Experimental Study on Two-Phase Closed Thermosyphon with Superhydrophilic and Superhydrophobic Surfaces

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1. Introduction

A heat pipe (HP) is a device in which a working fluid is contained in a closed channel and is a type of heat exchanger that may be applied to a nuclear power reactor cooling system. There was a study on concept of an emergency core cooling system that could be used in spent fuel tanks in reactor containment buildings using HP as a thermal diode [1]. Moreover, the design of a driven emergency cooling system using HP at WWER was proposed [2].

Two-phase closed thermosyphon(TPCT) is a type of HP. TPCT has a structure of wickless on the inner surface of the pipe, and the condenser section is located above the evaporator section so that condensate is returned to the evaporator using gravity.

This research conducted the analysis of heat transfer performance on surface modification of TPCT. TPCT has a structure of wickless on the inner surface of the pipe, and the condenser section is located above the evaporator section so that condensate is returned to the evaporator using gravity. It is very important to determine the inner diameter of the pipe to design more pipes per unit area in the research process. Therefore, in this experiment, a small diameter was set to the inner diameter (D_i) as 0.11mm of the copper pipe, and the Confinement number (C_o) as 0.245. However, the temperature instability in the evaporator section was confirmed due to the geyser phenomenon occurring in the small diameter of the pipe. Therefore, this research was conducted with the object of offsetting negative phenomenon such as geyser caused by the small diameter of the pipe.

2. Methods

2.1 Surface Modification

Fig. 1 is a diagram showing the process of applying super-hydrophilic surface modification to the copper tube [3]. The process of surface modification is as follows : First, to modify the inner surface of the copper tube, acid-resistant tape was attached to the outer surface of the copper tube to prevent contact with chemicals. Next, 70% nitric acid solution (HNO3) and distilled water were mixed in a 1:1 ratio at room temperature for about 1 minute, and then the tube was immersed in the mixed solution and etched. The etched tube was washed with distilled water so that no chemical solution was left on the surface. Next, after immersing in a mixture of 2.5M sodium hydroxide (NaOH) solution and 0.13M ammonium persulfate ((NH4)2S2O8) solution for 40 minutes, the temperature of the solution was maintained at 4℃. After surface treatment, the tube was washed with distilled water and the acid-resistant tape attached to the outer surface was removed. After washing the inside and outside of the tube once more, it was dried at 60° for 1 hour or more to completely remove moisture.

Fig. 1. Process of the Superhydrophilic(SH-philic) surface modification

Fig. 3 shows the superhydrophobic surface modification process, and the Self-Assisted Monolayer (SAM) coating method was used. The first process of SAM coating is etching. In etching process, a metallic plate is put in HCI solution to remove surface passivation. After etching, the surface goes through oxidation in the atmosphere and becomes hydrophilic. To complete SAM coating, the plate is put into normal-hexane solution after oxidation and nano-micro layer forms on its surface. After SAM coating, the surface becomes super-hydrophobic. In contrast to the extremely hydrophilic surface, the tensile force between the pores and water is weak, so the contact angle between the inner surface of the pipe and the water droplets is very large. In addition, the diameter of the pores also increases compared to the extreme hydrophilicity, producing relatively fewer bubbles [4]. However, when very hydrophobic surface modification was applied to the condensation rather than the evaporation part, the condensation water droplets cooled and condensed in the condensation part fell faster from the inner surface of the tube and were designed to supply enough condensation to the evaporation part. In other words, it is expected to improve heat transfer throughout the entire TPCT system, and in this experiment, very hydrophobic surface modification was applied to the condensation part.

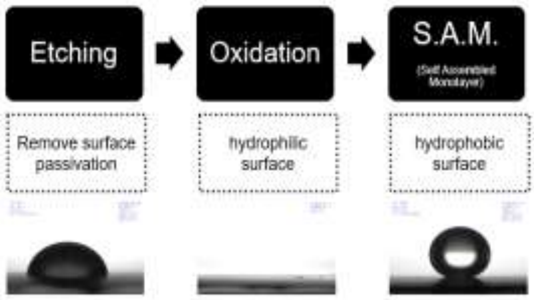


Fig. 2. Process of the Superhydrophobic(SH-phobic) surface modification

2.2 Experiment

Fig. 3 shows a schematic diagram and a photograph of the TPCT used in this experiment. TPCT has the following dimensions: the lengths of the evaporator, adiabatic and condenser parts were 300, 150, and 400 mm, respectively. The material of channel and the heater providing heat to the evaporator were copper. The internal diameter of the evaporation portion is 11 mm and is made of a copper mold. As can be seen in Fig. 3, Particularly in the evaporation section, the heater and the channel are integrally formed. The heater was connected to a power source to supply the heat for the evaporator. The condenser was cooled by cooling water flowing through the cooling jacket. The acrylic cooling jacket was supplied with coolant at 20℃ and flow rate from a connected chiller was 0.5965kg/s measured by flowmeter.

The experimental process was as follows. The vacuum pump connected to the valve at the bottom of the evaporator part was operated with an internal vacuum of 0.08 bar, and then the valve was closed. Then, the valve installed on the upper part of the device was opened and a certain amount of working fluid was injected by filling ratio (FR=0.25, FR=0.5, FR=0.75). After injecting working fluid, power was supplied to the heater using a power supplier. The input power increased from 100W to 1000W in 100W increments. Each input power was supplied about 45 minutes to reach steady state, and temperature data were collected at 1-second intervals.

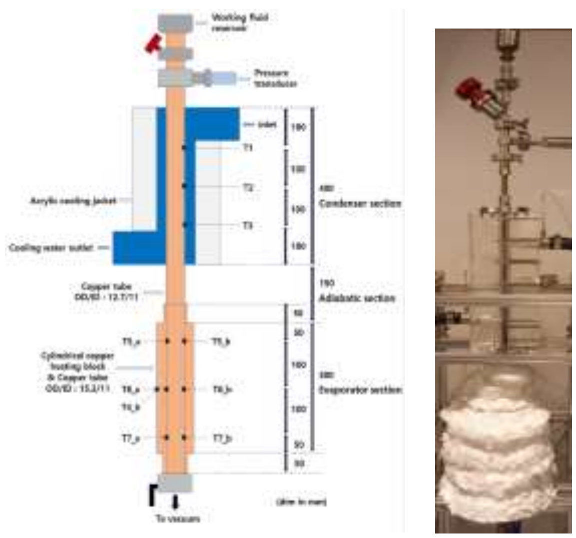


Fig. 3. Experiment Apparatus

3. Results

3.1 Geyser Phenomenon & Instability

Fig. 4 is the raw temperature data at the evaporative extreme hydrophilic surface and the condensing surface at the charge ratio (FR) = 0.25, and the phenomenon according to each input power is analyzed. At 100 W of input power, a geyser phenomenon with a small temperature vibration width appeared when a normal state was reached. At 200 W, a geyser phenomenon with a large temperature vibration width appeared. In Fig. 4(c), the fast geyser phenomenon in which the cycle is short due to the accelerated movement of steam at the input power of 300~400W could be found [4]. In Fig. 4(c), there is a section where the temperature distribution of T6>T5>T7 occurs, which is presumed to be a conclusion phenomenon caused by the condensation in the condensation part not sufficiently returning to the evaporation part.

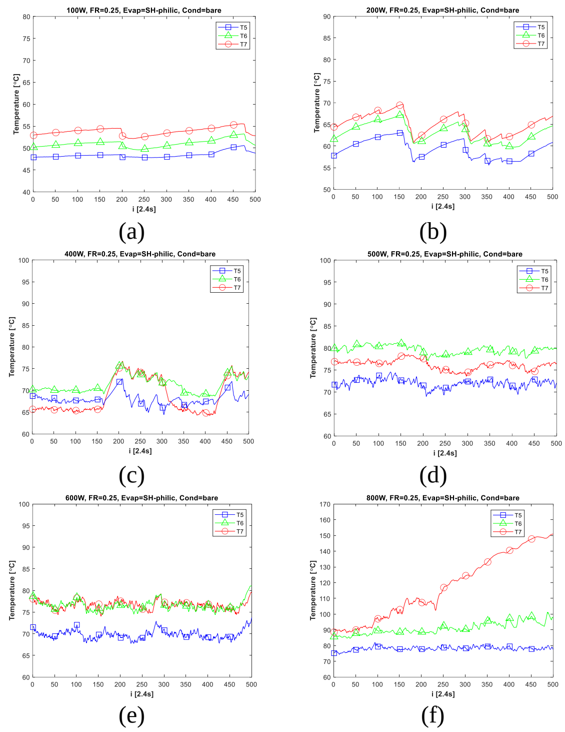
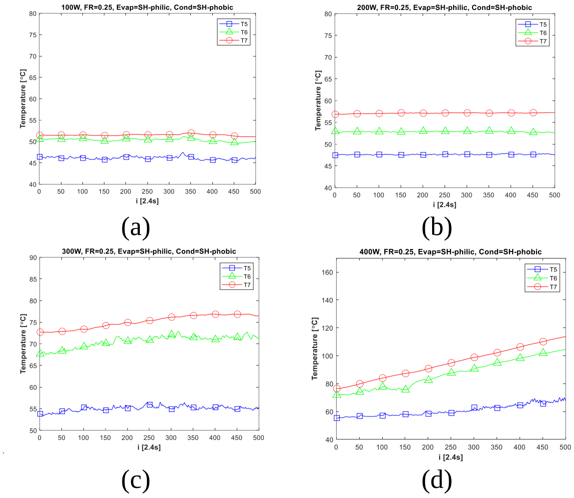


Fig. 4. Evap raw temperature of Evap = SH-philic, Cond = bare with FR=0.25

Fig. 5 is raw temperature at the SH-philic surface of the evaporated part with the SH-phobic surface of the condensed part at the charge ratio (FR) = 0.25.

Fig. 5(a) to (b) show a very stable state in which the amplitude of temperature vibration is constant at 100-200W of input power. This is because the extremely hydrophobic surface is not affected by the geyser phenomenon compared to the bare surface of the condensing unit. Fig. 5(c) and (d) showed a stable state with a small amplitude and a short cycle of temperature data when 300~400W. However, the temperature increased significantly compared to 100-200 W, and eventually dry out occurred. Through this, when the surface is SH-phobic at 300~400W, the heat transfer efficiency is greatly reduced compared to the bare surface. When it is 300 to 400 W, the amount of the condensate returning to the evaporator decreases, and it is determined that a rapid increase in temperature occurs in the evaporator.



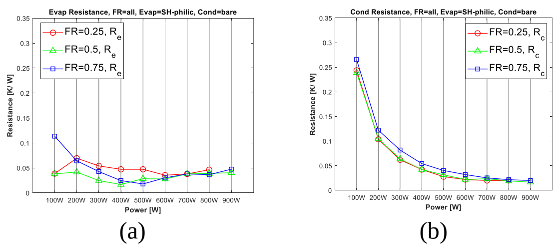
(a) (b)

(c) (d)

Fig. 5. Evap raw temperature of Evap = SH-philic, Cond = SH-phobic with FR = 0.25

3.2 Thermal Resistance

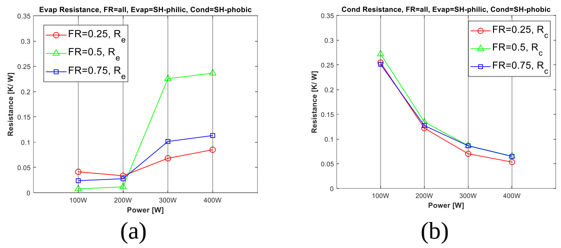
Fig. 6 shows the evaporation and condensation resistance at the evaporative SH-philic surface and the bare surface at all charge ratios (FR). In Fig. 6(a), it can be seen that when the input power is low, the evaporation unit has high thermal resistance. As the input power increases, the difference in the resistance of the evaporator decreases from 200 W or higher. The thermal resistance of the evaporation part is low in the order of FR=0.5, 0.75, and 0.25 since heat transfer in a stable state occurs when FR=0.75 and 500W, and the lower the heat resistance in the evaporation part, the better the heat transfer. Fig. 6(b) shows the resistance of the condensing unit, and it is lower in the order of FR=0.25, 0.5, and 0.75 in the entire input power section. This means that the smaller the amount of working fluid in the condensing unit, the more condensation occurs.



(a) (b)

Fig. 6. Evap and Cond resistance of Evap = SH-philic, Cond = bare with all FRs

Fig. 7 shows the evaporation and condensation resistance at all charge ratios (FR) on the SH-philic surface of the evaporation unit and the SH-phobic surface of the condensation unit. Fig. 7 (a) shows the evaporation resistance, and it is low in the order of FR=0.5, 0.75, and 0.25 in the 100-200W range of input power, but high in the 300-400W range. In addition, the thermal resistance of the evaporator tends to increase rapidly from 300 W. Fig. 7(b) shows the resistance of the condensing portion and means that more condensation occurs at less FR.



(a) (b)

Fig. 7. Evap and Cond resistance of Evap = SH-philic, Cond = SH-phobic with all FRs

The SH-phobic surface of the condensation part showed an increase in heat transfer performance at 100-200 W compared to the bare surface, and a decrease in heat transfer performance at 300-400 W. The main cause of the decrease in heat transfer performance is a rapid increase in heat resistance of the evaporator. This is because attached condensation occurs on the SH-phobic surface at 300~400W and the condensate is not easily returned to the evaporator, so it is expected that the surface temperature of the evaporator increases, the heat transfer efficiency decreases and the thermal resistance increases.

3. Conclusions

In this study, heat transfer performance was analyzed by applying surface modification inside the copper tube. Both the SH-philic surface modification of the evaporation section and the SH-phobic surface modification of the condensation section played a role in reducing geyser phenomenon. However, the SH-phobic surface modification of the condensation section caused a rapid increase in temperature (dry out) of the evaporated part due to the influence of attached condensation. Through this, when the SH-philic surface is applied in the evaporation part, it is more efficient than the bare surface to use the SH-phobic surface in the condensation section in a low power range of 100-200 W. On the other hand, it could be confirmed that the use of the SH-phobic surface for the condensation section in the power range of 300W or more rather reduced the heat transfer performance.

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