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Study of Vapor Contact Line Heat Transfer via Meniscus on Gold, Silicon and Copper Surfaces

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Abstract

The study of contact line heat transfer during boiling is of great importance in heat transfer mechanisms. With the rise in heat load in electronics cooling there is a limitation from conventional air and liquid cooling. The contact line of the departing bubble aligned with heater surface plays a greater significance due to the presence of solid, liquid & vapor interface or the triple interline region. The present study aimed to study heat transfer in various surface morphologies. Specimens with different surfaces tested are Copper, Silicon & Gold. The experimental theory, along with the results data, was also documented to support the difference in the results. The thermal conductivity of copper (401 W/m·K) is higher than Gold (315 W/m·K) and Silicon (148 W/m·K), but the change in hydrophilicity and surface wettability changes the overall heat transfer. Experimental results reveal that the heat flux for Silicon was maximum *i.e.* 3800 W/m^2 followed by Gold (3700 W/m^2) & Copper (3200 W/m^2). The difference in the heat transfer was due the surface morphology, wettability & hydrophilic nature of the surface. The contact angle was also measured for different samples using Goniometer which supports that contact line increases due to hydrophilic nature of the surface which give rise to increase in contact line and enhances the heat transfer.

Subject Areas

Heat Transfer, Two-Phase Heat Transfer, Vapor Contact Line

Keywords

Contact Line, Triple Interline, Heat Transfer, Morphology, Hydrophilic, Data Center Cooling Wettability

1. Introduction

Study of evaporation rate and heat transfer along the interface or contact line holds a greater importance in pool boiling heat transfer enhancements due to the occurrence of different phases at the same location. Heat transfer in the contact line region is significantly higher than the bulk heat flux during boiling thus this area needs a greater visualization in studying and developing mechanisms for the contact line region. A lot of previous studies have given focus on heat transfer along the outer periphery of bubble during boiling of liquid. These studies are mostly done by studying the meniscus in contact with the heated surface, as it can be interpreted that the nucleating bubble is very much like the meniscus. Study of meniscus can lead to better interpretation of heat transfer along the interface or the contact line region. However, a lot of research has been done on the stable or static meniscus rather than oscillating meniscus.

Kandlikar, Kuan and Mukherjee [1] stated in 2005 that there are a lot many advantages in studying of the stable meniscus, since it is easy to calculate the evaporation rate at a temperature based on input flow rate to make the meniscus stable. Study of heat transfer along this region is of great importance as it deals with the interface of three different phases i.e. solid, liquid and gas. These three different phases meet the heater surface and forms a contact line or the interface. To go deeper in studying the contact line Kandlikar, 2005 [1] and Raghupati, 2016 [2] stated in their research that this region is further classified as Non-Evaporating, Evaporating and Intrinsic meniscus region as shown in **Figure 1**.

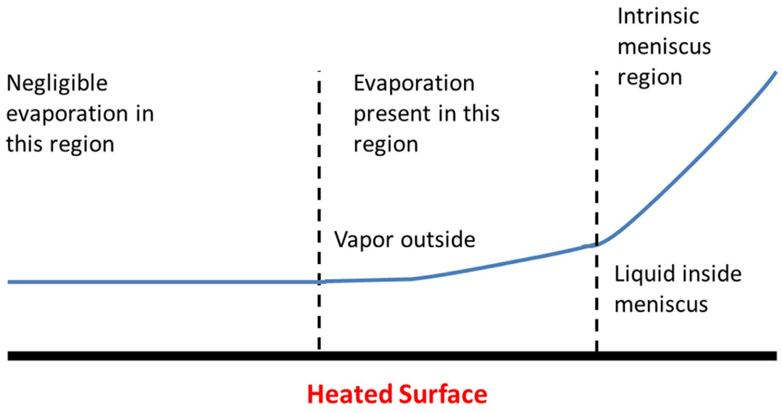

Figure 1. Schematic representing various regions of meniscus [1].

The region lying on the onset of meniscus has strong molecular attraction and Vander wall's forces between liquid molecules prevent it from evaporating thus this region is coined as a liquid vapor interface [1] [2]. As shown in the figure, as we move towards right the thickness of liquid surface increases leading to reduction of molecular attraction forces and separation from the contact line thus rate of evaporation increases drastically.

Liss, Ball, Martinelli & Coantic, 1980 [3] conducted the wind tunnel studies to examine the heat transfer on air water interface and stated that the evaporation rate varies with change in wind speed. Results revealed that heat transfer is enhanced when the water temperature is below the dew point temperature. In 1979

Holm, Goplen [4] in their research stated that Very high heat transfer rates have been observed near a triple interline, the junction of the vapor, the evaporating zone, and the non-evaporating zone. The advancements of interline dispersion is unpredicted, thus it cannot be controlled. To study the interline heat transfer capillary grooves were incorporated by means of which length & number of interline was controlled by the number and length of grooves. Thus, heat transfer was enhanced by flow of liquid into the groove by phenomenon called capillary action. Several factors which were studied includes the amount of heat transfer from the grooved plate, the variation in temperature along the wall separating the groove and the temperature difference between the top wall and surrounding vapor. Results revealed that restricting the thermal conduction path to triple interline there was a better study of local heat and mass transfer [4].

In 2007 Dhavaleswarapu, Chamarthy, Garimella & Murthy [5] studied the heat transfer mechanisms in two phase cooling devices like heat pipes, thermosiphons and two-phase cold plates. In all the above systems, it was proved that thin film evaporation which is critical mode of heat transfer along the solid-liquid and vapor junction. Due to very high heat transfer rate in this region the pressure gradient developed pulls the liquid in three phase regions. Evaporation is primarily due to the diffusion and convection heat transfer on the outer periphery on contact line. Surface tension also effects the diffusion heat transfer in this region, in 1995 Chang, Franses [6] stated that adsorption and tension dynamics are important either at constant surface area or at varying surface area conditions. In gas dispersions with growing bubbles, the change in adsorption on increasing the area is important. A lot of studies have been done on the study of tension dynamics with different liquid chemical properties and different mathematical model have been proposed.

The present research aims at studying the mechanisms and proposing the basic understanding of effect of surface morphology and contact line velocity on heat transfer at contact line region. Evaporation rate, heat transfer and heat flux along the contact line in stable meniscus will be studied. Different surface morphology to be tested are copper, silicon and gold-plated chip under stable meniscus for variable temperature range. The same sets of experiments will be analyzed and compared with establishing and developing the mechanisms for setting up an oscillating meniscus at 20Hz frequency and contact line velocity on heat transfer will be evaluated. Validation and support for the difference in heat transfer is also studied in the given research.

2. Experimental Setup

Materials: The three different heater surfaces which were tested are Copper, Silicon & Gold. Gold chip was made through electroplating of top surface of copper chip. The thickness of electroplating was controlled through the number of strokes of the spatula on the surface. To validate the readings 3, 50 & 150 strokes were selected, and heat transfer was studied.

Setup: Figure 2 and Figure 3 represent the schematic and actual setup of the meniscus formed with degassed water droplet. The drop sits on top of a heated smooth surface and is attached to the end of a stainless-steel needle. The needle, bent 90˚, is attached to the syringe pump which is used to control & maintain the flow rate. The system is easily customizable. Furthermore, all fittings that connects to the injection are controlled through LabVIEW and bed of the heater through Arcus Technology stepper motor to account for the minute height adjustments, the height is controlled through a LabVIEW concurrently with feedback control loop. Thermocouples used to measure the temperature of the specimens are connected through NI LabVIEW programming. The flow of liquid through syringe pump & the dimensions of meniscus are controlled manually (all the meniscus was formed with common height and base diameter. High speed camera was used to capture the images & record the evaporation rate. Heat is transferred to the chip using heater block which is connected & regulated through varying voltage across the heater.

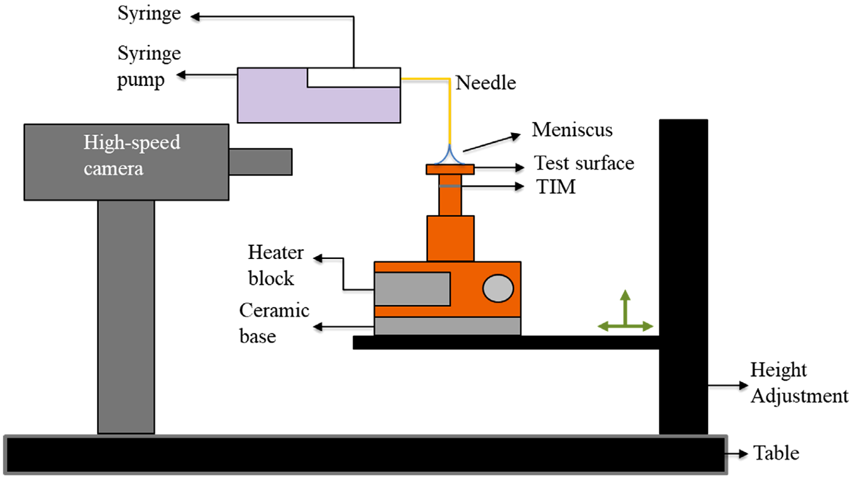

Figure 2. Schematic of Meniscus test setup (liquid supply through syringe pump).

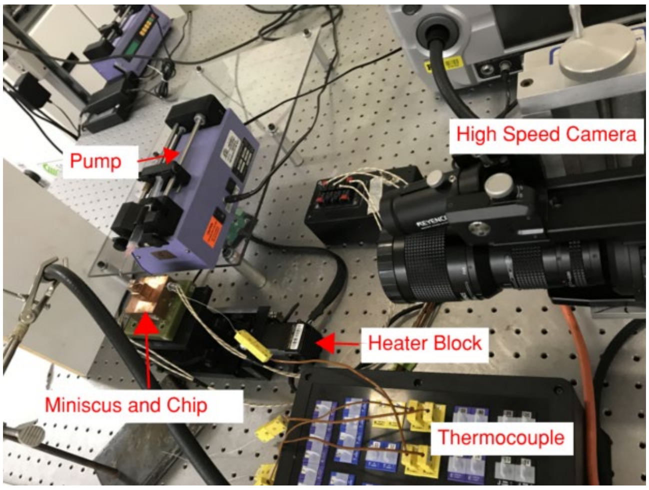

Figure 3. Actual test setup.

Mathematical Equation Used to Calculate Heat Transfer

$$M = \frac{H}{\left(4.2\frac{\text{KJ}}{\text{Kg}}\,^{\circ}\text{C}\right)\text{dt}}$$

where M = mass flow rate in kg/sec.

H = Heat flow rate in KW or KJ/sec.

4.2 kJ/kg ˚C is the specific heat of water.

dt = Is the change in temperature (*i.e.* difference in room temperature & meniscus temperature).

Note: for all the experiments the room conditions recorded are Room Temperature = 20-degree Celsius, Relative humidity = 66% - 68%, Pressure = 1.04 bar.

3. Methodology

A heater plate was connected to a power supply and kept below the test copper chip. A layer of thermal paste was applied to the connecting surface to have a thermally conductive layer in between and to avoid any air gap. The chip was provided with a hole on the side, near the upper surface which was used to connect to the thermocouple for the measurement of the surface temperature. The heater supplies voltage across the cartridge heater, which is in contact with the copper chip. The copper chip gets heated due to conduction. The temperature is measured using the thermocouple. A needle connected to the syringe dispenses the liquid on the surface. As the surface is hot, the droplet evaporates, and continuous flow rate from the syringe pump was adjusted so that the meniscus is under equilibrium (*i.e.* rate of evaporation matches with the input flow rate). This process was repeated 45, 55, 65, 75 & 85 degrees temperature and stable meniscus was observed and recorded using high speed camera.

4. Results and Discussion

The three different chips which were tested are Copper, Silicon & Gold. All the three samples were tested at temperatures of 45, 55, 65, 75 & 85 degrees and degassed water was used to encounter nucleation issues inside the meniscus. Figure 4 shows the heat flux v/s temperature for three different surfaces. Heat flux obtained for Silicon is 3801.29 W/m^2 followed by Gold (3705.19 W/m^2) & Copper (3191.66 W/m^2). Figure 5 shows the heat transfer per unit length of the meniscus. Results reveals that magnitude of heat transfer per unit area increases with increase in length of meniscus. The reason for this is more region inside the meniscus & high region of wettability. Figure 6 shows the contact angle for three different surfaces. The thermal conductivity of copper (401 W/m·K) is higher than Gold (315 W/m·K) and Silicon (148 W/m·K), but the change in hydrophilicity changes the overall heat transfer

Recording & Visualizing the Meniscus:

Meniscus visualization is the key to success for this entire experiment. Observing a stable and evaporating meniscus will allow the user of this test set up to obtain a better understanding of bubble nucleation at high heat fluxes. High speed camera was used to capture the characteristics of the bubble. Due to this restriction, meniscus visibility must be a driving factor in the design of the test setup. There is also a stage for the needle used to inject the fluid.

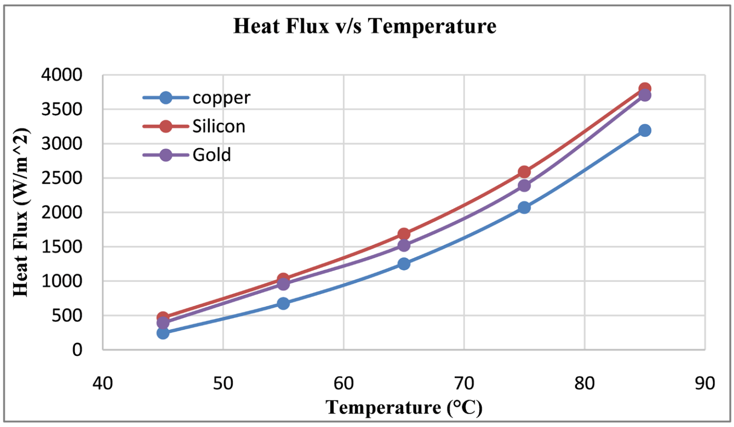

Figure 4. Plot for heat flux v/s temperature.

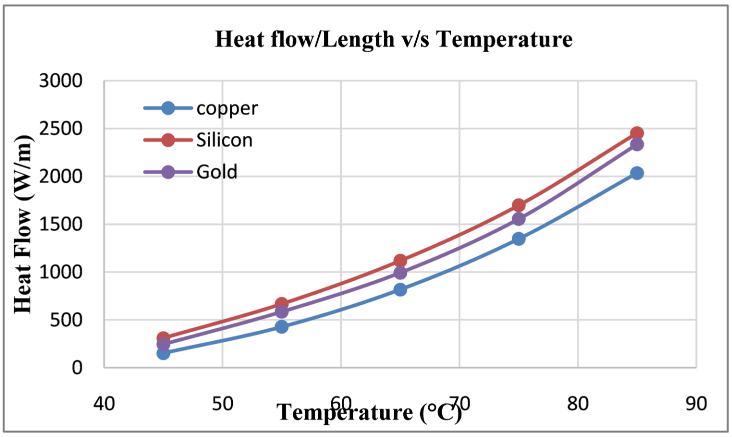

Figure 5. Plot for heat transfer per unit length v/s temperature.

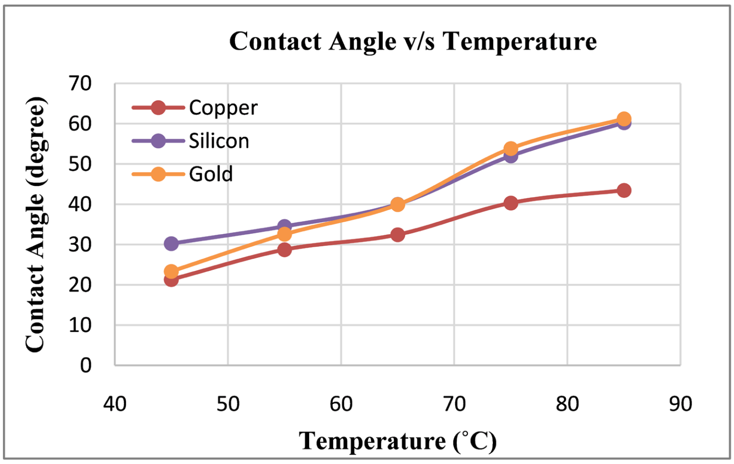

Figure 6. Plot for contact angle v/s temperature.

Electroplating Copper Surface with Gold

Electroplating of copper surface was done with gold electrolyte. Copper chip was connected to Anode and gold electrode with cathode, gold deposition from gold electrolyte takes place due to reduction & oxidation (Redox) reactions. It was well absorbed after testing on three different electrolyte surfaces that heat transfer in contact line is same as that of copper in copper chip electroplated with 3 & 50 strokes but after 150 strokes the heat transfer increases and remains constant. Images obtained in Figure 7 shows that the electron deposition in 3 & 50 strokes are non-uniform due to which the surface behaves as a copper and effect of gold is minimized.

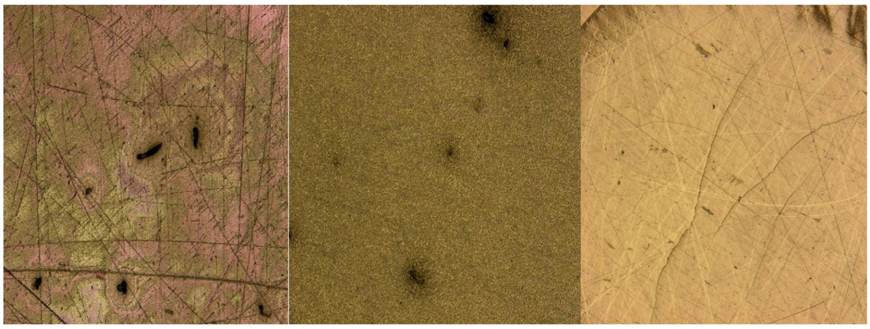

Figure 7. Copper surface with 3, 50 & 150 strokes of gold electroplating.

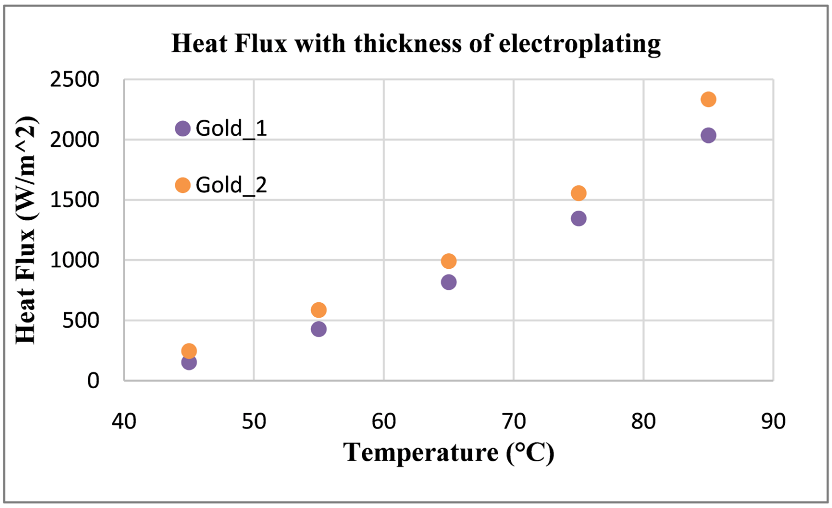

Figure 8. Variation of heat flux with thickness of electroplating.

The difference in heat transfer for all the three surfaces is due to the hydrophilicity & wettability. All the three surfaces are hydrophilic in nature, but silicon & gold behaves as super hydrophilic and due to which the contact line of meniscus increases, which then tends to increase which then tends to vary the heat transfer. For real surfaces, the equilibrium contact values vary between the advancing and the receding contact angle depending on the heterogeneities of the surface [7]. The equilibrium contact angle is obtained at thermodynamic equilibrium *i.e.*

when no mass transfer takes place. Birdi [8] pointed out that the evaporation behavior of the droplet with contact angle greater than 90˚ is different than if the contact angle is less than 90˚. It was found by Bourges-Monnier and Shanahan [9] that, for droplets with contact angle less than 90˚ the contact line is pinned and mass transfer due to evaporation is linear with time while, Cazabat [10] showed, for non-wetting case, the mass transfer due to evaporation is non-linear. **Figure 8** shows the variation of heat flux with thickness of electroplating.

5. Conclusion

A meniscus setup has been designed to understand the fundamental mechanisms of nucleate boiling and heat transfer in the contact line region through a heated meniscus. Various subsystems incorporated into the setup include a feedback loop, height adjustment, an injection system through syringe pump. The LabVIEW used for this setup incorporates control of the motor and recording the temperature through thermocouples sensor. A stage is used to vary the height of the needle and a syringe pump is used to fill the system with degassed water. Preliminary tests with the stable meniscus with different surface morphologies shows that the contact line heat transfer depends on the hydrophilicity of the surface which is maximum in silicon followed by gold & copper. This test can also be validated through formation of an oscillating meniscus with frequency of 10-15 Hz and heat transfer can be tested under same surface morphology.

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Conflicts of Interest

The authors declare no conflicts of interest.

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