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DROPWISE CONDENSATION ON SURFACES WITH GRADED HYDROPHOBICITY

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ABSTRACT

Dropwise condensation has shown the ability to increase condensation heat transfer coefficients by an order of magnitude over filmwise condensation. In standard dropwise condensation, liquid droplets forming on a sub-cooled non-wetting surface are removed from the surface by gravitational forces when the droplets reach a critical mass. The dependence on gravity for liquid removal limits the utilization of dropwise condensation in low gravity aerospace applications and horizontal surfaces. Presented in this study is a novel passive mechanism to remove droplets from a condensing surface using a surface energy gradient (wettability gradient) on the condensing surface. The wettability gradient creates a difference in contact angle across droplets condensing on the surface. The difference in contact angle across the droplets causes motion of the droplets to regions of increased wettability, without relying on additional forces. The movement of droplets away from the surface prevents flooding and allows for the condensation of new droplets on the surface. This paper presents an overall description of the wettability gradient mechanism and experimental condensation data acquired on surfaces with wettability gradients. A mechanism for creating the wettability gradients is also described, which involves varying the surface concentration of hydrophobic molecules through a self-assembled monolayer process.

BACKGROUND

As the electronics industry continues to push processor performance, the amount of power utilized by these devices grows [1]. System integrators face challenges in thermal management as consumers continue to demand smaller, more portable, and more rugged devices. For these devices to maintain a nominal operating temperature, the thermal management techniques involved must also continue to become more efficient and compact. An important process in the current thermal management architecture involves spreading the heat generated from these small electronics devices over a larger area so the heat can be dissipated to the ambient through traditional air cooled heat sinks [2]. The use of two-phase heat transfer devices such as heat pipes and thermosyphons to help spread heat has become common [3]. As the overall device package shrinks the area for the heat sink also decreases, causing larger thermal gradients and heat fluxes through the condensing sections of the two-phase heat transfer devices. A need arises for technologies resulting in a decrease in condenser thermal resistance without additional power consumption or moving parts.

For the past 60 years dropwise condensation has been studied for its ability to produce heat transfer coefficients an order of magnitude higher than filmwise condensation [4]. The mechanism of dropwise condensation is still debatable and much discrepancy exists in the literature on this topic [5]. However, the ability of dropwise condensation to increase heat transfer coefficients over filmwise condensation is well established. Research into dropwise condensation is inspired by economic incentives attainable if the heat transfer coefficients of dropwise condensation can be sustainable [6]. However, only recently have researchers been able to create surfaces which can maintain their properties and sustain the dropwise condensation mode over time [7]. Also, dropwise condensation relies almost solely on gravity to remove liquid droplets from the condensing surface and the performance is very sensitive to the orientation with respect to gravity.

Performances in both filmwise and dropwise condensation are further degraded by the absence of gravity. In the absence of gravity only drag forces are able to remove condensing droplets from a surface for recirculation. In a filmwise mode, capillary wicks can also remove fluid from a condensing surface [8]. Dropwise condensation is not possible in the condensing regions of a capillary driven heat pipe because the fluid must be able to wet the wick surface of the heat pipe. Dropwise condensation only occurs on non-wetting surfaces. A surface with graded wettability, a new mechanism studied in this paper, has both the ability to minimize condenser thermal resistance and passively remove liquid from the surface.

INTRODUCTION

An innovative dropwise condensation method using surfaces with varying hydrophobicity has been developed to improve condensation heat transfer coefficients over traditional dropwise condensation while overcoming the shortcomings involving gravity dependence and surface orientation. Usually a dropwise condensation surface is uniform with respect to its hydrophobic surface properties. On these traditional dropwise condensation surfaces, droplets must grow and coalesce until they are large enough to fall due to gravitational or shear forces. On surfaces with graded wettability the droplets can move away from the condensing surface without gravity [9]. Figure 1 shows a physical description on how the droplet motion is generated on a surface with decaying hydrophobicity. Since the surface is steadily decreasing from hydrophobic to hydrophilic, a droplet placed on the graded energy surface experiences two differing contact angles with the higher contact angle located on the more hydrophobic side of the droplet. The difference in contact angle across the droplet creates a driving force to push the droplet in the direction of increased wettability. It should also be noted that in order for a droplet to move on the gradient surface the advancing contact angle on the front side (more hydrophilic side) of the droplet must be less than the receding contact angle on the back side. Otherwise, the droplet will remained pinned on the surface. In other words, the gradient surface must have a low hysteresis (difference between advancing and receding contact angles) at all positions along the gradient for droplet motion to occur.

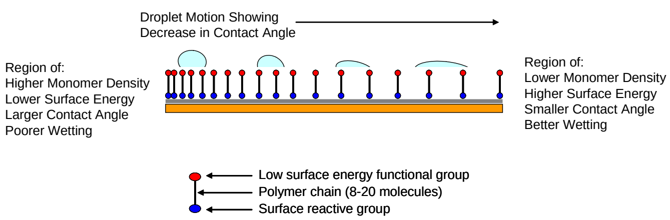

Fig. 1 The motion of droplets from the hydrophobic to hydrophilic side of a surface gradient is depicted. The creation of a surface energy gradient by varying the surface concentration of molecules with low surface energy is also depicted.

Previous research has shown that droplets condensing on a gradient surface can attain very high speeds. The fast movement of condensing droplets on a sub-cooled surface exposed to saturated steam was demonstrated by Lehigh University researchers using a chemically produced surface gradient [10]. The movement of these droplets was demonstrated on a 5 cm diameter copper disk with a radial gradient surface oriented horizontally. Droplets condensing on the surface moved from the center of the disk to the outer edges by the surface gradient. Due to the coalescence of droplets and constant addition of fluid to the surface by condensation, the droplets accelerate to very high speeds. Droplet speeds of over 30 cm/s were measured on the horizontal surface. The fast motion of the droplets on the surface causes an increase in the condensation heat transfer coefficient as compared to falling droplets [11]. The motion of the droplets is much less sensitive to gravity as the driving force is inherent in the energy of the surface. Due to the gravity independence, the heat transfer coefficient values are higher in comparison to traditional dropwise condensation surfaces oriented horizontally.

The creation of low hysteresis surfaces with graded wettability is currently performed by varying the surface concentration of a self-assembled monolayer with hydrophobic properties. Although any coating process resulting in graded wettability could be used, self-assembled monolayers are particularly suitable because of their small thicknesses (less than 2nm for the monolayer) and therefore negligible thermal resistance. Self-assembled monolayers have also been proven to produce low hysteresis, hydrophobic surfaces on a number of metallic surfaces. As shown in Figure 1, by varying the surface concentration of self-assembled molecules with low surface energy on the surface, the average local hydrophobicity can be controlled.

EXPERIMENTAL

A thermosyphoning two-phase test loop was fabricated to measure the condensation heat transfer coefficients attained from the condensation of saturated steam. A test loop schematic is shown in Figure 2. The loop consisted of a boiling chamber, condensation test section, transport lines and a valve for filling, venting and vacuuming. The boiling chamber evaporated liquid returning from the condensation test section. Vapor travels up the transport line above the liquid puddle in the condenser. Liquid from the condensing section first puddles in the bottom of the test section before travelling down the transport lines to the boiling chamber. A close up of the condensation test section is shown in Figure 3. The device shown in Figure 2 was used for gravity aided testing. A similar device was used for horizontal and against gravity testing with the boiling chamber located beneath the backside of the condensation test section. A wick structure was also used in the test performed against gravity to facilitate the removal of liquid from the end of the gradient surface to the transport line.

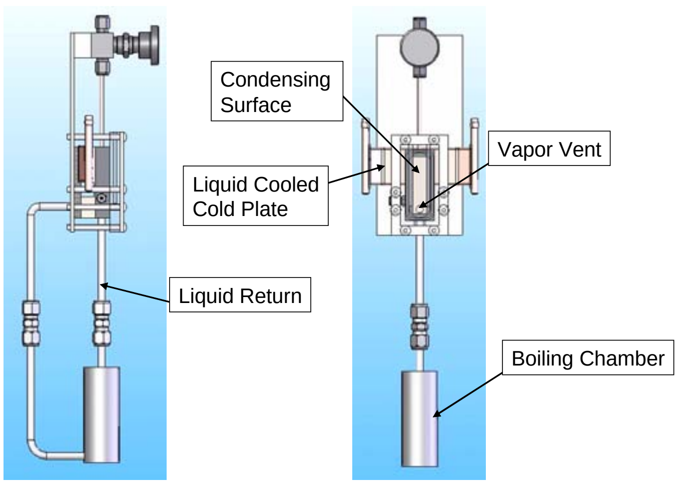

Fig. 2 A solids model of the thermosyphoning test system is shown.

The heat flux and heat transfer coefficients along the condenser were measured using a series of thermocouples as shown in the side view photograph of the test article in Figure 4. The sets of thermocouples allow for calculation of the heat flux by conduction calorimetry. Conduction calorimetry involves using the distance between the thermocouples, thermal conductivity of the copper material and difference in temperature between the thermocouples to calculate the heat flux through the plate. By knowing the distance between the thermocouple and the surface, as well as the calculated heat flux and thermal conductivity of the copper material, the temperature of the wall at the surface was extrapolated. The temperature of the saturated vapor was measured with a thermocouple located in the vapor space of the test section. Knowing the wall temperatures, heat fluxes and vapor temperature allowed for accurate calculation/measurement of the local wall heat transfer coefficient. It should be noted that a gap was machined in the copper plate between the connection port and condenser regions to prevent a thermal link between the two regions which would complicate heat transfer coefficient measurements due to conduction effects. The data reported here is a numerical average of the heat transfer coefficients measured in the three locations.

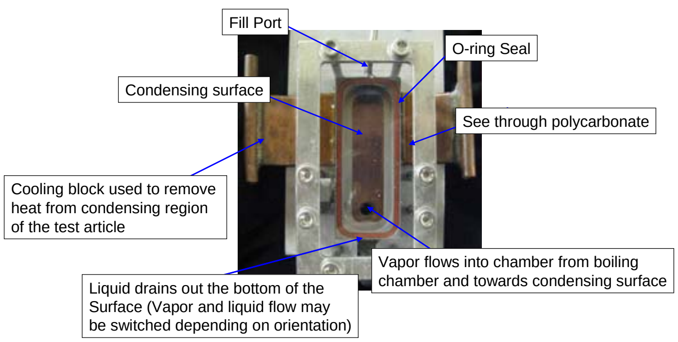

Fig. 3 A close up view of the condensation test section is shown.

Fig. 4 A side view of the test section is shown. Thermocouples inserted in the 9 holes are used to measure the heat flux and surface temperature of the condensing surface. A gap was also machined to prevent heat from leaking in through the vapor/liquid ports.

All condensation data was obtained using water as the working fluid. All tests were taken at a saturation temperature of 100°C under vacuum (not in open atmosphere). Data was acquired at four input powers (25W, 50W, 75W and 100W) over the 2.54cm by 1.27cm heat input section (heat fluxes ranged between 7.75 W/cm^2 and 31 W/cm^2). Data was acquired for three surfaces (filmwise, dropwise, and gradients) at four orientations (vertical, angled 45° gravity aided, horizontal and 5° against gravity). A plot of the four orientations tested is shown in Figure 5.

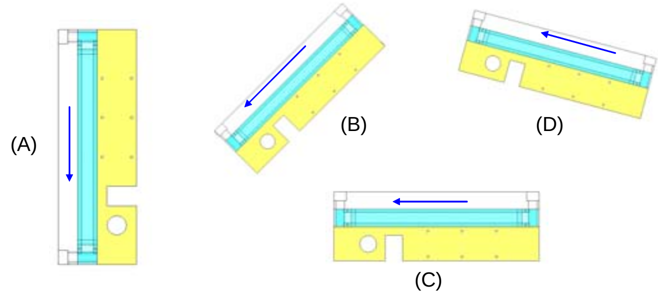

Fig. 5 This figure shows the various orientations to be tested including vertical (A), 45° angle gravity aided (B), horizontal (C) and 5° against gravity (D).

RESULTS

The vertical orientation on a wetted surface (Figure 5a) was tested first. A plot of the experimental results is shown in Figure 6. The most important piece of information in Figure 6 is the agreement of the filmwise test data with the Nusselt filmwise condensation model. The near perfect agreement validates the test section and method of heat transfer coefficient measurement for this study. The model verification also adds credibility to the often hard to accurately acquire dropwise condensation data. Dropwise condensation on the non-wetting surface produced heat transfer coefficients that were 5-8 times higher than filmwise condensation, a significant improvement. By condensing on the gradient surface, a 35% improvement in heat transfer coefficient was observed as compared to the dropwise condensation surface. The improvement in the vertical orientation was not expected to be excessive, since gravity alone is able to pull condensing droplet on a vertical surface rather quickly. The result does show evidence that a surface gradient adds some additional force to move the droplet in addition to gravity, resulting in increased performance.

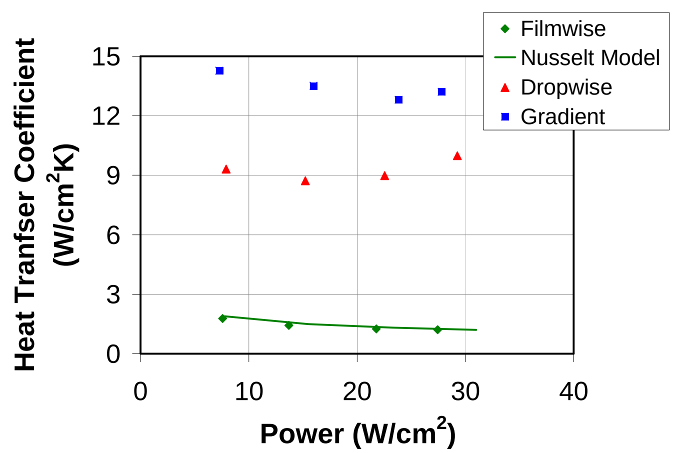

Fig. 6 A plot of experimentally measured heat transfer coefficients for a non-wetting, gradient and wetting surface in the vertical orientation (Figure 5A) are shown. The filmwise data compared well to the Nusselt model, validating the acquired data from the test section.

The test section was then tilted at a 45° angle (as shown in Figure 5B) and tested. The experimental data for the 45° orientation is shown in Figure 7. Again the filmwise heat transfer coefficient data matched well with the Nusselt model when modified for the partial loss of gravity. All modes of condensation showed reduced performance as compared to the vertical testing. The performance of the non-wetting surface fell about 65%. The gradient surface fell about 50%. However, the performance of the gradient surface was 200% better than the non-wetting surface at 45° as compared 35% in the vertical orientation. It seems that as gravity is reduced, the gradient surface is still able to maintain high droplet velocities required to keep the heat transfer coefficient high. Since the non-wetting surface relies solely on gravity for droplet motion, the reduction in performance is more rapid as gravity is removed.

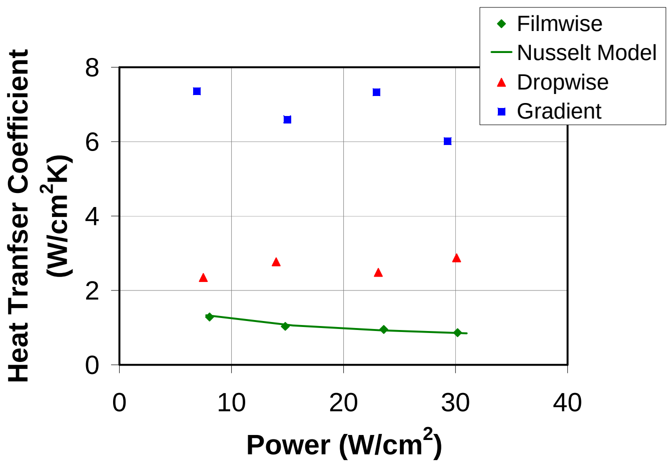

Fig. 7 A plot of experimentally measured heat transfer coefficients for a non-wetting, gradient and wetting surface angled at 45° (Figure 5A) are shown.

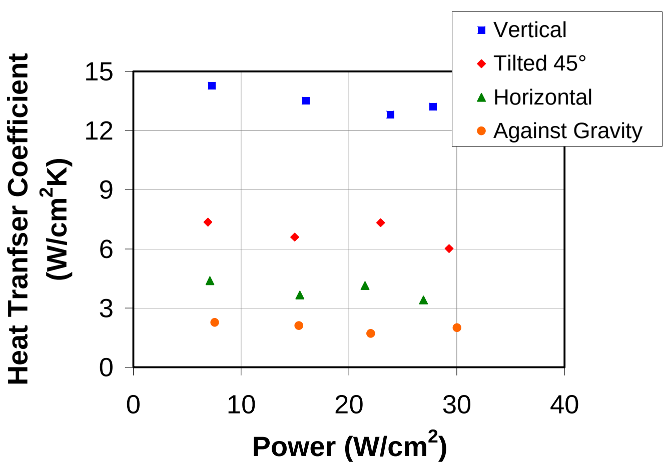

Fig. 8 A plot of all of the gradient surface condensation test data at multiple inclinations is provided.

The next test was performed in the horizontal orientation (Figure 5C). Data was only acquired with the gradient surface, although gathering data with both the uniformly non-wetting and wetting test articles was attempted. Without gravity to return condensing fluid to the boiling section, liquid just flooded the condensing region of both the uniformly non-wetting and wetting test articles. The heat transfer coefficients measured were <<500W/m^2-K at very low heat fluxes (less than 5 watts of power) since not enough driving forces was present to move heat through the poorly performing flooded heat transfer surfaces. The gradient surface was still able to move liquid droplets without the aid of gravity. The result was a heat transfer coefficient in excess of 3.5W/cm^2-K. As a reference this is approximately 3 times greater than the heat transfer coefficients measured on a wetting surface with the full aid of gravity. The data for the horizontal gradient surface test is plotted along with other gradient surface test data at other inclinations in Figure 8.

The final test was performed with the condenser operating against gravity (Figure 5D). The data is plotted in Figure 8. In this orientation the droplets have to be moved uphill in order to reach the end of the condensing section. A wick was inserted at the end of the condensing section to move liquid against gravity from the end of the gradient to the liquid return port. This could be avoided if the gradient ended at the liquid return port. However, the adiabatic gap section machined in the test article prevented the gradient from being close enough to the liquid return port. Inserting a piece of copper screen mesh worked well in transporting fluid from the gradient over the gap to the liquid return port. The measured heat transfer coefficients were much higher than the flooded dropwise and filmwise surfaces. However, there was some degradation in performance as compared to the horizontal testing. In order for the droplet to move uphill, they needed to grow until they spanned larger portions of the gradient to get additional driving force. The larger droplets required to move uphill resulted in more of the surface being coated with fluid, lessening heat transfer coefficients. However, the 2W/cm^2-K condensation heat transfer coefficients still exceed gravity aided filmwise condensation.

CONCLUSIONS

An innovative method for enhancing dropwise condensation using a wettability gradient has been verified experimentally. An experimental test system was fabricated and qualified by matching filmwise test data with the predictions of established heat transfer coefficient models. The qualified test section was used to measure heat transfer coefficients for traditional dropwise condensation and graded wettability surfaces at multiple locations. The gradient surface performed marginally better (35%) than the traditional dropwise condensation surface under vertical orientations. As gravity was reduced to a 45° angle, the gradient was better able to maintain its higher performance as compared to the non-wetting surface. Horizontally and against gravity, the gradient performed much better than the non-wetting surface as the non-wetting and wetting surfaces flood without gravity to remove condensing liquid. Heat transfer coefficients on a horizontal surface of 3.5W/cm^2-K were measure with a gradient surface. Against gravity, heat transfer coefficients of 2.0W/cm^2-K were measured with a gradient surface.

The use of graded wettability surfaces could be useful in multiple compact electronics cooling applications where orientation (gravity) is unknown and condenser fluxes are high. The surface gradient could also be used in aerospace applications where gravity is limited. The gradient surface could be integrated into passive two-phase heat transfer devices such as heat pipes, vapor chamber and loop heat pipes as well as actively pumped two-phase systems.

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