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# Thermal Performance of a Heat Pipe for Hybrid Control Rod in Advanced In-Core Decay Heat Removal System

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## 1. Introduction

The development of advanced passive decay heat removal system in nuclear power plant is a hot issue in these days due to severe accidents such as Fukushima [1] and Three Mile Island (TMI) accidents. However, in case of most of passive decay heat removal systems, the main function is characterized by how to feed additional coolant to the reactor core according to accident scenarios. In this research, an innovative hybrid heat pipe system is designed for advanced in-core decay heat removal concept. Heat pipe is a device that transfer heat from pipe`s hotter end to the colder end by phase change and convection of working fluid. The concept of the hybrid heat pipe system is that the control rod can have not only the original function of neutron absorber but also the function of the heat removal. If the function of heat pipe is applied to the control rods, the limited heat removal capacity can be extended because control rods are inserted to the reactor at initial state of accident using gravitational force. The neutron absorber-based heat pipe is designed to apply them to nuclear systems. However, thermosyphon and heat pipe are competitive as passive decay heat removal device in large scale [2,3]. Thus, stainless steel 316L thermosyphon and heat pipe having sheath outer diameter of 3/4 inch (17.4 mm inner diameter), and the length of 1000 mm were tested. Effects on whether there is a wick structure on the heat pipe or not on the heat removal capacity were studied. To confirm the heat removal capacity of heat pipe, and heat transfer coefficient were measured for each specimen.

## 2. Experimental Method

In this section geometry of thermosyphon and heat pipe and the experimental setup for evaluation of heat pipe performance are described.

### *2.1 Heat Pipe and Thermosyphon*

The heat pipe and thermosyphon have similar principle to transfer heat from evaporator section to condenser section. However, the condensed liquid at the condenser section return to the evaporator section using capillary force of wick structure in case of heat pipe while the thermosyphon uses gravitational force to transport the condensed liquid to evaporator section.

The heat pipe and thermosyphon tested in this study have same geometry. The wick of heat pipe consisted of 2 wraps of a stainless steel 304 wire screen mesh with a wire diameter of 0.11 mm and 3937 strands per meter (100 mesh). The test specimens were filled with 80 mL of water which approximately fill the whole volume of evaporator section.

### *2.2 Experimental Setup and Procedure*

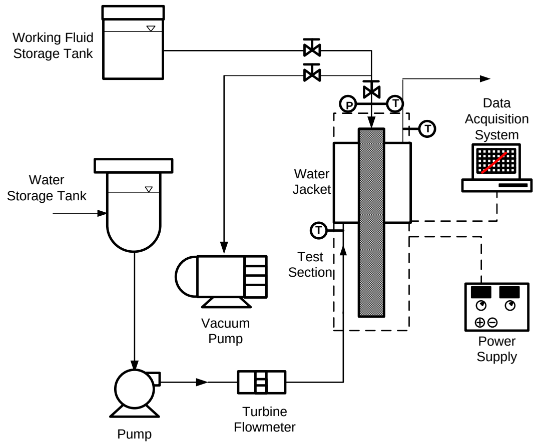


Fig. 1. Schematic diagram of heat pipe test facility.

Fig. 1 shows the heat pipe test facility. The test facility comprises a working fluid tank, a test section, a water jacket to condense the vapor, a pump that circulate coolant from water storage tank to the water jacket, a vacuum pump, and two copper electrodes on the top and bottom of the evaporator section that are connected to the power supply and heat the test section with the passing current.

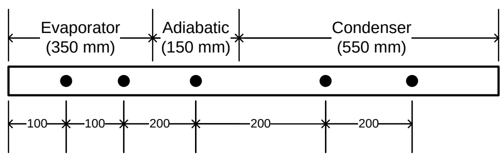


Fig. 2. Thermocouple locations on the test section.

Fig. 2 shows the TC locations on the test section. 3 K-type thermocouples are installed on the evaporator and adiabatic section of test section (two for evaporator section and one for adiabatic section), 2 T-type thermocouples are installed on the condenser section to record the temperature distributions according to given power. And then, we covered the test section with glass fiber insulator.

Table I: Experimental condition

| | |
|---|---|
| Length ratio (evaporator : adiabatic : condenser) | 350 : 150 : 500 |
| Heat input | 70 – 2200 [W] |
| Initial Pressure | 12.5 [kPa] |
| Fill ratio | 100 [%] |
| Wick type | 100-mesh SS304 screen mesh |
| Porosity, ε [4] | 0.62 |
| Permeability, K [5] | $1.93\times10^{-10}$ [$m^2$] |

Table 2 presents the experimental conditions. The experimental procedure is as follows. The pressure in the test section was set to 12.5 kPa to remove the non-condensable gas by using vacuum pump. And water was passed through the water jacket with mass flow rate of 0.3 kg/s. Then, the working fluid was charged to the test section and heated the test section step by step.

## 3. Results and Discussion

The temperature distributions according to given powers at the evaporator section, boiling curves, heat transfer coefficients for evaporator and condenser section, and overall heat transfer coefficient of each test section are described.

### *3.1 Temperature Distributions*

The temperature distributions according to given powers are shown to compare the heat transfer rates between heat pipe and thermosyphon.

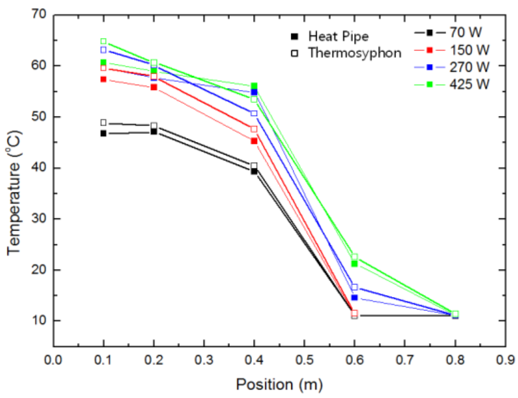


Fig. 3. Temperature distributions of thermosyphon and heat pipe (Q = 70 – 425 W)

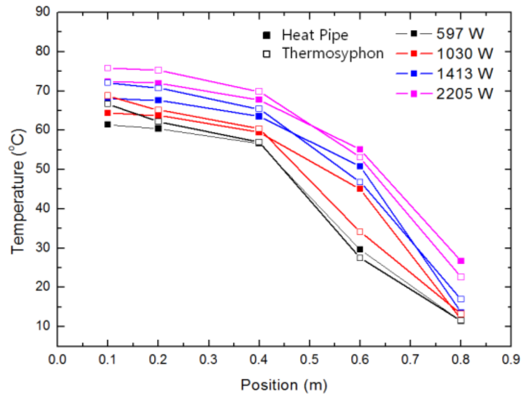


Fig. 4. Temperature distributions of thermosyphon and heat pipe (Q = 597 – 2205 W)

Figs. 3 – 4 compare inner wall temperatures of each test section which were calculated by Fourier law.

As shown in the Fig. 3, the temperatures for thermosyphon are slightly higher than those of heat pipe and similar temperature distributions at low power. However, the temperature difference between the evaporator section and condenser section decreases as the power increases at relatively higher power as shown in the Fig. 4. It resulted from the evaporation of working fluid in the evaporator section of heat pipe and thermosyphon. And the temperature differences of heat pipe are smaller than those of thermosyphon because capillary force provided by wick structure leads more effective convection (working fluid transport).

### *3.2 Boiling curves*

The boiling curves for heat pipe and thermosyphon were compared in this section.

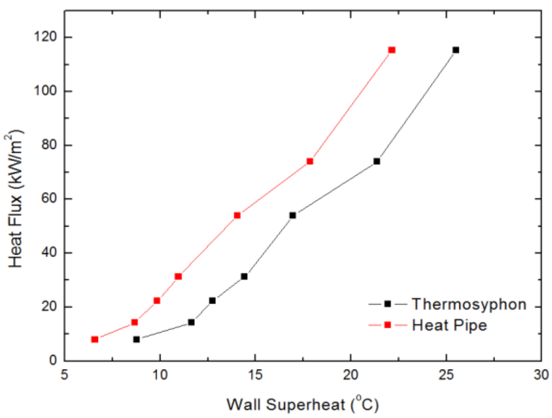


Fig. 5. Boiling curves of heat pipe and thermosyphon

As shown in the Fig. 5, boiling curve of heat pipe was shifted to the left comparing with that of thermosyphon. This trend shows the onset of nucleate boiling is also occurred earlier and the boiling heat transfer coefficients are enhanced due to wick structure of heat pipe. The effect of wick structure on the heat transfer coefficients will be described in later section.

### *3.3 Heat Transfer Coefficients*

The boiling and condensation heat transfer coefficients ($h_e$ and $h_c$) and overall heat transfer coefficients ($h_{overall}$) are calculated by using below equations [6,7]:

$$h_e = \frac{q_e''}{(\overline{T_e} - T_{sat})} \quad (1)$$

$$h_c = \frac{q_c''}{(T_{sat} - \overline{T_c})} \quad (2)$$

$$h_{overall} = \frac{q_e''}{(\overline{T_e} - \overline{T_c})} \quad (3)$$

where $q_e''$ and $q_c''$ are heat flux input and output, $\overline{T_e}$ and $\overline{T_c}$ are average temperature of evaporator section and condenser section, and $T_{sat}$ is 50 °C because the pressure in the test section is 12.5 kPa.

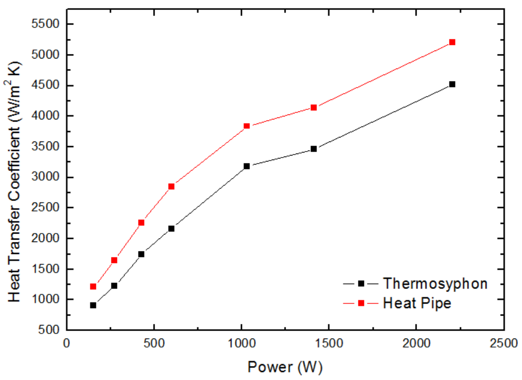


Fig. 6. Boiling heat transfer coefficients of thermosyphon and heat pipe

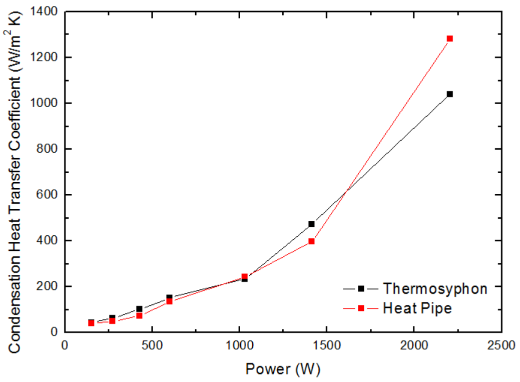


Fig. 7. Condensation heat transfer coefficients of heat pipe and thermosyphon

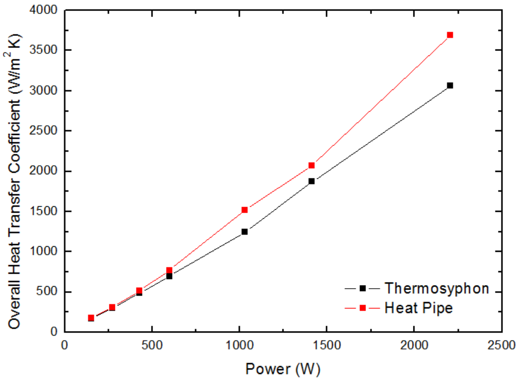


Fig. 8. Overall heat transfer coefficients of thermosyphon and heat pipe

As shown in the Fig. 6, boiling heat transfer coefficients of heat pipe (1210 – 5212 W/m$^2$K) were higher than those of thermosyphon (910 – 4526 W/m$^2$K) with 34 % of maximum enhancement. It was because there are numerous pores of several micrometers between the wires in screen wire mesh. The pores act as cavities. Therefore, these cavities are likely to be active cavity sites for heterogeneous nucleation, and more nucleation sites formed between wires could result in a higher boiling heat transfer coefficients and shit of boiling curve [8].

And the condensation heat transfer coefficients of heat pipe and thermosyphon are similar except power of 2200 W as shown in the Fig. 7.

The overall heat transfer coefficients of each test section were compared in the Fig. 8. The overall heat transfer coefficients at relatively low power are almost same due to the temperature difference between the evaporator section and condenser section. However, the heat transfer coefficients of heat pipe at relatively higher power were enhanced compared to those of thermosyphon because the temperature differences between evaporator section and condenser section of heat pipe are smaller than those of thermosyphon due to more effective convection (working fluid transport) through wick structure as described in Section 3.1.

## 3. Summary and Further Works

The concept of hybrid heat pipe for advanced in-core decay heat removal system was introduced for the complete passive decay heat removal. Thermosyphon and heat pipe are used competitively as passive heat removal device. To compare the heat transfer capacity of heat pipe and thermosyphon, experiments for the performance evaluation of thermosyphon and heat pipe were conducted.

The following results were obtained.

(1) The temperature difference between evaporator section and condenser section decreases as the given power increases.

(2) The decreases in temperature difference through the whole test section were magnified in case of heat pipe compared to those of thermosyphon because the capillary force enhanced convection.
(3) Boiling curve of heat pipe is shifted to the left compared to that of thermosyphon due to earlier onset of nucleate boiling and it induced enhanced boiling heat transfer coefficient.
(4) Heat pipe showed the enhanced boiling heat transfer coefficient with maximum enhancement of 34 % because the pores of wick structure act as active cavity sites and it results in more nucleate sites formation.
(5) The condensation and overall heat transfer coefficients for heat pipe and thermosyphon are similar at the relatively low power.
(6) At relatively high power, the enhanced overall heat transfer coefficients were observed in case of heat pipe due to smaller temperature difference between evaporator and condenser section.
(7) Thermal performances of heat pipe at high heat flux will be evaluated.
(8) Effect of wick on the heat pipe performance will be observed using various wick structures.
(9) Performance evaluation of heat pipe containing simulant of neutron absorber material will be conducted.

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