ENHANCED BOILING SURFACE WITH HYDROPHOBIC CIRCLE SPOTS EVAPORATOR OF LOOPED THERMOSIPHON

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ABSTRACT

Heat transfer characteristic of a closed two-phase thermosiphon with enhanced boiling surface is studied and compared with that of a copper mirror surface. Two-phase cooling improves heat transfer coefficient (HTC) a lot compared to single-phase liquid cooling. The evaporator surfaces coated with a pattern of hydrophobic circle spots (non-electroplating, 0.5 – 2 mm in diameter and 1.5 – 3 mm in pitch) achieve very high heat transfer coefficient and lower the incipience temperature overshoot using water as the working fluid. Sub-atmospheric boiling on the hydrophobic spot-coated surface shows a much better heat transfer performance. Tests with heat loads (30 W to 260 W) revealed the optimum thermosiphon performance. Hydrophobic circle spots coated surface with diameter 1 mm, pitch 1.5 mm achieves the maximum heat transfer enhancement with the boiling thermal resistance as low as 0.03 K/W.

INTRODUCTION

As the rapid increasing of heat generation from electronic components such as Central Processing Unit (CPU), thermal management has become a serious issue [1]. Liquid-vapor two-phase cooling is considered a very promising way for dissipating high heat fluxes of chips [2]. Release latent heat of phase change can lead to higher heat transfer coefficient compared with single phase cooling [3]. Thermosiphon is considered as an advanced heat transfer device. Description of conventional thermosiphons without wick structure, vapor-liquid circulation is driven by density difference. Vapor is condensed and changed into liquid flowing to the evaporator taking the advantage of gravity to assist [4]. As many researchers studied that the boiling performance deteriorates at sub-atmospheric pressures. Van Stralen investigated that bubble growth rates and frequency in nucleated boiling were greatly affected by various pressures [5]. Niro studied a higher system pressure led to a higher saturation temperature of working fluid and hence reduced the superheat necessary for boiling under a given heat flux [6]. With the aim of enhancing the boiling performance, using enhanced structure surface was found to be one promising way to reduce the evaporator surface superheat, lower the incipience overshoot and improve the bubble behaviours. Finned structure surfaces can transfer heat by the large area and then give a higher heat flux and lower surface temperature [7]. It was noted that blasted surfaces also can lead to higher heat transfer coefficient [8]. Some researchers found that surface wettability plays a significant role in boiling. Surfaces with hydrophilicity gave a higher critical heat flux (CHF) than normal surfaces. For hydrophobic surfaces, nucleate boiling was enhanced considerably with very low superheating [9] [10].

To optimize the performance of a loop thermosiphon, this work focuses on providing a detailed understanding of heat transfer enhancement of a mixed-wettability surface at sub-atmospheric pressures with water as the working fluid. We found that the heat transfer coefficient of patterned surfaces was enhanced by 3 times compared to that of an uncoated copper surface, with an evaporator surface temperature reduction of 10 K – 17 K corresponding to the heat flux changed from 30 kW/m^2 to 260 kW/m^2.

NOMENCLATURE

A	[m^2]	Evaporator surface area
d	[m]	Diameter
FR	[%]	Filling ratio
p	[m]	Pitch
Q	[W]	Heat transfer rate
R	[K/W]	Thermal resistance
T	[K]	Temperature

Subscripts

boil	Boiling
sat	Saturation
v	Vapor
cond	Condenser

EXPERIMENTAL APPARATUS

A schematic of the experimental setup is shown in Fig. 1. The setup used in the experiments consists of the evaporator and the condenser, and two connecting pipes of an internal diameter of 10mm. Both pipes are insulated in order to reduce heat loss. To activate this loop thermosiphon, the condenser is placed at 10mm higher than the evaporator, which helps the condensed liquid flow from the condenser to the evaporator continuously.

The evaporator is a rectangular chamber 50 mm in height, made of transparent polymer materials, which allows viewing of the liquid level inside the chamber and the bubble behaviors. The snake-tube heat exchanger, which works as a condenser, provides condensing power. Two smooth-walled pipes are used to separate liquid and vapor pathways to exclude both thermal and viscous interactions between counter-currents of vapor and liquid. The press-fitted O-ring is used on the bottom of the evaporator chamber for good sealing. Heating is provided by three cartridge heaters embedded firmly. A high temperature resistant and thermal conductive paste is used between the top of heating block and the bottom of evaporator surface to reduce thermal contact resistance.

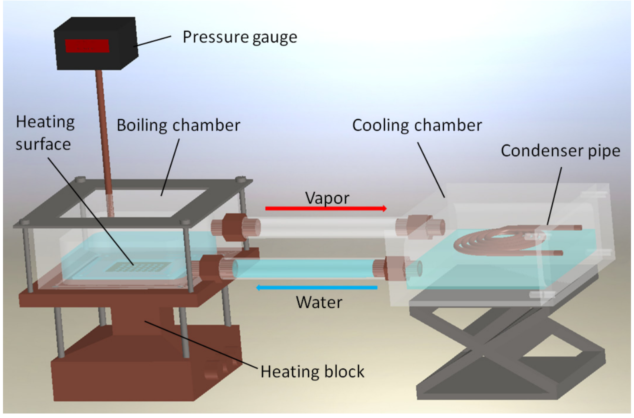

Figure 1 Schematic of a two-pipes loop thermosiphon

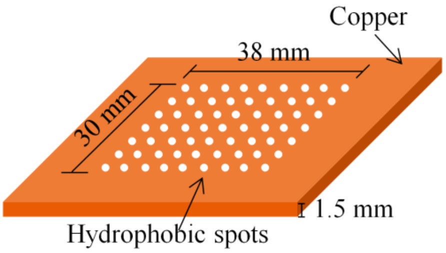

Figure 2 Non-electro plating mixed-wettability evaporator surface

Leakage check is carried out to ensure that the setup maintains a consistent performance over a long period of time. Initially at 10 kPa, the pressure of the closed system is found to increase by only 0.2 kPa after a 24-hour period, which is considered an acceptable amount of leakage. After charging and degassing, the system valve is closed and air initially dissolved in the test liquid can be removed by vacuum degassing for 2 hours prior to the measurement. Each experiment lasts 4 – 5 hours.

The operating principle is as follows: the working fluid is heated by the heater below the surface, and starts to boil on the evaporator surface. Then the vapor of the working fluid moves along the horizontal pipe driven by the pressure difference between the hot region and the cold region of the thermosiphon.

In the condenser chamber, the vapor flowing from the evaporation section is condensed into the liquid, and the heat is dissipated into the circulating cooling water in the annular tube. Finally, the liquid from the condenser returns to the evaporator by gravity forming a circulation system. The thermosiphon works by repeating this cycle. The whole experimental system is developed to monitor and control the various process parameters through a data acquisition system. The heat input Q is measured by thermocouples in the heat transfer block over 50 consecutive data. During the experiments, all the sides of heating block assembly are insulated to assure one-dimensional heat flow to the boiling evaporator surface. All measurements have been conducted in a steady state, which is judged by monitoring the outputs of the thermocouples. Various values of the heat load ranging from 30 to 260 W are tested. The thermal resistance is evaluated as the ratio of temperature difference to the heat input Q.

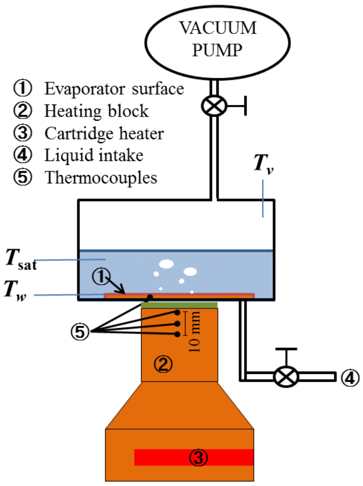

Figure 3 Temperature measurements of the thermosiphon

Fig. 3 describes the temperature measurement of the boiling chamber and heating block. The boiling thermal resistance is defined as the difference between T_w and T_{sat} divided by the heat input Q:

$$R_{boil} = \left(T_w - T_{sat}\right)/Q \qquad (1)$$

Here T_w is the wall temperature at the center of the evaporator surface measured by the thermocouple embedded in the hole inside, T_{sat} is the saturation temperature measured using the thermocouple immersed in the liquid.

Surface wettability is one of the critical aspects which can influence liquid-vapor phase change performance. The contact angle is always used to determine the wettability property. For surfaces with contact angles (CA) less than 90°, the surface is considered hydrophilic, whereas for those with CA > 90°, the surface is hydrophobic. Hydrophilic surfaces can significantly increase the CHF values and delay transition to the film boiling mode by facilitating liquid supply to spread the heated area. On the other hand, hydrophobicity promotes bubble generation and can result in a considerable enhancement of the HTC. Recently the coating technique has been improved and some hydrophobic surfaces are developed. We have used the non-electro plating with Ni-PTFE particles and its contact angle to water is over 150°. The copper mirror surface needs to be immersed into the solution with Ni and PTFE particles at around 85 °C for a few minutes.

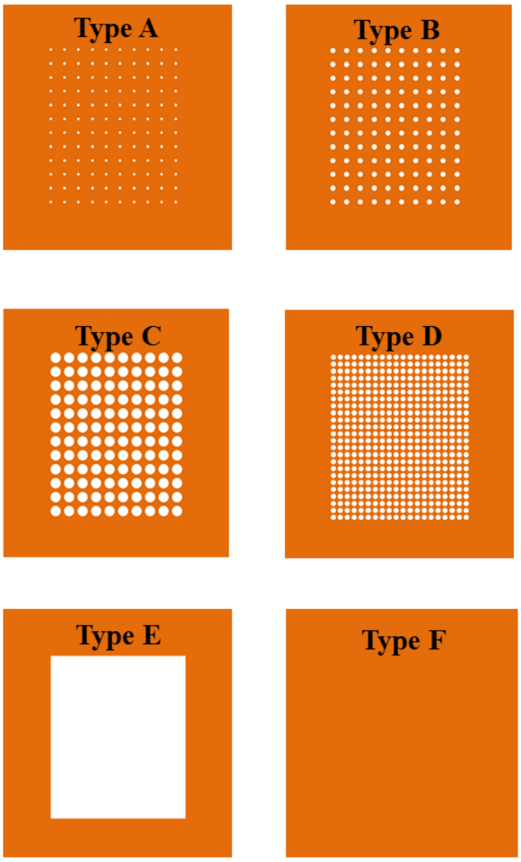

Figure 4 Patterned surfaces of Type A, B, C, D, E, and copper mirror surface Type F.

The surfaces we used in loop thermosiphon experiments are shown in Fig 4. Table 1 illustrates the pattern parameters of them, different diameters and pitches of coated spots. Particularly in the case of Type E surface, it is full covered with hydrophobic material on the heating area. Type F surface is mirror surface without any coating.

Table 1 Hydrophobic spot parameters on evaporator surfaces of Type A, B, C, D, E, and F.

Case	Spot diameter, d(mm)	Pitch, p(mm)	Heating area, A(mm^2)
Type A	0.5	3	1140
Type B	1	3	1140
Type C	2	3	1140
Type D	1	1.5	1140
Type E	Full cover	Full cover	1140
Type F	NA	NA	1140

RESULTS AND DISCUSSIONS

As seen from Fig. 5, there is the comparison of the experimental results of Type A, B, C, D, E, and F surfaces, at heat inputs from 30 to 260 W. Loop thermosyphon is influenced by many factors. The filling ratio (ratio of working fluid volume to total thermosyphon loop volume) is one of the key factors. In this experiment, optimal filling ratio of 27% is used to compare the boiling performance only. From the results of an analysis, it follows that the boiling thermal resistances of Type A – Type E surfaces are much lower than that of Type F. Rboil decreases accordingly with the increasing heating power due to the rising pressure in the system and more active nucleation sites. At increased pressure, decreasing surface tension, bubble departure diameter and increasing bubble frequency are achieved, which contribute to increasingly higher heat transfer coefficient.

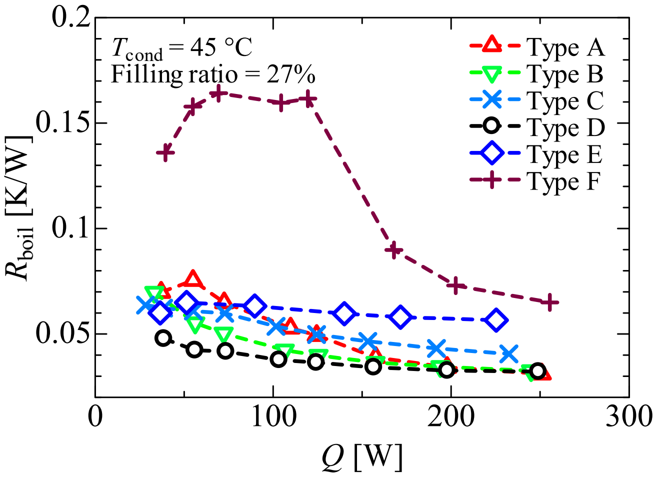

Figure 5 Comparison of experimental results of Type A – Type F. Boiling thermal resistance R_{boil} vs. the heat input Q. Filling ratio is 27%, condenser temperature is 45 °C.

The observations of the contrasting bubble behaviors are shown in Fig. 6 including Type A – Type F surfaces at 130 W heating powers. During the experiment, the camera is used to record the bubble performance. In the case of the uncoated surface (Type F) shown in Fig. 6, image F, an incipient overshoot caused by the big and intermittent bubble is visible as the surface temperature drops suddenly after boiling starts, while it is suppressed on the hydrophobic spot coated surfaces. This intermittent process may result in large, undesirable temperature oscillations at the heated surface. For the case of Type E surface, due to the full covered hydrophobic materials, the whole surface is covered by the vapor film, and it results in the larger superheat. These bubbles do not depart from the surface, instead, form a vapor film. A stable vapor film is observed, which influences the heat transfer efficiency of the surface, as shown in Fig. 6, image E.

The comparison among spots coated surfaces of Type A – Type D, because of the large density of spots, Type D surface gives the lowest boiling thermal resistance. A large amount of coated spots provide more opportunities for the bubble nucleation, as shown in Fig. 6, image D. For the case of Type A surface with spots diameter 0.5 mm, it is very difficult to start the nucleate boiling at such small area sites. There are still inactive spots on the surface when heat input is 130 W as seen from Fig. 6, image A. So the boiling thermal resistance is much larger than that of other spots coated surface at low heat flux.

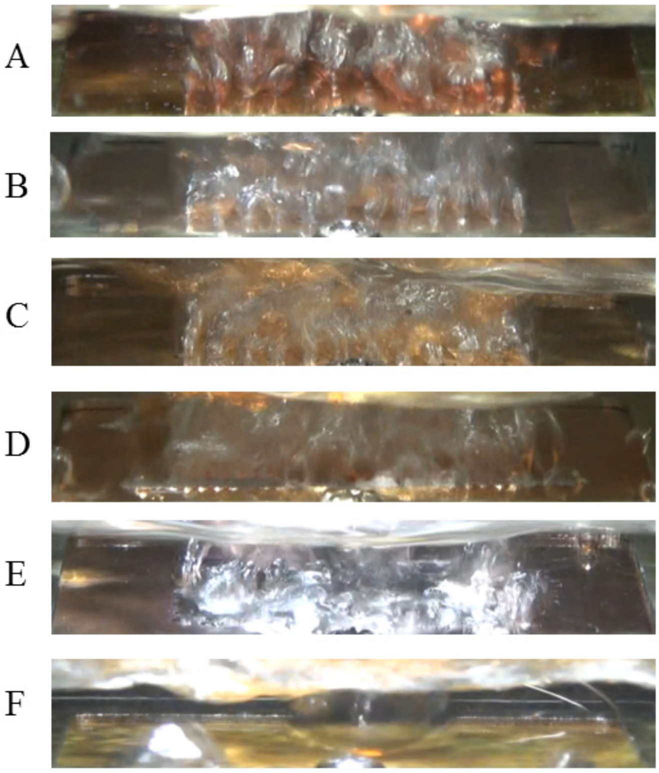

Figure 6 Bubble behaviors on surfaces of Type A – Type F. The operating pressure is 10 kPa, heat input is 130 W, and FR = 27%.

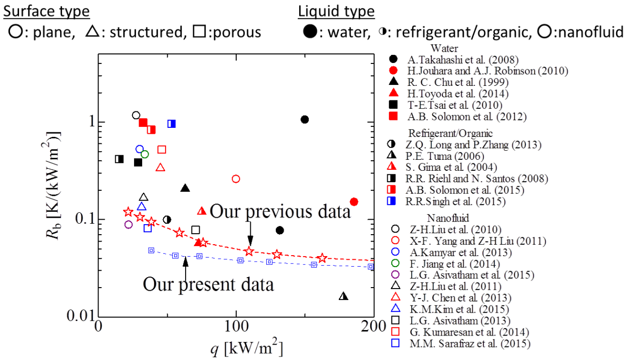

Figure 7 Comparison of the boiling thermal resistances of different working fluids and surface designs.

Due to the larger diameter spots, the larger bubbles are generated from Type C surface, which affect the frequency of bubble departure and HTC.

The status of development of thermosyphons and heat pipes in recent years is shown in Fig. 7. As can be seen in the figure, compared with the results of the other researchers, we obtain one of the best resluts that match the highest thermal performance across all heat loads. Through out efforts, changing the diameter and pitch of the coated spots, we enhance the HTC by more than 10% compared with previous results we got.

CONCLUSION

The experimental study of a two-phase loop thermosiphon for cooling CPU with a mixed-wettability evaporator surface has been carried out. Six surfaces are tested, and the results are discussed. A variety of heat transfer performance have been tested and discussed. Mixed-wettability surfaces show much better heat transfer boiling performance due to the steady bubble behavior compared with the copper mirror surface. The maximal reduction of the surface temperature is 17 K. For patterned surfaces, nucleate boiling is enhanced as the spots density increases.

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