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Boiling Curve and Droplet Evaporation Lifetime on Hot Hemispherical Copper Surface

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Abstract: ***The objective of this paper is to investigate the droplet evaporation lifetime and boiling curve on hot copper surface using ethanol liquid. We focus our study to find the Critical Heat Flux (CHF) and Leidenfrost temperature in the boiling curve. Copper material which has a high thermal conductivity, k was chosen as a test material. The copper material dimension was approximately 28.0 mm in height and 50.0 mm in diameter. The copper surface was modified into hemispherical surface in order to maximize the evaporation lifetime. The hemispherical surface was constructed using Electrical Discharge Machining (EDM). After completing the EDM process, the dimension of the hemispherical surface area was approximately 15.0 mm in depth and 30.0 mm in diameter. Meanwhile, ethanol liquid which has a low boiling point of 78 °C was chosen as a test fluid. The droplet diameter was approximately 3.628 mm. The impact height was set to be around 4.0 mm corresponding to drop impact velocity of 0.886 m/s. As a result, it was found that the critical heat flux (CHF) and Leidenfrost temperature range on hemispherical copper surface was approximately T_{CHF} = 100.4-117.7 °C and T_L = 170.0-175.8 °C, respectively.***

Keywords **:** ***Droplet, Evaporation lifetime, CHF, Leidenfrost temperature, Hemispherical surface***

I. INTRODUCTION

When a liquid impacts onto a hot material surface, evaporation process will take place and heat from the hot surface will be removed and transferred to the surroundings. Normally, heat can be removed from the hot surface by boiling [1-2] and evaporation process [3-4]. Therefore, boiling and evaporation process can be considered as two (2) important elements in cooling application in our daily life. Boiling process is widely used for distillation process, water heating, steam generation in power plant and many others. In boiling heat transfer study, boiling can be considered as one of the important elements which can enhance the thermal protection and thermal insulation system. New findings and results in boiling studies can give direct benefits to industrial area such as boiler application, nuclear reactor cooling system [5], surface coating technology, thermal insulation system and many other thermal engineering applications. In nuclear power plant, boiling and evaporation process is used during steam generation and during emergency cooling system. In boiling studies, Leidenfrost temperature [6-7] is the maximum limit point before the boiling condition shifts to film boiling [8-9]. For easy understanding, if we can increase this Leidenfrost temperature in the boiling curve, it means that we can improve the cooling capabilities in thermal application system. A few number of researchers had conducted drop impact research [10-14] and Leidenfrost studies [15-17] in order to study this complicated phenomena. For instance, Illias et al. [15] conducted an experimental work using hemispherical surface material made from stainless steel (304) to study the Leidenfrost temperature during liquid-solid contact. They found that the Leidenfrost temperature, for hemispherical stainless steel surface was approximately T_L = 193.6 °C.

In this paper, we investigated the critical heat flux (CHF) and Leidenfrost point (LFP) temperature on a hemispherical copper surface material. We focused our study on finding the CHF and LFP temperature. The copper material dimensions were 50.0 mm in diameter and 28.0 mm in height. The material was shaped into hemispherical surface using Electrical Discharge Machining (EDM).

II. EXPERIMENTAL CONDITIONS AND RELATED FORMULA

As mention before, we used ethanol liquid as a test liquid in the experimental work. The experimental conditions and liquid properties for ethanol are shown in Table 1 for easy reference. In order to calculate the actual droplet diameter during the experiment, Eq. (1) and Eq. (2) were used to calculate and predict the droplet diameter and size. Eq. (1) was used to measure the droplet diameter using the droplet volume formula. Meanwhile, Eq. (2) was used to theoretically predict the diameter based on the inner droplet dispenser diameter and liquid properties. From the calculation, the droplet diameter was approximately 3.628 mm which was similar with our previous report [15].

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Table 1: Experimental conditions and liquid properties

Droplet diameter, D_0 (mm)	3.628
Inner diameter of droplet dispenser, Ø (mm)	3.0
Density, ρ_{liq} (kg/m^3)	795
Surface tension, σ (N/m)	0.0219
Gravity, g (m/s^2)	9.81

$$V = \frac{4}{3}\pi r^3 \qquad (1)$$

$$d = \sqrt[3]{\frac{6\sigma d_{needle}}{\rho_{liq}\, g}} \qquad (2)$$

III. EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows the schematic diagram of the experimental apparatus. The experimental apparatus consisted of a droplet dispenser system, hot plate, retort stand and a temperature measurement system. The actual copper bar was approximately 50.0 mm in diameter and 28.0 mm in height. Meanwhile, the hemispherical surface area was 30.0 mm in diameter and 15.0 mm in depth. The hemispherical-shaped surface was constructed using Electrical Discharge Machining.

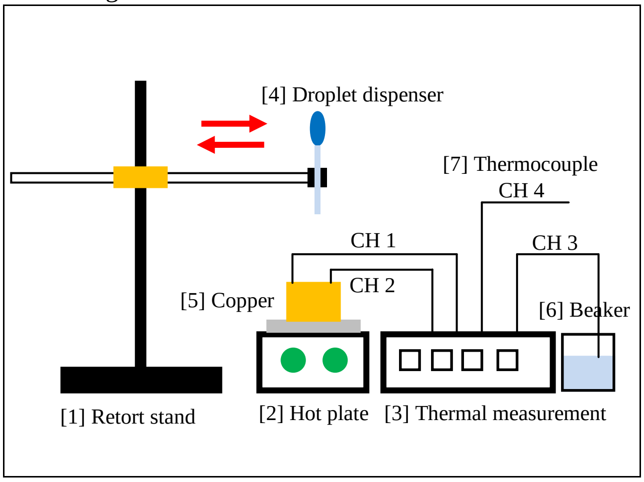

Figure 1: Schematic diagram of the experimental apparatus

The actual image of the hemispherical copper is shown in Figure 2. It was believed that by using this hemispherical surface, the accuracy of the evaporation lifetime of the ethanol droplet can be increased. The droplet also will stay inside the hemispherical area during the evaporation process. The copper surface was heated using a scientific hot plate which can be heated up to 500 °C. The temperature range for this experimental work ranged from T_w = 70 °C up to 220 °C. The copper material was put on top of the hot plate. The surface temperature was recorded using type K thermocouples. These thermocouples were inserted at two (2) different locations at the top of the copper surface in order to monitor the initial surface temperature. The thermocouples were connected directly to a temperature measuring device as shown in Fig.1. The average ethanol liquid temperature was approximately 28.8 °C. The impact height was around 4.0 mm (impact velocity = 0.866 m/s). In order to ensure the liquid temperature is the same during all drop test experiments, the ethanol liquid was emptied and refill for each experimental cycle. The thermocouple also was inserted into the ethanol beaker to monitor the ethanol droplet temperature. The evaporation lifetime during liquid-solid contact was recorded using a digital time recorder (smartphone) and all the data was systematically recorded.

Figure 2: Actual image of the hemispherical copper surface

IV. RESULTS AND DISCUSSION

Figure 3 shows the relationship between droplet evaporation lifetimes of ethanol droplet during impact onto a hot hemispherical copper surface. From Fig. 3, it is observed that the boiling curve is divided into three (3) main categories. This boiling mode is shown clearly by the purple (nucleate), blue (transition), and yellow (film) arrow in the graph. From Fig. 3, it is observed that the highest data recorded occurred at the surface temperature of T_w = 71.1 °C which is about 48.83 sec. Then, it seems like the droplet evaporation lifetime decreases slowly even when the surface temperature was increased. At the surface temperatures of T_w = 80.2 and 80.35 °C, the reading of evaporation lifetime was approximately 21.68 and 20.42 sec, respectively. When the surface temperatures reached T_w = 95.85 and 97.7 °C, the evaporation lifetime decreased very close to 1 sec. The evaporation lifetime during these surface temperatures were 1.37 and 2.0 sec, respectively. Finally, when the surface temperature neared the 100 °C point, the critical heat flux phenomena started to occur on the hot surface. The droplet evaporated very fast soon after it landed on the hot surface. These phenomena occurred below 1 sec. At the surface temperatures of T_w = 100.55, 101.65, 102.3 °C, the droplet evaporation reading were approximately 0.68, 0.86 and 0.64 sec, respectively. This CHF phenomenon continuously occurred on the surface even when the surface temperature reached nearly T_w = 117.7 °C (0.91 sec).When the surface temperature increased to T_w = 120.0 °C, it seemed like the evaporation lifetime increased a little bit to approximately1.15 sec.

This increasing value in evaporation lifetime continued at the surface temperatures T_w = 120.25 °C (1.60 sec), T_w = 120.3 °C (3.91 sec) and T_w = 121.0 °C (2.94 sec). Meanwhile, at the surface temperatures of T_w = 140.25 °C and T_w = 141.2 °C, the evaporation lifetime suddenly increased to a much higher value of about 11.72 sec and 11.92 sec, respectively. These sudden increases in droplet evaporation lifetime curve represent the transition boiling regime. The temperature range in the transition boiling regime is shown by the blue arrow in Fig. 3. When the surface temperature reached T_w = 170.7 °C, the evaporation lifetime recorded was quite high which was about 47.52 sec. In the experimental work, the highest evaporation lifetime recorded occurred at the surface temperature of T_w = 175.75 °C which was about 50.07 sec. This maximum limit in the evaporation lifetime is known as Leidenfrost temperature. Normally, after reaching the Leidenfrost point, the boiling condition will shift to film boiling regime. Suddenly, when the surface temperature reached about T_w = 183.4 °C, it seemed like the evaporation lifetime decreased a little bit to a value of 19.93 sec. This decreasing pattern of evaporation lifetime means that the boiling conditions have shifted to the fully developed film boiling regime, Finally, at the surface temperatures of T_w = 205.5 and 204.8 °C, the evaporation lifetime recorded were about 12.43 and 15.87 sec, respectively. In the film boiling regime, most of the evaporation lifetime showed a decreasing pattern.

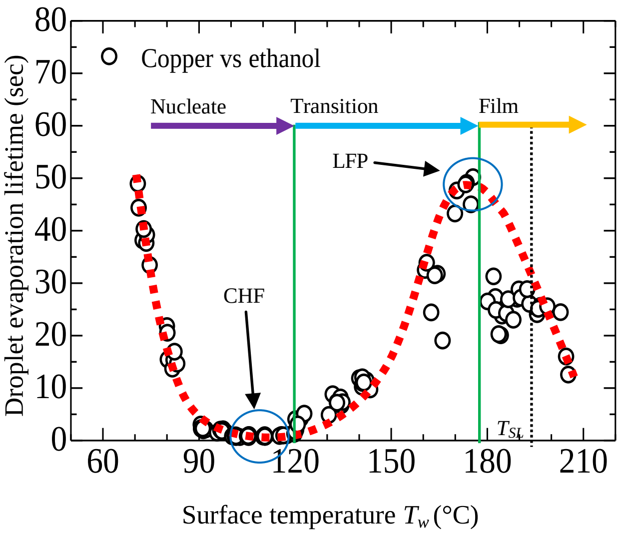

Figure 3: **Droplet evaporation lifetime versus copper surface temperature**

V. CONCLUSION

An experimental work has been conducted to investigate the droplet evaporation lifetime and boiling curve on hot copper surface using ethanol liquid. We focus our study to find the Critical Heat Flux (CHF) and Leidenfrost temperature in the boiling curve. From the experimental work, it can be concluded that the CHF occurred at approximately T_{CHF} = 100.4-117.7 °C on the hemispherical copper heated surface. Meanwhile, the Leidenfrost point (LFP) temperature for this experimental work occurred at approximately between T_L = 170.0-175.8 °C. Therefore, the objective for this experimental work was successfully achieved.

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