Feasibility study on Performance Enhancement of Copper-based Heat Transport Devices by Short-term Oxidation

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Abstract

Wettability and evaporation control is a key issue to enhance heat transport performance of heat transport devices such as heat pipes and vapor chambers. In this study, in order to enhance heat transport performance of copper-based heat transport devices, utilization of a high performance copper oxide film are proposed. This film has high wettability, which leads to strong evaporation performance of coolant and, as a result, to higher heat transport performance of the devices. The copper oxide film is generated by adjusting the oxidation temperature and time. In order to evaluate the wettability and evaporation characteristics, change in contact angle of a water droplet on the oxide film generated on a copper plate is investigated and droplet behaviors on a high temperature copper surface are evaluated with a high speed video camera. It is confirmed that the contact angle drastically decreases under short-term oxidations within 20 minutes and strongly depends on the oxidation temperature and time. In some cases, hydrophilic state where the contact angle is less than 10 degrees is also confirmed. In addition, the life time, which is the one from the first contact of the droplet onto the high temperature surface to the disappearance, shortens compared with that in a bare surface case. These findings suggest that highly controlled copper oxide film can enhance the heat transport performance of copper-based heat pipes and vapor chambers.

Keywords: Wettability, Contact Angle, Evaporation, Heat Transport Device, Copper Oxide Film

1. Introduction

With recent advance of electronics such as high performance computers and smart phones, high power LEDs, in-vehicle inverters, etc., development of higher performance of heat transport devices, which spreads the heat from the chip, are strongly expected. For example, in utilization of heat pipes[1] and vapor chambers[2] with sintered particles, meshes, or wires inside, the maximum heat transport performance basically results not only from latent heat of liquid but also capillary force and permeability of the porous wick, which conflict each other. In that sense, optimizing the porous structure has been an essential key issue in order to enhance the heat transport performance. In particular, functional porous structure such as biporous wicks that have coarse pores for vapor discharging and fine pores for liquid supplying by the capillary force has been focusing recently.[3] On the other hand, with the development of nanotechnology, many researchers have been trying to enhance the heat transport performance of the heat pipes by utilizing nanofluid that includes nanoparticles inside. Shafahi et al. reviewed these works and summarized that utilizing the nanofluid as the working fluid strongly contributes to enhancement of the heat transport performance such as reduction in heat thermal resistance and increase in maximum heat transport performance, due to its improved thermal conductivity.[4]

Aside from the techniques mentioned above, authors found out the fact that a copper oxide film generated under high-temperature and short-term conditions has high wettability in the studies of boiling heat transfer enhancement with nanoparticles, and utilized the oxide film as a first layer to assemble the nanoparticles.[5] Here, we focus again the following capillary limit model for the heat pipe’s maximum heat transport performance $Q_{\text{max}}$:

$$Q_{\text{max}} = \frac{KA\rho_L L}{\mu_i L_{\text{eff}}} \left[ \frac{2\sigma \cos \theta}{r_c} + \text{Gravity term} \right]$$  \hspace{1cm} (1)

Where $L$, $\mu_i$, $\rho_L$, and $\sigma$ are Latent heat, viscosity, density,
and surface tension of working liquid, respectively. \( K \) is permeability, \( r_c \) is capillary radius, \( A_w \) is area of cross section of the wick, \( L_{eff} \) is effective length of the heat pipe, and \( \theta \) is contact angle between working liquid and solid. Among these parameters, we haven’t discussed the effect of the contact angle \( \theta \) that shows wettability between the working liquid and the porous solid. Figure 1 shows a heat transport enhancing rate compared with the case of the contact angles of 70° and 50° when improving the wettability, that is to say, decreasing the contact angle \( \theta \). In both the cases, the enhancing rate gradually increase with decreasing the contact angle (improving the wettability). Where the referential contact angle is 70°, which almost corresponds to the contact angle of a water droplet and a bare copper surface, the maximum heat transport performance exceeds 3 times higher at a contact angle of 10°. Even at a based contact angle of 50°, the heat transport enhancing rate at \( \theta = 10° \) is approximately 1.5 times higher. This fact could prove that improving the wettability could be a promising technology for increasing the capillary force in a porous wick inside the copper-based heat pipes and vapor chambers without adjusting the porous structure. Also, if we can find a simple technique for the wettability improvement, there is a possibility that the heat transport performance of ready-made heat pipes is enhanced just by oxidizing them under high temperatures.

As to the conventional researches on the boiling and evaporation heat transfer by the copper oxide film, it used to be well-known that a long-term metal oxide film works as a thermal insulating layer also for boiling/evaporation heat transfer. However, Dhir et al.,[6] Chin et al.,[7] and Lee et al.,[8] discussed the effect of change in surface condition by oxidation on boiling heat transfer enhancement. However, it seems that the optimum oxidation condition for wettability and evaporation enhancements has not been clarified yet.

In this study, focusing on the copper oxide layer produced under short-term and low temperature conditions from 200°C to 350°C that is conceivably suitable oxidation regime for the wettability improvement, we evaluate the wettability improvement of a copper oxide film and its optimum oxidation conditions by estimating the change in contact angle between a water droplet and the copper oxide film. Furthermore, we demonstrate that a highly-controlled copper oxide film also contributes to evaporation heat transfer enhancement, which is the most important phenomenon in the heat pipe and the vapor chamber, by estimating a life time of a water droplet on the oxidized copper surface that is heated more than a saturated temperature of water.

2. Experimental Setup

A specimen utilized for oxidation is a non-oxidation copper square plate of 20 mm each side and 3 mm in thickness. The surface of this test plate is polished with a no.500 emery paper. This copper plate is heated on a plate heater as shown in Fig. 2 on the left. At first, the surface temperature of the hot plate is elevated up to a predetermined temperature, and then the copper test plate is set onto the surface of the hot plate. After the test plate is oxidized in a scheduled time, it is removed from the hot plate and naturally cooled. The oxidative atmosphere is laboratory one, and the room temperature is controlled approximately at 21°C for 24 hours in a dry mode. The indoor moisture is approximately 35%. The oxidation temperatures are 200, 250, 300, and 350°C. The oxidation times are in the range from 2 minutes to 25 minutes mainly at the interval of 5 minutes. Totally, we prepared 36 specimens. After the oxidation, a droplet of distilled water is dropped onto the oxidized copper test plate in order to estimate a contact angle, \( \theta \), between the droplet and the test plate as shown in Fig. 2 on the right is measured by the \( \theta \)/2 method. In consideration of practical application of this technique to heat transport devices, the contact angle is measured at the surface temperatures of 30, 50, 70, and 90°C. Furthermore, a single droplet is dropped onto the heated oxidized-copper-
plate in order to evaluate evaporation characteristics on the copper oxide film. This experiment is usually called Leidenfrost experiment. Figure 3 is an experimental setup of the Leidenfrost experiment. A heat transfer block of 60 mm in diameter and 70 mm in height is a cylindrical copper one with three cartridge heaters at the bottom. The oxidized copper test plate mentioned above is attached onto the top surface of the block with a thermal grease at the interface, and the surface temperature of the test plate is gradually elevated. The surface temperature is measured with a non-sheathed K type of thermocouple of 100 μm in wire diameter. After the surface temperature reach the predetermined temperature that is higher than a saturated temperature of water, the distilled water droplet of approximately 2 mm in diameter is dropped onto the oxidized copper plate from height of 10 mm. Under these conditions, we can maintain the Weber number of the droplet to be less than 10, in which the droplet shortly before the first contact to the heated surface is stably spherical by surface tension effect. The droplet behavior with boiling/evaporation is visualized with a high speed camera and also the life time, which is the time from first contact of the droplet onto the surface to the disappearance, are evaluated. The surface temperature is measured from 100°C up to a wetting limit temperature at the interval of 3 Kelvins. After the surface temperature exceeds the wetting limit temperature, the droplet starts bouncing on the heated surface due to declined wettability.

3. Results and Discussion

Figures 4, 5, and 6 express the contact angles of the droplet on the oxidized copper plate at the oxidation temperatures of 200, 250, and 300°C, respectively. The horizontal axis is the oxidation time. From these figures, it is confirmed that the contact angle is sharply reduced within 10 minutes, which indicates that the wettability between the water droplet and the oxidized copper surface drastically improves under short-term oxidation. Furthermore, it seems to be shorter to obtain the high wettability surface with increasing the oxidation temperature. On the other hand, the contact angle doesn't show the big change in 10–20 minutes and becomes approximately constant especially in the cases of the 250°C oxidation. Figure 7 on the right shows a photograph of the contact angle on the oxidation film generated at 250°C and 20 minutes oxida-
tion and the contact angle is less than 10 degrees. When the oxidation time exceeds 20 minutes, there are the cases that the contact angle starts increasing again especially at 300°C, which means that the wettability worsens. It is predicted that if the wettability worsens more by long-term oxidation, the conventional knowledge that the oxide film inhibits boiling heat transfer could be confirmed. For the oxidation temperatures of 200, 250, 300, and 350°C, the minimum contact angles are 18.2, 8.0, 8.2, and 8.4 degrees, respectively, which obviously show completely hydrophilic condition, whereas the contact angle of the water droplet on a bare copper surface is approximately 70 degrees.

Here, we show interesting results of change in surface color of the oxidized copper plate as shown in Fig. 8. The horizontal axis is heating temperature and the vertical axis is heating time. From this figure, it’s obvious that the surface color changes as the heating time increases and the heating temperature rises. For instance, focusing on the heating temperature of 200°C, the color changes from bare copper color, purple, darkish gray and then to really beautiful golden color. The value on each surface is the contact angle of the water droplet on a bare copper surface is approximately 70 degrees.

Figure 9 shows the life time characteristics of the droplet fallen onto a heated oxidized-copper-plate. Here, the test copper plates are oxidized at 200°C for 10 minutes, 250°C for 20 minutes, 300°C for 20 minutes, and 350°C for 20 minutes. The data around the wetting limit temperature is also shown in close-up in Fig. 9 on the bottom. The horizontal axis is the initial surface temperature. It is obvious that, in a low superheat temperature regime from 100°C to 110°C, the life time of the droplet on the oxidized copper plate is much lower than that in the bare surface case. This suggests that the copper oxide film also highly enhance the evaporation performance by the wettability improvement. However, the effects of the oxidation tem-
perature is not obvious. On the other hand, the wetting limit temperature for each oxidized copper plate drastically increases, that is more than 15 Kelvin from 130°C (that is a wetting limit temperature for a bare copper surface) to 145°C at the oxidation temperature of 350°C for 20 minutes. This fact indicates the possibility that the copper oxide film would enhance the critical heat flux of boiling heat transfer by the wettability improvement.

4. Conclusion

In this study, we focused on wettability improvement by a copper oxide film and evaluated the effects of the oxidation time and temperature on it. The contact angle was reduced within 10 minutes, which proved that the wettability of the copper oxide film was drastically improved by short-term and low temperature oxidation. Some data showed hydrophilic condition where the contact angle is less than 10 degrees. Also, our study clarified that, in order to generate stable hydrophilic copper oxide layer, the copper bare plate should be oxidized at 250°C for 15 to 25 minutes or at 300°C for 15 to 20 minutes. Of course, as the thickness of the oxidation film is approximately 200–1,500 Å, the oxidation doesn’t work as a thermal insulating layer. In addition, it was proven that this copper oxide film strongly enhance the evaporation heat transfer performance because the life time of the droplet shortens in a low superheat regime. Also we confirmed that the wetting limit temperature was also increased by more than 15 Kelvin compared with the case for the bare copper surface, which would enhance the critical heat flux of the boiling heat transfer.

References

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