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THE EFFECT OF SUBSTRATE CONDUCTION ON THE THERMAL PERFORMANCE OF A FLAT PLATE PULSATING HEAT PIPE

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ABSTRACT

Pulsating Heat Pipes (PHPs) are proposed as one of promising cooling techniques of high heat flux devices. PHPs can be classified into two groups, tubular PHPs made from a capillary tube bent into many turns and Flat-Plate PHPs (FP-PHPs) which have channels engraved on a base plate. The biggest difference between two PHPs is the heat conduction through the solid wall of FP-PHP, while the conduction effect in tubular PHPs is negligible. Therefore, there are two main heat transfer paths in FP-PHPs, axial conduction through the solid wall and heat transfer by rapid self-sustained oscillation of working fluid. However, there also exists transverse conduction between neighboring channels through thin channel wall. The transverse conduction influences on the heat transfer by working fluid, since it reduces the thermally created oscillating motion of working fluid. By restricting the transverse conduction, the thermal performance of FP-PHPs was enhanced by more than 30% due to larger amplitude oscillation of working fluid. Moreover, early start-up and smaller fluctuation in evaporator temperature were obtained by confining the transverse conduction.

NOMENCLATURE

A_C	[m^2]	Cross sectional area
D_{crit}	[mm]	Critical diameter to form slug-train unit
g	[m/s^2]	Acceleration of gravity
k	[W/mK]	Thermal conductivity
Q_{in}	[W]	Input power
R_{th}	[K/W]	Thermal resistance
T	[℃]	Temperature

Special characters

ρ	[kg/m^3]	Fluid density
σ	[N/m]	Surface tension

Subscripts

a	Adiabatic section
ave	Average
c	Condenser
e	Evaporator
f	Liquid
g	gas

INTRODUCTION

Along with advancement in electronic device, high heat flux thermal management has become a core technology determining the total performance of the devices. Moreover, following trend of miniaturization of electronic devices, cooling device also should be thin and minimized. The thermal management system consists of heat source, heat sink, and thermal spreader. Conventional heat pipes (Figure 1) are widely used as the thermal spreader and effectively transfer heat without any help of external power source. The conventional heat pipes consist of sealed container with small amount of working fluid in it and inner wall of the container is composed of wick structure. The wick structure is necessary for the fluid circulation but it causes significant thermal performance degradation of miniaturized heat pipes. Pulsating heat pipes (PHPs), introduced by Akachi [1], are suggested as a promising solution for this thermal problem. Working fluid is partially filled in meandering capillary tube in the form of closed loop, then due to the capillary action, alternation of liquid slugs and vapor plugs are formed inside the tube (Figure 2). Thermally driven oscillation of the slugs/plugs occurs without any external power source and wick structure. The heat transfer mechanism of PHPs is said to be comprised of sensible heat transfer due to the fluid oscillation and the latent heat transfer by condensation and evaporation or boiling.

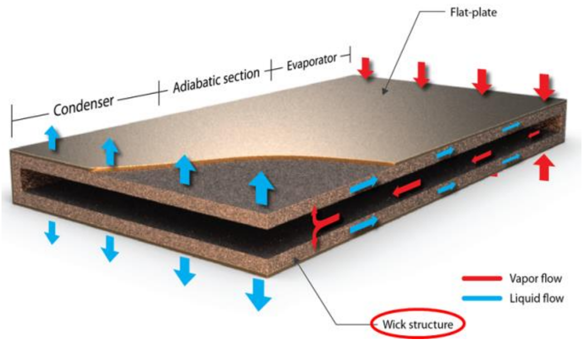


Figure 1 Conventional heat pipe

PHPs can be designed in two ways: Tubular PHP (T-PHP) is made by bending tubes in serpentine arrangement and Flat plate PHPs (FP-PHPs) have channels engraved on a base plate as shown in Figure 3. Since there is almost no limitation in radius of curvature of channels, it can be made of higher channel density (channels/unit volume). However, the conduction through the substrate of FP-PHPs is expected to have a large impact on total thermal performance of FP-PHPs while the conduction effect through the tube wall of T-PHPs can be neglected. The substrate conduction not only provides an additional heat transfer path but also is expected to affect the sensible and latent heat transfer by working fluid.

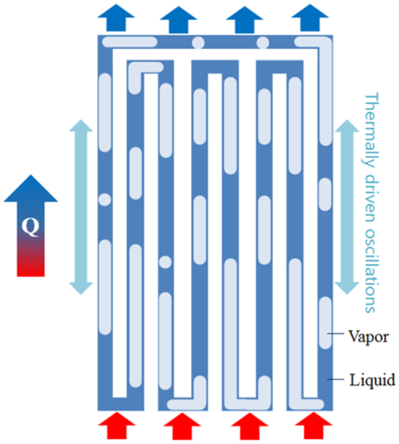


Figure 2 Schematic diagram of Pulsating Heat Pipes

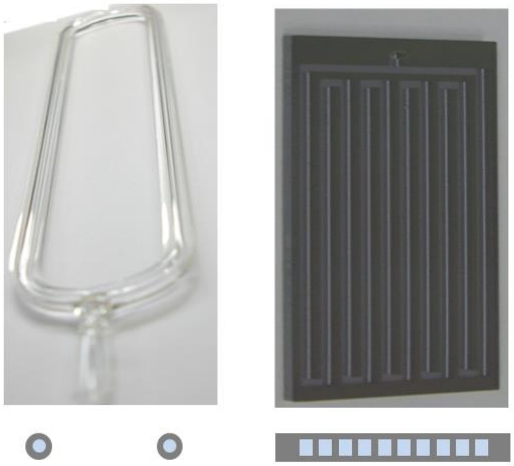


Figure 3 Tubular PHP and flat plate PHP

LITERATURE REVIEW

Since known to have good thermal performance, PHPs are actively investigated recently [2]. There are many parameters affecting the operation of PHPs and lots of experimental investigations have been done. Charoensawan et al. [3] investigated the effect of geometrical parameters such as tube diameter, length of evaporator and condenser, number of turns and operational parameter like inclination angle and physical parameter of working fluid. Xu et al. [4] conducted the flow visualization of glass T-PHPs and observed quasi-sine wave oscillation with using methanol as working fluid.

Not only experimental investigation, analytical investigation also has been performed. Shafii at al. [5] provided analytical model describing the oscillating flow of fluid slugs/plugs, considering heat transfer by phase change. They concluded that sensible heat exchange is the dominant heat transfer mechanism while latent heat transfer only helps the oscillating motion. There suggested few models to describe the fluid motion like spring-damper model which is suggested by Ma et al. [6] However there is still no model predicting the fluid motion and clearly explaining the heat transfer mechanism, so investigation is continually conducted.

To apply in microelectronics cooling, Khandekar at al. [7] conducted a study on aluminium based FP-PHPs and confirmed that various parameter such as tube diameter and inclination angle affect the thermal performance of FP-PHPs. Also they mentioned that conduction through the channel wall is expected to badly affect the thermal performance of FP-PHPs by making temperature distribution of substrate uniform, called heat balancing effect. However, no experiment has been done for verifying the assertion.

To see the effect of substrate conduction, Smoot et al. [8] made T-PHPs embedded in copper block. However, the transverse conduction effect was not investigated. Inoue et al. [9] provided a simulation result that shows different constant temperature condition for different channel induces more active oscillating motion than the uniform temperature condition. This result can support the assertion that the uniform temperature distribution has a bad influence on thermal performance of PHPs, but it is not verified with experimental results.

To experimentally investigate the effect of transverse conduction on the heat transfer by fluid motion in PHPs, the temperature distribution and thermal performance change are compared and analyzed. Flow visualization is also done to see the effect on the fluid motion by high speed photography.

EXPERIMENTAL APPARATUS AND METHOD

The flat plate PHP is engraved in silicon wafer using Deep Reactive Ion Etching (DRIE) technique [10]. As shown in Figure 4, 10 parallel square channels forming closed loop are engraved in 1mm thick silicon base. Width of 1mm and depth of 0.5mm channels are spaced 0.5mm apart to each other. To visualize the fluid flow, 1mm thick transparent glass plate is attached by anodic bonding method. The critical channel diameter for forming slug-train unit is determined by the equation (1) and the hydraulic diameter (0.67mm) of the FP-PHP is small enough for working as PHP. Dimensions of the FP-PHP are 20mm × 50mm and the total length of interconnected channels is 441mm having inner volume of 221μm^3.

$$D_{crit} = 1.84\sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}} \qquad (1)$$

To prohibit the transverse conduction through channel wall, the basic silicon based FP-PHP is treated with additional processing; cutting the channel walls with width of several μm as shown in Figure 5.

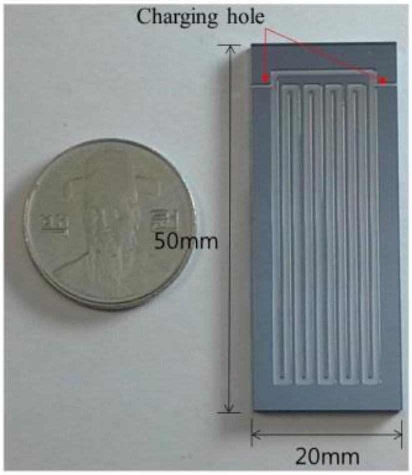


Figure 4 Fabricated silicon based FP-PHP

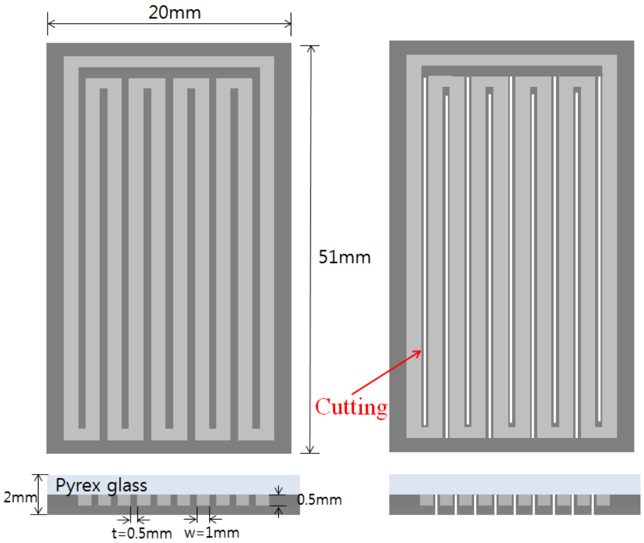


Figure 5 Schematic diagram of FP-PHP w/o and w/ cutting

The FP-PHP is evacuated, to have internal pressure less than 10^{-3}mTorr, for removing non-condensible gas and then charged with ethanol using the system in Figure 6. The filling ratio is set to be around 50% which is widely known as the optimum filling ratio for good thermal performance.

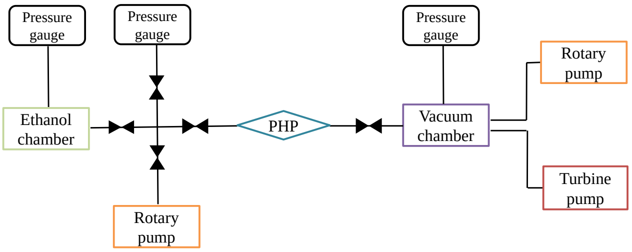


Figure 6 Evacuation and charging system

The experimental apparatus is constructed as shown in Figure 7. To reduce the heat loss, the test section is located in the vacuum chamber (less than 10^{-2} Torr). The length of condenser and the evaporator section is 30% and 20% of that of PHP respectably and rest of it is adiabatic section. The condenser absorbs heat by circulating cold water into copper block located right behind the PHP. At the evaporator section, the heat is supplied by the Ni-Cr heater sputtered at the back side of the PHP, and connected to DC power supply to offer Joule heating. The evaporator is located at the bottom of the PHP which stands vertically. To measure the temperature, 15 K-type thermocouples are located at the back side of the silicon substrate with positioning of Figure 8. The measured temperature information is obtained by DAQ system and high speed camera is used for flow visualization.

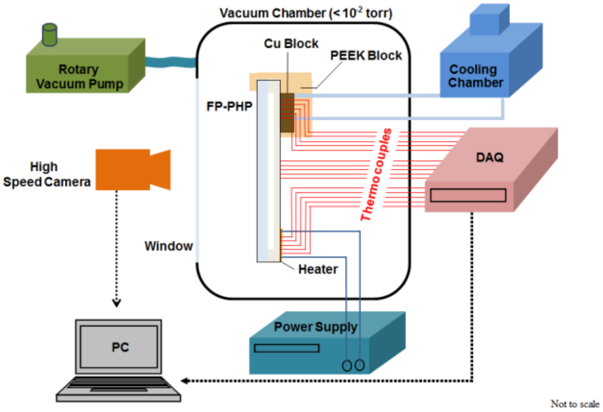


Figure 7 Schematic diagram of the experimental setup

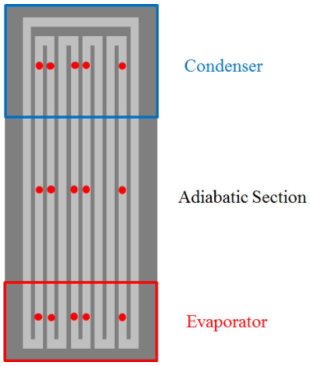


Figure 8 Position of thermocouples for measuring wall temperature

The thermal ability difference and the change in flow patterns of the FP-PHP w/o cutting and the FP-PHP w/ cutting were observed at the above experimental setup.

THE FLOW PATTERN CHANGE WITH INPUT POWER

Figure 9 is input power-thermal resistance graph of FP-PHP w/o cutting. The thermal resistance is obtained by using equation (2) with measured temperature of evaporator and condenser.

$$R_{th}\ [\mathrm{K/W}] = \frac{\overline{T_e}-\overline{T_c}}{Q_{in}} \qquad (2)$$

where Q_{in} , $\overline{T_e}$, $\overline{T_c}$ represent the input power, average temperature of evaporator and condenser respectively.

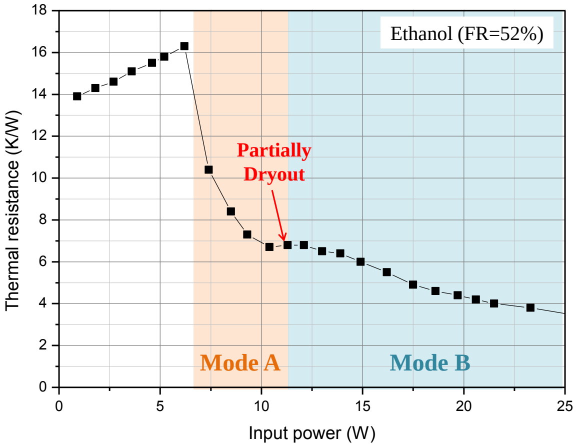
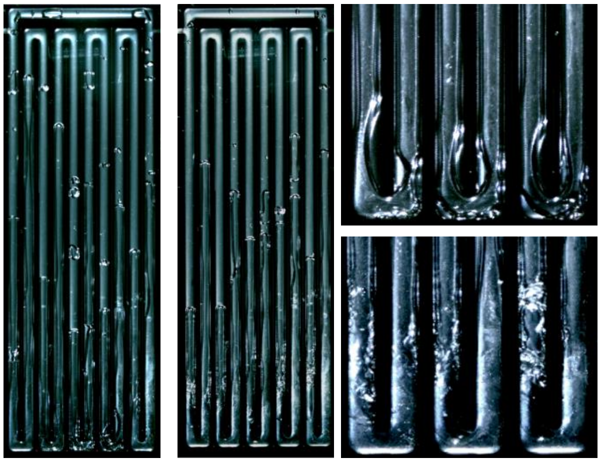


Figure 9 Variations of thermal resistance and flow patterns of FP-PHP w/o cutting with respect to the input power

As the thermal resistance changes with the input power, there are two modes according to flow pattern change. After the PHP starts to operate, the thermal resistance decreases as the input power increases at mode A. At certain input power, there exists partially dryout at the evaporator section with small increase of thermal resistance. After the partially dryout point, there happens active nucleate boiling at liquid film. Figure 10 shows different flow pattern at mode A (Q=10W) and mode B (Q=13W). There exists liquid film surrounding vapor plugs. At the evaporator section, liquid pool is observed at the corners at mode A, while part of the liquid film at the evaporator is dried at mode B.

THE EFFECT OF TRANSVERSE CONDUCTION ON THERMAL CHARACTERISTICS OF FP-PHP

To see the effect of transverse conduction on the thermal performance of FP-PHPs, experiments on FP-PHP w/o cutting and FP-PHP w/ cutting were performed. As a representative index of thermal ability, thermal resistance is compared in Figure 11 with varying input power.



(a) (b) (c)

Figure 10 Flow pattern of (a) mode A (Q=10W) and (b) mode B (Q=13W) and (c) comparison of flow patterns at the evaporator

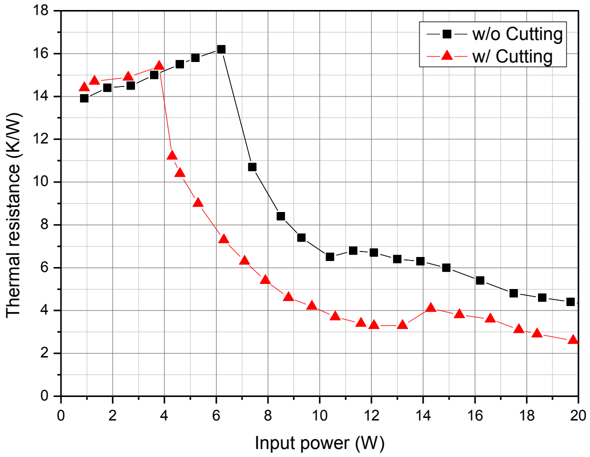


Figure 11 Comparison of thermal resistance between FP-PHP w/o cutting and FP-PHP w/cutting

By simply restricting the transverse conduction through substrate, more than 30% of improvement overall was obtained. This improvement is due to stable oscillating motion by preventing the substrate from thermal equalization, obtained by conductive heat transfer between channels. To compare thermal ability in detail, wall temperature variation with time should be looked in. Figure 12 is the time-evaporator wall temperature graph with stepwise varying input power. By interpreting the graph, it can be concluded that FP-PHP w/ cutting (a) starts to oscillate at lower input power, (b) has stable oscillating motion compared to FP-PHP w/o cutting, and (c) has better thermal performance overall.

There appears a ‘stop-over phenomenon’ [11], which is temporary termination of oscillating motion and it takes quite a long time to restart the oscillation, normally observed at low input power condition. However, by restricting the transverse conduction, we can alleviate this phenomenon. The evaporator wall temperature variation at Q=7W is compared at Figure 13.

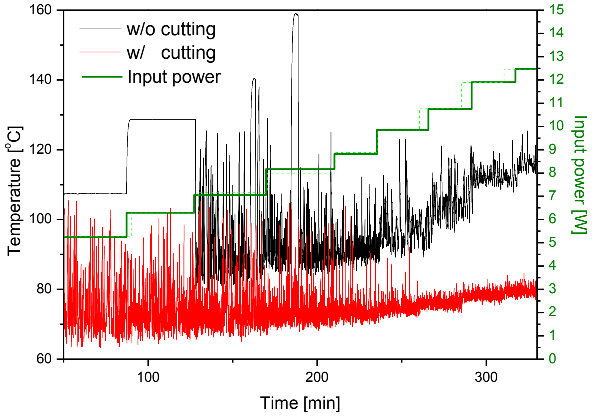


Figure 12 Comparison of evaporator wall temperature

The maximum temperature of the FP-PHP w/o cutting reaches up to 160℃ due to the stop-over. While FP-PHP w/ cutting has consistent oscillating motion and even though it undergoes an instantaneous stop, it starts to oscillate immediately by easily breaking the balance of vapour plugs. This difference can be seen at Figure 13, which compared the evaporator wall temperature variation at Q=7W. Due to the consistent oscillating motion, FP-PHP w/ cutting has more than 55℃ lower maximum temperature.

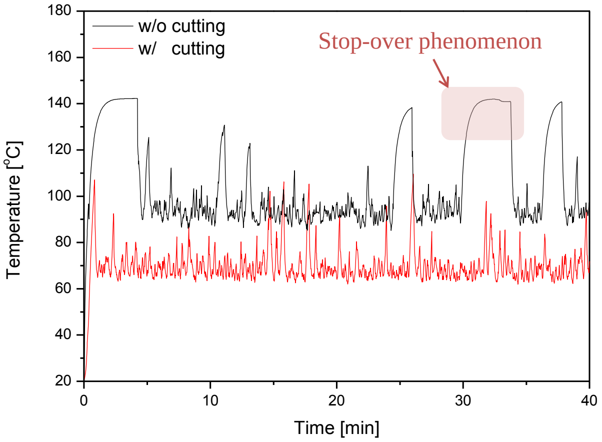


Figure 13 Variation of evaporator wall temperature at Q=7W

The better thermal performance or lower thermal resistance basically means a small temperature difference between evaporator and condenser. The reason why the restriction of the transverse conduction can reduce the temperature difference can be explained with flow pattern change.

THE EFFECT OF TRANSVERSE CONDUCTION ON THE FLUID MOTION IN FP-PHP

Thermal performance of PHP is greatly influenced by the flow pattern of working fluid. The fluid pattern of the fluid changes with input power. At low input power condition, it shows slug flow pattern with small oscillating amplitude, and as the input power increases, the oscillating amplitude also increases. At high input power condition, it changes to slug-annular flow pattern which has long vapor plug whose length is comparable to total channel length at one channel and has slug flow pattern at the next channel consists of short vapor plugs or vapor bubbles coming through condenser. Slug-annular flow pattern is normally known to have better thermal performance than slug flow pattern [11] and similar thermal performance trend was observed in FP-PHPs studied in this paper.

The FP-PHP w/ cutting starts to show slug-annular flow pattern at lower input power than the FP-PHP w/o cutting. At the same input power (Q=10W), the FP-PHP w/o cutting has slug flow pattern while the FP-PHP w/ cutting shows slug-annular flow pattern with better thermal performance. The reason of the difference can be explained by the difference in motion of vapor plug residing the evaporator section. Figure 14 provides the variation in displacement of vapour plug meniscus with time at two channels located in the middle. Larger amplitude oscillation is observed in the FP-PHP w/ cutting and vapour plug meniscus reaches directly to evaporator and condenser section, while small amplitude oscillation with the meniscus staying at the adiabatic section was seen in the FP-PHP w/o cutting. Arrival of hot gas phase fluid to the condenser and cold liquid phase fluid to the evaporator results in active phase change and direct heat transfer from hot side to cold side, which make the thermal performance improved.

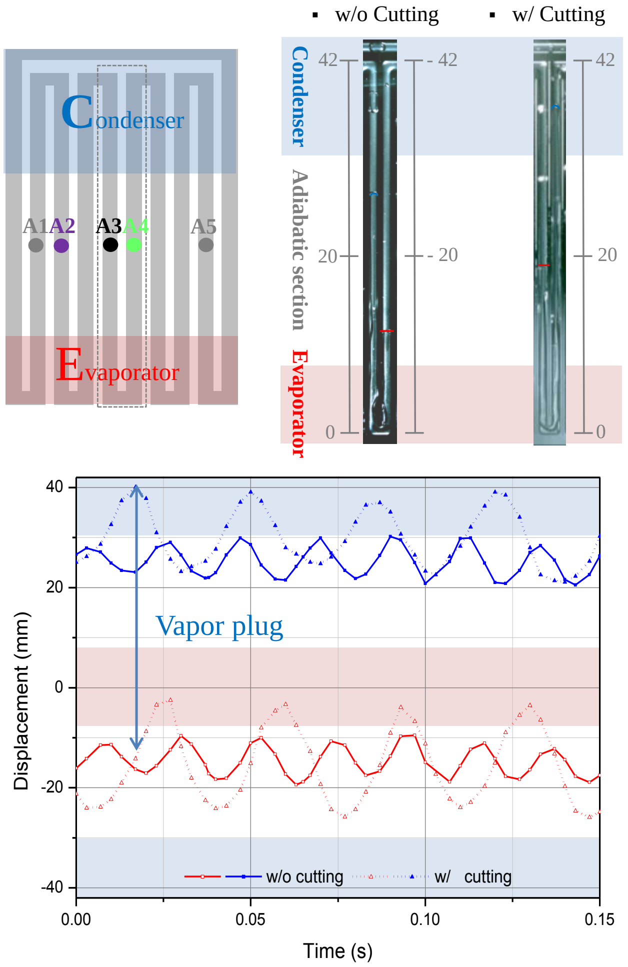
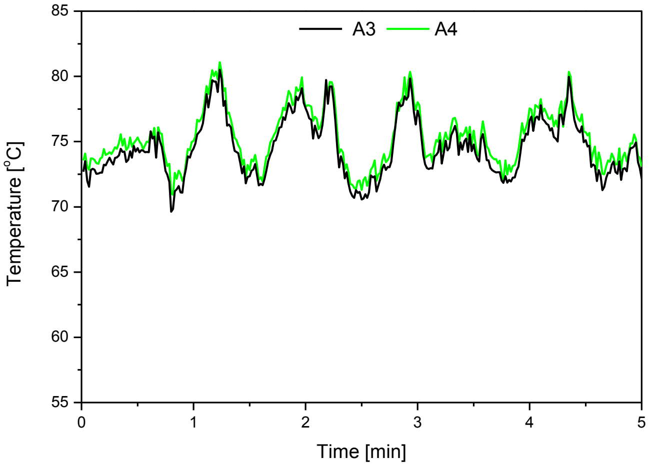
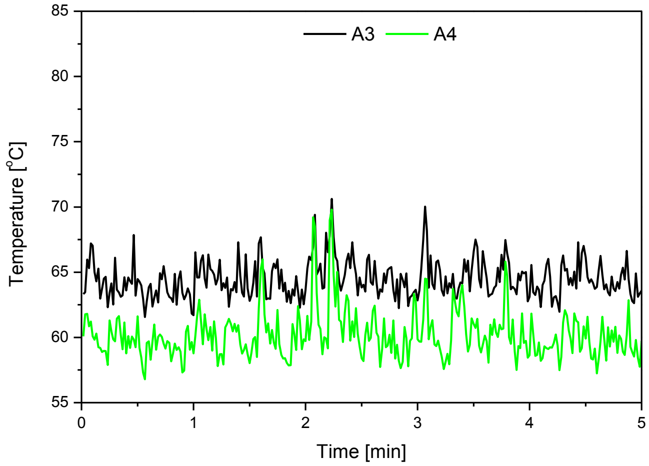


Figure 14 Variation in displacement of vapour plug meniscus with time at Q=10W

The flow pattern change is because the temperature equalization through the wall between channels is blocked and non-uniform temperature distribution is maintained as shown in Figure 15. The temperature of neighboring channels is almost same in the FP-PHP w/o cutting while there exists 5℃ in average and 10℃ in maximum temperature difference in the FP-PHP w/ cutting. Since heat is not lost to colder neighboring channel and the temperature difference is maintained, the FP-PHP w/ cutting can have directional flow pattern with better thermal performance.



(a) FP-PHP w/o cutting



(a) FP-PHP w/ cutting

Figure 15 Temperature difference between neighboring channels in the adiabatic section at Q=10W

CONCLUSION

The effect of transverse conduction on the thermal performance and fluid flow pattern was investigated. PHPs operate with fluid oscillation by thermally driven pressure perturbation. The transverse conduction results in uniform temperature distribution which has an effect of decreasing the driving potential of the working fluid oscillation, causing flow pattern change and degraded thermal performance.

To see the effect of the transverse conduction on the flow pattern, fluid flow was visualized by high speed camera. PHPs have slug flow pattern at the low input power and the oscillation amplitude increases with increasing input power. At the higher input power, it shows slug-annular flow pattern with large amplitude comparable to the channel length. Since the FP-PHP w/ cutting has lager amplitude oscillating motion which directly supplies hot gas phase fluid to cold condenser section and cold liquid to hot evaporator section, and has better thermal performance eventually. FP-PHP w/ cutting shows slug-annular flow pattern at lower input power which makes increased heat transfer by working fluid and more than 30% of overall enhancement in thermal performance.

FP-PHP w/ cutting has a non-uniform temperature distribution which helps the fluid to oscillate more easily. Therefore, the FP-PHP w/ cutting starts to operate at lower input power, and has small temperature variation and low maximum temperature due to stable oscillating motion. The stable operation and lower evaporator temperature of the FP-PHP w/ cutting can work as strength to be used as thermal spreader, so it can be suggested as an improved design of FP-PHPs having improved thermal ability.

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