as in nuclear power plants. The presence of these vapor films can also reduce liquid–solid drag

Baumeister et al. **[15]** report maintaining stable film boiling for small droplets in air down to a surface temperature less than a degree above saturation, while Wachter et al. **[16]** found a similar for water droplets in film boiling in dry air at a surface temperature as low as 75ºC. In fact,

Wachters argues that the absolute minimum surface temperature for the Leidenfrost phenomenon is equal to the wet-bulb temperature of the surrounding atmosphere; to quote his explanation

"When the drop bottom temperature has a value below the boiling point, the narrow layer under the drop contains a mixture of vapor and air. In this mixture the vapor concentration is in equilibrium with the drop bottom temperature. However, at the outer rim of the drop bottom the dry surroundings. This is a one-way diffusion which involves a drift velocity of the gas mixture and generates a radial pressure gradient, higher than the atmospheric pressure".

The explanation appears plausible, but the quantitative expressions have not been worked out.

Baumeister and Wachters both emphasize the need for extremely smooth surface and suppression of disturbances in the droplet to achieve these extremely low temperatures. The droplets are initially deposited on quite hot surfaces which are then cooled to low temperatures.

Too rapid cooling of the surface leads to premature collapse, presumably because the droplet oscillations have not been adequately damped out in this time. With care, a wire can be inserted into the droplet to damp out the oscillations; the droplet is then partially supported by surface tension on the wire, and the unconstrained force balance is upset. Both of these workers also used test surfaces that were slightly concave underneath the droplet, and this undoubtedly contributed to droplet stabilization.

2.5 Application:

1. Leidenfrost effect has been used for the development of high sensitivity ambient mass Spectrometry. Under the influence of Leidenfrost condition the Levitating droplet does not release molecules out and the molecules are enriched inside the droplet. At the last moment of droplet evaporation all of the enriched molecules release in a short time domain and thus increase the sensitivity.

2. The effect causes the water to levitate on the evaporated gas vapor.

3. Movement can be changed by adjusting the surface texture and temperature.

4. A heat engine based on the Leidenfrost effect has been prototyped. It has the advantage of extremely low friction.

5. The Leidenfrost point may also be taken to be the temperature for which the hovering droplet lasts longest. Thus Leidenfrost effect can also be called as nature's hovercraft.

6. Water can be made to boil without any bubbling if a surface is specially treated means the temperature of the surface being above of 'Leidenfrost Temperature' so that the vapor cushion does not break down.

Failure of tube walls of steam boiler is a common problem. In a nuclear reactor with boiling coolant, the transition from nucleate to film boiling occurs at constant heat flux and can be accompanied by a very large increase in wall temperature, most descriptively called burnout.
Conversely, once a reactor has had a coolant flow failure and surface has become very hot, film boiling will occur, and one way to make a small amount of coolant contact a large amount of surface is to spray it in as a fog. This technique, spray or fog cooling, has been tested, and it is a variant of the convective Leidenfrost phenomenon in that major interest is attached to the impact characteristics of the droplets on the surface.

2.6 Boiling and Leidenfrost Effect:

Let us consider a pan where water to be heated from below by a flame or electric heat source. As the water warms, air molecules are driven out of solution in the water, collecting as tiny bubbles in crevices along the bottom of the pan (Fig. 1a). The air bubbles gradually inflate, and then they begin to pinch off from the crevices and rise to the top surface of the water (Figs. 1b–f). As they leave, more air bubbles form in the crevices and pinch off, until the supply of air in the water is depleted. The formation of air bubbles is a sign that the water is heating but has nothing to do with boiling.

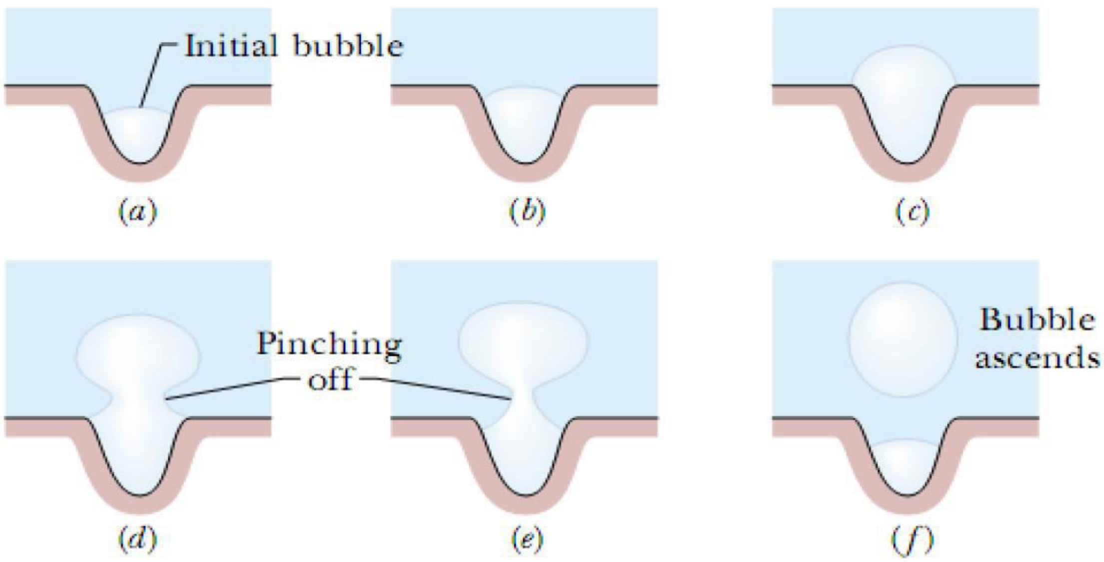
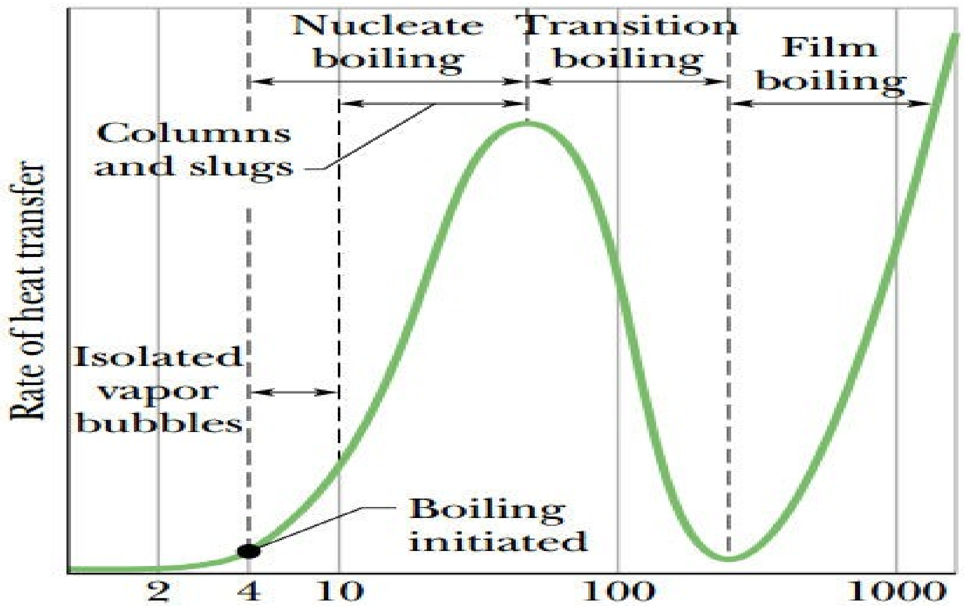


Figure 2.3 (a) A bubble forms in the crevice of a scratch along the bottom of a pan of water.
(b -f) The bubble grows, pinches off, and then ascends through the water.

Water that is directly exposed to the atmosphere boils at what is sometimes called its normal boiling temperature TS. For example, TS is about 100ºC when the air pressure is 1 atm. Since the water at the bottom of your pan is not directly exposed to the atmosphere, it remains liquid even when it superheats above TS by as much as a few degrees. During this process, the water is constantly mixed by convection as hot water rises and cooler water descends



Temperature of pan above Ts(°C)

Figure 2.4 Boiling curve for water

If the pan's temperature is continuing to increase, the bottom layer of water begins to vaporize, with water molecules gathering in small vapor bubbles in the now dry crevices, as the air bubbles do in Fig. 1. This phase of boiling is signaled by pops, pings, and eventually buzzing. The water almost sings its displeasure at being heated. Every time a vapor bubble expands upward into slightly cooler water, the bubble suddenly collapses because the vapor within it condenses. Each collapse sends out a sound wave. Once the temperature of the bulk water increases, the bubbles may not collapse until after they pinch off from the crevices and ascend part of the way to the top surface of the water. This phase of boiling is labeled "isolated vapor bubbles" in the boiling curve.

If the pan's temperature is more increased, the clamor of collapsing bubbles first grows louder and then disappears. The noise begins to soften when the bulk liquid is sufficiently hot that the vapor bubbles reach the top surface of the water. There they pop open with a light splash. The water is now in full boil.

If the pan's temperature is further increased the vapor bubbles next become so abundant and pinch off from their crevices so frequently that they coalesce, forming columns of vapor that violently and chaotically churn upward, sometimes meeting previously detached "slugs" of vapor.

The production of vapor bubbles and columns is called nucleate boiling because the formation and growth of the bubbles depend on crevices serving as nucleating sites (sites of formation).

If the pan's temperature is raised past the stage of columns and slugs, the boiling enters a new phase called the transition regime. Then each increase in the pan's temperature reduces the rate at which energy is transferred to the water. The decrease is not paradoxical. In the transition regime, much of the bottom of the pan is covered by a layer of vapor. Since water vapor conducts energy about an order of magnitude more poorly than does liquid water, the transfer of energy to the water is diminished. The hotter the pan becomes, the less direct contact the water has with it and the worse the transfer of energy becomes.
At this stage, the whole of the bottom surface is covered with vapor. Then energy is slowly transferred to the liquid above the vapor by radiation and gradual conduct ion. This phase is called film boiling.

2.7 Jearl Walker's Experiment:

An experiment was carried out by Jearl Walker, a physicist of Cleveland State University to figure out the elementary relationship between the lifetime of drops and pan temperature. Drops of water having uniform size were released from a syringe to the hot plate and the survival time of the drop was measured. The data was plotted and the graph shows a curious peak.

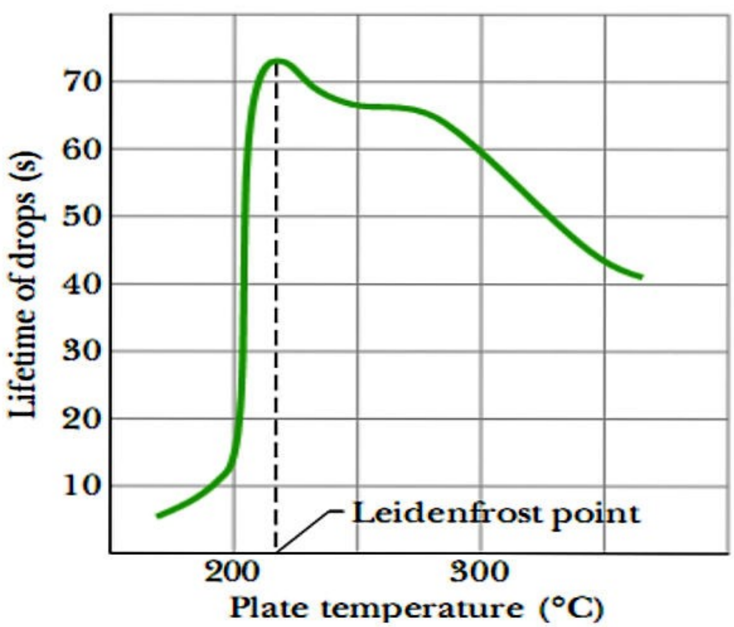


Figure2.5 Drop lifetime on a hot plate

When the plate temperature was between 100 and about 200ºC, each drop spread over the plate in a thin layer and rapidly vaporized. When the plate temperature was about 200ºC, a drop deposited on the plate beaded up and survived for over a minute. At even higher plate temperatures, the water beads did not survive quite as long. The temperature corresponding to the peak in a graph is generally known as the Leidenfrost point

CHAPTER 3

EXPERIMENTAL SETUP AND PROCEDURE

3.1 View of Experimental Setup

The setup we used during our experiment can be expressed by the following figure-

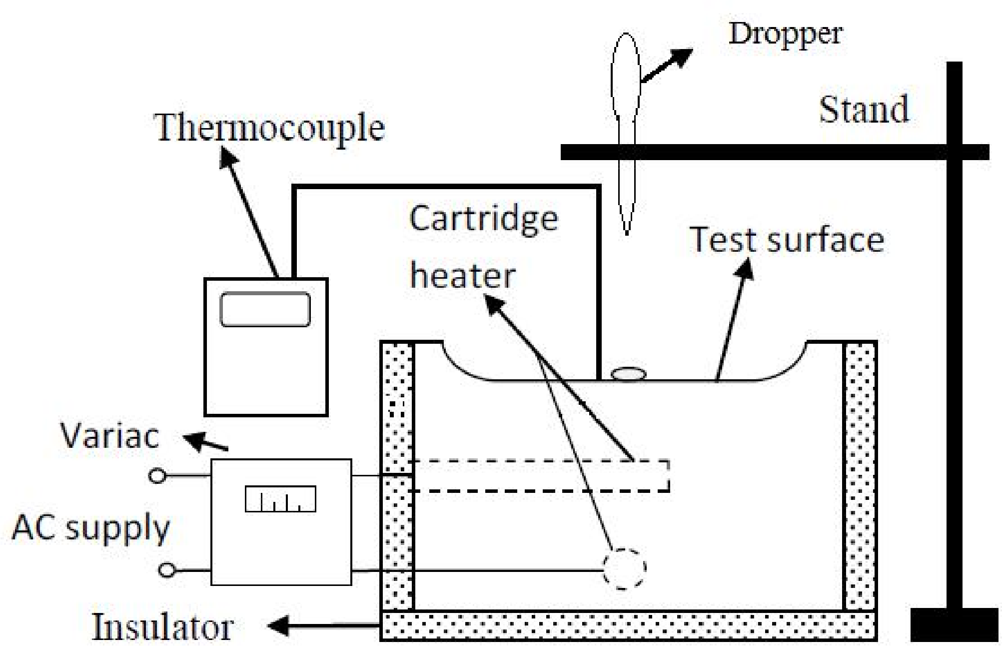


Fig-3.1 Schematic diagram of the experimental setup

In the experimental setup we can see a metal block inside which two heater is inserted. The heaters are located perpendicular to each other. The heaters are connected with a variac that supply constant voltage. The temperature of the work surface is measured by using a K-type thermocouple. Small droplets of liquid are placed at the test surface with the help of a dropper. The dropper is held stationary by using a stand. An insulator (asbestos) is used to cover the metal block.

3.2 Apparatus:

In our experiment we used three metal blocks and four liquids to determine the Leidenfrost effect for various liquid on different material. Various electrical and mechanical equipment were used in the experiment. The detailed description of experimental apparatus and experimental procedure are presented in this chapter.

Thus, apparatus used in this experiment are-

- Metal blocks:
-
    1. Mild steel
    2. Aluminum
    3. Brass

    All metal blocks are of 77mm diameter and 76mm height, with a grooved section at the centre of the block

- Working liquid

    1. Acetone:
        Formula: C_3H_6O
        Boiling Point: 56°C
        Latent heat of vaporization: 31.3 kJ/mol

    2. Ethanol:
        Formula: C_2H_6O
        Boiling Point: 78.37°C
        Latent heat of vaporization: 38.56 kJ/mol

    3. Methanol
        Formula: CH_3OH
        Boiling Point: 64.7°C
        Latent heat of vaporization: 38.278 kJ/mol

4. Distilled water:
    Formula: H_2O
    Boiling Point: 100°C
    Latent heat of vaporization: 40.68 kJ/mol

- Heater
- Variac
- Thermocouple
- Stand
- Glass box
- Dropper
- Asbestos

3.2.1 Metal block

3.2.1.1 Construction Process:

As we discussed earlier in this chapter that we used three metal blocks of Brass, Aluminum and Mild Steel for determining the evaporation time and Leidenfrost temperature. The three metal blocks we used in our experiment had same dimension. Diameter of each block was 77mm and height was 76mm. A groove was made at the center of the block with the help of milling machine and HSS cutting tool. The diameter of the groove was 40mm and depth was 5 mm. Two holes of 12.5mm diameter was drilled inside the block for housing the heater. The holes were perpendicular to each other. First one was 25.5mm beneath and the second one was 51mm beneath the test surface. Surface finish was very important for the experiment. We used different grades of emery paper to provide desired surface finish. At first rough finishing was done by using emery paper of grade 300 and then gradually we used grades of 400,600,800,1000. Finally a mirror finish was provided by using a paper of grade 1200.

3.2.1.2 <u>Brass:</u>

Fig 3.2 Brass Block

Brass is a metal alloy made of copper and zinc; the proportions of zinc and copper can be varied to create a range of brasses with varying properties. It is a substitutional alloy: atoms of the two constituents may replace each other within the same crystal structure.

Brass has higher malleability than bronze or zinc. The relatively low melting point of brass (900 to 940 °C, 1652 to 1724 °F, depending on composition) and its flow characteristics make it a relatively easy material to cast. By varying the proportions of copper and zinc, the properties of the brass can be changed, allowing hard and soft brasses. The density of brass is approximately 8.4 to 8.73 grams per cubic centimeter. Thermal conductivity of brass is 109 W/mK.

3.2.1.3 <u>Aluminium:</u>

Fig 3.3 Aluminum Block

Aluminum is a chemical element in the boron group and is a silvery-white, soft, nonmagnetic, ductile metal. Aluminum is the third most abundant element (after oxygen and silicon), and the most abundant metal. It is remarkable for the metal's low density and for its ability to resist corrosion due to the phenomenon of passivation. Melting point of aluminum is 660°C and thermal conductivity is 205 W/mK.

3.2.1.4 Mild Steel:

Fig 3.4 Mild Steel Block

In mild steel also known as plain-carbon steel, the main interstitial alloying constituent is carbon in the range of 0.12–2.0%. It is now the most common form of steel because its price is relatively low while it provides material properties that are acceptable for many applications. Low-carbon steel contains approximately 0.05–0.15% carbon making it malleable and ductile. Mild steel has a relatively low tensile strength, but it is cheap and easy to form; surface hardness can be increased through carburizing.

Melting point of mild steel is very high (1425-1540°C) and thermal conductivity is low (43 W/mK)

3.2.2 Working Fluid:

Four fluids were used in our test. In this article we will discusses about the liquids used in our experiment.

3.2.2.1 Methanol:

Methanol, also known as methyl alcohol, wood alcohol, wood naphtha or wood spirits, is a chemical with the formula CH_3OH. Methanol acquired the name "wood alcohol" because it was once produced chiefly as a byproduct of the destructive distillation of wood. Modern methanol is produced in a catalytic industrial process directly from carbon monoxide, carbon dioxide, and hydrogen.

Methanol is the simplest alcohol, and is a light, volatile, colorless, flammable liquid with a distinctive odor very similar to that of ethanol (drinking alcohol). However, unlike ethanol, methanol is highly toxic and unfit for consumption. At room temperature, it is a polar liquid, and is used as an antifreeze, solvent, fuel, and as a denaturant for ethanol.

Methanol is produced naturally in the anaerobic metabolism of many varieties of bacteria, and is commonly present in small amounts in the environment. As a result, there is a small fraction of methanol vapor in the atmosphere. Over the course of several days, atmospheric methanol is oxidized with the help of sunlight to carbon dioxide and water.

Methanol burns in oxygen, including open air, forming carbon dioxide and water:

$2\ CH_3OH + 3\ O_2 \rightarrow 2\ CO_2 + 4\ H_2O$

3.2.2.2 Ethanol:

Commonly referred to simply as alcohol or spirits, ethanol is also called ethyl alcohol, and drinking alcohol. It is the principal type of alcohol found in alcoholic beverages produced by the fermentation of sugars by yeasts. It is a neurotoxic psychoactive drug and one of the oldest recreational drugs used by humans. It can cause alcohol intoxication when consumed in sufficient quantity. Ethanol is used as a solvent, an antiseptic, a fuel and the active fluid in modern (post-mercury) thermometers. It is a volatile, flammable, colorless liquid with a strong chemical odor. Its structural formula CH_3CH_2OH, is often abbreviated as C_2H_5OH orC_2H_6O.

3.2.2.3 Acetone:

Acetone is a colorless, volatile, flammable organic solvent. Acetone occurs naturally in plants, trees, forest fires, vehicle exhaust and as a breakdown product of animal fat metabolism. This agent may be normally present in very small quantities in urine and blood; larger amounts may be found in the urine and blood of diabetics. Acetone is toxic in high doses.

Acetone is a manufactured chemical that is also found naturally in the environment. It is a colorless liquid with a distinct smell and taste. It evaporates easily, is flammable, and dissolves in water. It is also called dimethyl ketone, 2-propanone, and beta-ketopropane. Acetone is used

to make plastic, fibers, drugs, and other chemicals. It is also used to dissolve other substances. It occurs naturally in plants, trees, volcanic gases, forest fires, and as a product of the breakdown of body fat. It is present in vehicle exhaust, tobacco smoke, and landfill sites. Industrial processes contribute more acetone to the environment than natural processes.

3.2.2.4 Distilled Water

Distilled water is water that has many of its impurities removed through distillation process. Distillation involves boiling the water and then condensing the steam into a clean container. Distil water is colorless, tasteless liquid. It does not have any kind of smell. Distil water is used for various industrial purposes where impurities presented in the normal water can be harmful.

Boling temperature of distil water is high compared to the other chemicals used in our experiment.

3.2.3 Variac:

Fig 3.5 Variac used in the experiment

Variac (fig 3.5) provides variable voltage to run different types of operations or the operation that requires different voltage in times. We used voltages ranges from 20-250 volts by this power source.

It is connected to the power supply unit to provide variable power (heat input) by varying voltage output.

TABLE 3.1: VARIAC SPECIFICATION

Phase	3ϕ
Rated capacity	300 W
Rated frequency	60 Hz
Input voltage	220 volt

3.2.4 Heater:

Fig 3.6 Heater with 250 kw capacity

Heater (fig 3.6)is used to heat the test surface. In our experiment we used two heaters with rated capacity of 250 KW. The heaters were placed perpendicular to each other and placed inside the holes drilled earlier in the metal block. First one was located 1 inch beneath the test surface. The distance between two heaters was 1 inch.

3.2.5 <u>Dropper and Syringe:</u>

Fig 3.7 Dropper and syringe used in experiment

Dropper and Syringe (fig 3.7) was used to hold the liquid and pour droplets of it on the test surface of metal block. We used droppers for 4.5mm diameter drops of liquid and syringes for 1.5mm and 2.25mm diameters of liquid. This provided the ability to vary drop sizes.

3.2.6 <u>Glass Box:</u>

Fig 3.8 Glass box for safety purpose

Glass box (fig 3.8) was used for safety purpose in this experiment. It prevented hot liquid droplet from coming in contact with our eyes and camera lens. It also reduced heat loss to the surrounding from the block. We used four glass plates of 1x1 dimensions and a wooden block to make the box. The glass plates were fixed with the wooden block using screw and glue.

3.2.7 <u>Thermocouple:</u>

Fig 3.9 K-type thermocouple meter

In our experiment we used a K type (fig 3.9) thermocouple. The range of the thermocouple meter was 0-1700°C. The tip of the thermocouple was placed at the center of the metal block where we wanted to put our liquid droplet.

3.2.8 <u>Asbestos:</u>

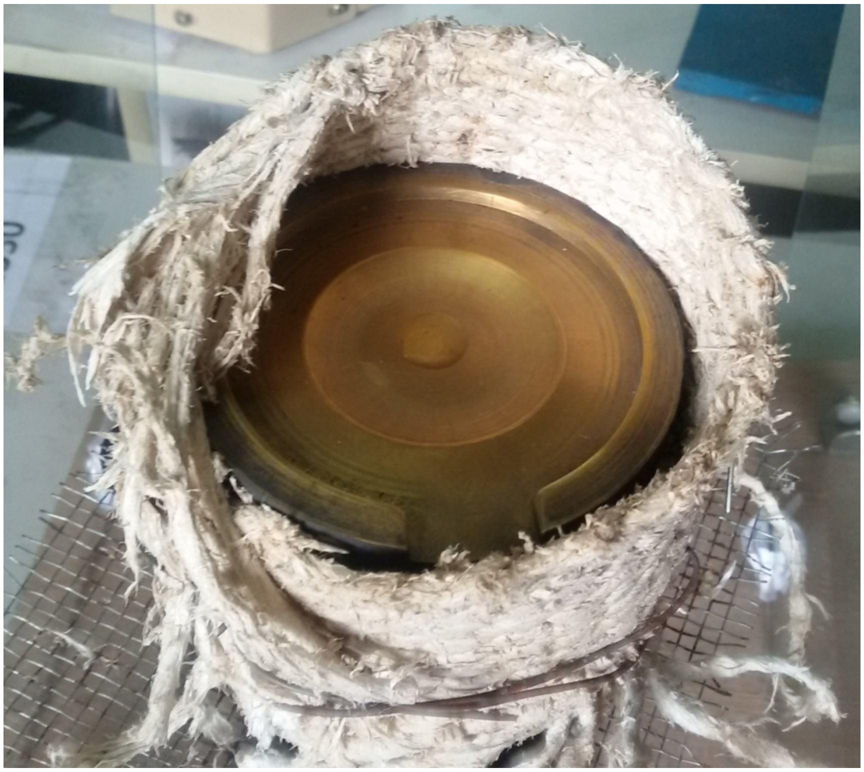


Fig 3.10 Asbestos covering test metal

Asbestos is mainly a heat resistive substance. The test metal block was covered by this asbestos. It helped to maintain a stable temperature of the block by reducing the amount of heat loss from the block to the surrounding. Another purpose of using asbestos is safety. As the metal block temperature is very high it could have burnt anything that came in contract with it. By using asbestos the danger of getting burnt was reduced.

3.2.9 Stand:

Fig 3.11 Stand for holding dropper and syringe

Stand was used to hold the dropper and the syringe at a fixed distance from the test surface of the block. For our experiment the distance was 25 mm.

3.3 Experimental Procedure:

The sessile drop apparatus was used to study the evaporation characteristics of droplet on a heated surface. From figure 3.1, we can see that the experimented block was heated from the bottom with the help of two cartridge heaters. The power supply to the block was regulated using a variac to achieve desired surface temperature of the test surface. When the temperature reached at a predetermined value, a droplet of working liquid was dropped gently to the center of the heating surface with a dropper; complete evaporation time was measured by a stopwatch. The droplet temperature was equal to the room temperature (30ºC±5%) when it was dropped. The surface temperature was sensed by a K type thermocouple meter whose probe was in direct contact with the center of the test surface and the digital temperature reading was taken from the meter. Few numbers of observed phenomena during the droplet evaporation was captured using a video camera. The droplet's diameter was calculated from the total measured volume of 30 droplets at room temperature considering each droplet to be a little sphere. To reduce error, this was done three times and the average diameter was taken.
When the plate temperature reached at a steady state the dropper was filled with liquid and mounted. Bottom of the dropper was pressed slowly and a droplet was formed on the tip of the dropper until the droplet weight becomes sufficient to detach from the tip. The stopwatch was used to record the time of evaporation of droplets and its accuracy was 0.01sec. To minimize the measured time error, three evaporation times were recorded for each temperature and then averaged together. The experiment conducted for the test surface temperature with an increment of 25 ºC up to the test surface temperature 350ºC.

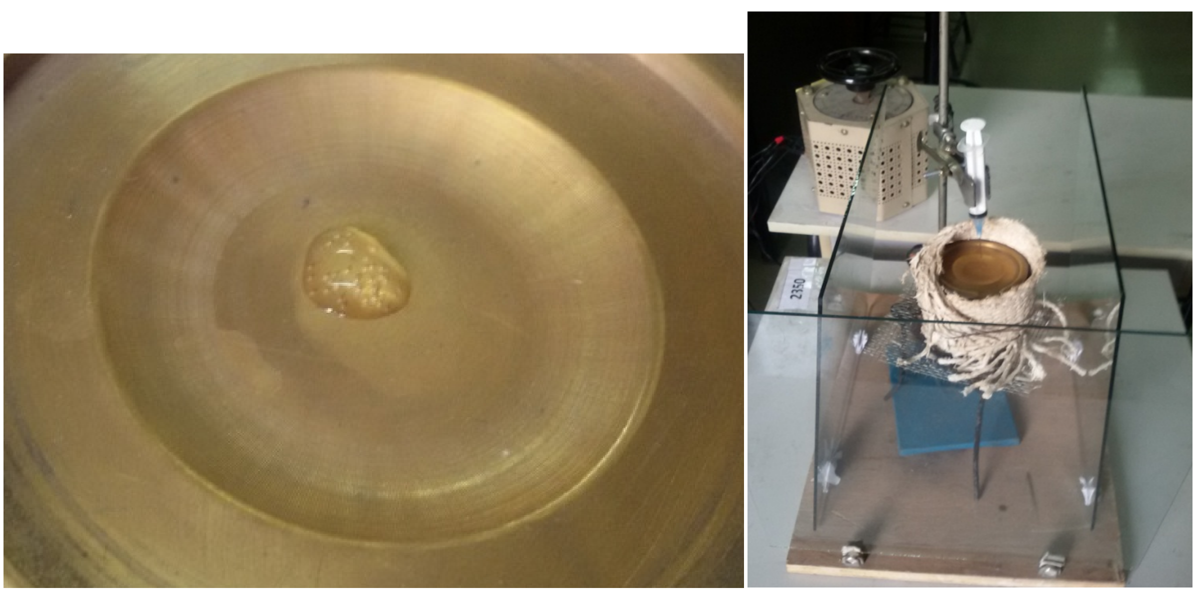


Fig 3.12 Experimental Setup

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Analysis of Experimental Data:

In this Experiment droplet evaporation time has been investigated as a function of test surface temperature for three test metal surfaces(aluminum, mild steel and brass), four different liquid (water, methanol, ethanol and acetone) and three different droplet diameters (1.5mm,2.25mm,4.5mm). A numerous number of graphs have been obtained within a temperature range from 50 to 350^{0}C. The graphs found from the experiment have shapes just opposite of a typical boiling curve, as expected which is defined as the "Inverse Boiling Curve‟.

This is because in typical boiling curve, heat flux is plotted as a function of temperature difference. And in this experiment, evaporation time has been plotted as a function of test surface temperature. The droplet getting higher heat flux will evaporate quickly, and so the time and heat flux relationship is just opposite and it has become evident in the experimental graphs. At Leidenfrost point a stable vapor layer is formed between the liquid and solid surface as a result the heat flux entering into the liquid reduces and the time required for evaporation increases. After crossing the Leidenfrost temperature, the time for evaporation reduces due to the increase of heat flux entering in liquid droplet as a result of radiation.

A sample boiling curve has been shown for reference here:

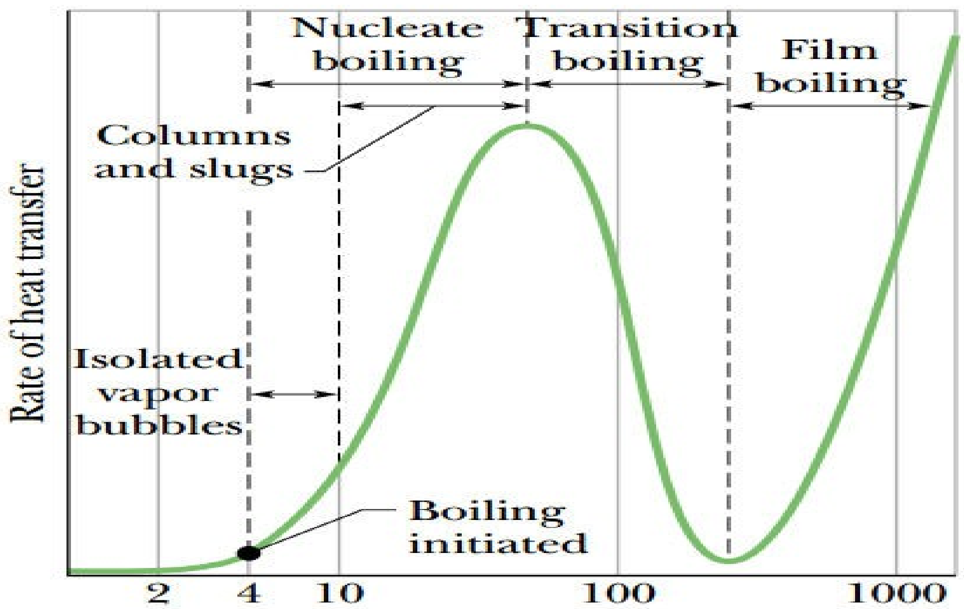


Fig 4.1: Boiling Curve for water

4.2 <u>Diameter Variation:</u>

The figure **(Fig 4.2)** below shows vaporization time of Acetone on Aluminium surface. The graph we obtained is just opposite of a typical boiling curve. At first the time required for evaporation is very high. With the increase of temperature the time required for evaporation reduces and becomes minimum at about 120^0C. At this temperature nucleate boiling takes place. With further increase of temperature, a vapor layer develops and the heat flux supplied to the liquid droplet falls eventually. Due to this, total vaporization time increases. A stable vapor layer forms at around 175^0C and time required to evaporate the droplet is maximum. This temperature is called Leidenfrost temperature. After 175^0C, the radiation heat transfer becomes dominating which increases the heat flux and decreases the total vaporization time.

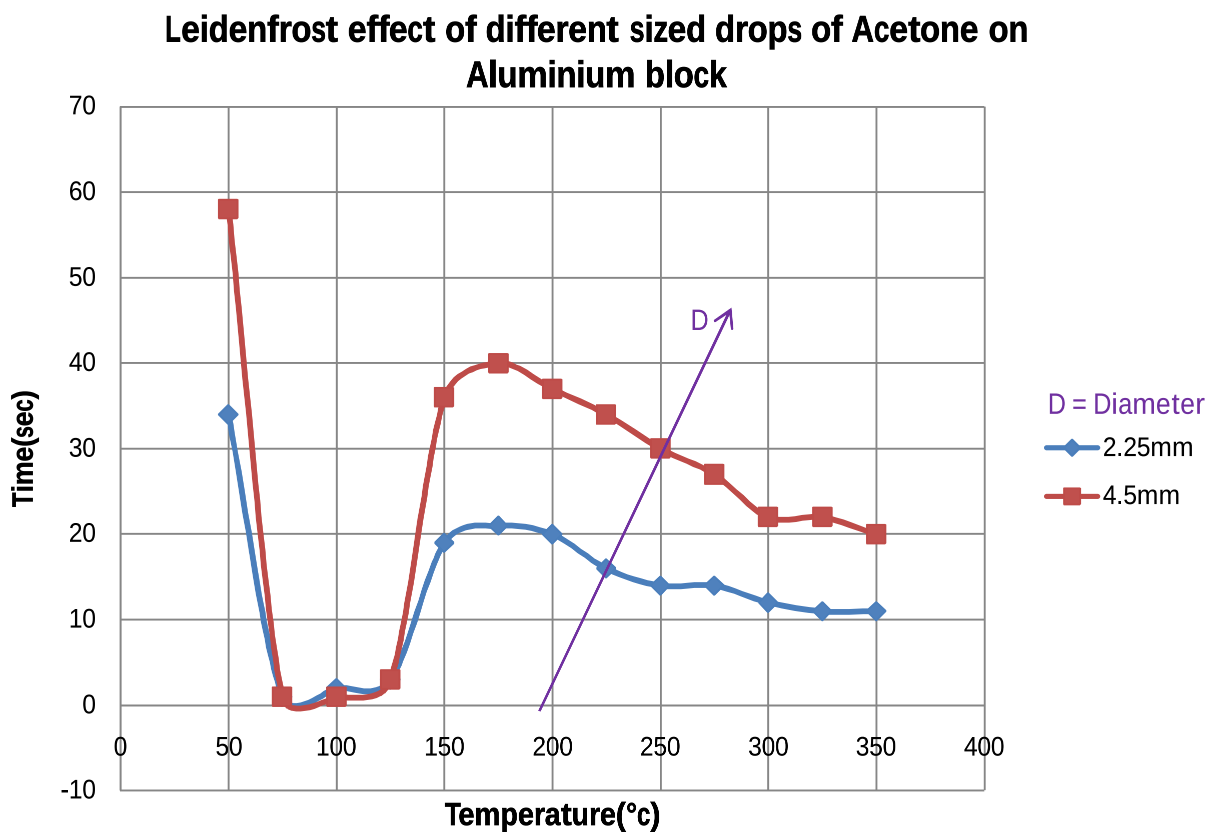


Fig 4.2: Evaporation time of Acetone on Aluminium block

Now coming to the time variation due to diameter, we find that the droplet of larger diameter has significantly higher vaporization time than the lower sized droplet. The reason for this is simply the amount of liquid in the drop. A bigger droplet will have more liquid than a smaller one. For this reason the bigger droplet of liquid takes more time to evaporate. It must be noted however that the nature of the curve for both diameters is exactly the same, opposite to a boiling curve.

Using a 1.5mm diameter drop was not possible with Acetone due to limitations of experimental apparatus.

The time required for evaporating liquid corresponding to Leidenfrost temperature(175^{0}C) is 21 sec for the smaller drop and 40 sec for the larger drop of acetone.

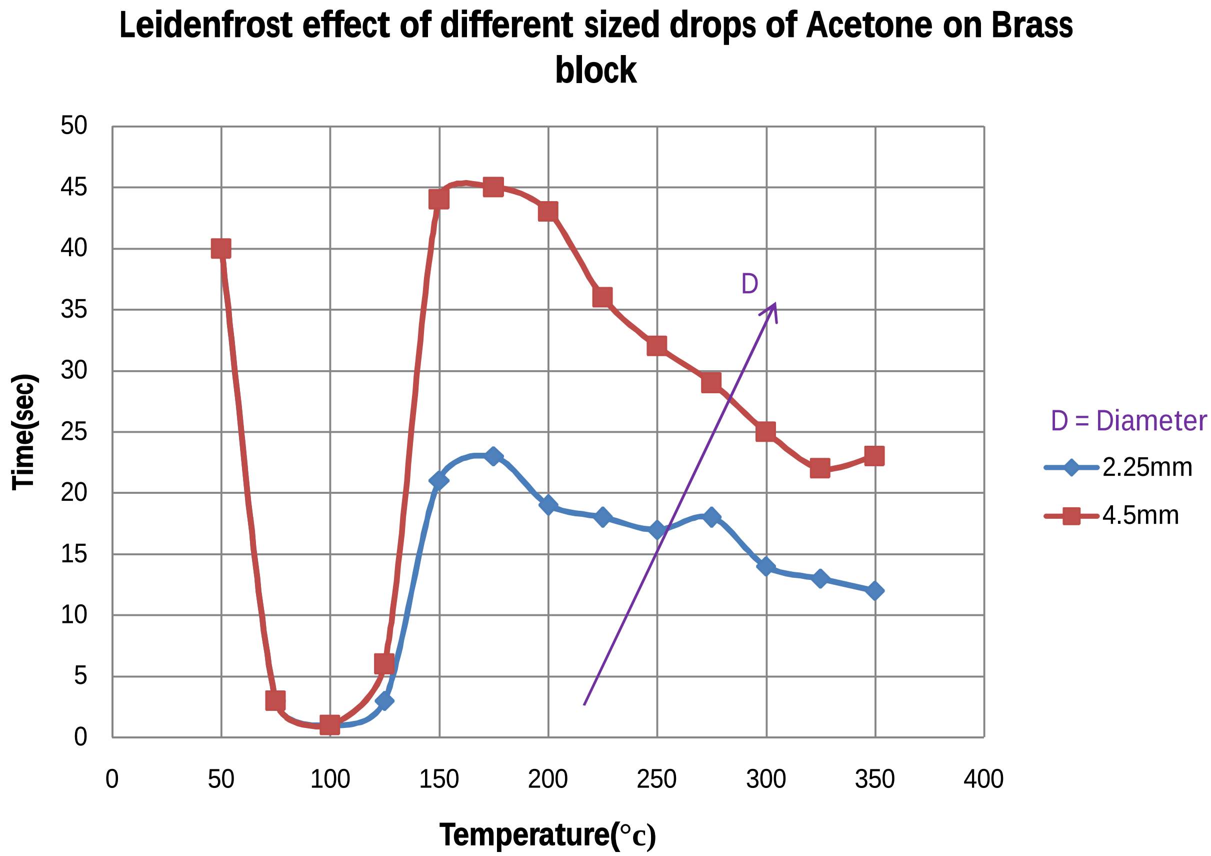


Fig 4.3: Evaporation time of Acetone on Brass block

A similar comparison of diameter has been done in **Fig 4.3,** using acetone on Brass. The results are similar with maximum evaporation time at around 175^{0}C and the corresponding times are 23 sec and 45 sec for the smaller and larger diameter drop respectively.

Another comparison of diameter has been done in **Fig 4.4,** using acetone on Mild Steel. The results are similar with maximum evaporation time at around 175^{0}C and the corresponding times are 17 sec and 37 sec for the smaller and larger diameter drop respectively.

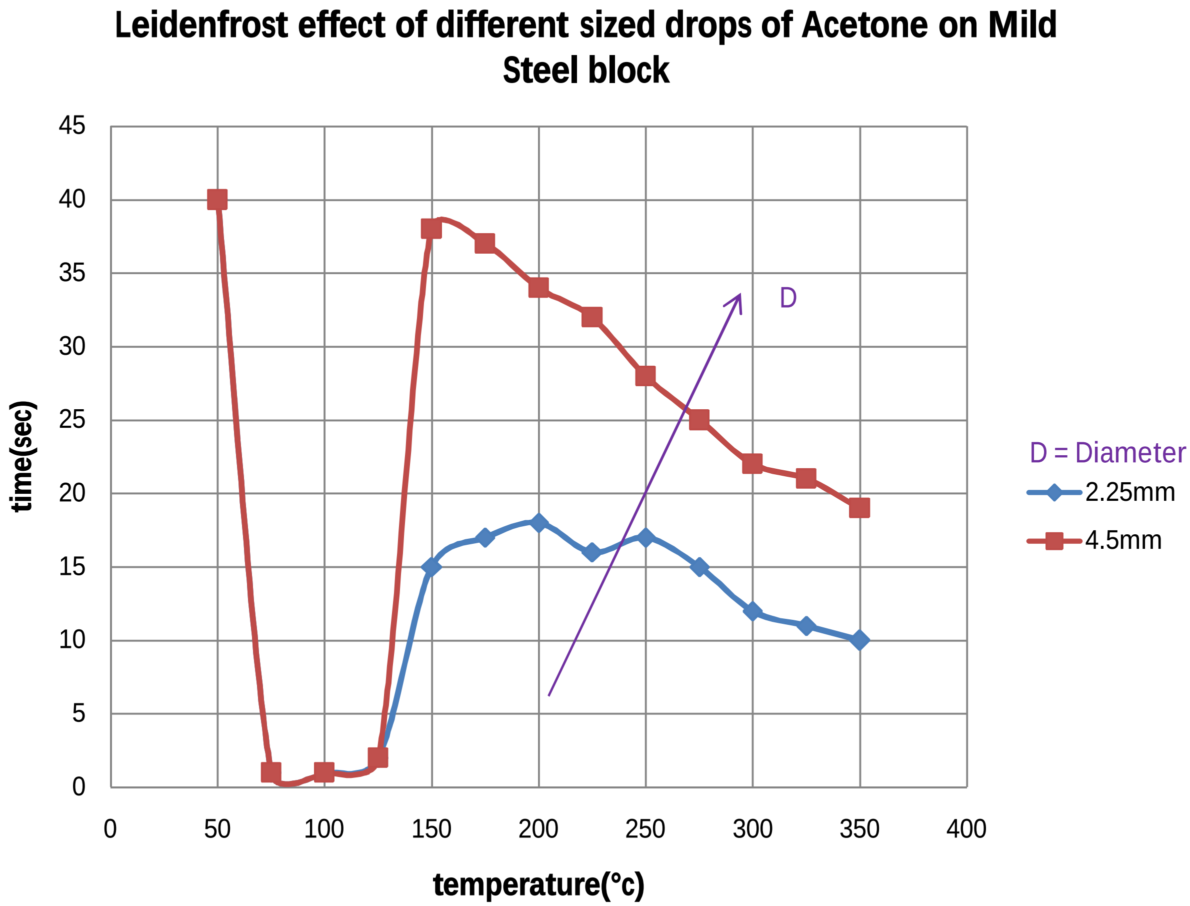


Fig 4.4: Evaporation time of Acetone on Mild Steel block

Next comparison of diameter has been done in **Fig 4.5,** using Distilled Water on Mild Steel. The results are similar to Acetone with maximum evaporation time at around 200^0C and the corresponding times are 39 sec , 60 sec and 140 sec for 1.5mm, 2.25mm, 4.5mm diameter drop respectively.

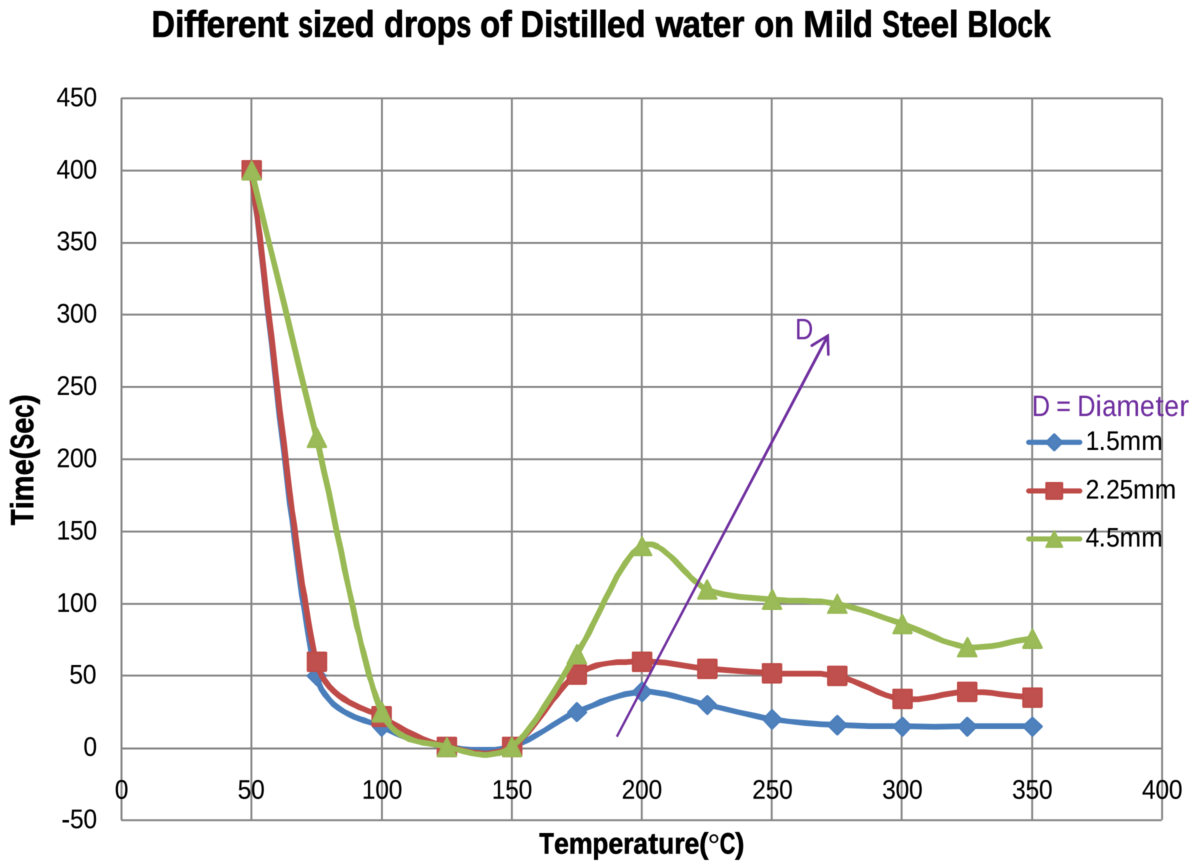


Fig 4.5: Evaporation time of Distilled Water on Mild Steel block

Similarly comparison of diameter has been done in **Fig 4.6,** using Distilled Water on Brass. The results are similar with maximum evaporation time at around 200^{0}C and the corresponding times are 42 sec , 70 sec and 141 sec for 1.5mm, 2.25mm, 4.5mm diameter drop respectively

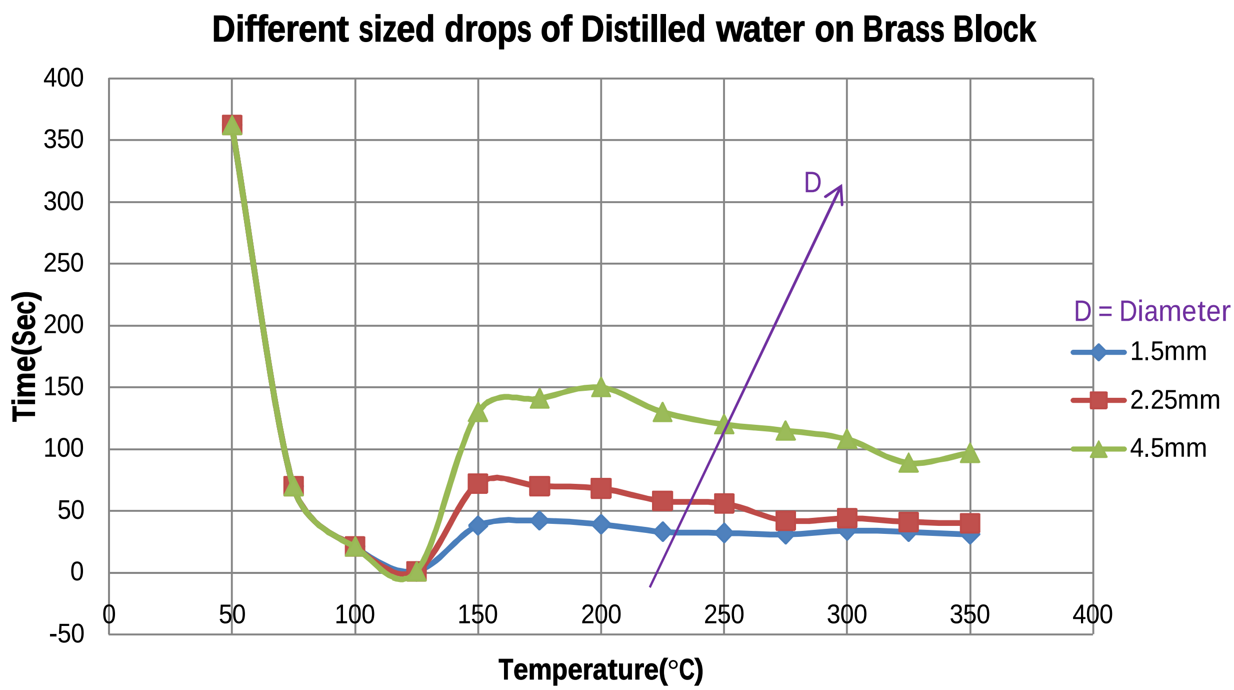


Fig 4.6: Evaporation time of Distilled Water on Brass block

Now comparison of diameter has been done in **Fig 4.7,** using Distilled Water on Aluminium. The results are similar with maximum evaporation time at around 200^0C and the corresponding times are 25 sec , 64.66 sec and 143 sec for 1.5mm, 2.25mm, 4.5mm diameter drop respectively

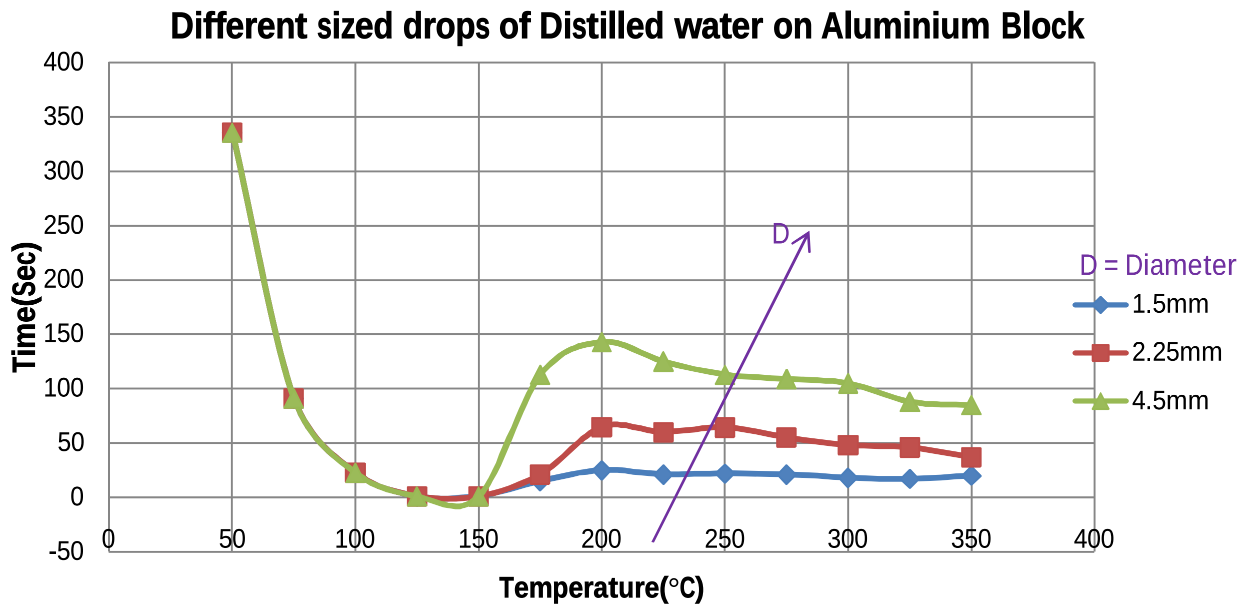


Fig 4.7: Evaporation time of Distilled Water on Aluminium block

Now comparison of diameter has been done in **Fig 4.8,** using Ethanol on Aluminium. The results are similar with maximum evaporation time at around 175^{0}C and the corresponding times are 29 sec and 55 sec for the 2.25mm and 4.5mm diameter drops respectively.

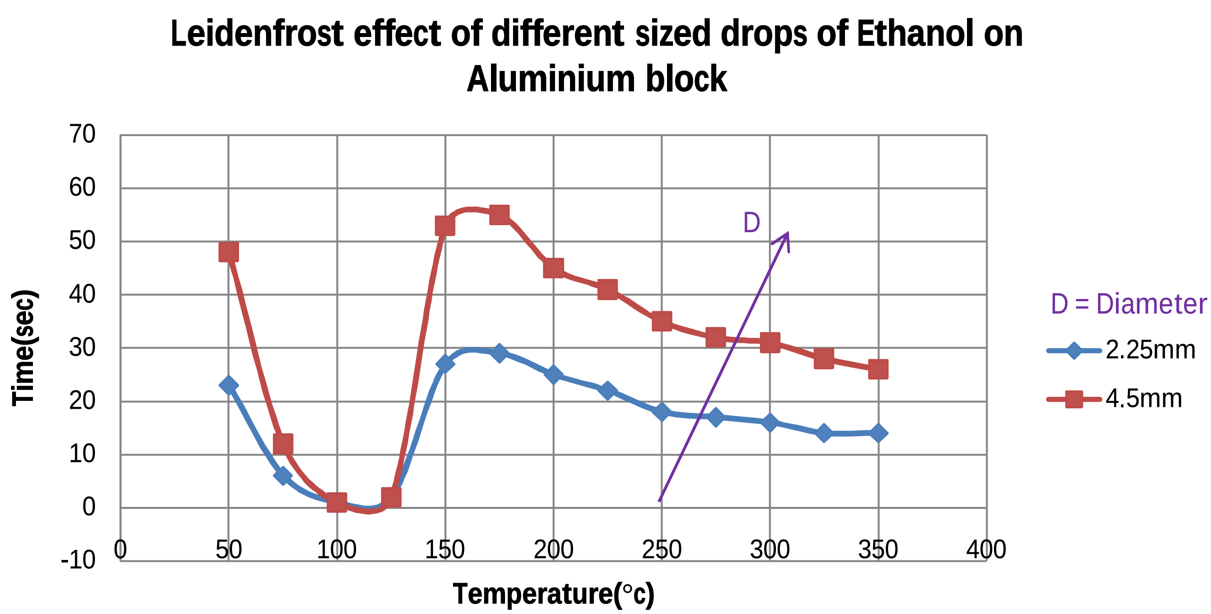


Fig 4.8: Evaporation time of Ethanol on Aluminium block

Comparison of diameter has been done in **Fig 4.9,** using Ethanol on Brass. The results are similar with maximum evaporation time at around 175^{0}C and the corresponding times are 28 sec and 56 sec for the 2.25mm and 4.5mm diameter drops respectively.

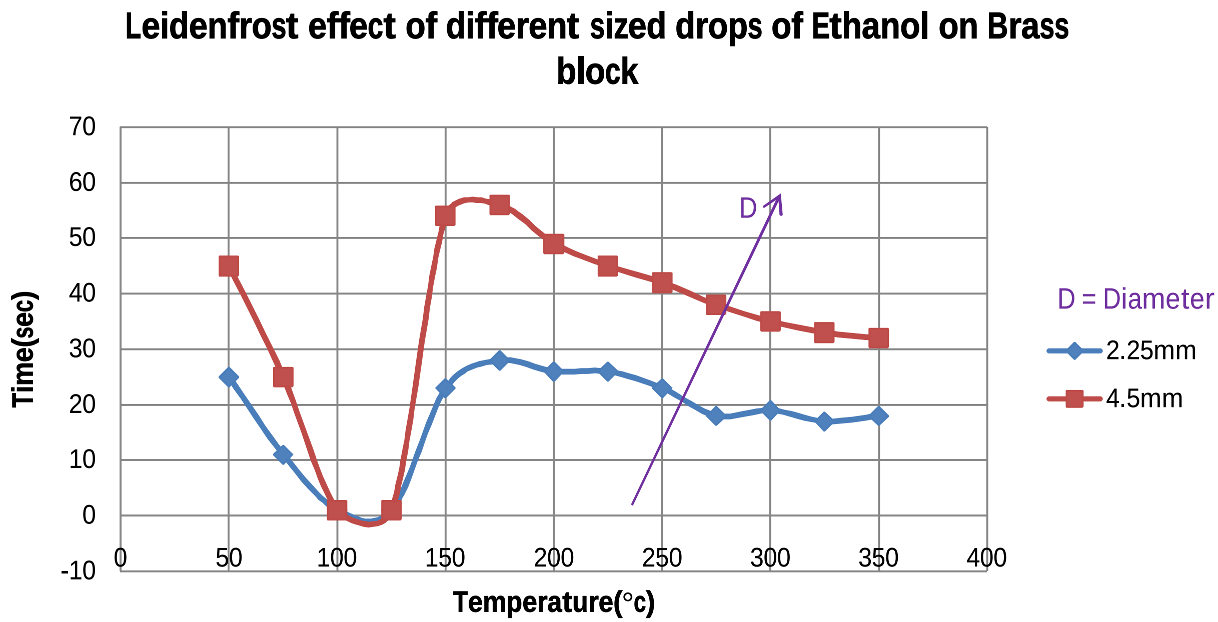


Fig 4.9: Evaporation time of Ethanol on Brass block

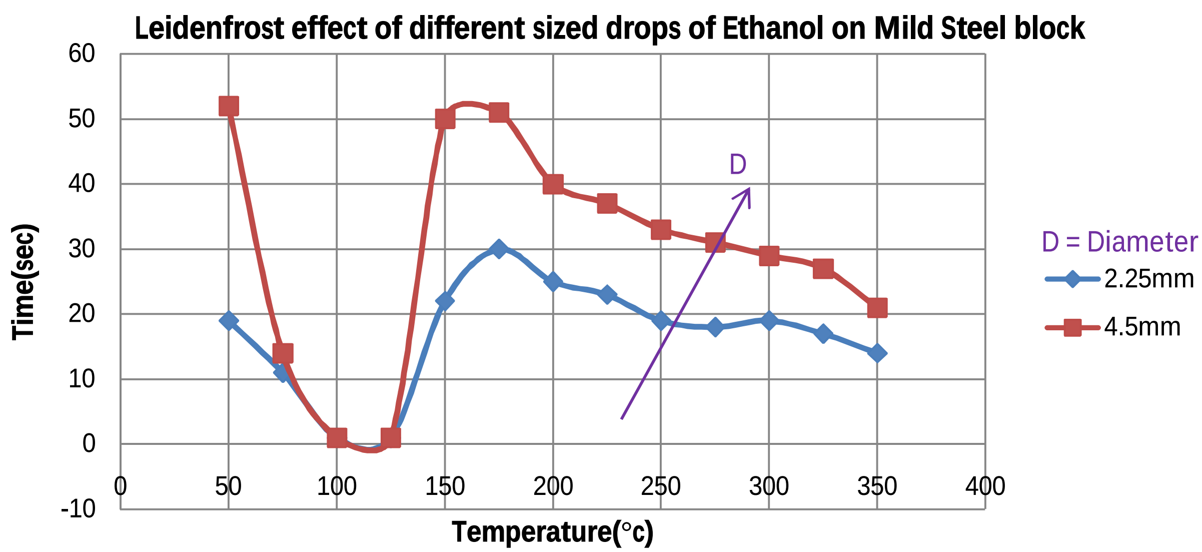


Fig 4.10 : Evaporation time of Ethanol on Mild Steel block

Comparison of diameter has been done in **Fig 4.10,** using Ethanol on Mild Steel. The results are similar with maximum evaporation time at around 175^{0}C and the corresponding times are 30 sec and 51 sec for the 2.25mm and 4.5mm diameter drops respectively.

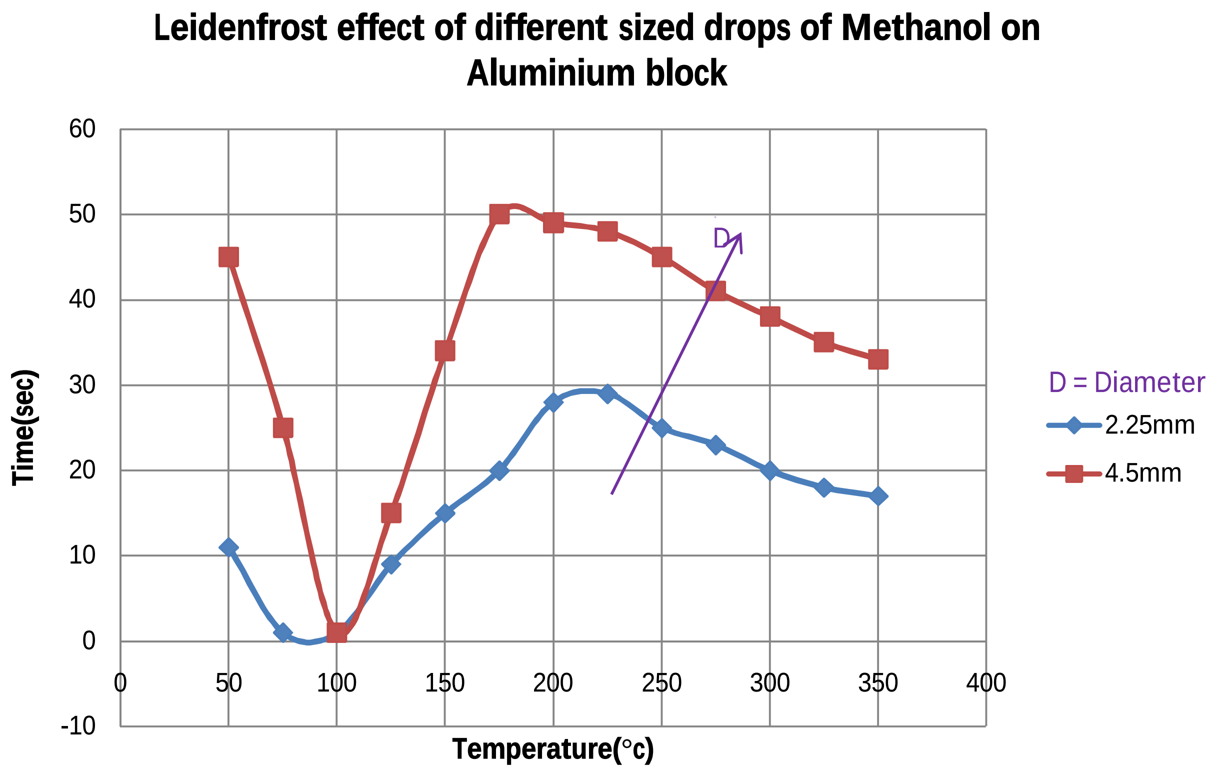


Fig 4.11 : Evaporation time of Methanol on Aluminium block

This time comparison of diameter has been done in **Fig 4.11,** using Methanol on Aluminium. The results are similar with maximum evaporation time at around 200^{0}C and the corresponding times are 28 sec and 49 sec for the 2.25mm and 4.5mm diameter drops respectively.

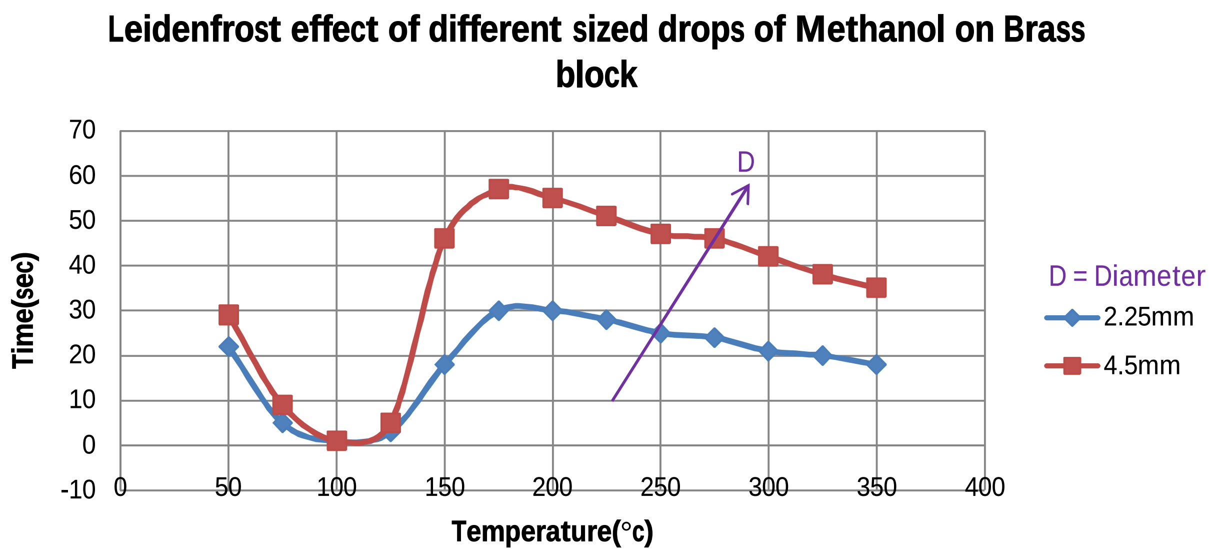


Fig 4.12 : Evaporation time of Methanol on Brass block

Here comparison of diameter has been done in **Fig 4.12,** using Methanol on Brass. The results are similar with maximum evaporation time at around 175^{0}C and the corresponding times are 30 sec and 57 sec for the 2.25mm and 4.5mm diameter drops respectively.

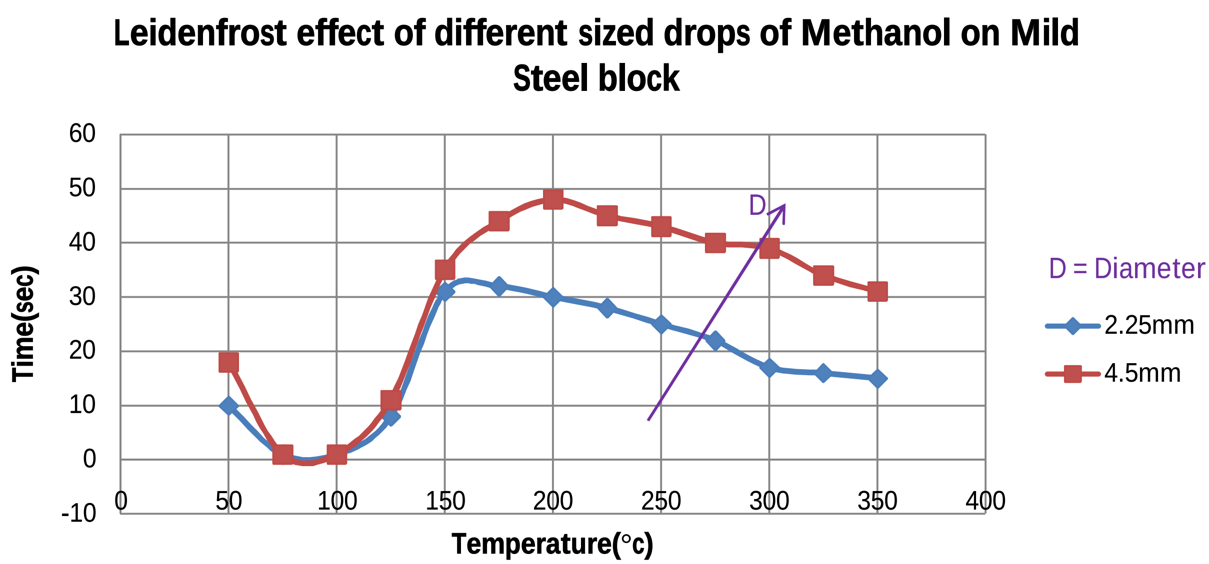


Fig 4.13 : Evaporation time of Methanol on Mild Steel block

Comparison of diameter has been done in **Fig 4.13,** using Methanol on Mild Steel. The results are similar with maximum evaporation time at around 200^0C and the corresponding times are 30 sec and 48 sec for the 2.25mm and 4.5mm diameter drops respectively.

4.3 Material Variation:

We kept the liquid fixed and changed the metal surfaces while plotting Fig. 4.14 to Fig. 4.17. For each liquid, we have plotted the total droplet vaporization time as a function of surface temperature of four different metal surfaces. We find a general trend that, vaporization time required for a specific liquid at a specific temperature is different for different metal surfaces. It happens due to different values of specific heat, thermal conductivity and density of the metal. For all cases, if specific heat, thermal conductivity and density of metal are high, Leidenfrost point time will be high. In this experiment, brass takes the maximum time, then aluminum and mild steel respectively. The droplet diameter used here was 4.5mm for all liquids

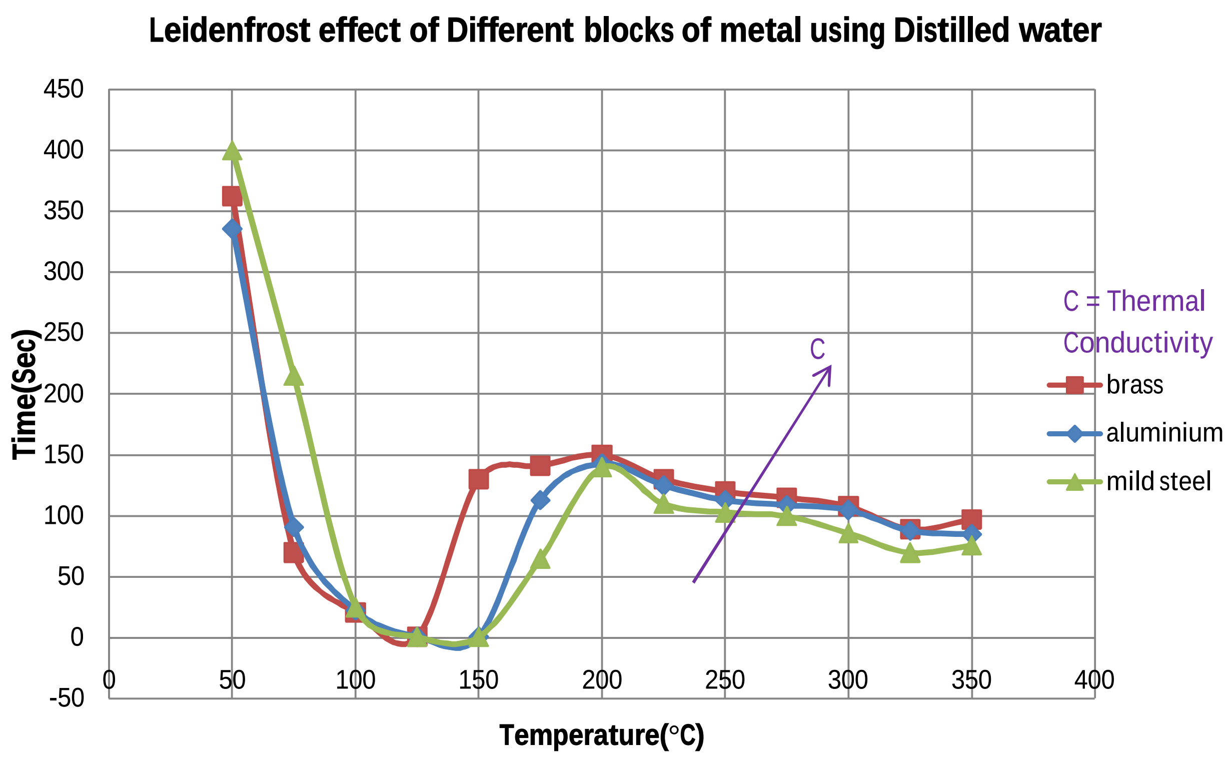


Fig 4.14 : Evaporation time of different blocks of metal using Distilled water (4.5mm)

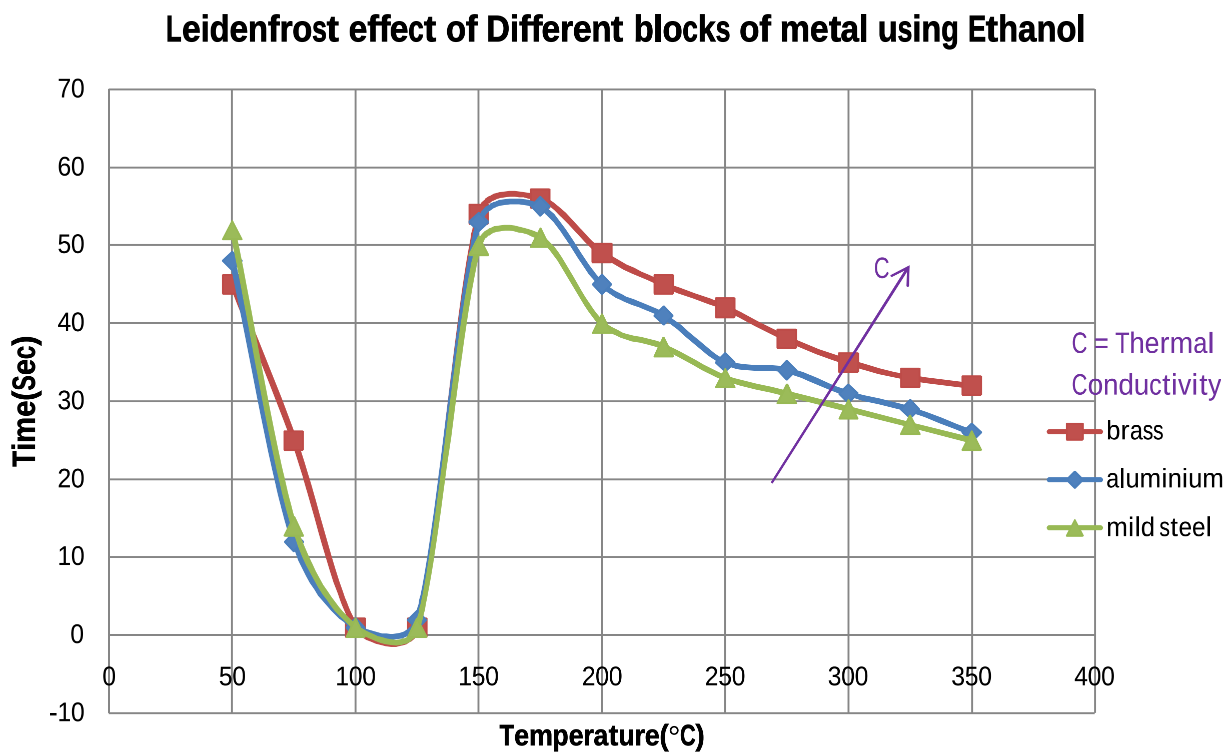


Fig 4.15 : Evaporation time of different blocks of metal using Ethanol(4.5mm)

In **Fig 4.14** evaporation times of distilled water on different metals have been compared and we observe that Brass takes the most time for vaporization. This supports our theoretical predictions based on thermal conductivity, density and specific heat. In **Fig 4.15** the same has been done for Ethanol.

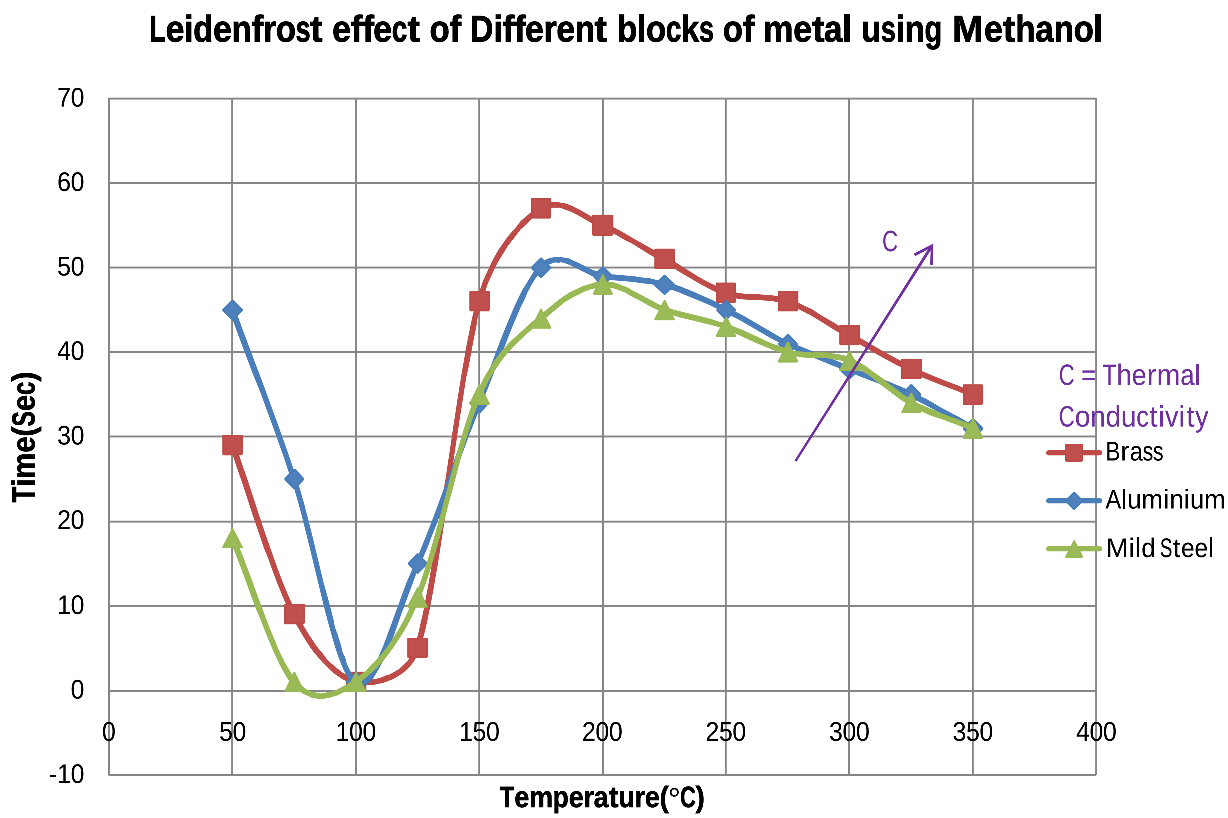


Fig 4.16 : Evaporation time of different blocks of metal using Methanol(4.5mm)

In **Fig 4.16** evaporation times Methanol on different metals have been compared and again we observe that Brass takes the most time for vaporization, thus supporting our theoretical predictions based on thermal conductivity, density and specific heat

In **Fig 4.17** a similar comparison of metals has been done using acetone as the liquid and identical results were obtained.

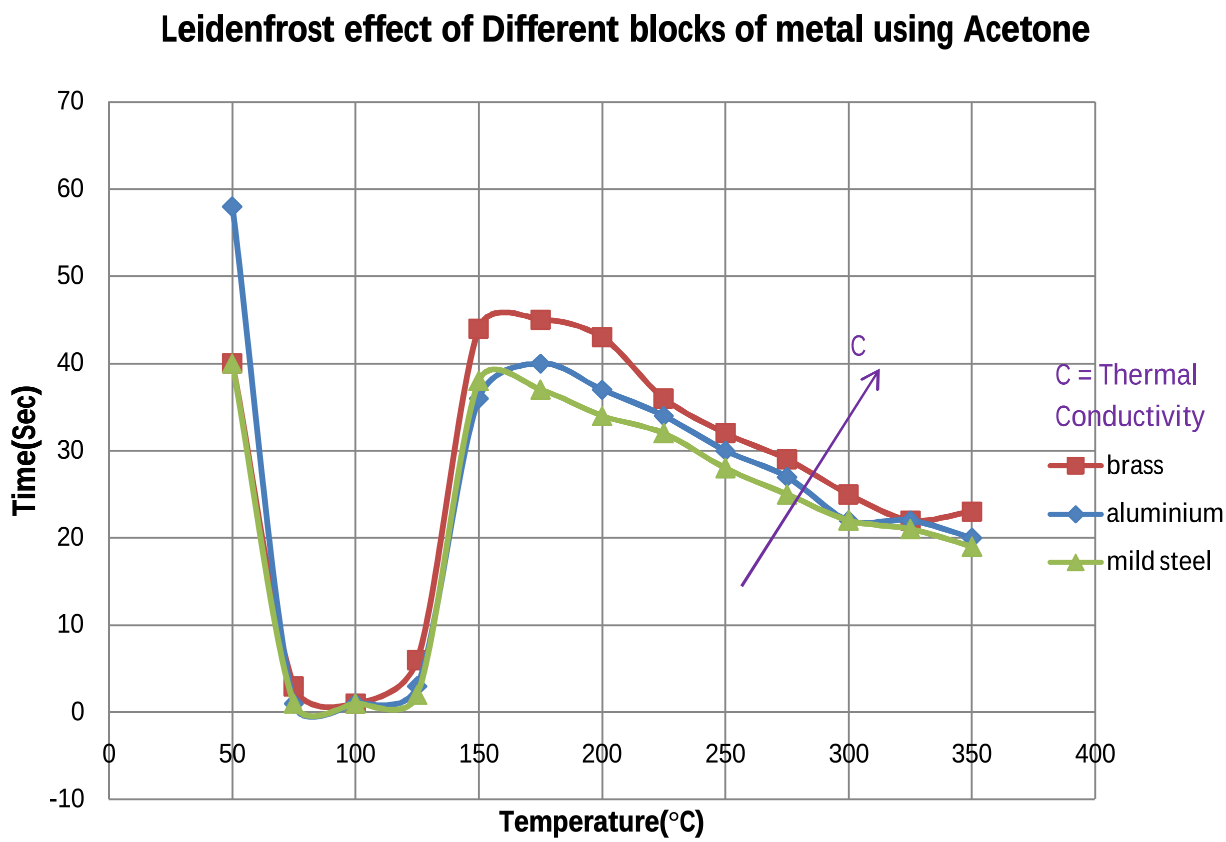


Fig 4.17 : Evaporation time of different blocks of metal using Acetone(4.5mm)

4.4 Liquid Variation:

In this experiment we have plotted evaporation time of different liquids on a specific metal surface (Figure 4.18 to Figure 4.20). Different liquids on a specific metal surface took different time to evaporate.

A liquid having a higher latent heat of vaporization should take more time to evaporate. Water has the maximum heat of vaporization compared to methanol and ethanol so it should take the highest time to evaporate

Evaporation time and Leidenfrost point temperature of the liquid also depends on the specific heat, thermal conductivity and density of the liquid. Higher the specific heat, thermal conductivity and density of the liquid Leidenfrost temperature should be lower,

Evaporation time also depends on boiling temperature of the liquid. The liquid which has higher boiling point will take more time to evaporate.

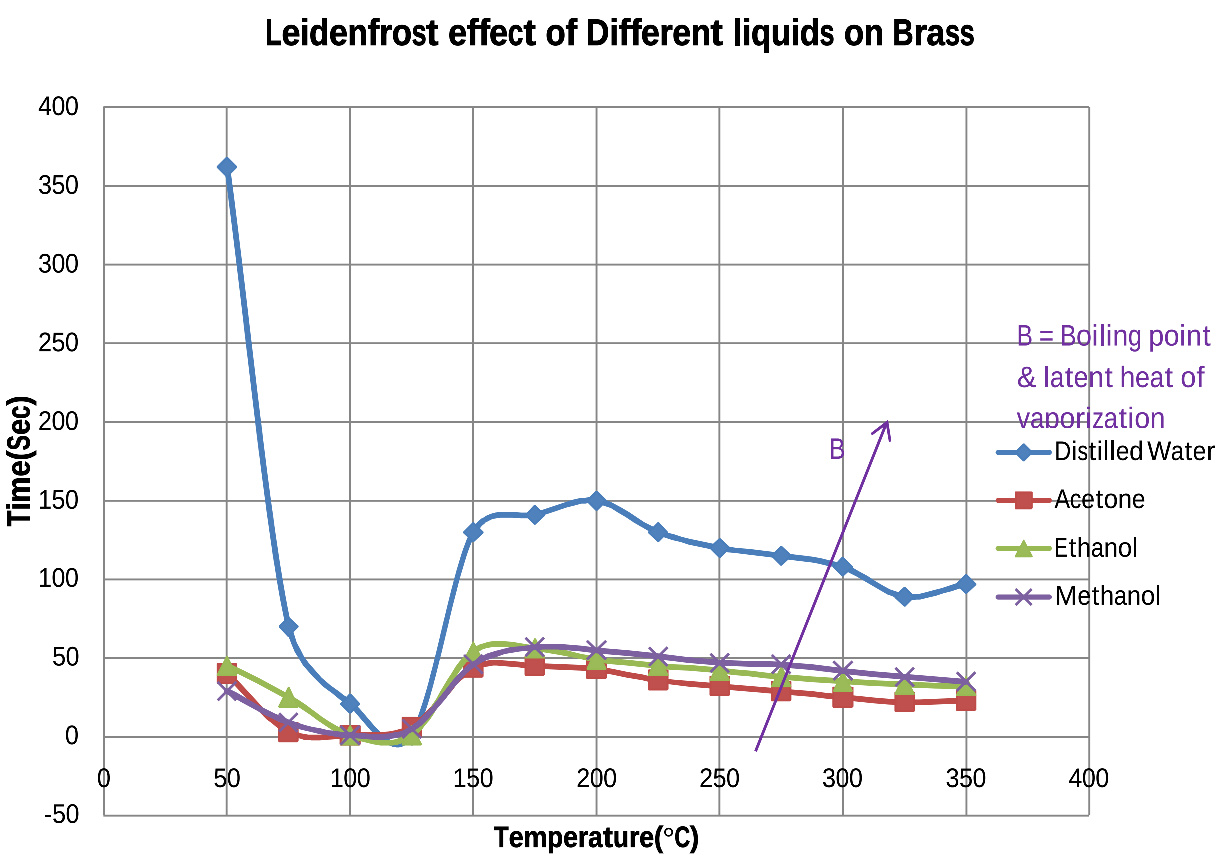


Fig 4.18: Evaporation time of Different liquids on Brass block

We see from **Fig 4.18** that Distilled Water has the highest evaporation time.

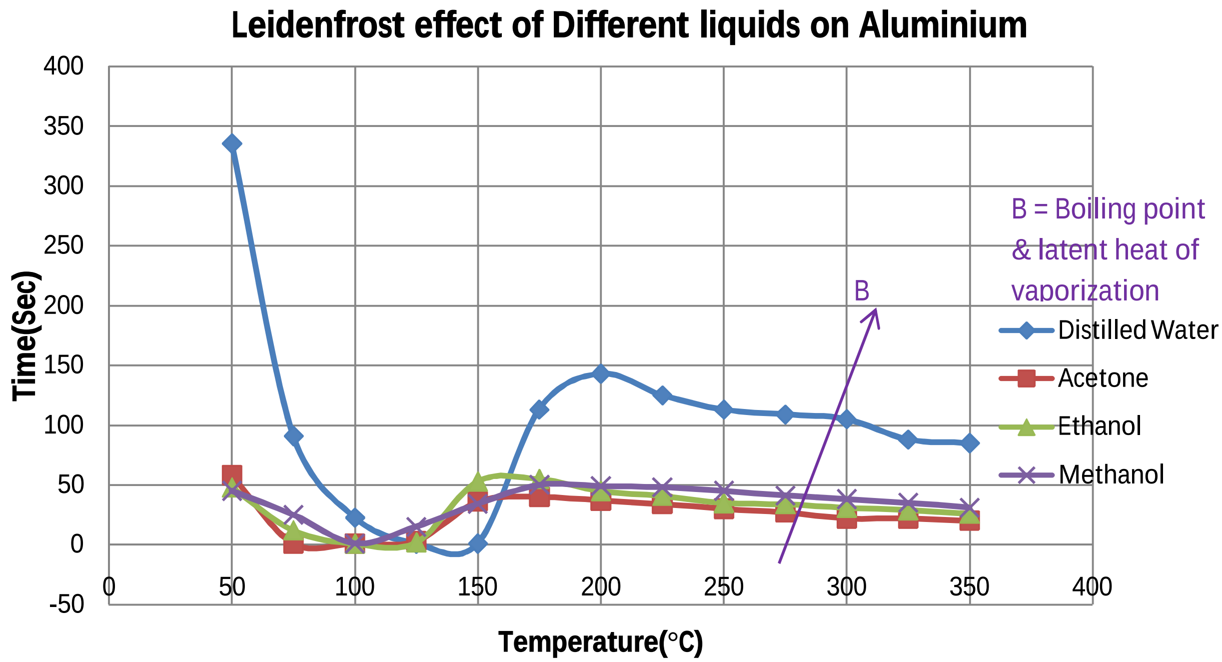


Fig 4.19 : Evaporation time of Different liquids on Aluminium block

From all three graphs (**Fig 4.18-4.20)** we find that the evaporation times vary based on liquids according to the expected nature. Distilled Water always has the highest time due to high latent heat of vaporization, low specific heat, thermal conductivity and density and high boiling temperature

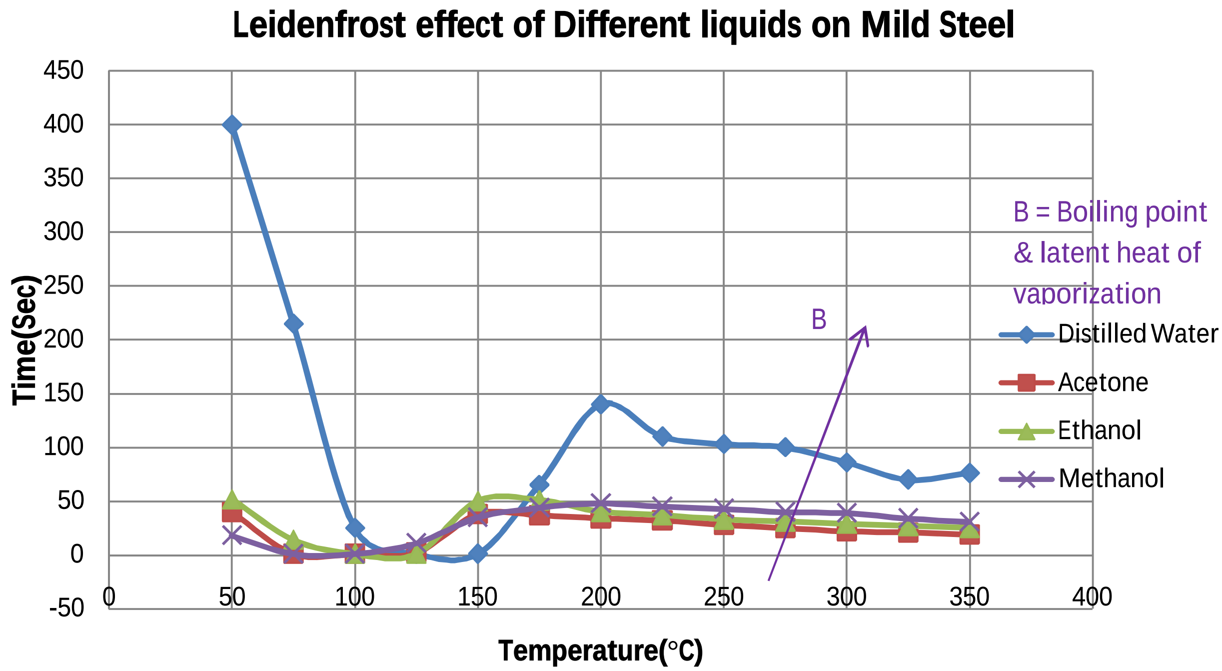


Fig 4.20 : Evaporation time of Different liquids on Mild Steel block

Water has highest boiling point (100^0C) comparing to methanol (64.7^0C) ,ethanol (78.3^0C) and acetone (56^0C) so water takes highest time to evaporate.

4.5 <u>Overall Comparison:</u>

In this comparison we have used the maximum evaporation time of each metal-liquid combination, i.e the Leidenfrost time and plotted it against the thermal conductivity of metals.

It is evident that higher thermal conductivity results in higher Leidenfrost time. This is because high thermal conductivity allows fast heat transfer from the metal to the vapor film, keeping the vapor film stable and thus preventing direct contact of the drop with the metal surface. This is true until about 200 °C because after that the system becomes quite stable and thermal conductivity hardly has an effect on the evaporation time.

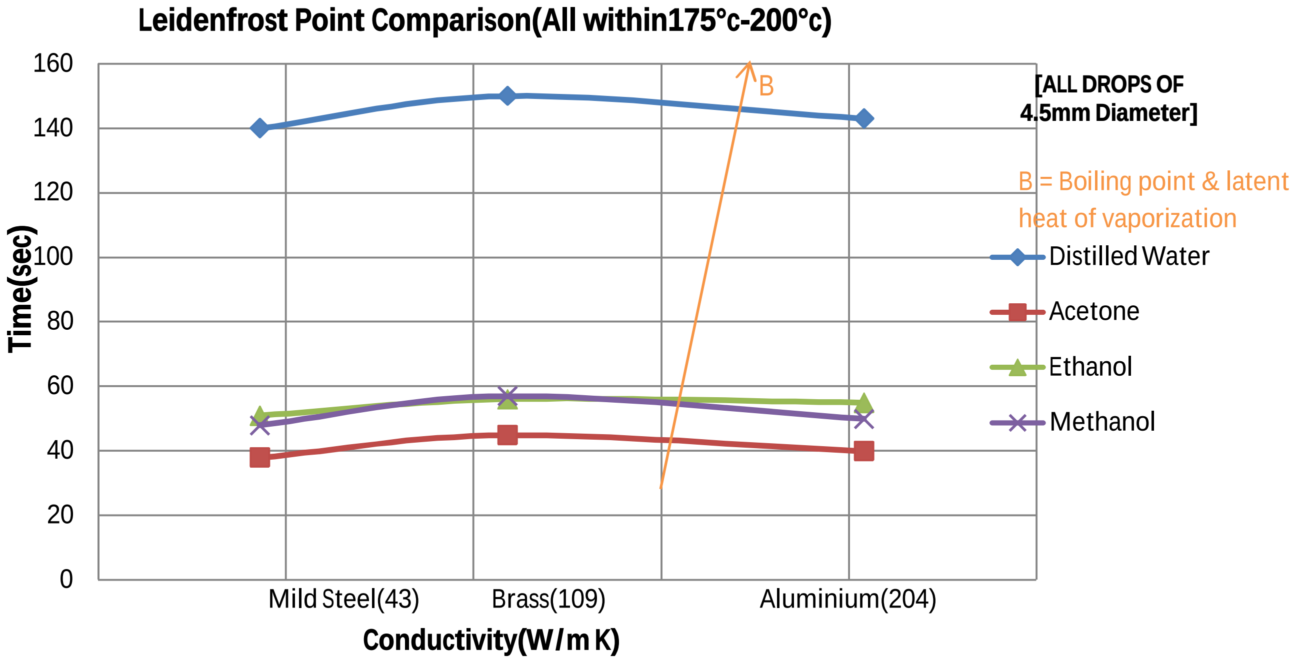


Fig 4.21 : Leidenfrost Time comparison of 4.5mm liquid drops basing on Thermal Conductivity of metals

Fig 4.21 shows the variation of Leidenfrost time with metals(Thermal conductivity). The reason for a slight drop in time for Aluminium is its lower density compared to Mild Steel and Brass. Brass has the highest vaporization time at its Leidenfrost point. The droplet diameter considered here is 4.5mm

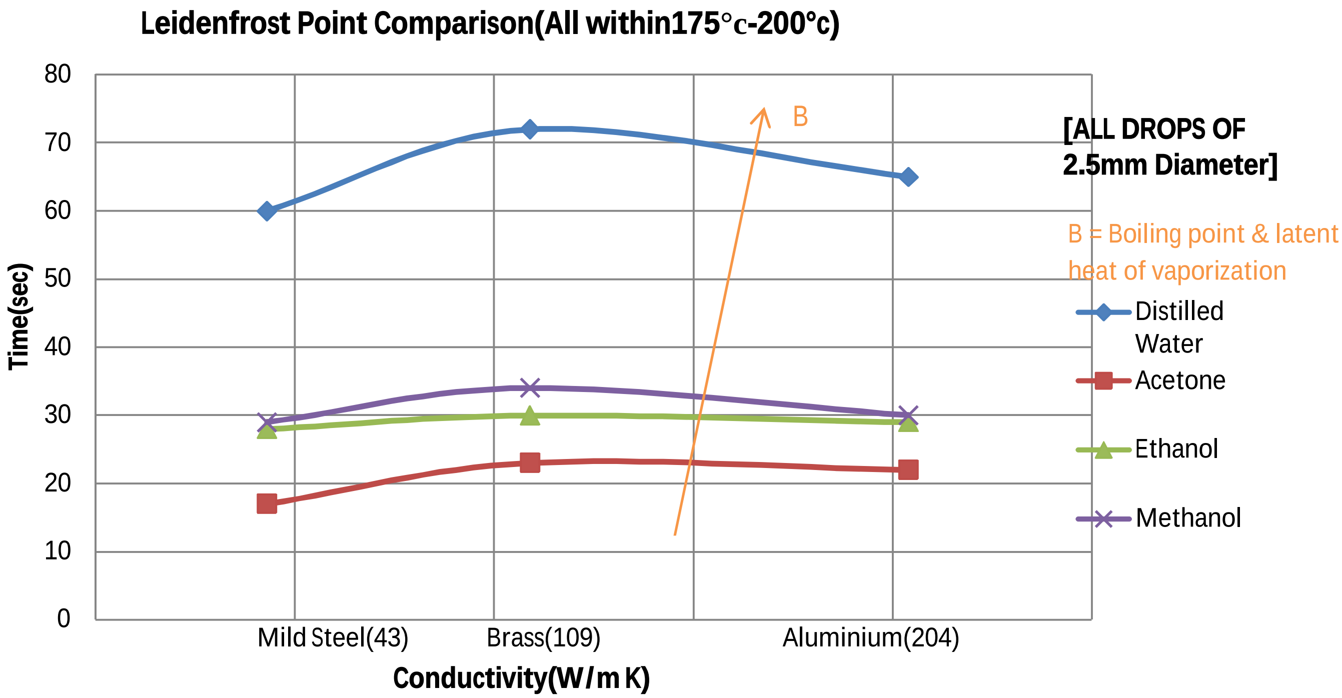


Fig 4.22 : Leidenfrost Time comparison of 2.25mm liquid drops basing on Thermal Conductivity of metals

In **Fig 4.22** a similar comparison has been done using 2.25mm liquid drops, the results are similar and supports our theoretical predictions.

4.6 Results:
4.6.1 Table of Experimental Results:

The experimental results have been tabulated below for 4.5mm drops of liquid in all cases.

Table 4.1

Aluminium Block		
Liquid	**Leidenfrost Time (sec)**	**Leidenfrost Temperature (^{0}C)**
Acetone	40	175
Ethanol	55	175
Methanol	49	200
Distilled Water	143	200

Table 4.2

Brass Block		
Liquid	**Leidenfrost Time (sec)**	**Leidenfrost Temperature (^{0}C)**
Acetone	45	175
Ethanol	56	175
Methanol	57	175
Distilled Water	141	200

Table 4.3

Mild Steel Block		
Liquid	**Leidenfrost Time (sec)**	**Leidenfrost Temperature (^{0}C)**
Acetone	37	175
Ethanol	51	175
Methanol	48	200
Distilled Water	140	200

4.6.2 Analysis of experimental results:

4.6.2.1 Effect of latent heat of vaporization:

A liquid having a higher latent heat of vaporization should take more time to evaporate. This phenomenon is verified in our experiment (Figure 4.18 to Figure 4.20). Water has the maximum heat of vaporization compared to methanol and ethanol so it takes the highest time to evaporate among the all liquids for different metal surfaces (Aluminum, Brass and Mild steel).

4.6.2.2 Effect of thermal conductivity and density of metal:

Higher thermal conductivity results in higher Leidenfrost time. This is because high thermal conductivity allows fast heat transfer from the metal to the vapor film, keeping the vapor film stable and thus preventing direct contact of the drop with the metal surface. Thermal conductivity is 109 W/mk for brass, 204 W/mk for aluminum and 43 W/mk for mild steel (1% carbon). So the mild steel has the lowest thermal conductivity. Again Aluminium has the least density among the three metals. It is found from the **Fig 4.21** and **Fig 4.22** that the Leidenfrost time is higher for Brass than Mild Steel due to thermal conductivity, but it drops again for Aluminium due to its lower density.

4.6.2.3 Effect of specific heat, thermal conductivity and density of liquid:

Evaporation time and Leidenfrost point temperature of the liquid depends on the specific heat, thermal conductivity and density of the liquid. Higher the specific heat, thermal conductivity and density of the liquid Leidenfrost time will be lower as we observe in the experiment.

4.6.2.4 Effect of boiling temperature of liquid:

Evaporation time also depends on boiling temperature of the liquid. The liquid which has higher boiling point will take more time to evaporate. In this experiment we observe this phenomenon as water has highest boiling point (100^0C) comparing to methanol (64.7^0C) ,ethanol (78.3^0C) and acetone (56^0C) so water takes highest time to evaporate

4.7 Discussion:

1. Surface finish is very important for determining the Leidenfrost temperature. In our experiment we tried to make the test surface as smooth as possible.
2. The chemicals used in our experiment might not be 100% pure, but we tried to use the purest chemicals available. Slight deviation in results due to impurity may be neglected.
3. The temperature readings may often vary due to numerous conditions, so to avoid any error temperature was re-checked several times. The variac was adjusted in a way as to maintain a constant temperature when liquid was dropped.
4. It was always a priority to reduce human error as much as possible when taking time readings.
5. Heat loss from the block was kept minimum to maintain a stable block temperature and surrounding environmental conditions were kept constant as far as possible.

CHAPTER 5

CONCLUSIONS

5.1 Conclusion:

Leidenfrost phenomenon is a complex process involving many parameters. In order to get a clear view of the process further investigation of experimental and theoretical model is necessary. From our experiment conducted on Leidenfrost phenomenon we can conclude the following things.

1. At the beginning of the experiment when the temperature is low time for evaporation is very high, because heat transfer to the drop is very low.

2. For all liquids evaporation time is usually lowest in the nucleate boiling region around 100^0C -135^0C.

3. At Leidenfrost temperature the heat entering in the liquid is minimum due to the vapor film created between the liquid and solid surface as a result, the evaporation time is maximum at that point.

4. Larger drop size results in higher evaporation time for all liquids, because larger drop has higher volume of liquid.

5. Before Leidenfrost point convective heat transfer is dominant and after Leidenfrost point radiation heat transfer becomes dominant.

6. The graph prepared by plotting evaporation time against temperature is just opposite to the conventional boiling curve.

7. Leidenfrost temperature is always in the same temperature region for all liquids on each metal and the region is 175^0C to 200^0C. This is because Leidenfrost point is independent of types of liquids and metals.

8. Water has the highest Leidenfrost time for all test blocks, due to its higher boiling point, latent heat of vaporization, specific heat and thermal conductivity.

5.2 Further Work:

Modern age is being adorned with the advancement of technology every day. The more we advance the more we will be able to keep pace with the growing technology. This advancement of technology is basically the consequence of the never ending desire of human to have the latest inventions of the science era. Thus more experiments and more work is necessary to meet this desire in every research sector so as in the Leidenfrost phenomenon like:

1. The Leidenfrost Phenomenon on composite materials.

2. The Leidenfrost Phenomenon for cryogenic fluids.

3. The Leidenfrost effect for mixture of two or more liquids (mixture of ethanol and methanol, etc.)

5.3 Recommendations:

1. In our research we used three metal blocks. More blocks can be used to determine and verify the Leidenfrost effect.

2. Instead of using four working liquid we can use more test liquids of different nature.

3. Liquids having larger specific heat can be used to find the Leidenfrost phenomenon.

4. We increased the temperature of the test surface at an increment of 25^0C. This increment can be smaller which may provide more accurate curve.

5. Leidenfrost phenomenon may be experimented with higher temperature range (up to 500^0C and more).

6. The theoretical value of Leidenfrost point can be obtained by using correlation and compared with the experimental value.

APPENDIX A

DATA COLLECTION

A1 Acetone on Aluminum Block (2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	38	32	31	33.67
75	1	1	1	1
100	3	1	3	2.33
125	3	2	5	3.33
150	21	18	19	19.33
175	18	23	21	20.67
200	24	20	19	21
225	18	14	17	16.33
250	14	13	16	14.33
275	17	12	13	14
300	10	14	13	12.33
325	13	10	12	11.67
350	10	12	12	11.33

A2 Acetone on Mild Steel (2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	45	39	38	40.67
75	1	1	1	1
100	1	1	1	1
125	2	1	2	1.67
150	16	17	14	15.67
175	19	17	16	17.33
200	18	14	19	17
225	16	15	16	15.67
250	18	19	16	17.67
275	14	15	17	15.33
300	13	14	11	12.67
325	10	13	11	11.33
350	10	11	9	10

A3 Acetone on Brass (2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	45	38	39	40.67
75	2	4	2	2.67
100	1	1	1	1
125	3	4	3	3.33
150	20	23	22	21.67
175	24	25	20	23
200	18	21	19	19.33
225	20	19	17	18.67
250	16	18	17	17
275	21	16	18	18.33
300	13	14	17	14.67
325	11	15	12	12.67
350	13	13	12	12.33

A4 Ethanol on Aluminum (2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	23	25	25	24.33
75	6	7	7	6.67
100	1	1	1	1
125	2	2	3	2.33
150	20	15	16	17
175	33	27	29	29.67
200	26	27	23	25.33
225	25	23	19	22.33
250	19	21	21	20.33
275	17	17	15	16.33
300	18	13	19	16.67
325	17	15	14	15.33
350	12	18	13	14.33

A5 Ethanol on Mild Steel (2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	19	21	17	19
75	12	10	13	11.67
100	1	1	1	1
125	1	1	1	1
150	22	25	22	23
175	31	28	33	30.67
200	25	25	26	25.33
225	21	25	23	23
250	20	20	18	19.33
275	16	21	19	18.67
300	16	22	19	19.67
325	17	16	18	17
350	13	16	14	14.33

A7 Ethanol on Brass (2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	23	26	27	25.33
75	11	13	9	11
100	1	1	1	1
125	1	1	1	1
150	23	24	21	22.67
175	25	27	30	27.33
200	26	27	25	26
225	24	27	29	26.67
250	22	25	24	23.33
275	21	19	16	18.67
300	19	17	21	19
325	15	16	20	17.67
350	20	15	19	18.67

A6 Methanol on Aluminum (2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	13	10	11	11.33
75	1	1	1	1
100	1	1	1	1
125	11	10	7	9.33
150	16	17	12	15
175	21	20	18	19.66
200	31	25	21	28.33
225	27	32	30	29.67
250	24	26	27	25.62
275	26	21	23	23.35
300	21	18	22	20.33
325	16	21	18	18.31
350	18	21	14	17

A8 Methanol on Mild steel (2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	11	9	12	10.67
75	1	1	1	1
100	1	1	1	1
125	10	7	9	8.66
150	30	28	33	30.33
175	35	31	30	32.68
200	29	31	31	30.34
225	30	26	29	28.67
250	21	26	29	25.33
275	24	19	23	22.34
300	19	16	18	17.68
325	15	19	16	16.67
350	13	17	16	15.33

A9 Methanol on Brass (2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	22	21	23	22
75	7	4	5	5.34
100	1	1	1	1
125	3	2	4	3
150	20	17	19	18.67
175	33	29	30	30.66
200	31	30	29	30
225	27	30	28	28.33
250	27	26	23	25.33
275	25	27	22	24.67
300	23	20	22	21.66
325	22	20	19	20.33
350	19	17	18	18

A11 Acetone on Aluminum (4.50mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	59	60	57	58
75	1	1	1	1
100	1	1	1	1
125	3	3	4	3.33
150	36	34	39	36.33
175	41	42	38	40.33
200	38	40	35	37.67
225	34	36	33	34.33
250	31	30	29	30
275	28	25	30	27.67
300	25	21	22	22.67
325	22	24	20	22
350	23	21	19	20.66

A10 Acetone on Mild Steel (4.50mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	42	39	41	40.67
75	1	1	1	1
100	1	1	1	1
125	3	2	2	2.33
150	39	38	37	38
175	37	39	36	37.33
200	35	33	36	34.67
225	34	30	32	32
250	29	30	27	28.67
275	25	24	27	25.33
300	20	24	23	22.33
325	23	21	19	21
350	21	20	18	19.67

A12 Acetone on Brass (4.50mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	41	39	42	40.67
75	3	4	2	3
100	1	1	1	1
125	7	5	6	6
150	42	45	47	44.67
175	46	43	44	45.33
200	41	45	43	43
225	38	35	37	36.67
250	30	34	33	32.33
275	31	28	30	29.67
300	27	24	26	25.67
325	24	22	23	22
350	22	23	25	23.33

A13 Ethanol on Aluminum (4.50mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	47	49	48	48
75	15	13	12	12.33
100	1	1	1	1
125	3	2	3	2.67
150	54	54	52	53.33
175	53	57	56	55.33
200	48	43	42	45.67
225	43	41	40	41.33
250	37	35	34	35.33
275	31	33	32	32
300	33	30	31	31.33
325	28	27	30	28.33
350	27	25	28	26.67

A14 Ethanol on Mild Steel (4.50mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	54	50	53	52.33
75	13	16	15	14.67
100	1	1	1	1
125	1	1	1	1
150	51	50	49	50
175	53	50	51	51.33
200	42	39	40	40.33
225	38	35	39	37.33
250	35	32	31	33.67
275	30	33	32	31.67
300	31	28	29	29.33
325	29	26	28	27.67
350	23	21	20	21.33

A15 Ethanol on Brass (4.50mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	46	43	47	45.33
75	25	24	26	25
100	1	1	1	1
125	1	1	1	1
150	53	56	54	54.33
175	53	59	57	56.33
200	50	51	48	49.67
225	46	47	43	45.67
250	41	43	42	42
275	39	40	37	38.67
300	33	36	37	35.33
325	32	35	33	33.33
350	34	33	31	32.67

A16 Distilled Water on Aluminium(1.5mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	335	335	337	335.67
75	91	92	90	91
100	23	21	24	22.67
125	1	1	1	1
150	1	1	1	1
175	14	14	16	14.7
200	23	27	25	25
225	20	19	22	20.33
250	23	20	23	22
275	20	22	23	21.67
300	17	17	19	17.69
325	15	17	16	16
350	21	22	19	20.67

A17Distilled Water on Aluminium(2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	335	335	337	335.67
75	91	92	90	91
100	23	24	21	22.667
125	1	1	1	1
150	1	1	1	1
175	20	23	21	21.33
200	65	63	65	64.33
225	58	60	61	59.67
250	63	65	65	64.33
275	53	55	56	54.67
300	48	48	47	47.66
325	46	44	45	46
350	38	35	37	36.67

A18 Distilled Water on Aluminium(4.5mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	335	335	337	335.67
75	91	92	90	91
100	23	24	21	22.667
125	1	1	1	1
150	1	1	1	1
175	114	114	115	114.33
200	143	146	142	143.67
225	124	124	126	124.67
250	114	112	113	113
275	111	109	108	109.33
300	105	105	104	104.67
325	88	88	89	88.33
350	87	85	85	85.67

A19 Distilled Water on Brass (1.5mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	364	362	362	362.67
75	70	70	71	70.33
100	20	24	21	21
125	1	1	1	1
150	39	40	37	38.67
175	43	41	43	42.33
200	41	38	39	39.33
225	33	32	34	33
250	32	31	31	31.33
275	32	32	31	31.67
300	33	35	34	34
325	31	33	34	32.67
350	31	33	30	31.33

A20 Distilled Water on Brass(2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	364	362	362	362.67
75	70	70	71	70.33
100	20	24	21	21
125	1	1	1	1
150	73	73	71	72.33
175	68	70	72	70
200	68	69	68	68.33
225	59	57	59	58.33
250	58	58	57	56.67
275	44	42	41	42.33
300	43	46	44	44.33
325	41	38	42	40.33
350	40	41	39	40

A21 Distilled Water on Brass(4.5mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	364	362	362	362.67
75	70	70	71	70.33
100	20	24	21	21
125	1	1	1	1
150	132	130	129	130.33
175	143	140	142	141.67
200	150	153	148	150.33
225	132	131	128	130.33
250	119	121	120	120
275	115	117	115	115.67
300	108	109	109	108.67
325	88	90	91	89.67
350	97	98	96	97

A22 Distilled Water on Mild Steel(1.5mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	405	398	400	401
75	53	49	52	51.33
100	17	13	15	15
125	1	1	1	1
150	1	1	1	1
175	28	23	24	25
200	42	40	37	39.67
225	33	28	30	30.33
250	20	23	19	20.67
275	15	18	17	16.67
300	13	17	15	15
325	14	16	17	15.67
350	16	14	14	15.33

A23 Distilled Water on Mild Steel(2.25mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	410	400	413	407.67
75	57	65	61	61
100	20	25	21	22
125	1	1	1	1
150	1	1	1	1
175	54	49	51	51.33
200	63	60	61	61.33
225	52	56	55	54.33
250	51	55	48	51.33
275	48	52	49	49.67
300	33	37	34	34.67
325	42	37	38	39
350	38	36	32	35.33

A24 Distilled Water on Mild Steel(4.5mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	413	398	400	403.67
75	218	215	214	215.67
100	25	23	28	25.33
125	1	1	1	1
150	1	1	1	1
175	64	69	63	65.33
200	139	141	145	141.67
225	113	109	110	110.67
250	107	100	103	103.33
275	103	100	98	100.33
300	84	89	82	88.33
325	68	70	74	70.67
350	80	73	77	76.67

A25Methanol on Aluminium Block(4.5mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	42	47	48	45.67
75	26	21	29	25.33
100	1	1	1	1
125	15	16	13	14.67
150	34	39	31	34.67
175	55	51	45	50.33
200	49	48	51	49.33
225	48	46	52	48.67
250	47	43	45	45
275	44	38	41	41
300	36	41	38	38.33
325	32	38	36	35.33
350	35	33	33	33.67

A26Methanol on Mild Steel(4.5mm)

Temperature (^{0}C)	Time 1	Time 2	Time 3	Average time
50	22	16	17	18.33
75	1	1	1	1
100	1	1	1	1
125	9	14	10	11
150	39	32	35	35.33
175	49	41	43	44.33
200	51	46	48	48.33
225	42	49	45	45.33
250	43	46	41	43.33
275	38	41	43	40.67
300	41	38	37	38.67
325	31	37	35	34.33
350	35	28	31	31.33

A27 Methanol on Brass (4.50mm)

Temperature(^{0}C)	Time 1	Time 2	Time 3	Average time
50	34	28	26	29.33
75	7	12	9	9.33
100	1	1	1	1
125	8	3	5	5.33
150	46	51	43	46.67
175	63	59	51	57.67
200	55	50	59	54.67
225	52	51	50	51
250	47	51	45	47.67
275	50	47	42	46.33
300	38	47	42	42.33
325	42	35	38	38.33
350	33	38	36	35.67

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