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Preliminary Experiments of Large-scale Water Heat Pipe as Passive Cooling System in Nuclear Power Plants

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1. Introduction

The heat pipe is passive heat transfer device that transport heat through the circulation of the working fluid driven by capillary pumping force and have been widely used in various engineering fields such as electronics or aerospace industries. Concepts of integrating heat pipe as a passive cooling system for nuclear power plants have been suggested with advantages of highly effective heat transfer capacity, simple design, and passive operation without the need of external power. Applying heat pipes to the thermal management system in a nuclear reactor can enhance safety by providing passive operation at atmospheric pressure conditions which can eliminate the accident scenario that occurred in a conventional reactor such as SBO or LOCA. In the previous studies, a wickless heat pipe or loop-type heat pipe was applied for passive decay heat removal in spent nuclear fuel pool. A. Rosidi et al. conducted an experimental study with a 6m wickless copper heat pipe for spent fuel storage pool cooling application. The authors used graphene nanofluid to enhance the thermal conductivity with a thermal resistance of 0.015ºC/W [1]. Y.Kuang et al. proposed a numerical model of a large-scale separate ammonia heat pipe used for passive cooling of spent fuel pool and validated the experimental results which showed a heat transfer capacity of 14.4kW [2]. J. Choi et al. proposed an air-cooled fork-end water heat pipe for long-term passive cooling of spent fuel pool in a nuclear power plant and a theoretical analysis model was developed and validated [3]. Y. S. Jeong et al. and K. M. Kim proposed the hybrid heat pipe for a passive cooling device for spent nuclear fuel dry storage cask [4,5]. A hybrid heat pipe contains neutron absorber material in the evaporator section to prevent the re-criticality accidents of SNF. Compared to the normal dry storage cask, the temperature decreased from 290.0 to 262.6ºC with the application of five hybrid heat pipes per assembly. The hybrid heat pipe was fabricated for experimental study with a 1m long stainless-steel pipe containing screen mesh wick installed in the inner wall and b4c pellet inside the evaporator section.

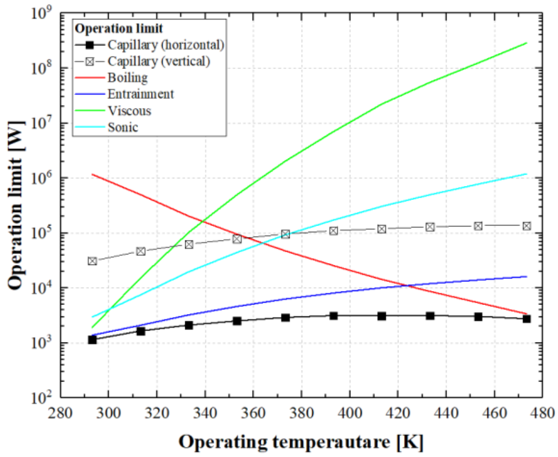
In the previous research, large-scale heat pipe experiments were mainly conducted with the gravity-assisted wickless heat pipe. Wickless heat pipes were preferred in previous nuclear reactor application research due to easy fabrication, high thermal capacity and low flow resistance in axial direction. However, to cool the nuclear system during the transportation, the heat pipe should be also operated at the horizontal condition without the gravity assisted. Therefore, the experimental study of the large-scale heat pipe containing capillary wick should be performed and validated with the theoretical analysis results. The cylindrical shape heat pipe was selected to minimize the design complexity and size with simple design. Also, the water was used as a working fluid with the advantages of high latent heat, high surface tension and high chemical stability.

The heat pipe test facility was set up and a 4m-scale heat pipe including a capillary structure at the inner wall was fabricated to evaluate the thermal performance of a large-scale heat pipe and validate the thermal limit prediction for the application of the passive cooling system in nuclear power plants.

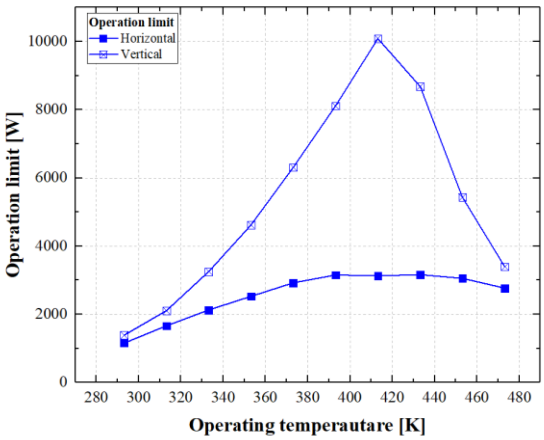
2. Design of large-scale heat pipe

The thermal performance of the heat pipe should be predicted accurately because the heat transfer capability of the heat pipe can significantly influence to the thermal limit and the size of the reactor. Therefore, it is important to provide the experimental data of the large-scale heat pipe containing capillary wick structure to validate the previous theoretical prediction results. In this study, the operation limit of the 4m-scale heat pipe was evaluated preliminarily and will be verified through the further experimental results.

The operation limit is the maximum heat transfer capacity of the heat pipe at certain operating temperature determined by properties of working fluid or geometry of the heat pipe. When the applied heat exceeds the operation limit, the dry-out occurred in the evaporator and the heat removal through the heat pipe failed. Based on the operation limit correlations from S. Kucuk [6], the heat transfer capability of the 4m-scale heat pipe at horizontal and vertical position was compared as shown in Fig. 1. Among the various operation limits, the capillary limit dominant in horizontal condition and the entrainment limit and boiling limit is dominant at vertical condition. In horizontal condition, the driving force of the working fluid circulation is capillary pumping force occurred in the wick structure. Therefore, the wick design that can enhance the driving force at the horizontal condition should be selected to enhance the capillary limit. In case of the vertical position, the capillary limit is much higher than the horizontal condition because the gravity effect also circulates the working fluid together with the capillary force.



(a) Capillary limit comparison



(b) Operation limit comparison

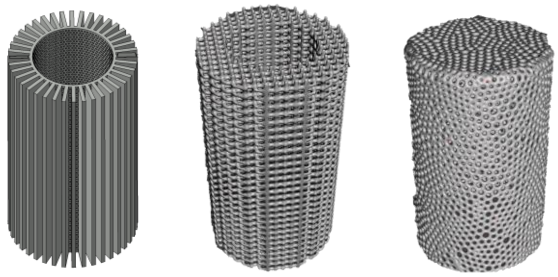
Fig. 1. Comparison of operation limit of 4m-heat pipe in vertical and horizontal condition

3. Experiment

3.1 Heat pipe fabrication

To apply a heat pipe as a passive cooling component in nuclear power plant systems, a 4m-scale capillary heat pipe was prepared for the experiment. As the distance of working fluid circulation increases on a large scale, it is sensitive to the axial pressure drop. The groove wick with the characteristic of high permeability was selected as the capillary structure at the adiabatic and condenser section. To overcome the pressure the screen mesh wick having a smaller pore size was applied only at the evaporator section to enhance the capillary pumping force and maintain the high permeability at the same time.

Fig. 2 shows the capillary wick structure manufactured with a metal 3D-printing technique with stainless steel powder. Using the metal 3D-printing technique, the porosity and pore size of the wick structure can be easily adjusted, and a complex structure which has been difficult with conventional techniques can be produced. Also, applying various types of wick structures for each section of the heat pipe are possible by assembling the different parts of the wick with various combinations which can enhance the thermal capacity of the heat pipe. The wick will be fabricated and injected into the straight cylindrical pipe to be installed at the inner wall of the heat pipe. Four types of wick structures are being considered for large-scale heat pipes as shown in Fig. 2 and 3. Fig. 3. is the 5-layer sintered wick manufactured with a conventional method. The sintered wick was selected as a large heat pipe porous medium because of its high capillary pumping force and easy manufacturing using a 3D printer.



(a) (b) (c)

Fig. 2. Configuration of 3D-printed wick (a) Screen-groove wick (b) Screen mesh wick (c) Sintered wick

Fig. 3. Configuration of 5-layer sintered wick

Table I: 4m-heat pipe design parameters

Parameters	Value
Pipe O.D. / I.D. [mm]	25.4 / 22.0
Pipe Length [mm]	4000
Pipe material	Stainless steel / Titanium
Wick structure	Screen-groove wick (Evp) Groove wick (Adi, Con)
Working fluid	Water
Fill ratio [%]	100

3.2 Experimental setup

Fig. 4 shows the large-scale water heat pipe test facility, which is consists of a heat pipe test section, furnace heater, cooling jacket, vacuum pump, back-pressure regulator, and working fluid storage tank. Twenty K-type thermocouples were installed along the heat pipe outer wall with constant spacing for temperature distribution measurement for a given conditions as shown in Fig. 5. Two K-type

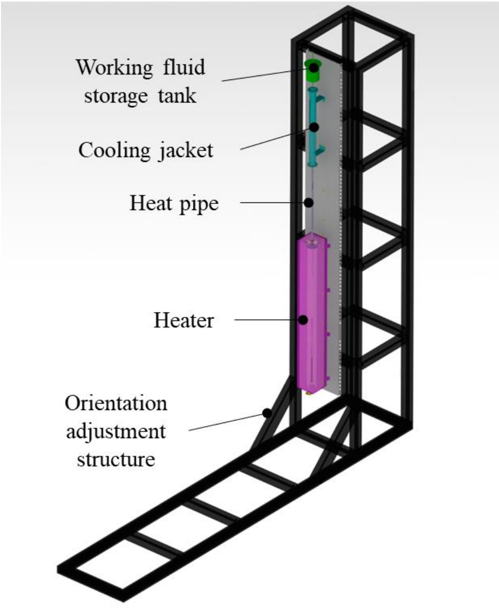


Fig. 4. Configuration of 4m-scale heat pipe test facility

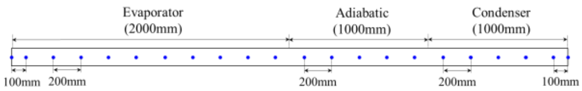


Fig. 5. Location of thermocouples

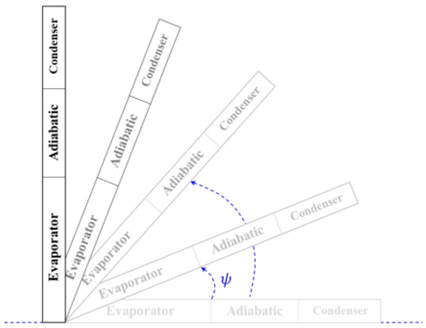


Fig. 6. Various orientation conditions of heat pipe

thermocouples were installed at the top and bottom sides of the test sections to measure the vapor temperature at the evaporator and condenser sections. The inlet and outlet temperature of the cooling water were measured for thermal efficiency evaluation. To test the thermal performance of the heat pipe at various inclination angles, the test facility can adjust the orientation freely from horizontal to vertical conditions as shown in Fig. 6. The experimental procedure is as follows: (1) remove or inject the non-condensable gas into the test section using the vacuum pump and back-pressure regulator until it reaches to the target initial pressure. (2) inject the working fluid inside the test section. (3) apply power to the evaporator section using the furnace heater. (4) circulate the water through the cooling jacket located in the condenser section. (5) increase power for each step and measure the wall temperature distribution when it achieves steady state. Table. II shows the experiment conditions.

Table II: Experimental conditions.

Parameters	Value
Heat pipe length [mm]	4000
Length ratio	Evp:Adi:Con = 2:1:1
Orientation [°]	0 ~ 90
Initial pressure [bar]	0.2 ~ 20
Heat load [W]	~ 3000

4. Conclusions

Integrating heat pipe as a passive cooling system of the nuclear power system has been studied with the advantages of passive operation, simple design, and high thermal performance. Compared to the conventional heat pipes which were used for electronic devices or industries, the scale of the heat pipe applied for nuclear power plants is larger to transport heat over long distance. To predict the thermal margin and the size of the heat pipe cooling system accurately, the thermal limit of the large-scale heat pipe evaluated theoretically of should be verified with the experimental results. 4m-long heat pipe test section and the test facility will be constructed to obtain experimental data of the large-scale heat pipe containing a capillary wick.

For further work, an experiment with a 4m-scale water heat pipe containing a capillary wick structure will be conducted with various orientation and power conditions. Based on the experimental results, the predicted thermal limit will be validated for more accurate thermal limit prediction for the nuclear reactor application.

ACKNOWLEDGEMENT

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REFERENCES

[1] A. Rosidi, N. Putra, M. H. Kusuma, Effect of graphenenano-fluid on heat pipe thermal performance for passive heat removal in nuclear spent fuel storage pool, IOP Conference Series: Earth and Environmental Science, Vol.105, p.012030, 2018.
[2] Y. Kuang, Q. Yang, W. Wang, Thermal analysis of a heat pipe assisted passive cooling system for spent fuel pools, International Journal of Refrigeration, Vol.135, p.174-188, 2022.
[3] J. Choi, C. Lim., H. Kim, Fork-end heat pipe for passive air cooling of spent nuclear fuel pool, Nuclear Engineering and Design, Vol. 374, p. 111081, 2021.
[4] Y. S. Jeong, K. M. Kim, I. G. Kim, I. C. Bang, Hybrid heat pipe-based passive in-core cooling system for advanced

nuclear power plant, Applied Thermal Engineering, Vol.90, p.609-618, 2015.
[5] K. M. Kim and I. C. Bang, Effective energy management design of spent fuel dry storage based on hybrid control rod-heat pipe, International Journal of Energy Research, Vol. 45, p.2160-2176, 2021.
[6] S. Kucuk, “A comparative investigation of heat transfer capacity limits of heat pipes”, Master thesis, 2007.

NOMENCLATURE

Adi	adiabatic section
Con	condenser section
Evp	evaporator section
Q	heat input, power [W]
ψ	tilt angle