Droplet Evaporation and Leidenfrost Phenomena on Metallic Surfaces

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Under the supervision of
Dr. Aloke Kumar Mozumder

In partial fulfillment of the
Requirement for the Degree
Of
Bachelor of Science in Mechanical Engineering

DEDICATION

This dissertation is dedicated to those who believes in us.

DECLARATION

We, the students of Mechanical Engineering Department, Military Institute of Science & Technology (MIST), Mirpur Cantonment, Dhaka, hereby declare that the presented paper is the Consequence of the accomplishment of the project and thesis on "**Droplet Evaporation and Leidenfrost Phenomena on Metallic Surfaces**" under The Supervision of Dr. Aloke Kumar Mozumder, Professor of 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. Sessile drop of three different liquids namely Distilled Water, Methanol and Ethanol having diameter of 1.3mm was used These liquid were dropped as sessile droplets from heights of 20mm and 50mm to conduct the experiment for a wide range of solid surface temperatures of 50-320ºC. Three solid surfaces of Brass, Aluminum and Mild Steel were used to conduct the experiment. Graphs were plotted by placing evaporation time of liquids against surface temperature of metal blocks. The temperature at which time required for evaporation is maximum is called the Leidenfrost point. These variations in liquid types, heights of droplets and metals have been done to present a clear statement that the Leidenfrost temperature range does not change for a certain liquid. The only change obtained from varying liquid, height and metal is the time of evaporation. Among these three liquids, the liquid which has higher boiling point will take more time to evaporate. Water has highest boiling point (100ºC) compared to methanol (64.7ºC) and ethanol (78.3ºC). So water takes the highest time to evaporate. Among the three metal surfaces, aluminium has the maximum thermal conductivity of 205W/mK & mild steel has the minimum thermal conductivity of 43W/mK. Higher thermal conductivity results in higher Leidenfrost time 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. But due to some unknown error, the leidenfrost time we got for water on aluminium surface is 112.03s and for water on mild steel, it is 114.72s. Here too, water takes higher time to evaporate and the temperature is 180ºC. So, for all the metal blocks and test liquids dropped from different heights used in this experiment, Leidenfrost temperature is within the range of 150ºC -180ºC and a specific temperature for each liquid. This concludes to the fact that Leidenfrost point for a certain liquid does not change for any parameter.

CHAPTER 1
INTRODUCTION

1.1 Introduction

When a liquid drop falls upon a very hot solid plate, an insulating vapor layer is immediately formed between the drop and hot surface. As a result, the heat transfer rate becomes considerably less than that in the case of direct contact, i.e. nucleate boiling. This phenomenon was first investigated by J. G. Leidenfrost after whom it is named. This phenomenon has been identified by Boutigny [1843] for the first time as “spheroidal state,” as the bubbles take the shapes of spheres.

A common technique used for determining the Leidenfrost temperature requires measuring evaporation time of liquid sessile droplets of a given initial volume over a range of surface temperatures to produces a droplet evaporation curve. The curve displays droplet evaporation time versus surface temperature and exhibits the distinct heat transfer regimes. In the single-phase regime, characterized by long evaporation times, heat from the surface is conducted through the liquid film and is dissipated by evaporation at liquid-gas interface. In the nucleate boiling regime, vapor bubble production and corresponding heat flux increase dramatically, thus decreasing the droplet life-time. The upper limit of the nucleate boiling regime, known as critical heat flux (CHF), corresponds to the maximum heat flux and the minimum drop life-time. In the transition regime, a discontinuous insulating vapor layer develops beneath portions of the droplet leading to reduced evaporation rates and increased drop lifetime. At the lower end of the transition boiling regime, referred to as the “Leidenfrost Temperature” (LFP), the vapor layer grows substantially to prevent any significant contact between the drop and surface and the droplet evaporation time reaches its maximum value. At surface temperatures above the LFP, the droplet remains separated from the surface by a thin vapor layer through which heat is conducted.

The liquid masses are supported on a film of vapor formed by evaporation from lower surface of the liquid. Heat is transferred to the liquid by conduction through the vapor film and by radiation from the hot surface. Surface tension causes small liquid droplet to assume a nearly spheroidal shape, giving rise to the historical use of term spheroidal state as a synonym.

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 three different liquids as methanol, ethanol, distilled water.

1.2 Objectives

1. To determine Leidenfrost 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 heights of droplets, type of metal and finally temperature.

3. To obtain graphs by plotting temperature vs. evaporation time for different combinations of liquids of different droplet heights and metals.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

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', a 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).

2.2 Literature Review

The definitive experiment reported by Leidenfrost are on the evaporator of quiescent, relatively small masses of liquid resting on a spoon at temperatures up to red heat. Leidenfrost proposed using droplet evaporation time to measure surface temperature–a good idea, but falsely predicted. It is evident that Leidenfrost did not realize that he was conducting boiling experiment– boiling for him meant nucleate boiling; indeed, he refers to the droplet becoming more “fixed”, i.e. rigid or stable in the fire.

The 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. below the temperature of the Leidenfrost point (but still above boiling temperature). 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.

Leidenfrost effect has been used in some potentially dangerous demonstrations, such as dipping a wet finger in molten lead **[1]** or blowing out a mouthful of liquid nitrogen both enacted without injury to the demonstrator **[2]**. The latter is potentially lethal; particularly should one accidentally swallow the liquid nitrogen **[3]**.

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 complicated **[4]** 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 effect was also described by the eminent Victorian steam boiler designer, Sir William Fairbairn 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 **[5]**, he cited the work of Pierre Hippolyte Boutigny (1798-1884) and Professor Bowman of King's College, London 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 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. **[6]**

It has been demonstrated that it is possible to stabilize the Leidenfrost vapour layer of water by exploiting superhydrophobic surfaces. In this case, once the vapour layer is established, cooling never collapses the layer, and no nucleate boiling occurs; the layer instead slowly relaxes until the surface is cooled. **[7]**

Thompson and Rumford [1804] believed that a stratum of air adhere strongly to the metal surface, even beneath the drop; the poor conductance of heat through the air layer accounted for the slow evaporation. He was aware that heat conducted to the droplet supplied the latent heat of vaporization.

2.3 Boiling Modes

Boiling is the rapid vaporization of a liquid, which occurs when a liquid is heated to its boiling point, the temperature at which the vapor pressure of the liquid is equal to the pressure exerted on the liquid by the surrounding atmosphere. The higher the pressure the higher the boiling point. he process is characterized by the formation of vapor bubbles which grow and subsequently detach from the surface. Vapor bubble growth and dynamics depend, in a complicated manner, on the excess temperature, the nature of the surface and thermophysical properties of the fluid, such as its surface tension. In turn, the dynamics of vapor bubbles formation affect fluid motion near the surface and therefore strongly influence the heat transfer coefficient.

Boiling may occur under various condition. For example, in pool boiling the liquid is quiescent and its motion near the surface is due to free convection and to mixing induced by bubble growth and detachment. In contrast, for forced convection boiling fluid motion is induced by external means, as well as by free convection and bubble induced mixing. Boiling may also be classified according to whether it is subcooled or saturated. In subcool boiling, the temperature of the liquid is below the saturation temperature and bubbles formed at the surface may condense in the liquid. In contrast, the temperature of the liquid slightly exceeds the saturation temperature in saturated boiling. Bubbles formed at the surface are then propelled through the liquid by buoyancy forces, eventually escaping from a free surface.

2.4 Pool Boiling

Boiling at the surface of a body immersed in an extensive pool of motionless liquid is generally referred to as pool boiling. This type of boiling process is encountered in a number of applications, including metallurgical quenching process, flooded tube and shell evaporator (with boiling on the shellside), immersion cooling of electronic components, and boiling of water in a pot on the burner of a stove. The nature of pool boiling process varies considerably depending on the conditions at which boiling occurs. The level of heat flux, the thermochemical properties of the liquid and vapor, the surface material and finish, and physical size of the heated surface all may have an effect on the boiling process.

Saturated pool, as shown in Figure 2.1 has been studied extensively. Although there is sharp decline in the liquid temperature close the solid surface, the temperature through most of the liquid slightly above saturation. Bubble generated at the liquid–solid interface therefore rises to and are transported across the liquid–vapor surface. An appreciation for underlying physical mechanism may be obtained by examining the boiling curve.

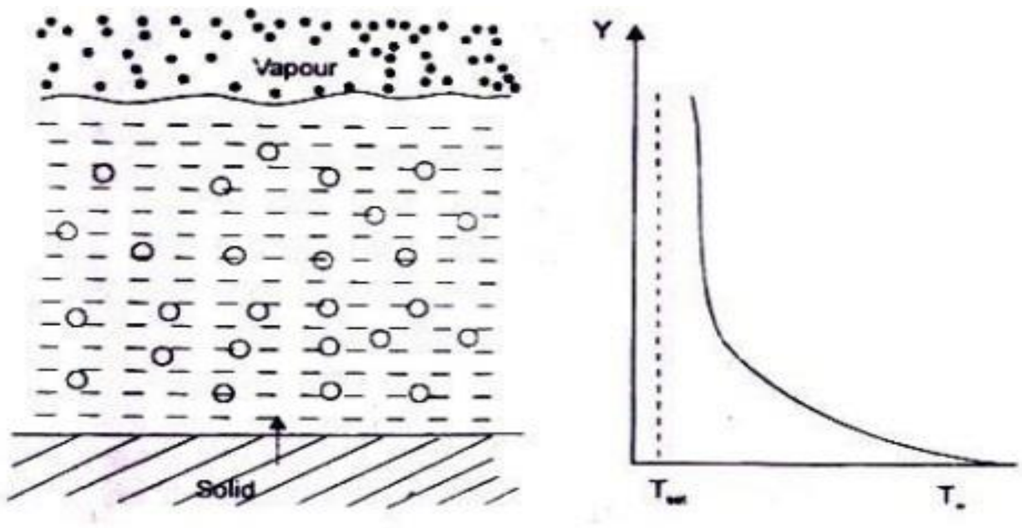

Figure 2.1: Temperature distribution in saturated pool boiling [Incropera and Dewitt [2000]

2.5 The Boiling Curve

Nukiyama was the first to identify different regimes of pool boiling. The heat flux from a horizontal nichrome wire to saturated water was determined by measuring the current flow I and potential drop E. The wire temperature was determined from knowledge of the manner in which its electrical resistance varied with temperature. This arrangement is referred to as power-controlled heating, wherein the wire temperature T_s (hence the excess temperature ΔT_s) is the dependent variable and the power setting (hence the heat flux q_s'') is the independent variable.

The Boiling Curve is defined as the heat flux q_s'' versus wall superheater, $T_w - T_{sat}$ plot on a paper. The Boiling Curve is shown in Figure 2.2. It is evident that as power is applied the heat flux increases, at first slowly and then very rapidly, with excess temperature.

2.6 Modes of Pool Boiling

An appreciation for the underlying physical mechanisms may be obtained by examining the different modes, or regimes, of pool boiling. These regimes are identified in the boiling curve of Figure 2.2. The specific curve pertains to water at 1 atm, although similar trends characterize the behavior of other fluids.

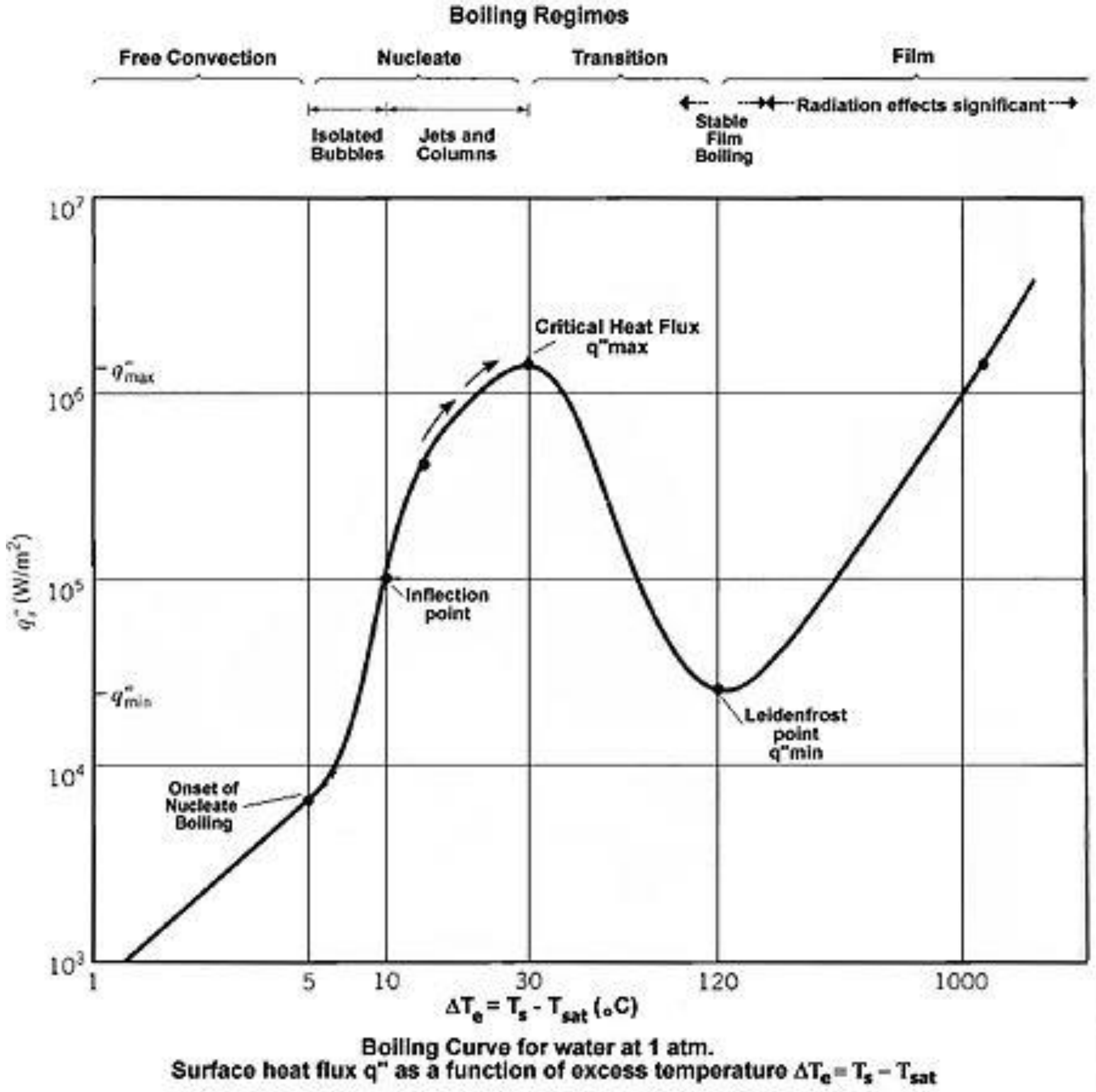

Figure 2.2: Typical boiling curve for water at 1 atm

2.6.1 Free Convection Boiling

Free convection is a mechanism, or type of heat transport, in which the fluid motion is not generated by any external source (like a pump, fan, suction device, etc.) but only by density differences in the fluid occurring due to temperature gradients. In free convection, fluid surrounding a heat source receives heat and by thermal expansion becomes less dense and rises. The surrounding, cooler fluid then moves to replace it. This cooler fluid is then heated and the process continues, forming a convection current; this process transfers heat energy from the bottom of the convection cell to top. When a liquid starts to boil during free convection is known as free convection boiling. In this case, no bubble of vapor is generated and the heat transfer occurs due to convection of the fluid.

2.6.2 Nucleate Boiling

Nucleate boiling is a type of boiling that takes place when the surface temperature is hotter than the saturated fluid temperature by a certain amount but where the heat flux is below the critical heat flux. For water, as shown in the Figure 2.2, nucleate boiling occurs when the surface temperature is higher than the saturation temperature (T_S) by between 10 °C (18 °F) to 30 °C (54 °F). The critical heat flux is the peak on the curve between nucleate boiling and transition boiling. The heat transfer from surface to liquid is greater than that in film boiling.

2.6.3 Critical Heat Flux

Critical heat flux (CHF) describes the thermal limit of a phenomenon where a phase change occurs during heating (such as bubbles forming on a metal surface used to heat water), which suddenly decreases the efficiency of heat transfer, thus causing localized overheating of the heating surface. For water, the critical flux has been shown in the Figure 2.2 where it occurs when surface temperature is higher than the saturation temperature (T_S) by 30 °C (54 °F). At this time, the heat flux become maximum. At the point of this maximum, considerable vapor is being formed, making it difficult for liquid to continuously wet surface.

2.6.4 Transition Boiling

Transition boiling is also known as unstable film boiling or partial film boiling. Transition boiling just after the critical flux point. For water, transition boiling occurs when the surface temperature is higher than the saturation temperature (T_S) by b between 30 °C (54 °F) to 120 °C (248 °F) which can be observed from Figure 2.2. Bubble formation in this region is so rapid that a vapor film or blanket begins to form on the surface. At any point on the surface, conditions may oscillate between film and nucleate boiling, but the fraction of the total surface covered by the film increases with increasing temperature. As the thermal conductivity of the vapor is much less than that of the liquid, heat flux decreases with increasing temperature.

2.6.5 Film Boiling

Film boiling occurs when the heat flux is minimum. The temperature at which the heat flux is minimum is referred to as the Leidenfrost Temperature. the surface is completely covered by a vapor blanket. Heat transfer from the surface to liquid occurs by conduction through the vapor. It was Leidenfrost who in 1756 observed that water droplets supported by the vapor film slowly boil away as they move about a hot surface. As the surface temperature is increased, radiation through the vapor film become significant and the heat flux increases with increasing temperature. For water, film boiling occurs when the surface temperature is higher than the saturation temperature (T_S) by 120 °C (248 °F) or more and that can be observed from Figure 2.2.

2.7 Leidenfrost Point

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.

2.8 Leidenfrost’s Experiment

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. After placing the drop of water into the spoon he noticed that glowing iron around the drop is darker than the rest. He deduced that "the matter of light and fire from the glowing iron is suddenly snatched into the water" 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 10s. Additional drops lasted only a few seconds. **[8]**

Figure 2.3: A water droplet experiencing Leidenfrost effect on a hot stove plate

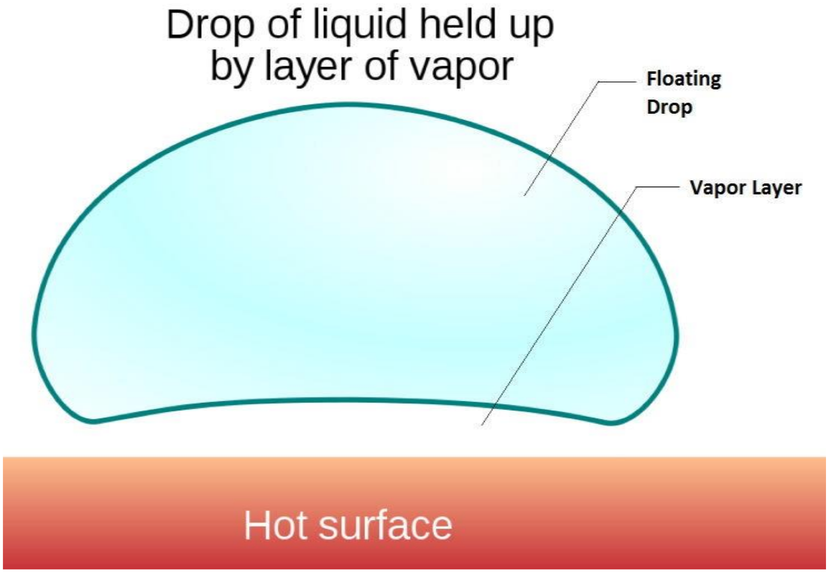

Figure 2.4: A Leidenfrost drop in cross section

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 (Figure 2.4). 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.

2.9 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 that is shown in Figure 1(a). The air bubbles gradually inflate, and then they begin to pinch off from the crevices and rise to the top surface of the water that is shown in Figure 2(b–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.

Water that is directly exposed to the atmosphere boils at what is sometimes called its normal boiling temperature T_S. For example, T_S is about 100ºC when the air pressure is 1 atm. Since the water at the bottom of the pan is not directly exposed to the atmosphere, it remains liquid even when it superheats above T_S by a few degrees. During this process, the water is constantly mixed by convection as hot water rises and cooler water descends. 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 Figure 2.5. 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 its 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

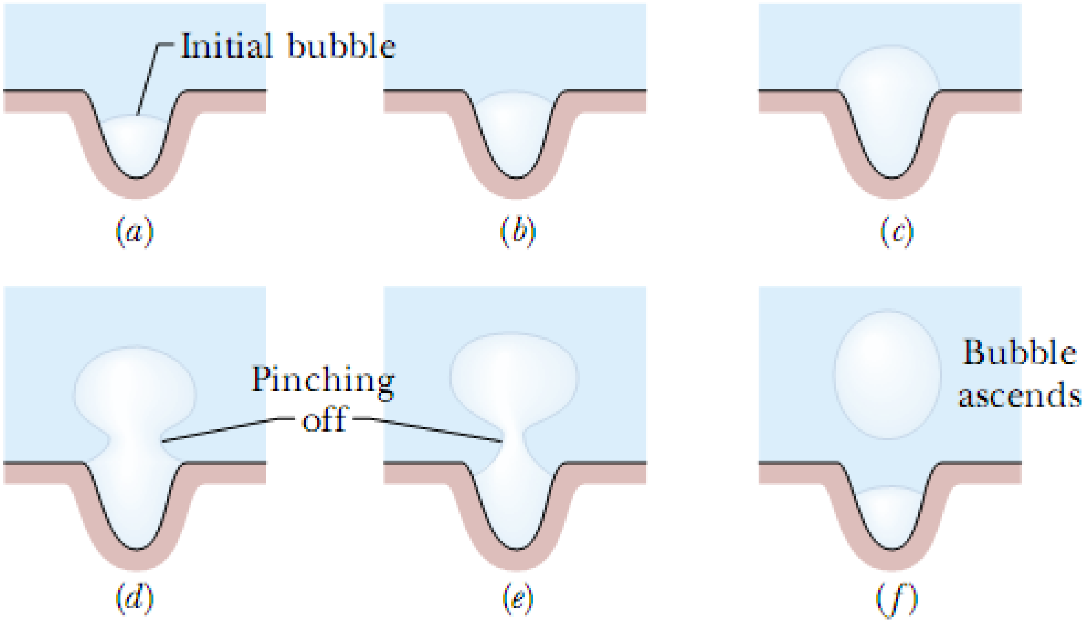

Figure 2.5: (a) A bubble forms in the crevice of a scratch along the bottom of a pan of water. (b–f) The bubble grows, pinches off, and then ascends through the water.

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 conduction. This phase is called film boiling. The fact that a water drop is long lived when deposited on metal that is much hotter than the boiling temperature of water was first reported by Hermann Boerhaave in 1732. It was not investigated extensively until 1756 when Johann Gottlob Leidenfrost published "A Tract About Some Qualities of Common Water." In addition, the temperature corresponding to the peak in a graph is called the Leidenfrost Temperature. When the temperature of the plate is less than the Leidenfrost Temperature, 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 Temperature, 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 Figure 2.5. 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 0.2 *mm* thick at its center, it dramatically slows the vaporization of the drop.

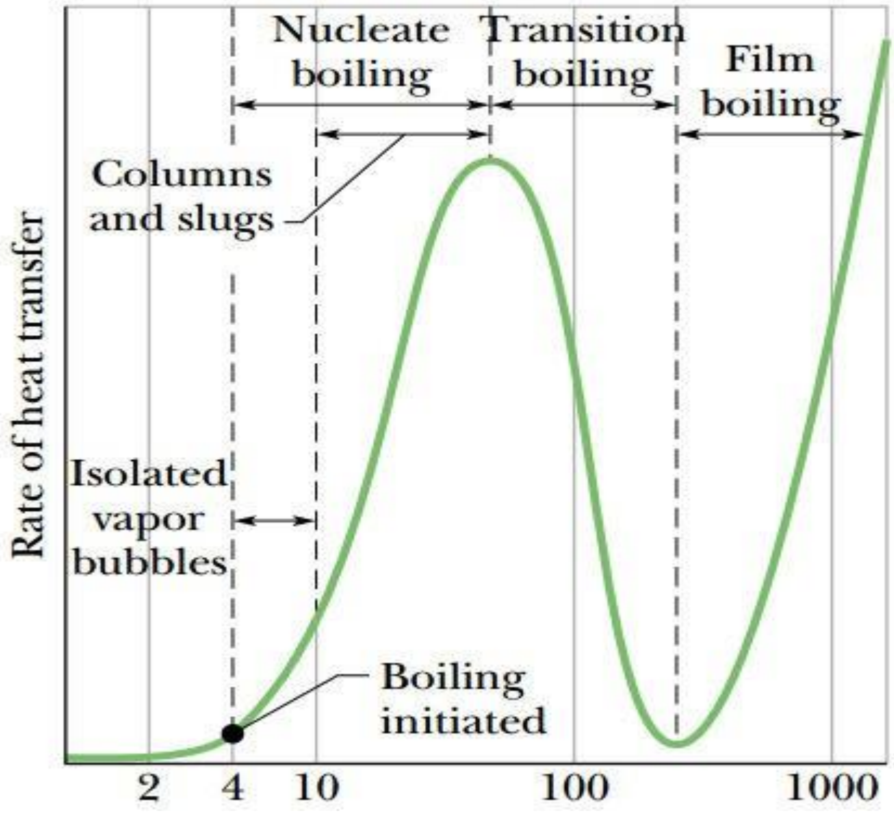

Figure 2.6: Boiling curve for water

2.10 Jearl Walker's Experiment

Jearl Walker of Cleveland State University performed an experiment for finding an elementary relationship between 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. 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. **[9]**

2.11 Application

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

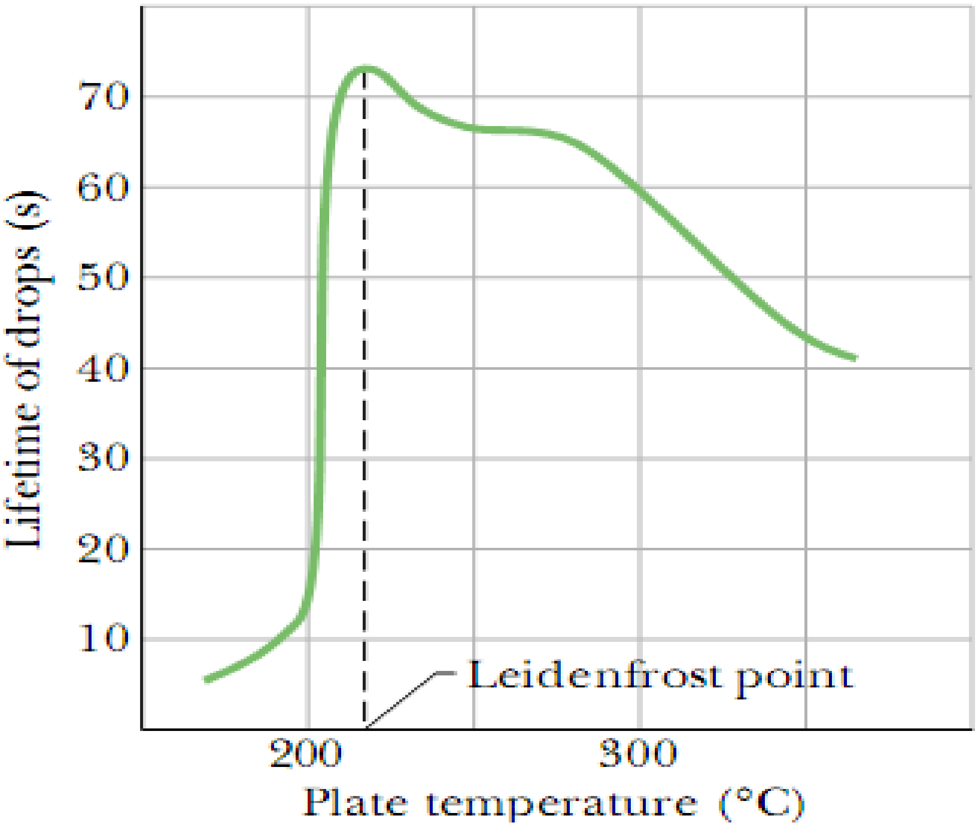

Figure 2.7: Drop lifetimes on a hot plate.

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.

Several other applications of the phenomenon are closely related in basic mechanism to those above:

1. The use of a water spray to cool steel billets or the rolls in rolling mill operations.
2. Water spray during continuous casting.
3. The design of quick response steam generators by spraying liquid on a hot surface.
4. The stable operation of a steam iron with a changing water inventory.
5. Film cooling of a rocket nozzle, either by breakdown of a continuous liquid film or direct spray injection.
6. Cool-down of cryogenic liquid storage tanks and transfer lines during filling. An interesting corollary problem is the possibility of minimizing cryogenic liquid loss by deliberate production of a vapor film next to the wall by film boiling.
7. Use of air-dropped solutions to control forest fires.
8. 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. **[10]**
9. Movement can be changed by adjusting the surface texture and temperature.
10. A heat engine based on the Leidenfrost effect has been prototyped. It has the advantage of extremely low friction. **[11]**
11. 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.

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**:**

In the experimental setup we can see a metal block inside which two heaters are 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 syringe. The syringe is held stationary by using a stand. An insulator (asbestos) is used to cover the metal block.

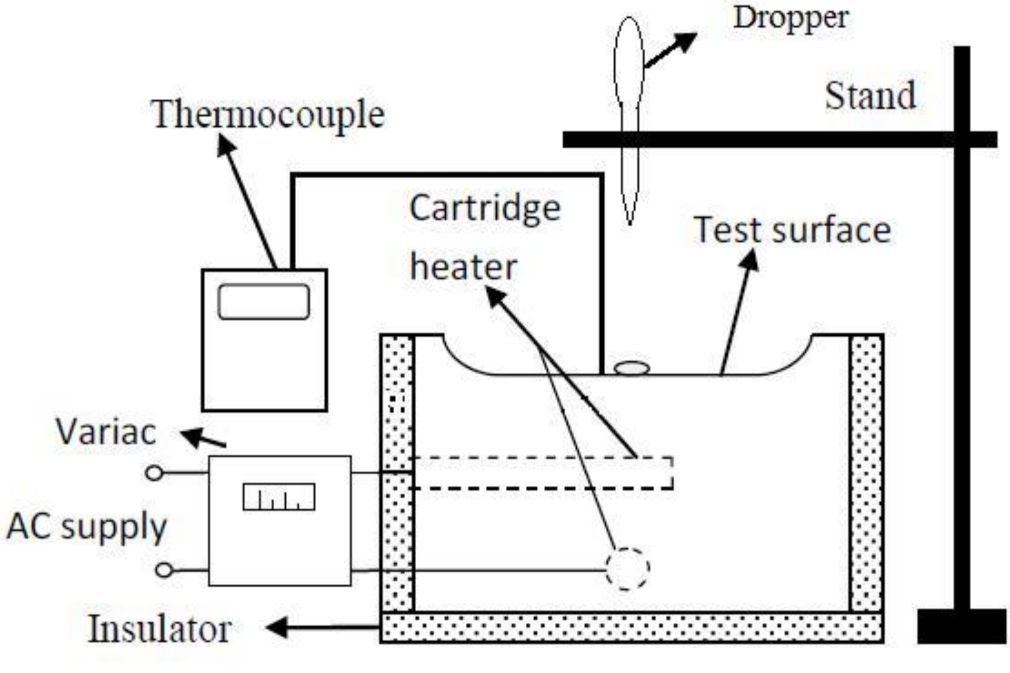

Figure 3.1: Schematic diagram of the experimental setup

3.2 Apparatus

In our experiment we used three metal blocks and three 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-

1. Metal blocks:
    a. Mild Steel
    b. Aluminium
    c. Brass

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

2. Working liquids:

    a. Ethanol:

        Formula: C_2H_6O

        Boiling Point: 78.37°C

        Latent heat of vaporization: 38.56 kJ/mol

    b. Methanol:

        Formula: CH_3OH

        Boiling Point: 64.7°C

        Latent heat of vaporization: 38.278 kJ/mol

    c. Distilled water:

        Formula: H_2O

        Boiling Point: 100°C

        Latent heat of vaporization: 40.68 kJ/mol

3. Heater
4. Variac
5. Thermocouple
6. Stand
7. Glass box
8. Syringe
9. Asbestos

3.2.1 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. Another hole of 1.5mm diameter and 37 mm was drilled for inserting thermocouple. 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.

3.2.1.1 Brass

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.

Figure 3.2: Block made of Brass

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 Aluminium

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 204 W/mK.

3.2.1.4 Mild Steel

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).

Figure 3.3: Block made of Aluminium

Figure 3.4: Block made of Mild Steel

3.2.2 Working Fluid

Three 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 or C_2H_6O.

3.2.2.3 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. Distilled water is colorless, tasteless liquid. It does not have any kind of smell. Distilled 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

Variac (figure 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.

Table 3.1: Variac Specification

Phase	**3ϕ**
Rated Capacity	300W
Rated frequency	60Hz
Input Voltage	220V

Figure 3.5: Variac

3.2.4 Heater

Heater (figure 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.

Figure 3.6: Heater

3.2.5 Syringe

Figure 3.7: Syringe

Syringe (figure 3.7) was used to hold the liquid and pour droplets of it on the test surface of metal block. Syringe was coupled with the stand and fixed at different heights to drop the droplets. We used syringes for 1.3mm diameters of liquid.

3.2.6 Glass Box

Glass box (figure 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 Thermocouple and Thermocouple Meter

In our experiment we used a K type (figure 3.9) thermocouple. The range of the thermocouple meter was 0-500^{o}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 Asbestos

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.

Figure 3.8: Glass Box

Figure 3.9: K Type Thermocouple Meter

Figure 3.10: Asbestos covering test metal

3.2.9 Stand

Stand was used to hold the syringe at a fixed distance from the test surface of the block. For our experiment, the distance was 20 mm & 50mm.

Figure 3.11: Stand

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 syringe; 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 60 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 syringe was filled with liquid and mounted. Bottom of the syringe was pressed slowly and a droplet was formed on the tip of the syringe 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 10ºC up to the test surface temperature 200ºC and with an increment of 20ºC up to the test surface temperature 320ºC.

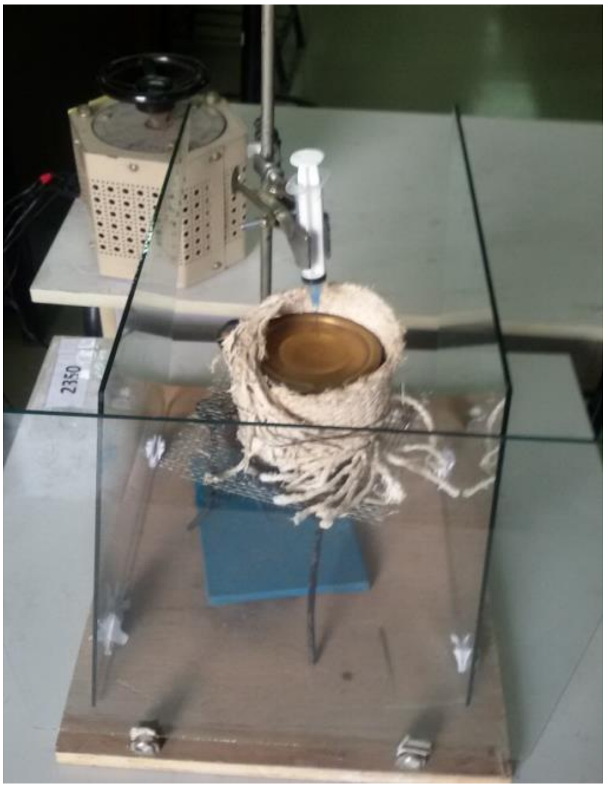

Figure 3.12: Experimental Setup

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), three different liquids (water, methanol and ethanol) and one droplet diameter (1.3mm) and two different sessile droplet heights (20mm and 50mm). A numerous number of graphs have been obtained within a temperature range from 50 to 320ºC. 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:

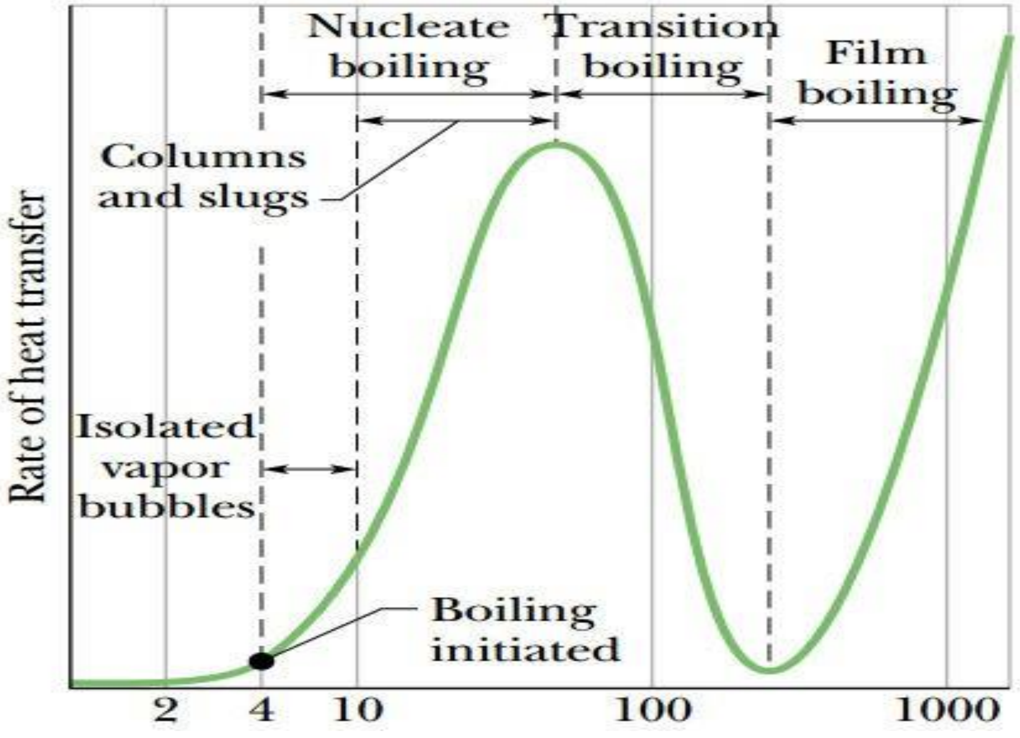

Figure 4.1: Boiling Curve for water

4.2 Height Variation

The figure (Figure 4.2) below shows vaporization time of Distilled Water on Brass 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 130ºC. 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 180ºC and time required to evaporate the droplet is maximum. This temperature is called Leidenfrost temperature. After 180ºC, the radiation heat transfer becomes dominating which increases the heat flux and decreases the total vaporization time.

Now coming to the time variation due to height, we find that the droplet dropped from 20mm height has significantly higher vaporization time than the droplet dropped from 50mm height. The reason for this is simply the amount of velocity and kinetic energy present in the drop. A droplet dropped from 50mm height will have more velocity and kinetic energy than a droplet dropped from 20mm height. Due to this reason the droplet dropped from 50mm height will have a significantly greater chance of splitting and increasing the contact area of water surface with the heated surface. Thus the heat transfer increases due to the increased area.

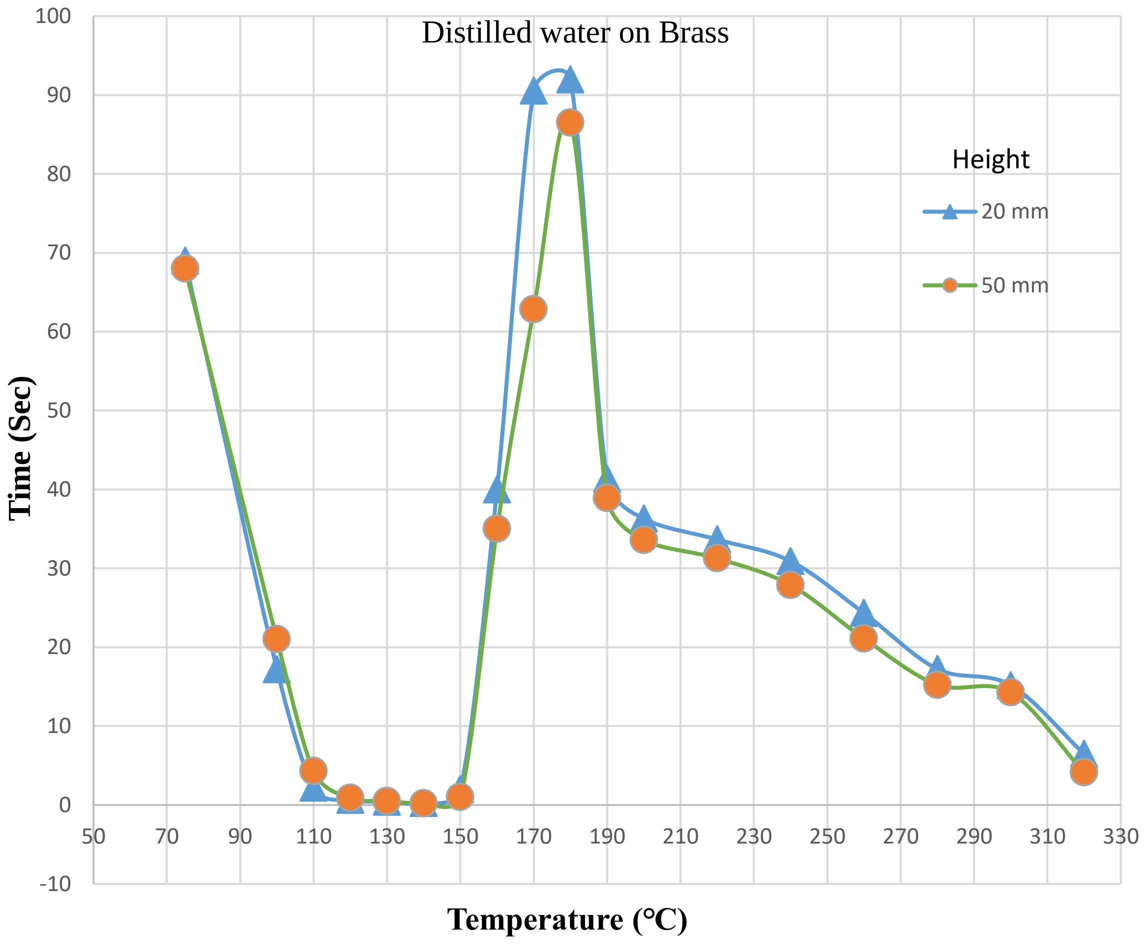

Figure 4.2: Evaporation Time of Distilled Water on Brass for Different Heights

Thus the water takes the highest time to evaporate. It must be noted however that the nature of the curve for both heights is exactly the same, opposite to a boiling curve.

The time required for evaporating water droplet corresponding to Leidenfrost temperature(180ºC) is 91.95 seconds for the droplet dropped from 20mm height and 86.5 seconds for the droplet dropped from 50mm height.

A similar comparison of height has been done in Figure 4.3**,** using Water on Aluminium. The results are similar with maximum evaporation time at around 175ºC and the corresponding times at 180ºC are 112.03 seconds for the droplet dropped from 20mm height and 94.76 seconds for the droplet dropped from 50mm height respectively.

A similar comparison of height has been done in Figure 4.4**,** using Distilled Water on Mild Steel. The results are similar with maximum evaporation time at around 175ºC and the corresponding times at 180ºC are 114.72 seconds for the droplet dropped from 20mm height and 101.69 seconds for the droplet dropped from 50mm height respectively.

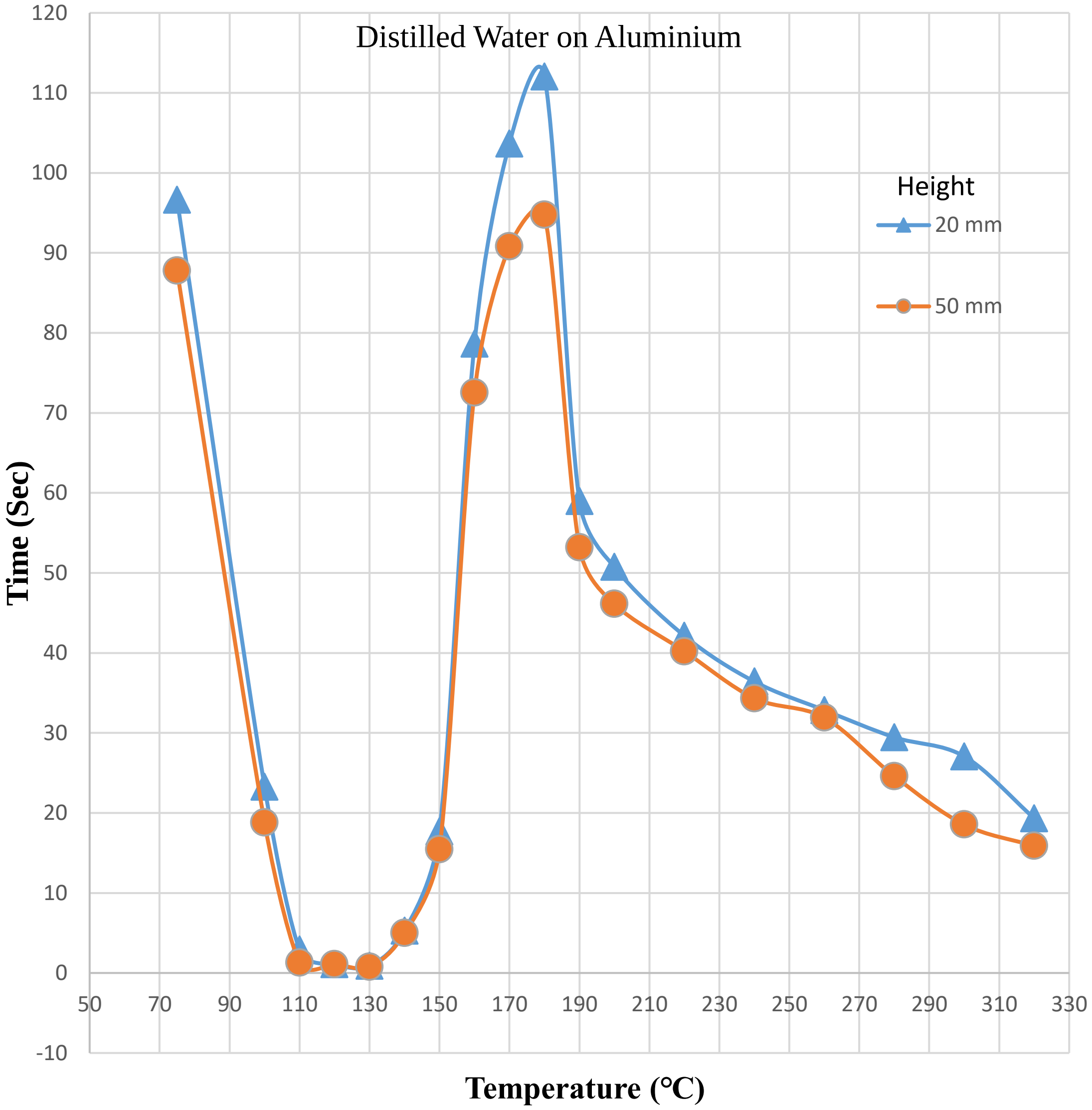

Figure 4.3: Evaporation Time of Distilled Water on Aluminium for Different Heights

Next comparison of height has been done in Figure 4.5**,** using Methanol on Brass. The results are similar with maximum evaporation time at around 160ºC and the corresponding times at 160ºC are 33.99 seconds for the droplet dropped from 20mm height and 30.82 seconds for the droplet dropped from 50mm height respectively.

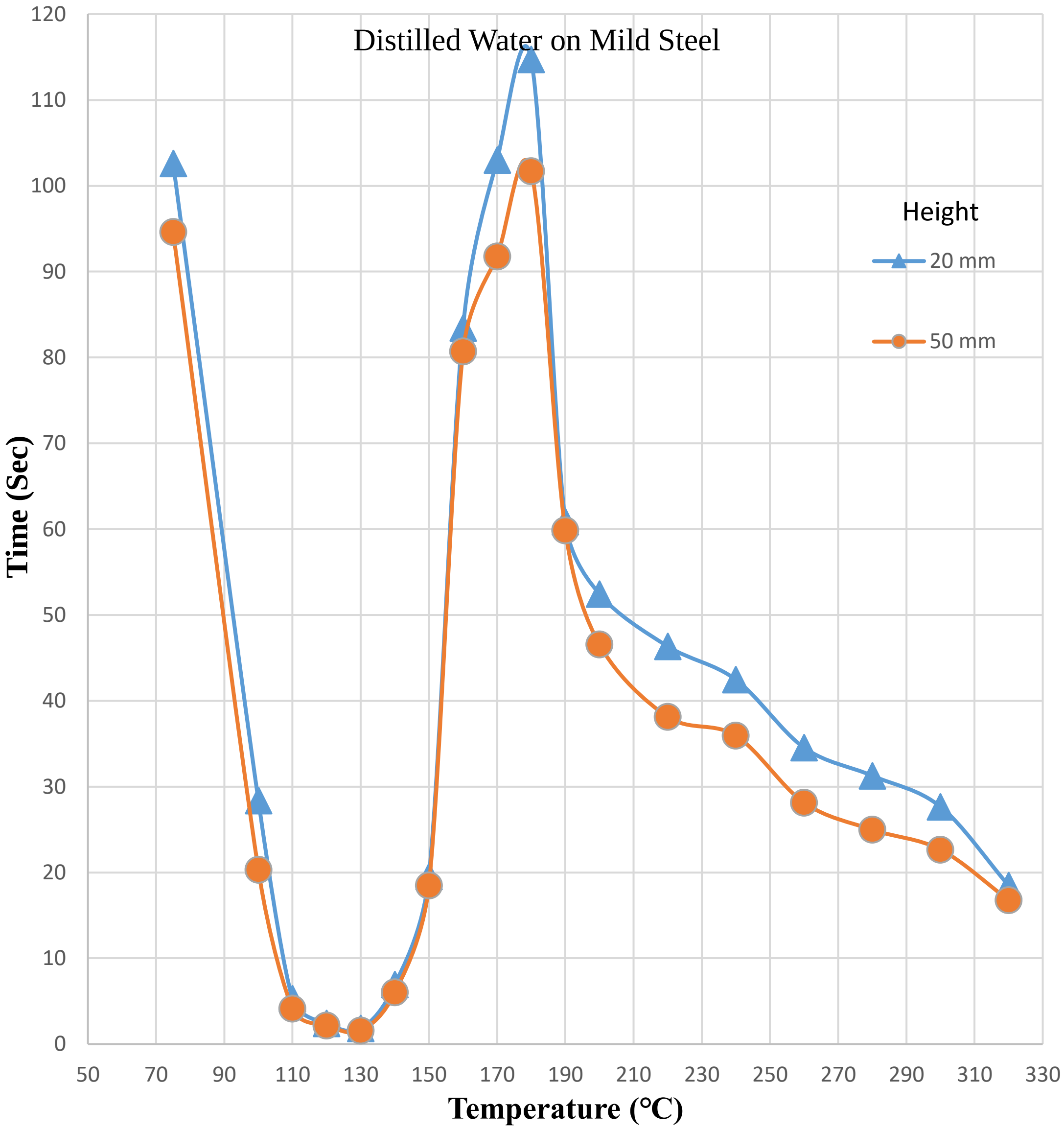

Figure 4.4: Evaporation Time of Distilled Water on Mild Steel for Different Heights

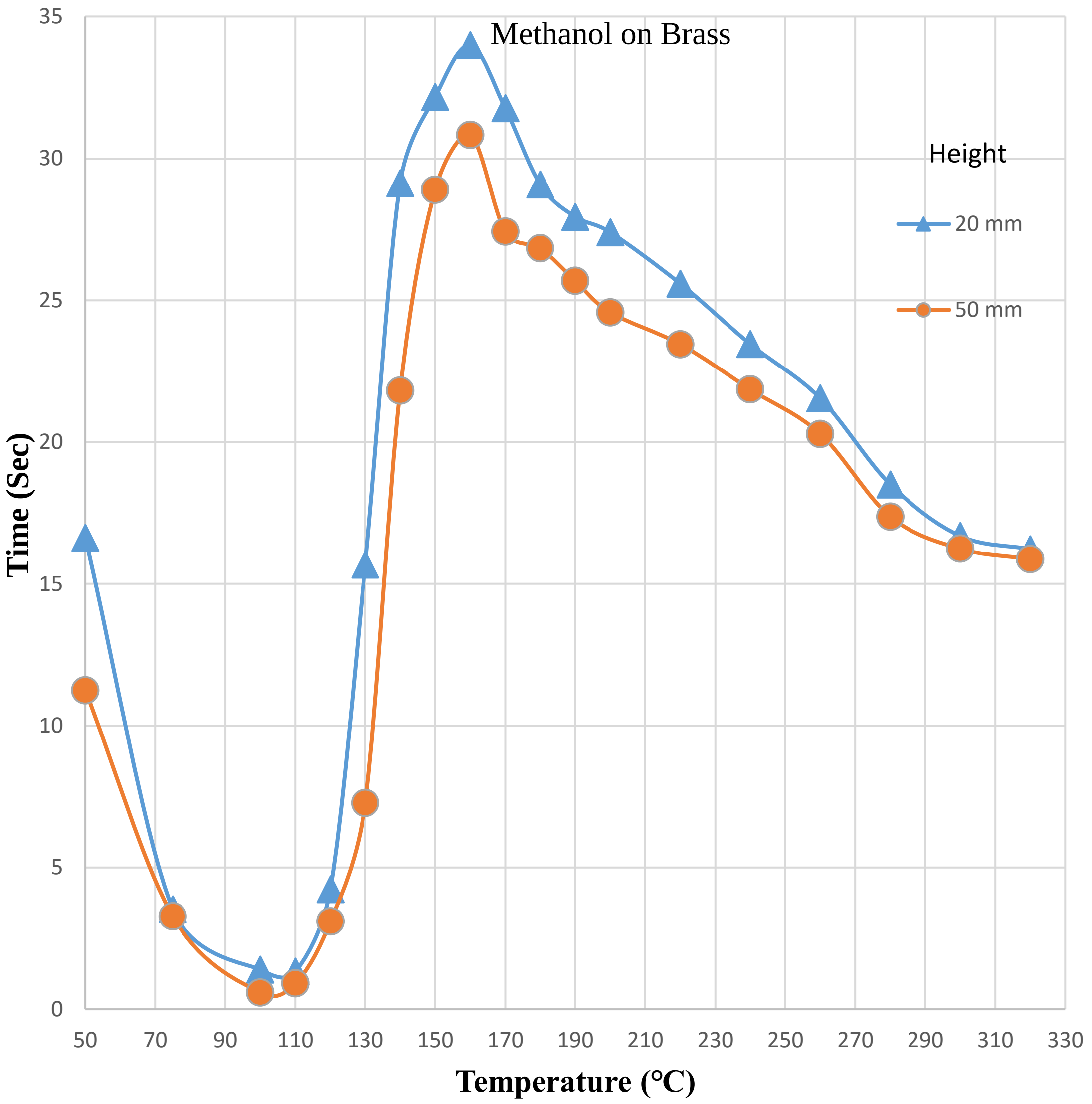

Figure 4.5: Evaporation Time of Methanol on Brass for Different Heights

Now comparison of height has been done in Figure 4.6**,** using Methanol on Aluminium. The results are similar with maximum evaporation time at 150ºC and the corresponding times at 150ºC are 39.85 seconds for the droplet dropped from 20mm height and 36.90 seconds for the droplet dropped from 50mm height respectively.

Now comparison of height has been done in Figure 4.7**,** using Methanol on Mild Steel. The results are similar with maximum evaporation time at 160ºC and the corresponding times at 160ºC are 32.13 seconds for the droplet dropped from 20mm height and 29.54 seconds for the droplet dropped from 50mm height respectively.

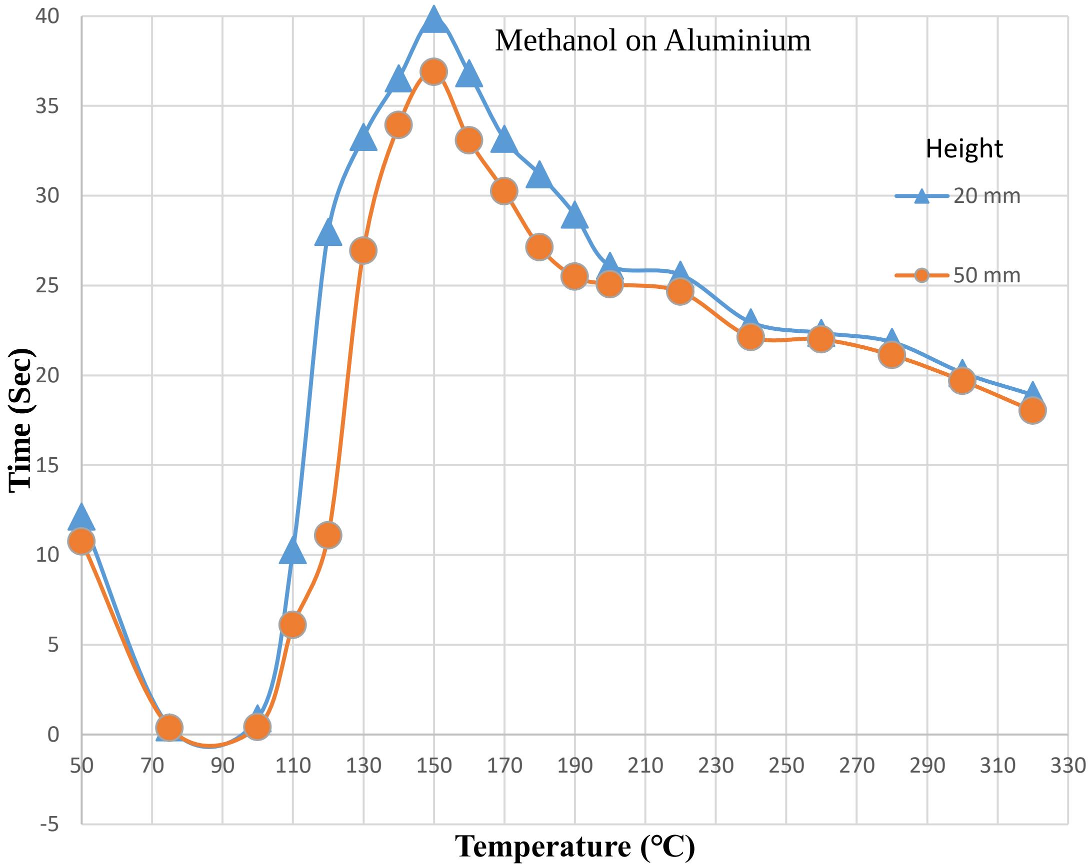

Figure 4.7: Evaporation Time of Methanol on Aluminium for Different Heights

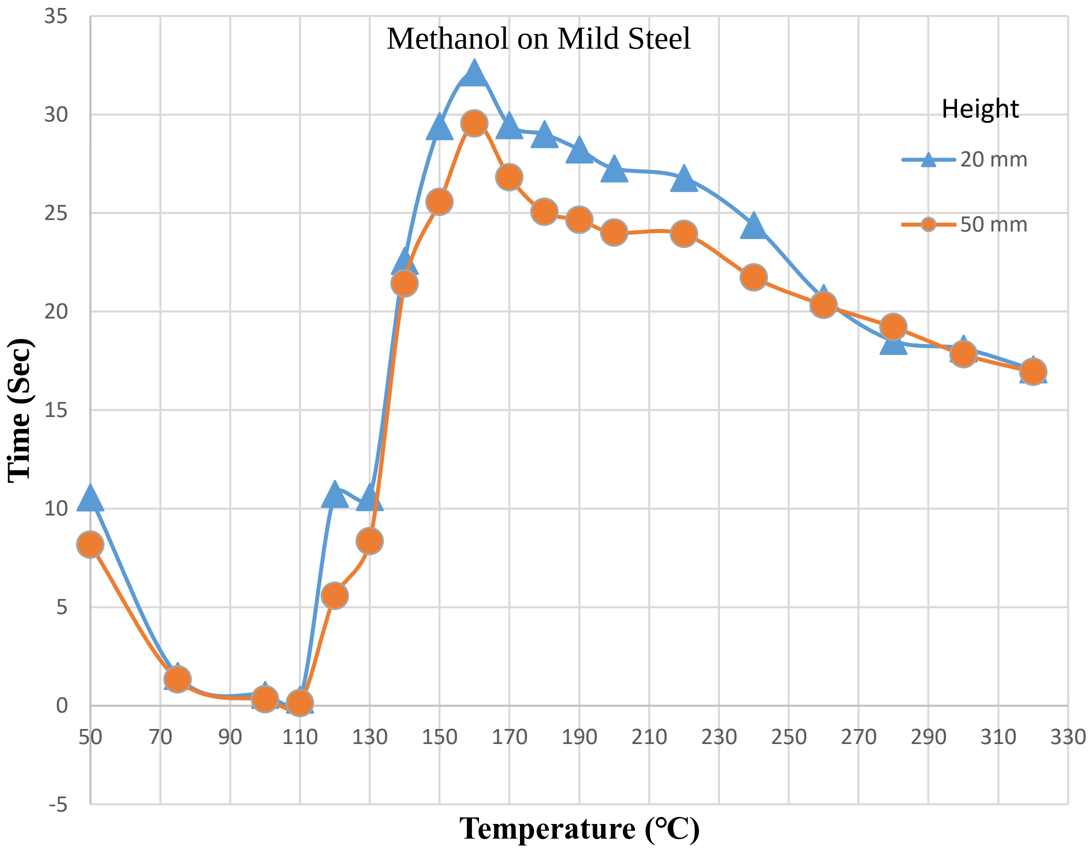

Figure 4.6: Evaporation Time of Methanol on Mild Steel for Different Heights

Now comparison of height has been done in Figure 4.8**,** using Ethanol on Brass. The results are similar with maximum evaporation time at 150ºC and the corresponding times at 170ºC are 30.34 seconds for the droplet dropped from 20mm height and 29.10 seconds for the droplet dropped from 50mm height respectively.

Now comparison of height has been done in Figure 4.9**,** using Ethanol on Aluminium. The results are similar with maximum evaporation time at 160ºC and the corresponding time at 160ºC are 30.17 seconds for the droplet dropped from 20mm height and 28.48 seconds for the droplet dropped from 50mm height respectively.

Now comparison of height has been done in Figure 4.10**,** using Ethanol on Mild Steel. The results are similar with maximum evaporation time at 160ºC and the corresponding time at 160ºC are 32.14 seconds for the droplet dropped from 20mm height and 30.10 seconds for the droplet dropped from 50mm height respectively.

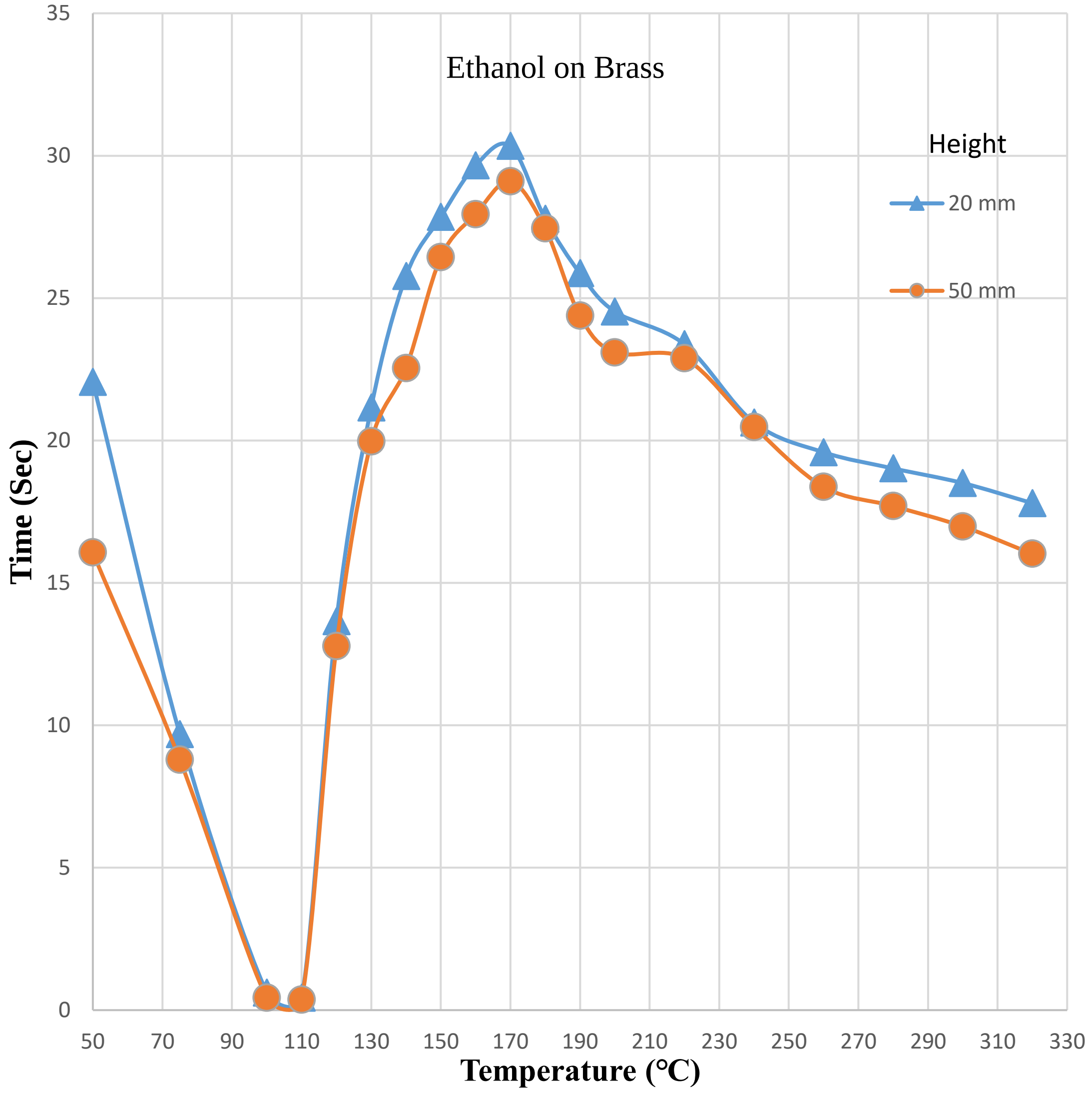

Figure 4.8: Evaporation Time of Ethanol on Brass for Different Heights

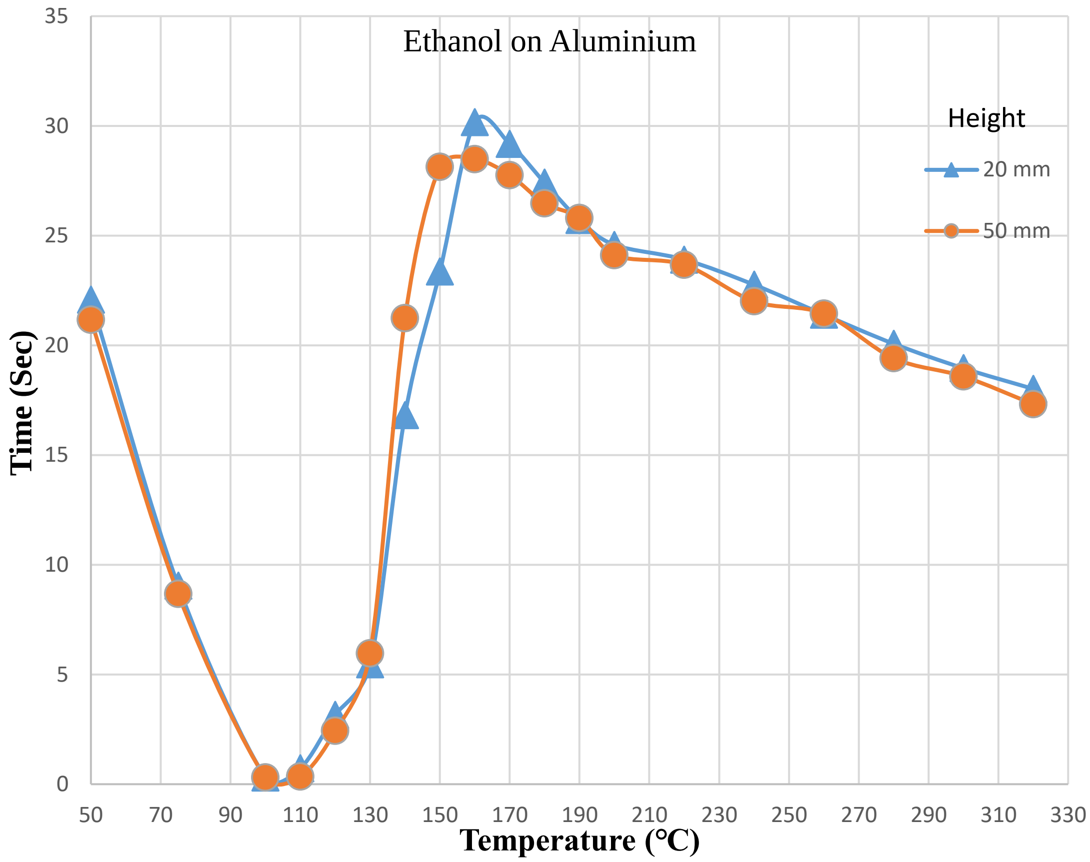

Figure 4.10: Evaporation Time of Ethanol on Aluminium for Different Heights

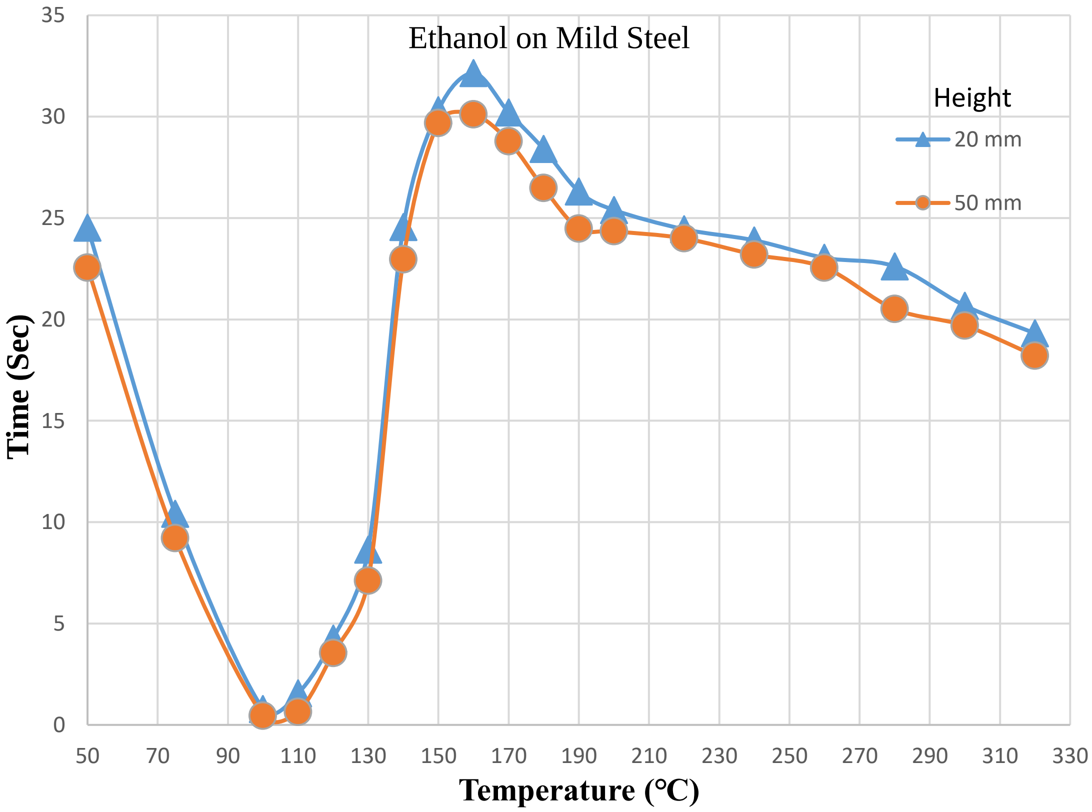

Figure 4.9: Evaporation Time of Ethanol on Mild Steel for Different Heights

4.4 Liquid Variation

In this experiment we have plotted evaporation time of different liquids on a specific metal surface (Figure 4.11 to Figure 4.13). 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 higher. Evaporation time also depends on boiling temperature of the liquid. The liquid which has higher boiling point will take more time to evaporate.

From all three graphs (Figure 4.11-4.13) 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, high specific heat, thermal conductivity and density and high boiling temperature.

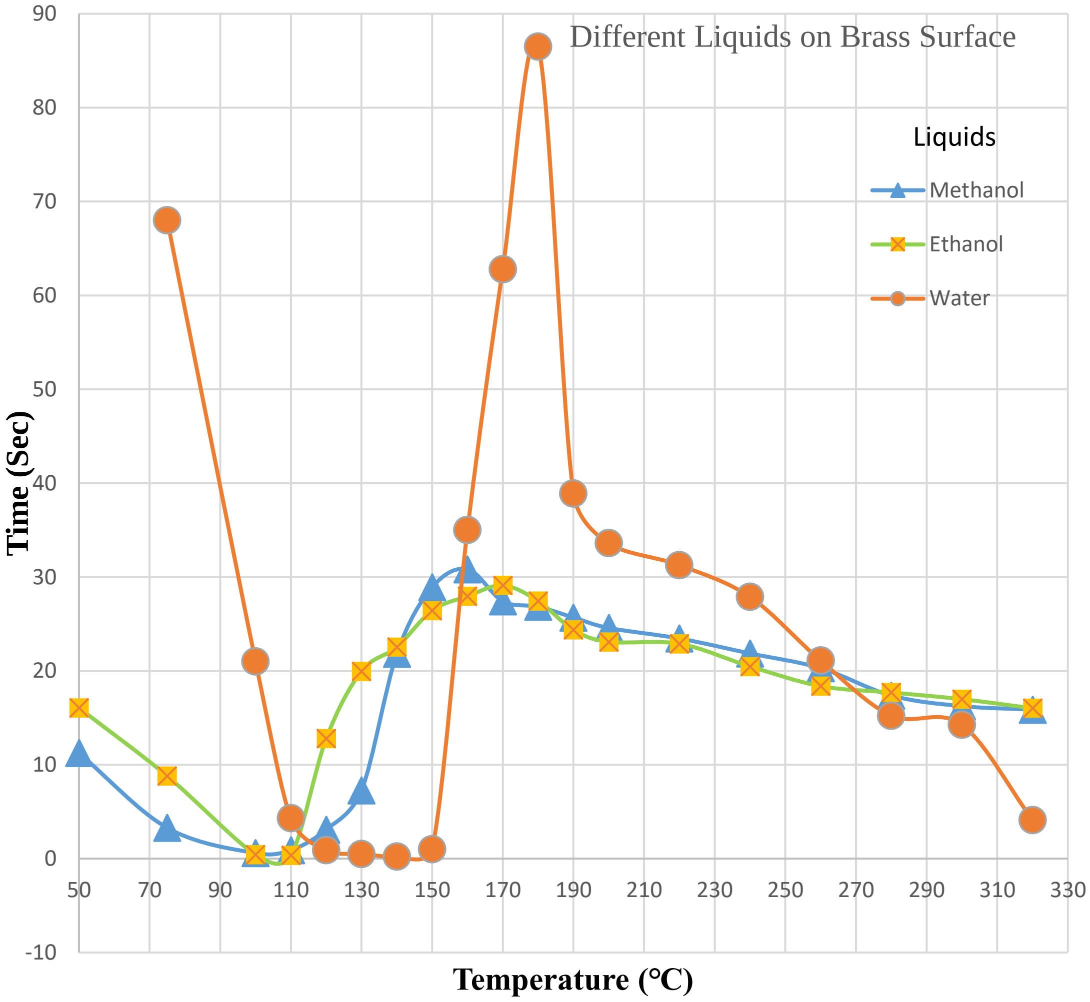

Figure 4.11: Evaporation Time of Different Liquids on Brass Block

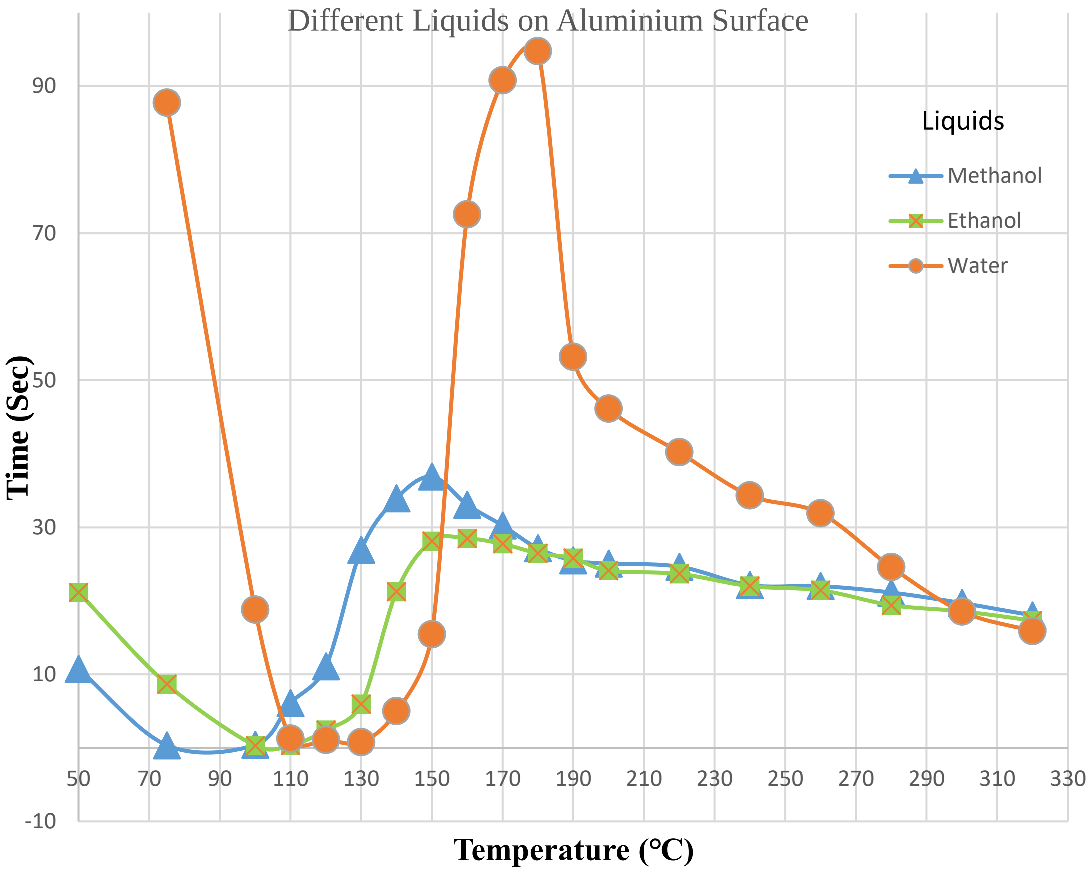

Figure 4.12: Evaporation Time of Different Liquids on Aluminium Block

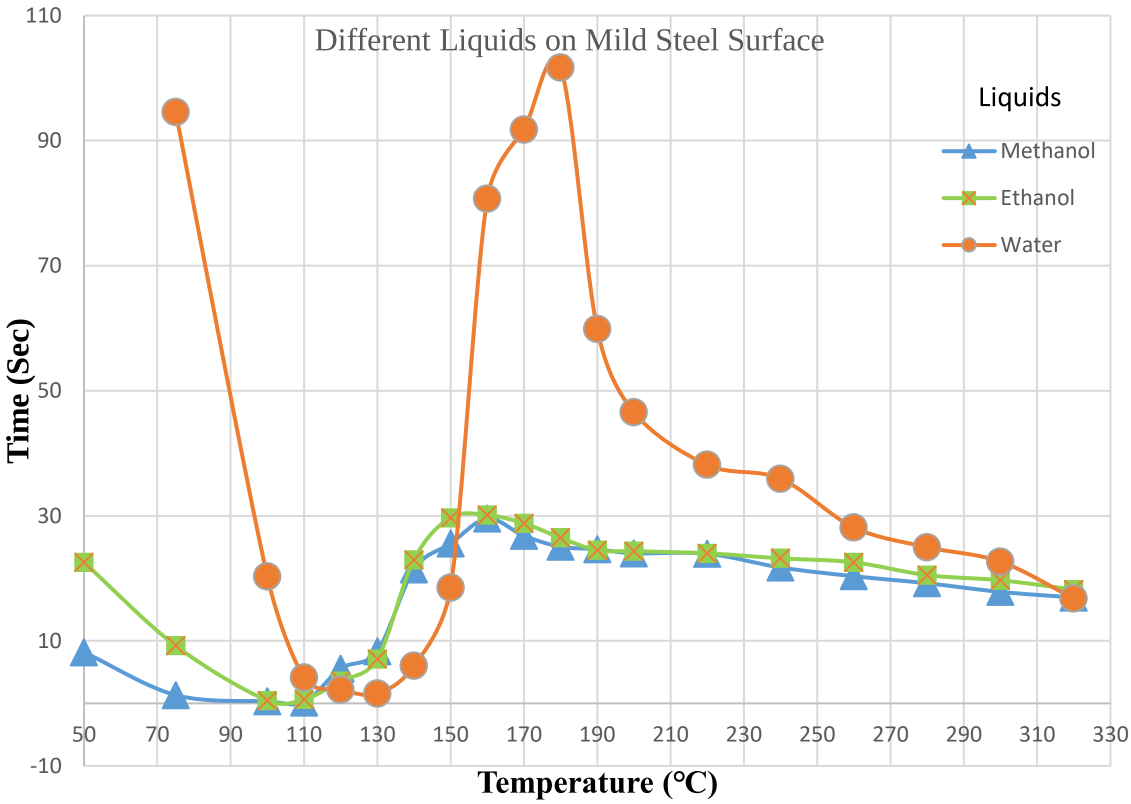

Figure 4.13: Evaporation Time of Different Liquids on Mild Steel Block

Water has highest boiling point (100ºC) comparing to methanol (64.7ºC) and ethanol (78.3ºC) so water takes highest time to evaporate.

4.4 Material Variation

We kept the liquid fixed and changed the metal surfaces while plotting Figure 4.14 to Figure 4.16. For each liquid, we have plotted the total droplet vaporization time as a function of surface temperature of three 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. The height the droplet was dropped from is 50mm.

In Figure 4.14 evaporation times of distilled water on different metals have been compared and we observe that Mild Steel takes the most time for vaporization. In Figure 4.15 the same has been done for Methanol. Here we see that vaporization time was highest for Aluminium and the lowest vaporization time was for Mild Steel.

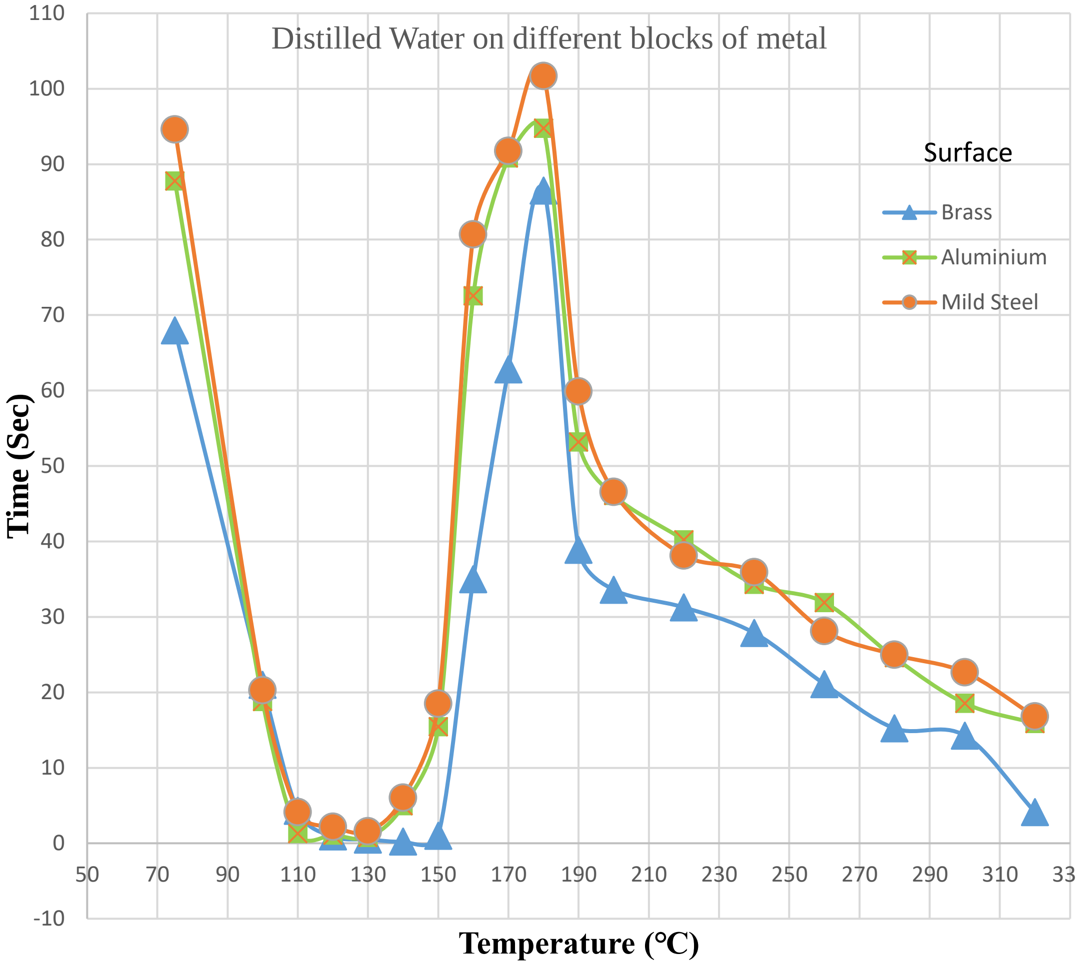

Figure 4.14: Evaporation Time of Distilled Water on Different Blocks

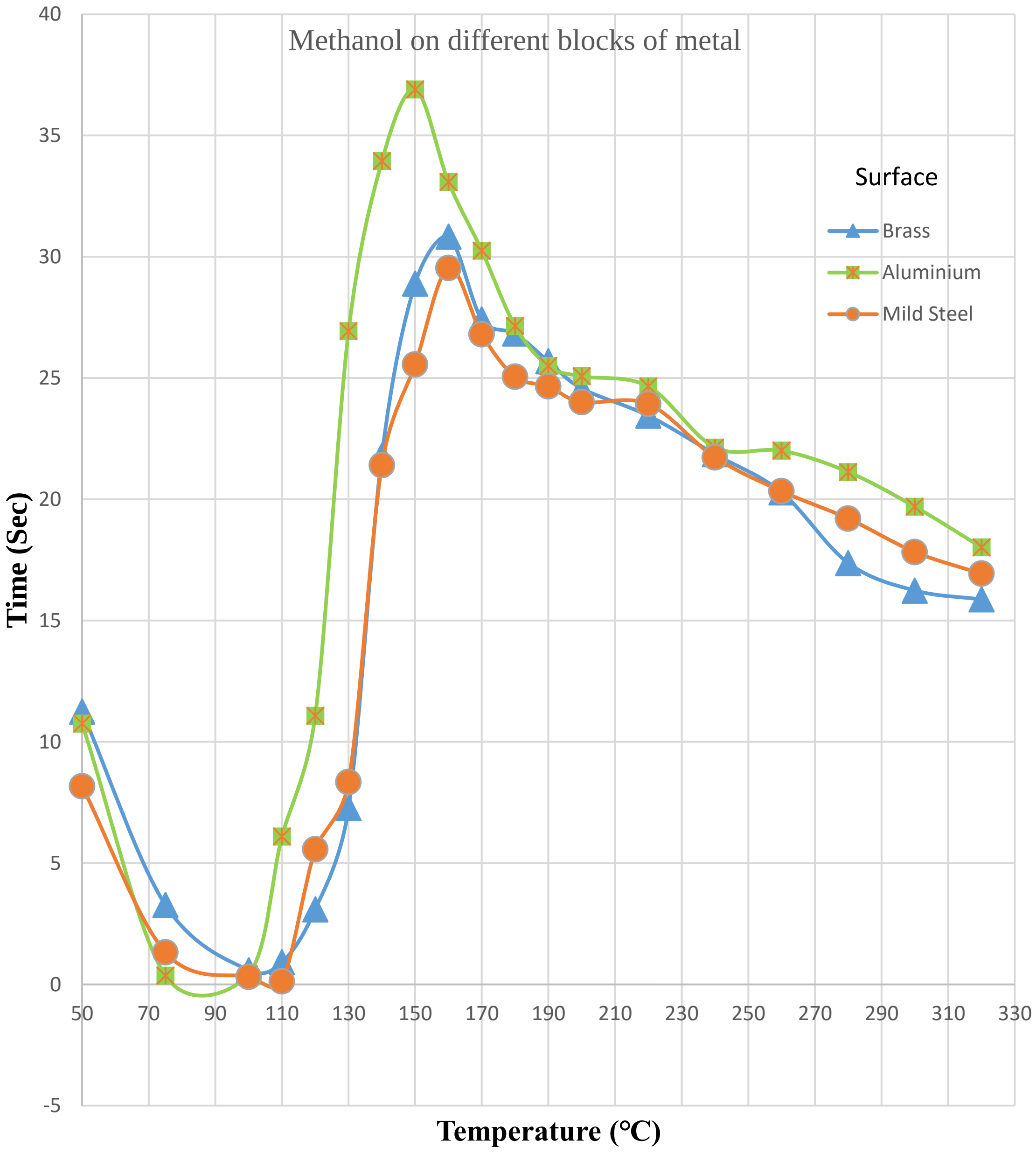

Figure 4.15: Evaporation Time of Methanol on Different Blocks of Metal

In Figure 4.16 evaporation times of Ethanol on different metals have been compared and again we observe that Mild Steel takes the most time for vaporization while Aluminium takes the least time.

We assume that due to an unknown error in this experiment, we didn't get the expected result.

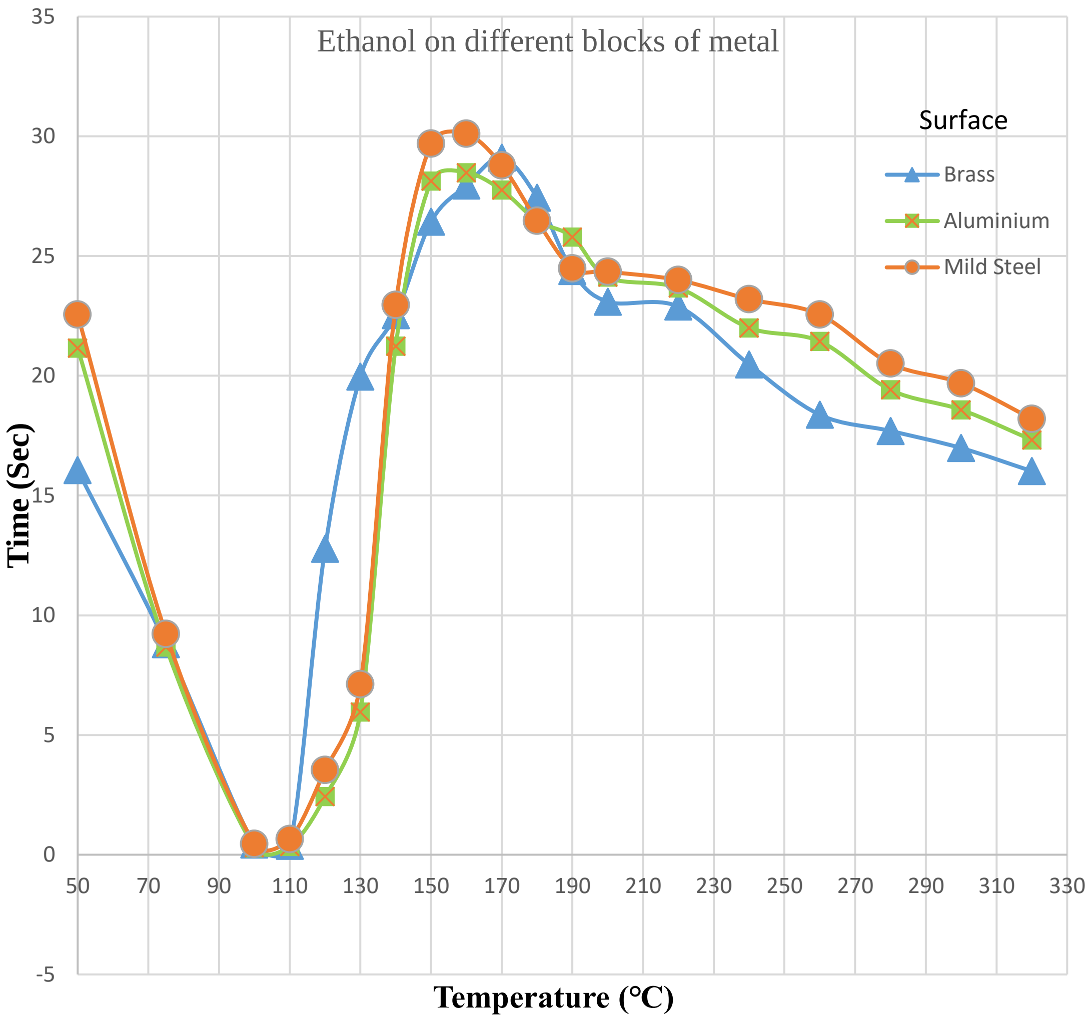

Figure 4.16: Evaporation Time of Ethanol on Different Blocks of Metal

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.

4.5 Results

4.5.1 Table of Experimental Results

The experimental results have been tabulated below for droplets dropped from 20mm height in all cases.

Table 4.1: Leidenfrost temperature and time of different liquids on Brass surface

Liquid	**Leidenfrost Time (sec)**	**Leidenfrost Temperature (⁰C)**
Distilled Water	91.95	180
Methanol	33.99	160
Ethanol	30.34	170

Table 4.2: Leidenfrost temperature and time of different liquids on Aluminum surface

Liquid	**Leidenfrost Time (sec)**	**Leidenfrost Temperature (⁰C)**
Distilled Water	112.03	180
Methanol	36.82	160
Ethanol	30.17	160

Table 4.3: Leidenfrost temperature and time for different liquids on Mild Steel surface

Liquid	**Leidenfrost Time (sec)**	**Leidenfrost Temperature (⁰C)**
Distilled Water	114.72	180
Methanol	32.13	160
Ethanol	32.14	160

4.5.2 Analysis of Experimental Results

4.5.2.1 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 4.11 to Figure 4.13). 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).

4.5.2.2 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 theoretically proven 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. But due to an unknown error, the result was different where it was observed that for distilled water, leidenfrost time was highest for mild steel and lowest for brass; for methanol it was highest for aluminium and lowest for mild steel; for ethanol it was highest for mild steel and lowest for aluminium.

4.5.2.3 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 higher as we observe in the experiment.

4.5.2.4 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^{0}C) comparing to methanol (64.7^{0}C) and ethanol (78.3^{0}C). So water takes highest time to evaporate.

4.5.2.5 Effect of the Height the Droplets Were Dropped from

Droplets were dropped from two different heights (20mm and 50mm). It can be observed from the graphs that for 50mm height parameter the droplet takes less time to evaporate. Due to kinetic energy, the droplets hit the surface with more force when dropped from 50mm height rather than 20mm height. This energy acts as the force to split the droplets in many parts. As the droplets are divided into many smaller parts, it increases the droplets' surface area that can transfer more heat flux from the surface resulting in decrease of evaporation time. So, greater height results in less evaporation time.

4.6 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 Conclusions

1. Heat transfer is lower at low temperature and it takes higher time to evaporate.
2. Leidenfrost temperature is always same for a certain liquid i.e. the leidenfrost temperature for distilled water obtained is always 180ºC.
3. Leidenfrost temperature is independent of material of the surface and heights.
4. 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.
5. Because of greater height, the droplet splits into many smaller parts when it hits the surface, the surface area increases and it takes shorter time to evaporate. So, greater height results in lower evaporation time for all liquids.
6. The graph prepared by plotting evaporation time against temperature is just opposite to the conventional boiling curve.
7. For all liquids evaporation time is usually lowest in the nucleate boiling region around 100-150ºC.
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 three working liquids, 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 25ºC from 50ºC up to 100ºC, 10ºC from 100ºC upto 200ºC and 20ºC from 200ºC up to 320ºC. This increment can be smaller which may provide more accurate curve.

5. Leidenfrost phenomenon may be experimented with higher temperature range (up to 500ºC 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 Distilled Water dropped on Brass Surface from 20mm Height

Temperature (⁰C)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	400	398	396	398
75	71	67	69	69
100	18.26	16.19	17.18	17.21
110	2.31	2.16	2.10	2.19
120	.64	.62	.63	0.63
130	.41	.44	.42	0.42
140	.27	.24	.21	0.24
150	2.01	1.99	2	2
160	41	38	41	40
170	91.57	91.21	88.81	90.53
180	92.31	91.96	91.58	91.95
190	41.87	40.97	41.15	41.33
200	36.5	36.3	36.1	36.3
220	34.15	33.85	32.95	33.65
240	30.97	30.91	30.85	30.91
260	24.35	24.33	24.31	24.33
280	17.32	17.18	17.22	17.24
300	15.25	15.16	15.16	15.19
320	6.53	6.42	6.46	6.47

A2 Distilled Water dropped on Brass Surface from 50mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	396	392	388	392
75	70	67	64	67
100	23	21	19	21
110	4.31	4.28	4.31	4.3
120	1.1	.9	.7	0.9
130	.52	.49	.49	0.5
140	.24	.22	.20	0.22
150	1.2	.9	.9	1
160	35.55	35.25	34.20	35
170	63.2	62.9	62.3	62.8
180	86.8	86.5	86.3	86.5
190	39.2	38.9	38.6	38.9
200	33.9	33.7	33.2	33.6
220	31.44	31.32	31.02	31.26
240	27.92	27.90	27.82	27.88
260	21.2	21.1	21.0	21.1
280	15.25	25.23	15.21	15.23
300	14.28	14.26	14.22	14.26
320	4.16	4.10	4.10	4.12

A3 Methanol dropped on Brass Surface from 20mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	16.66	16.62	16.58	16.62
75	3.55	3.53	3.48	3.52
100	1.42	1.39	1.36	1.39
110	1.35	1.33	1.31	1.33
120	4.26	4.23	4.20	4.23
130	15.72	15.69	15.63	15.68
140	29.20	29.16	29.13	29.13
150	32.20	32.17	32.14	32.17
160	34.15	33.96	33.86	33.99
170	31.80	31.77	31.74	31.77
180	29.14	29.08	29.02	29.08
190	28.0	27.96	27.86	27.94
200	27.82	27.54	26.84	27.4
220	25.63	25.55	25.59	25.59
240	23.54	23.46	23.38	23.46
260	21.60	21.50	21.55	21.55
280	18.54	18.50	18.46	18.50
300	16.72	16.69	16.66	16.69
320	16.25	16.23	16.21	16.23

A4 Methanol dropped on Brass Surface from 50mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	11.30	11.28	11.17	11.25
75	3.30	3.29	3.25	3.28
100	0.63	0.58	0.53	0.58
110	0.98	0.96	0.82	0.92
120	3.11	3.09	3.07	3.09
130	7.28	7.26	7.24	7.26
140	21.90	21.80	21.70	21.80
150	29	28.90	28.80	28.90
160	30.85	30.82	30.79	30.82
170	27.45	27.42	27.39	27.42
180	26.90	26.85	26.77	26.84
190	25.70	25.64	25.70	25.68
200	24.60	24.57	24.54	24.57
220	23.50	23.45	23.40	23.45
240	21.88	21.84	21.86	21.86
260	20.30	20.28	20.26	20.28
280	17.42	17.40	17.29	17.37
300	16.30	16.28	16.14	16.24
320	15.88	15.86	15.87	15.87

A5 Ethanol dropped on Brass Surface from 20mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	22.10	22.06	22.02	22.06
75	9.74	9.69	9.64	9.69
100	.65	.60	.55	0.60
110	.45	.42	.39	0.42
120	13.78	13.60	13.57	13.65
130	21.20	21.16	21.12	21.16
140	25.75	25.77	25.76	25.76
150	27.86	27.84	27.82	27.84
160	29.71	26.61	29.66	29.66
170	30.39	30.34	30.29	30.34
180	27.84	27.78	27.72	27.78
190	25.90	25.86	25.82	25.86
200	24.56	24.52	24.48	24.52
220	23.40	23.34	23.37	23.37
240	20.65	20.63	20.61	20.63
260	19.60	19.58	19.56	19.58
280	19.05	19.02	18.99	19.02
300	18.10	18.05	18	18.05
320	17.10	17.8	17.6	17.8

A6 Ethanol dropped on Brass Surface from 50mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	16.08	16.06	16.04	16.06
75	8.90	8.80	8.70	8.80
100	.44	.46	.42	0.42
110	.34	.36	.38	0.36
120	12.82	12.74	12.78	12.78
130	19.92	20	19.96	19.96
140	22.58	22.50	22.54	22.54
150	26.45	26.43	26.41	26.43
160	28	27.94	27.88	27.94
170	29.20	29	29.10	29.10
180	27.48	27.44	27.40	27.44
190	24.41	24.35	24.38	24.38
200	23.06	23.09	23.12	23.09
220	22.89	22.87	22.88	22.88
240	20.50	20.48	20.46	20.48
260	18.40	18.37	18.34	18.37
280	17.71	17.67	17.69	17.69
300	17	16.98	16.96	16.98
320	16.04	16.00	16.02	16.02

A7 Distilled Water dropped on Aluminium Surface from 20mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	435	431	433	433
75	97	96.56	96.36	96.64
100	23.43	22.50	22	23.28
110	2.88	2.92	2.90	2.90
120	1.10	1.09	1.88	1.09
130	0.89	0.91	0.90	0.90
140	5.28	5.26	5.27	5.28
150	17.65	17.66	17.64	17.66
160	78.64	78.63	78.65	78.64
170	103.67	103.66	103.65	103.65
180	112.03	112.00	112.03	112.03
190	58.98	58.97	58.96	58.97
200	50.74	50.73	50.73	50.74
220	42.14	42.13	42.12	42.13
240	36.46	36.39	36.41	36.42
260	32.90	32.82	32.83	32.85
280	29.47	29.43	29.45	29.45
300	27.12	27.04	27.06	27.06
320	19.33	19.35	19.33	19.33

A8 Distilled Water dropped on Aluminium Surface from 50mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	437	433	435	435
75	87.80	87.72	87.76	87.76
100	19.00	18.75	18.80	18.80
110	1.27	1.26	1.27	1.27
120	1.11	1.08	1.09	1.094
130	0.79	0.79	0.78	0.79
140	4.98	5.00	4.96	4.98
150	15.48	15.46	15.46	15.46
160	73.00	72.50	72.54	72.54
170	91.00	90.80	90.81	90.82
180	94.76	94.65	94.79	94.76
190	55.00	51.17	50.00	53.20
200	47.59	46.12	45.59	46.12
220	38.38	40.00	40.30	40.20
240	34.33	33.59	34.00	34.33
260	32.00	29.99	31.50	31.91
280	24.59	24.33	24.10	24.60
300	19.19	17.94	18.54	18.54
320	16.68	15.93	15.01	15.88

A9 Methanol dropped on Aluminium Surface from 20mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	13.96	12.17	11.99	12.14
75	0.45	0.41	0.39	0.40
100	0.856	0.90	0.91	0.90
110	11.36	10.66	10.07	10.26
120	28.05	28.03	28	28
130	33.28	33.26	33.25	33.28
140	37	36.55	36.43	36.54
150	41.78	38.99	39.65	39.85
160	37.34	35.87	36.76	36.82
170	33.65	33.10	33.00	33.16
180	30.85	31.54	31.15	31.18
190	29.78	28.96	28.90	28.94
200	28.43	25.92	25.88	26.09
220	25.67	25.56	25.12	25.60
240	24.91	23	22.32	22.94
260	22.38	22.36	22.32	22.36
280	22.54	21.56	21.56	21.85
300	20	21.54	19.96	20.14
320	18.50	18.88	18.91	18.91

A11 Methanol dropped on Aluminium Surface from 50mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	10.78	10.72	10.76	10.75
75	0.33	0.38	0.36	0.36
100	0.45	0.43	0.41	0.42
110	5.90	6.00	6.17	6.12
120	12.19	11.06	11.00	11.08
130	27.37	26.99	26.49	26.94
140	34.98	33.85	33.93	33.94
150	37.00	36.90	36.89	36.90
160	33.09	33.056	33.067	33.08
170	30.85	30.12	30.23	30.25
180	27.50	27.15	26.88	27.14
190	25.05	26.00	25.38	25.49
200	26.54	25.06	25.00	25.07
220	24.35	24.67	24.65	24.65
240	23.98	22.10	22.06	22.13
260	22.07	22.00	22.01	22.00
280	21.92	21.19	21.10	21.12
300	20.34	19.65	19.63	19.70
320	18.09	17.99	18.06	18.02

A10 Ethanol dropped on Aluminium Surface from 20mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	23.48	22.01	21.99	22.08
75	9.07	9.06	9.05	9.06
100	0.36	0.32	0.30	0.308
110	0.72	0.75	0.71	0.729
120	3.33	3.40	3.00	3.15
130	5.56	5.46	5.40	5.46
140	17.43	16.89	16.76	16.82
150	24.00	23.35	23.00	23.36
160	31.12	30.08	30.00	30.17
170	29.82	29.10	28.99	29.18
180	27.46	27.43	27.41	27.41
190	26.12	25.67	25.70	25.72
200	24.60	24.56	24.58	24.58
220	24.87	23.78	23.50	23.91
240	22.75	22.83	22.69	22.76
260	21.78	21.38	21.29	21.4
280	21.04	20.01	20.00	20.07
300	19.43	18.78	18.94	18.96
320	18.04	18.07	18.03	18.01

A12 Ethanol dropped on Aluminium Surface from 50mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	21.96	20.95	21.09	21.16
75	9.04	8.65	8.50	8.68
100	0.28	0.29	0.30	0.29
110	0.38	0.31	0.32	0.34
120	2.56	2.42	2.39	2.42
130	6.12	5.96	5.96	5.95
140	21.43	21.24	21.10	21.23
150	28.34	28.13	28.07	28.13
160	28.456	28.38	28.48	28.48
170	28.28	27.80	27.39	27.75
180	26.78	26.38	26.46	26.47
190	26.00	25.89	25.48	25.80
200	24.15	24.12	24.10	24.11
220	24.28	23.64	23.57	23.67
240	22.05	22.01	22	22.00
260	21.50	21.46	21.40	21.44
280	19.45	19.37	19.40	19.41
300	19.43	18.57	18.46	18.58
320	17.67	17.12	17.28	17.32

A13 Distilled Water dropped on Mild Steel Surface from 20mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	386.08	384.94	385.60	385.54
75	102.72	102.66	102.48	102.62
100	28.40	28.37	28.34	28.37
110	5.31	5.29	5.27	5.29
120	2.46	2.44	2.42	2.42
130	1.87	1.80	1.79	1.82
140	7.0	6.94	6.88	6.94
150	19.60	19.56	19.52	19.56
160	83.50	83.45	83	83.45
170	103.5	103.1	102.3	103
180	114.82	114.72	114.62	114.72
190	60.95	60.92	60.74	60.87
200	52.53	52.45	52.37	52.45
220	46.55	46.45	46.05	46.35
240	42.52	42.40	42.46	42.46
260	34.60	34.48	34.54	34.54
280	31.35	31.30	31.22	31.29
300	27.75	27.68	27.52	27.65
320	18.5	18.44	18.47	18.47

A15 Distilled Water dropped on Mild Steel Surface from 50mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	385.32	384.78	383.22	384.44
75	95.20	94.80	93.8	94.60
100	20.40	20.30	20.20	20.30
110	4.16	4.12	4.14	4.14
120	2.15	2.19	2.20	2.18
130	1.60	1.56	1.58	1.58
140	6.09	5.97	6.03	6.03
150	18.48	18.46	18.5	18.48
160	80.75	80.63	80.69	80.69
170	91.81	91.75	91.69	91.75
180	101.81	101.69	101.75	101.69
190	59.90	59.84	59.87	59.87
200	46.60	46.54	46.57	46.57
220	38.16	38.14	38.12	38.14
240	35.94	35.94	35.93	35.93
260	28.15	28.11	28.13	28.13
280	25	24.98	24.96	24.98
300	22.68	22.66	22.64	22.66
320	16.76	16.78	16.8	16.78

A14 Methanol dropped on Mild Steel Surface from 20mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	10.60	10.57	10.54	10.57
75	1.54	1.51	1.48	1.51
100	.50	.54	.58	0.54
110	.32	.29	.26	0.29
120	10.78	10.74	10.7	10.74
130	10.55	10.58	10.55	10.58
140	22.60	22.56	22.52	22.56
150	29.42	29.38	29.4	29.40
160	32.13	32.11	32.15	32.13
170	29.48	29.44	29.46	29.46
180	29.1	28.9	29	29.00
190	28.26	28.30	28.16	28.22
200	27.30	27.26	27.22	27.26
220	26.80	26.77	26.74	26.77
240	24.42	24.39	24.36	24.39
260	20.71	20.65	20.68	20.68
280	18.54	18.48	18.51	18.51
300	18.18	18.15	18.03	18.12
320	17.10	17.05	17	17.05

A16 Methanol dropped on Mild Steel Surface from 50mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	8.20	8.17	8.14	8.17
75	1.35	1.32	1.29	1.32
100	.33	.32	.28	0.31
110	.14	.10	.12	0.12
120	5.60	5.58	5.53	5.57
130	8.39	8.33	8.27	8.33
140	21.45	21.41	21.37	21.41
150	25.60	25.55	25.50	25.55
160	29.56	29.54	29.52	29.54
170	26.85	26.80	26.75	26.80
180	25.10	25.05	25.00	25.05
190	24.70	24.65	24.60	24.65
200	24.10	23.90	24	24.00
220	23.98	23.86	23.92	23.92
240	21.76	21.73	21.70	21.73
260	20.36	20.33	20.30	20.33
280	19.25	19.23	19.12	19.20
300	17.85	17.80	17.81	17.82
320	16.96	16.93	16.90	16.93

A17 Ethanol dropped on Mild Steel Surface from 20mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	24.56	24.53	24.50	24.53
75	10.50	10.40	10.30	10.40
100	.79	.77	.75	0.77
110	1.60	1.56	1.52	1.56
120	4.30	4.26	4.22	4.26
130	8.70	8.64	8.58	8.64
140	24.60	24.56	24.52	24.56
150	30.40	30.32	30.24	30.32
160	32.2	32.14	32.08	32.14
170	30.16	30.12	30.08	30.12
180	28.8	28.6	28	28.4
190	26.41	26.31	26.21	26.31
200	25.65	25.45	25.1	25.40
220	24.54	24.50	24.42	24.44
240	23.85	22.65	23.10	23.20
260	22.64	22.56	22.60	22.56
280	20.55	20.50	20.45	20.50
300	19.73	19.70	19.66	19.69
320	19.22	19.20	19.18	19.20

A18 Ethanol dropped on Mild Steel Surface from 50mm Height

Temperature (ºC)	Time 1 (s)	Time 2 (s)	Time 3 (s)	Average Time (s)
50	22.57	22.53	22.55	22.55
75	9.24	9.18	9.21	9.21
100	.46	.44	.45	0.45
110	.68	.62	.62	0.64
120	3.57	3.49	3.53	3.53
130	7.14	7.11	7.07	7.11
140	23.0	22.92	22.96	22.96
150	29.1	29.09	29.07	29.09
160	30.20	30.0	30.10	30.10
170	28.81	28.77	28,79	28.79
180	26.52	26.42	26.47	26.47
190	24.58	24.48	24.38	24.48
200	24.44	24.24	24.34	24.34
220	24.12	23.95	23.9	23.99
240	23.22	23.20	23.15	23.19
260	22.85	22.35	22.45	22.55
280	20.54	20.50	20.47	20.51
300	19.72	19.69	19.66	19.69
320	18.23	18.21	18.19	18.21

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