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Experimental Investigation of Heat Transfer Characteristics of Multiple Heat Pipe with Inclination

Myung Jin Jeong, Ye Sung Kim and Hyoung Kyu Cho*
Department of Nuclear Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Korea
**Corresponding Author: chohk@snu.ac.kr*

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1. Introduction

The heat pipe cooled microreactor (HPMR) is a type of microreactor that utilizes heat pipes for passive removal of heat from the reactor core. The HPMR offers several advantages, including a compact size, easy transportation, and improved system reliability and safety. Since the successful demonstration of the KRUSTY reactor in 2018, interest in HPMRs has grown among various microreactor concepts. It has been researched not only for space reactors but also for land-based reactors, such as LANL's MegaPower [1], Westinghouse's eVinci [2], and China's NUSTER-100 [3].

The typical HPMR core currently under research consists of a monolith, a solid structure incorporating multiple heat pipes and fuel rods. The heat generated by the fuel is transferred to the power conversion system via heat pipes. Land-based HPMRs are designed to generate several MWe, requiring the integration of thousands of heat pipes and fuel rods within the monolith. This dense integration leads to high temperature gradient within the monolith, which cause high thermal stresses.

Seoul National University developed a heat pipe thermal analysis code [4] and a multiphysics analysis tool for the HPMR [5], which has predicted high thermal stresses within the monolith [6]. To mitigate these high stress, potential solutions such as adjusting heat sink temperature or using different types of heat pipes have been proposed.

In this study, multiple heat pipe experiment was conducted using different types of heat pipe to investigate the heat transfer characteristics that may arise in the reactor core when employing various heat pipe designs. This paper introduces the experimental setup and presents the results of the multiple heat pipe experiment using two different types of heat pipes.

2. Experimental setup

2.1. Experimental device

The details of the experimental setup are presented in Table I. The basic design parameters of the heat pipes are the same as that in previous single heat pipe experiment [7]. The heating section consists of a hexagonal SS316 block containing 3 heat pipes and 13 heaters, with a total power output of 6.5 kW. The geometry of the heating section is shown in Fig. 1. To investigate the heat transfer characteristics associated with using different types of heat pipes, two types of heat pipe were employed. The specific geometry and wick structure of each heat pipe are presented in Table II and III.

Table I: Specification of the multiple HP experiment

Heat pipe working fluid	Sodium	Number of heat pipes	3
Heat pipe wall material	SS316	Monolith material	SS316
Length (Evap.-Adia.-Cond.)	1m (0.3–0.4–0.3 m)	Heat pipe OD	19.05 mm
Number of heater rods	13	Heater rod OD	9 mm
Maximum power	6.5 kW	Monolith width	7.11 cm
Coolant	Air	Max. coolant flow rate	0.07 kg/s

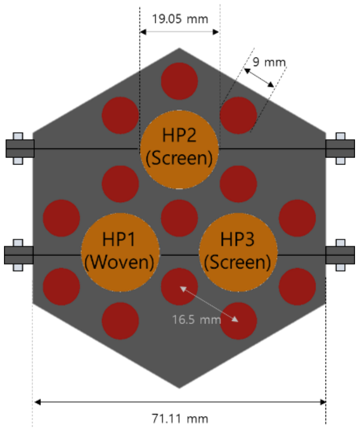


Fig. 1. Cross-sectional view of heating block.

Table II: Specification of the screen wick heat pipe

Outer diameter	19.05 mm	Wall thickness	1.27 mm
Mesh number	#400	Wire diameter	0.026 mm
Screen wick thickness	0.063 mm (14 layers)	Artery type	Annulus
Annulus thickness	0.1 mm	Sodium amount	~ 50 g

Table III: Specification of the woven wick heat pipe

Outer diameter	19.05 mm	Wall thickness	1.27 mm
Wire diameter	0.25 mm	Wire angle	45°
Sodium amount	~ 50 g		

The experiment was designed to observe the effects of different inclination angles, as shown in Fig. 2. Based on the horizontal condition, a positive angle is defined as the orientation in which the evaporator section of the heat pipe is tilted downward, while a negative angle refers to the orientation in which the evaporator section is tilted upward.

The cooling section features air-water dual structure, where the heat pipes are cooled using air, and a water jacket is installed outside the airflow path to measure heat loss. Since the air was in direct contact with the condenser section of the heat pipe, a preheater was installed before the inlet of the flow path to heat up the air to 100 °C, preventing excessive cooling of the heat pipe, as the melting temperature of sodium is approximately 97 °C.

The temperatures of the heat pipes and heating block were measured using K-type thermocouples. As shown in Fig. 3, the wall temperatures of the heat pipes were measured at a total of 7 locations.

Additionally, to further verify the operation of the heat pipe, an observation window was installed in the cooling section. As shown in Fig. 4 below, we can see that the active part is reddish due to the higher wall temperature.

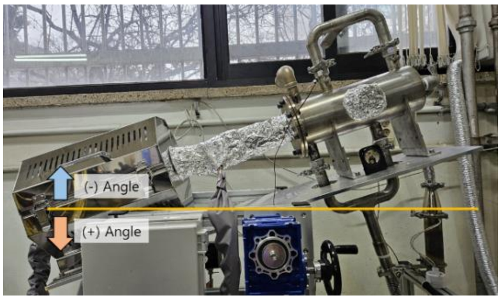


Fig. 2. Overall experimental device with inclination.

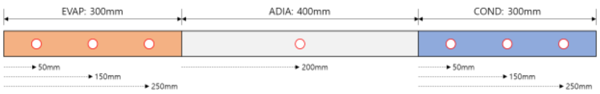


Fig. 3. Thermocouple position of the heat pipe.

Fig. 4. Observation of the heat pipe activation.

2.2. Experimental procedure

The heating power was increased stepwise once the wall temperature of the heat pipe reached a steady-state. The heat removal rate by air cooling was calculated based on the temperature difference between the inlet and outlet with the measured mass flowrate. The heat loss late was determined by comparing the heat removal rate of the air with the heating power input as shown in Eqs (1) and (2).

(1) $Q_{\text{air}} = \dot{m}_{\text{air}}(h_{\text{air,out}} - h_{\text{air,in}})$
(2) $Q_{\text{loss}} = Q_{\text{input}} - Q_{\text{air}}$

where Q: heat transfer rate (W), $\dot{m}$: mass flowrate (kg/s), h: enthalpy (J/kg)

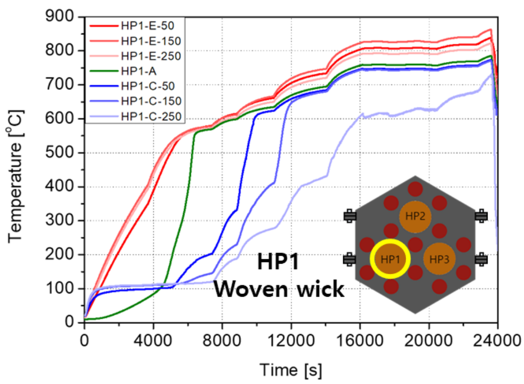
To ensure the integrity of the experimental apparatus and prevent damage to the heat pipe, the experiment was terminated once a certain temperature threshold was reached.

3. Experimental results

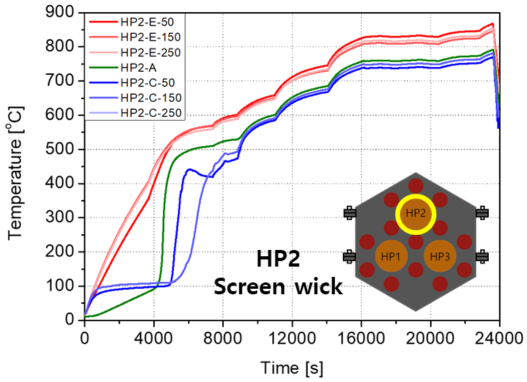
3.1. Difference between heat pipes

Fig. 5 presents the overall results of the horizontal experiment. As the power increases, the temperature difference between the evaporator and the condenser decreases. This means that the heat pipe is gradually activated to the condenser end, and the temperature difference between the evaporator and the condenser can be used to evaluate the heat transfer performance of the heat pipe. When the heat pipe is fully activated, the heat loss was approximately 40% of heating power.

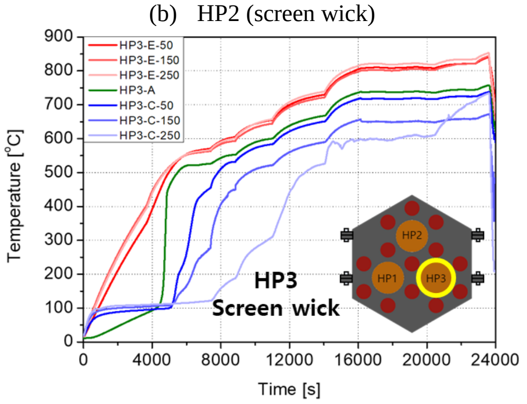
The experimental results indicate that the woven wick heat pipe operates more slowly and exhibits lower heat transfer performance compared to the screen wick heat pipe. Additionally, despite both having the same screen wick structure, a performance difference was observed between HP2 and HP3. This discrepancy may be attributed to fabrication errors in the heat pipe manufacturing process or deformation of the internal wick structure due to long-term high-temperature operation.



(a) HP1 (woven wick)



(b) HP2 (screen wick)



(c) HP3 (screen wick)

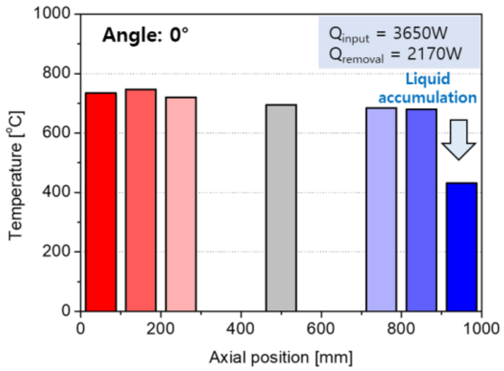
Fig. 5. Experimental results for horizontal condition.

3.2. Inclination effect

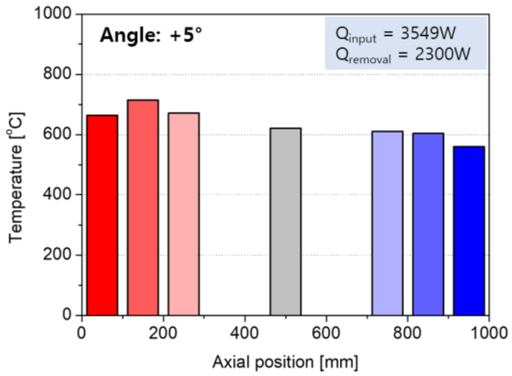
Fig. 6 illustrates the steady-state temperatures of HP1 (woven wick) under horizontal (0°), +5° inclination, and -5° inclination conditions. As shown in the figure, the temperature at the end of the condenser section is excessively low compared to the other sections. This phenomenon has been observed in other research [8] and is attributed to the accumulation of working fluid at the end of the condenser section due to a high filling ratio.

For positive inclination (Fig. 6-(b)), the accumulation of working fluid in the condenser section was alleviated, allowing the heat pipe to perform more effectively compared to the horizontal orientation. Conversely, for negative inclination (Fig. 6-(c)), the accumulation of working fluid reappeared, and the temperature at the end of the evaporator section was approximately 100 °C higher than in the horizontal and positive inclination conditions. This behavior due to the weak capillary force of the woven wick, which leads to partial dryout in the negative inclination condition, where the working fluid cannot fully return to the end of the evaporator.

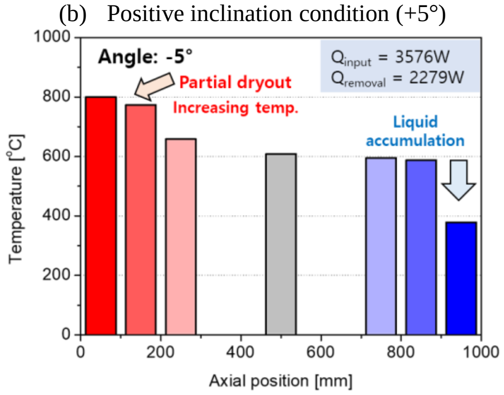
Fig. 7 presents the temperatures of HP3 (screen wick) under horizontal (0°), +5° inclination, and -5° inclination conditions. Unlike HP1, the temperature variations due to inclination are less pronounced, indicating that the effect of inclination depends on the wick structure and characteristics.



(a) Horizontal condition

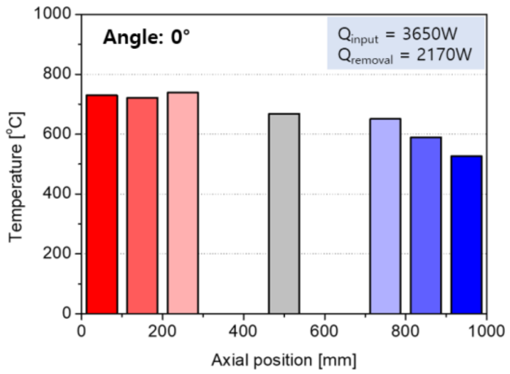


(b) Positive inclination condition (+5°)

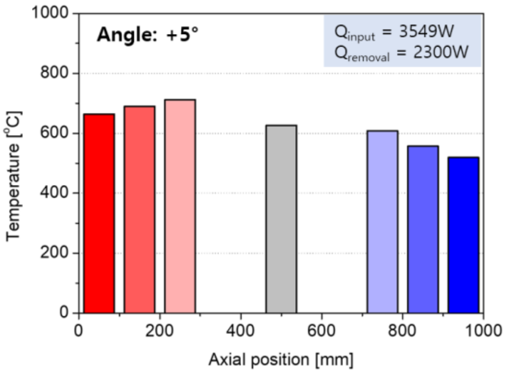


(c) Negative inclination condition (-5°)

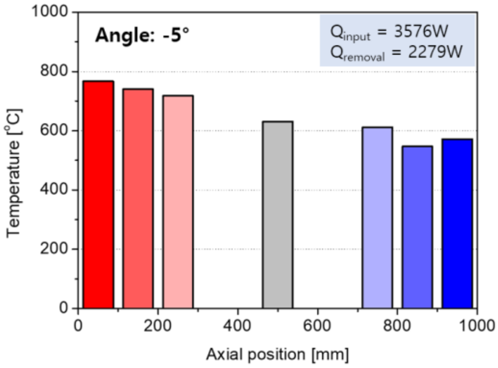
Fig. 6. Experiment results with different inclination (woven wick).



(a) Horizontal condition



(b) Positive inclination condition (+5°)



(c) Negative inclination condition (-5°)

Fig. 7. Experiment results with different inclination (screen wick).

Fig. 8 shows the overall thermal resistance of heat pipes with different inclination angle. Thermal resistance was calculated using difference between average temperature as presented in Eq (3).

$$(3)\ R = \frac{T_{evap} - T_{cond}}{Q}$$

where R : thermal resistance (K/W), T : average temperature of each section (K), Q: heat transfer rate (W)

With positive angle, thermal resistance is decreased by preventing liquid accumulation. However, with negative angle, partial dryout and liquid accumulation make thermal resistance of heat pipe higher.

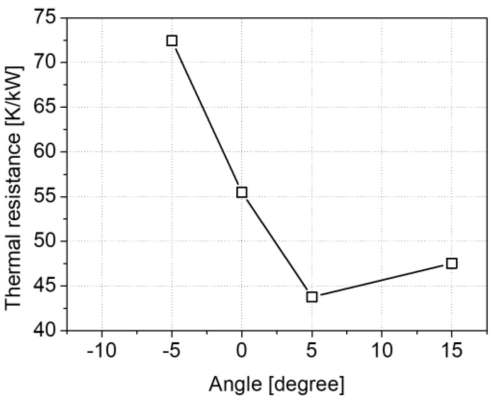


Fig. 8. Overall thermal resistance of heat pipes.

4. Conclusion

This study investigated the heat transfer characteristics of multiple heat pipes under various conditions, focusing on different wick structures and inclination effects. An experimental setup was developed to evaluate the performance of woven wick and screen wick heat pipes under horizontal, positive inclination, and negative inclination conditions.

The experimental results showed that woven wick heat pipes exhibited lower heat transfer performance compared to screen wick heat pipes. Additionally, despite having the same wick structure, performance difference was observed. This could be due to the potential fabrication inconsistencies or deformation of wick structure due to long-term high-temperature operation. Therefore, manufacturing actual HPMRs in the future will require refinement and validation of the fabrication process to ensure uniform heat pipe performance.

The effect of inclination varied depending on the type of the heat pipe. For the woven wick heat pipe, which has weak capillary force, positive inclination improved heat transfer performance by reducing working fluid accumulation in the condenser section, while negative inclination led to partial dryout in the evaporator section. In contrast, the screen wick heat pipe showed less sensitivity to inclination.

Future research will focus on expanding experimental conditions to cover a wider range of heating power and inclination angles. Additionally, heat pipe failure scenario will be investigated to enhance the reliability and robustness of HPMR designs. The experimental data obtained from this study will be utilized for the validation of heat pipe thermal analysis code and the multiphysics analysis tool currently under development at Seoul National University.

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