Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 23-24, 2019

Experimental Study on the Cooling Performance of a Rod Type Heat Pipe for Passive Cooling System

Jonghwi Choi [a, b], Sangmin Park [b], Changhwan Lim [c], Hyungdae Kim [b*]
[a]*Korea Atomic Energy Research Institute, Daejeon, Republic of Korea*
[b]*Nuclear Engineering department, Kyung Hee University, Yongin, Republic of Korea*
[c]*Korea Electric Power COperation Engineering & Construction Company, Gimcheon, Republic of Korea*
[*]*Corresponding author: hdkims@khu.ac.kr*

1. Introduction

After the Fukushima nuclear power plant accident in 2011, the importance of passive safety facilities in all systems of nuclear power plants was increased. Research about passive cooling system, which remove decay heat were conducted and applied in various area in the Nuclear power generation system, including core. However, there were cases of spent fuel pool exploding in the Fukushima NPP unit 4. This shows that even if the decay heat of spent fuel is not large, it can lead to accidents if left unattended for a long time in the SBO situation. In-reactor spent fuel storage pool can be a constant problem because they exist not only in existing large NPP (Nuclear Power Plant), but also in the latest trend, SMART (System-integrated Modular Advanced Reactor) which is SMR designed by KAERI.

Heat pipe is a phase-change heat transfer device filled with working fluid in a closed pipe. The driving force of the working fluid is suitable as a passive cooling device because it uses natural energy such as gravity, capillary and centrifugal forces. Recently, research on passive cooling system using heat pipe is being conducted in the nuclear industry. China designed the passive cooling system using heat pipes for the spent fuel pool of CAP1400 models and carried out CFD analysis and experiments on it [1-4]. Xiong et al. and Wang et al. checked the effect of the type of working fluid, the temperature of the heat source and the air flow rate of the heat sink on the overall heat transfer, and confirmed that under experimental conditions, the target decay heat is removed with 1,594 heat pipes. Japan's Mochizuki et al. proposed the conceptual design with heat pipes for core cooling and calculated heat transfer performance based on thermal resistance model [5, 6].

A recent study carried out an experimental and analytical study of a particular reactor, or an analysis study that lacked an experiment. Therefore, there are no general analysis result that have been validated to be used in a variety of designs. Therefore, in this study, air-cooled experiments using heat pipes are performed, the results are discussed, and an analysis is performed to compare.

2. Experiments and Analysis

2.1 Experimental setup

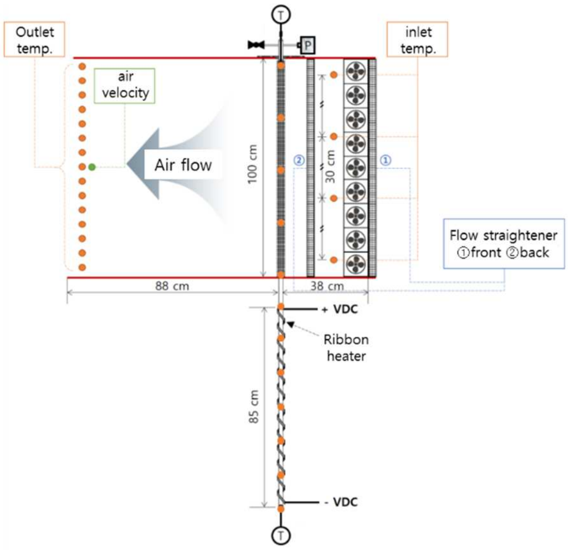

Fig.1. Schematic of the experimental apparatus

Fig.1 is a schematic of the experimental apparatus and is largely divided into heat pipes and air-cooled ducts. The heat pipe can be made in various shapes but is designed in a rod type for installation at existing power plants without compromising integrity. Given the actual application as the insertion to the guide tube of fuel rod assembly, the length of the evaporator is expected to be 12 m, which is the length of the fuel rod, but the length had to be reduced to perform the experiment. However, based on the theory of thermal resistance, the surface area of the evaporator does not significantly affect the heat transfer in the spent fuel pool environment because the thermal resistance of the condenser is very large compared to that of the evaporator [7]. Fin is installed to improve the heat transfer area of condensation.

The length of the rod type heat pipe used in the experiment is 0.85 m of the evaporator, 1 m of the condenser and 0.15 m of the insulation respectively and has an internal diameter of 19.05 mm and a thickness of 0.8 mm. The number of fin is 217 and has an external diameter of 9.225mm. The temperature was measured inside and on the surface of the heat pipe. The pressure of the internal working fluid was also measured.

The width of air duct is 0.12 meters and length is 1.3 meters. There are 9 fans at the front of the duct for air blowing. The air temperature at the front and back of the condenser were measured by 4 and 15 thermocouple respectively. A flow straightener is installed on the front of the condenser to make the flow distribution even.

Table 1. Test condition for air-cooled experiment

Property	value
Power	100W ~ 600W
Averaged air velocity	0.9 m/s
Averaged inlet air temperature	28 ℃

The temperature was measured using Omega's T-type SMPW and the Accuracy is ±1℃. The internal pressure of the heat pipe is measured with a SETRA's 3550 model pressure gauge and has 0.25 %FS in the range of 0 ~ 103.4 kPa. The flow rate of air was measured using E+E electronik's EE75 model and the accuracy is ±0.03 m/s in the range of 0.06~2 m/s. The heat pipe filling valve uses TK-Fujikin's 4DVN-SW-APP to maintain vacuum.

The evaporator was insulated after being wrapped in a ribbon heater which using DC power. The air-cooled ducts were also insulated too. The uncertainty analysis has been performed with k=2, 95% confidence intervals for the entire experimental apparatus and less than 20% for the high output range.

2.2 Test condition

Table 1 briefly shows the experimental conditions. The air was selected at a flow rate of 0.9 m/s and 28 ℃, assuming natural convection conditions. The maximum output of the heater is selected by considering the measurement range of the internal pressure sensor.

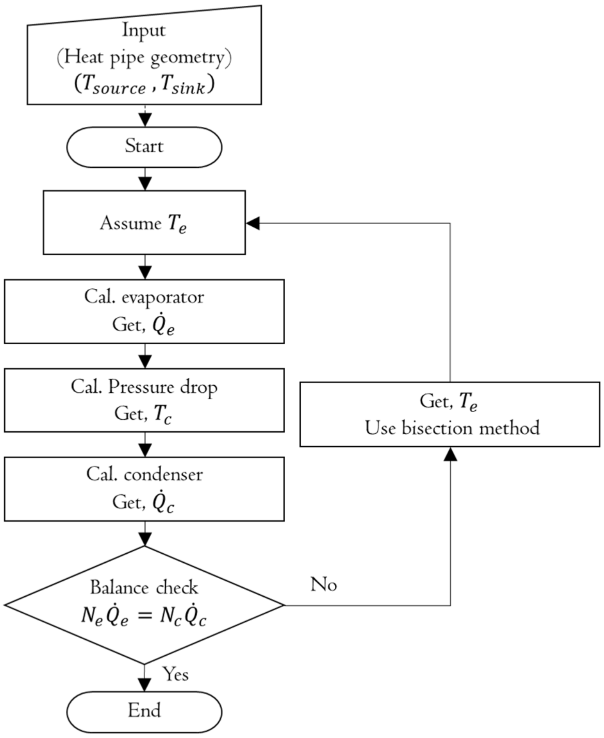

Fig.2. algorithm sequence diagram of heat transfer analysis

2.3 Heat transfer analysis

Analysis was performed using MATLAB R2014a to compare with the experimental results. Fig.2 is an algorithm sequence diagram. Based on the Eq (1), the script was written using a thermal resistance circuit model and Accuracy was verified by comparing the results of the experiments of the Fork-end Heat Pipe [7].

$$\dot{Q} = \frac{\Delta T}{\sum R}, \quad \mathrm{R} = \begin{cases} \dfrac{1}{h(\pi D L)} & (convection) \\ \dfrac{\ln(D_o/D_i)}{2\pi k L} & (conduction) \end{cases} \qquad (1)$$

3. Result and Discussion

3.1 Heat removal performance of heat pipe

The cooling performance of the heat pipe is obtained using Eq (2). At this point, the air temperature of the inlet and outlet was used as an average value at each measuring point. Fig.3 shows the cooling capacity of the heat pipe according to the heating capacity of the heater. The cooling capacity obtained using Eq (2) can be verified to be reliable when compared with the injection heat.

$$\dot{Q}_{HP} = \dot{m}_{air} c_{p,air} (T_{out} - T_{in}) \\ = \rho_{air} v_{air} A c_{p,air} (T_{out} - T_{in}) \qquad (2)$$

Fig.4 shows the cooling performance and the temperature change of the evaporator in the high power range. The temperature of the wall and working fluid at the bottom of the evaporator is below 120 ℃ in experimental range. The actual spent fuel storage pool has a saturation temperature of 120 ℃ at the bottom end due to the hydraulic pressure corresponding to 12 m. It has been confirmed that heat pipe can be cooled to 600W at temperatures of working fluid below 120 ℃, which means that the temperature of the reservoir can be cooled to 600W without increasing to the saturation temperature.

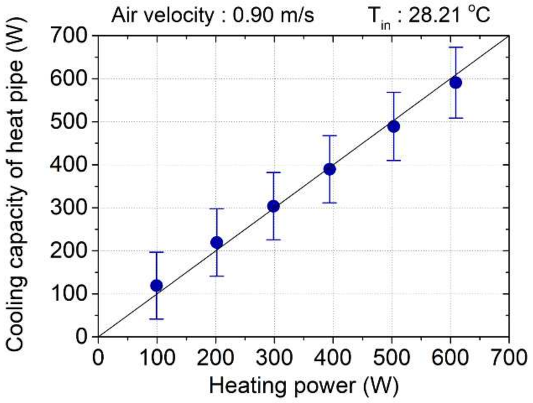

Fig.3. Cooling capacity of heat pipe with heating power

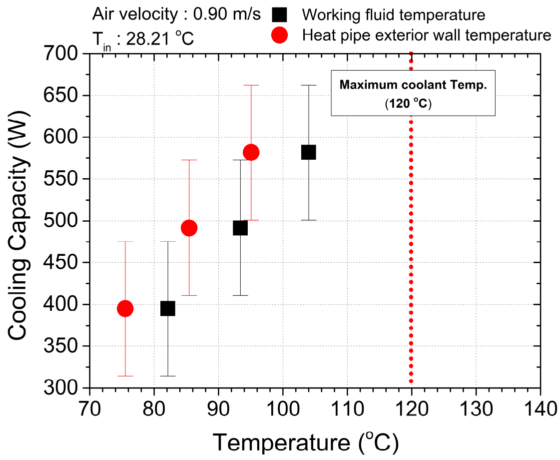

Fig.4. Working fluid and heat pipe exterior wall temperature with cooling capacity

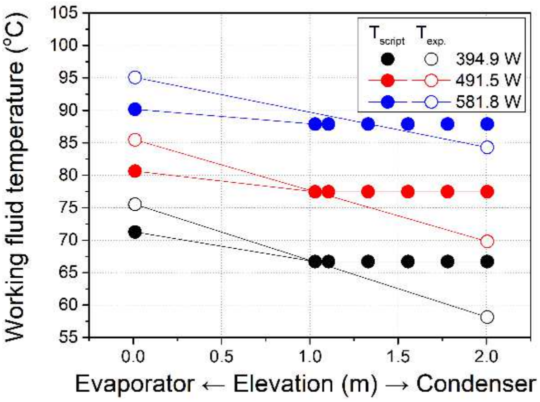

Fig.5. Comparison of working fluid temperature between experiment and analysis

3.2 Comparison experimental result with analysis

Fig.5 compared operating fluid temperature by cooling capacity with experimental and analytical results. For the same cooling capacity, the experimental value was measured higher on the evaporator and lower on the condenser. The larger the cooling capacity, the smaller the difference is, and the average value of the experimental and analytical values is almost identical. The reason for this error is that the temperature difference between the evaporator and the condenser is expected to be small because the analysis does not simulate all the specific processes of complex phase change heat transfer.

4. Conclusion

This paper carried out an air-cooling experiment with a reduced rod type heat pipe for the passive cooling system of the spent fuel storage pool of both commercial NPP and SMR and carried out analysis through MATLAB R2014a script to comparison with experimental result.

The results of the experiment confirmed that the cooling capacity relative to the injection heat quantity is well matched and that it can be cooled down to 600W while satisfying the boundary conditions.

The results of the analysis were qualitatively predicted and the average value was well matched. However, quantitative values cannot be considered accurate and the analysis must be carried out using a precision tool. The experiment should also be carried out on a wider range to increase the accuracy of the analysis.

ACKNOLEDGEMENT

This work was supported by a grant from the National Research Foundation of Korea (NRF No. 2016M2C6A 1004894) funded by the Korea government (MSIT).

REFERENCES

[1] Z. Xiong, H. Gu, M. Wang and C. Ye, “The thermal performance of a loop -type heat pipe for passively removing residual heat from spent fuel pool”, Nuclear Engineering and Design, Volume 280, 2014, pp. 262-268.

[2] Z. Xiong, M. Wang, H. Gu and C. Ye, “Experimental study on heat pipe heat removal capacity for passive cooling of spent fuel pool”, Annals of Nuclear Energy, Volume 83, 2015, pp. 258-263.

[3] Z. Xiong, C. Ye, M. Wang and H. Gu, “Experimental study on the sub-atmospheric loop heat pipe passive cooling system for spenf fuel pool”, Progress in Nuclear Energy, Volume 79, 2015, pp. 40-47.

[4] M. Wang, M. Zheng, C. Ye, Z. Qiu and Z. Xiong, “An experimental study of closed loop two-phase thermosyphon for spent fuel pool passive cooling”, Proceeding of the 2016 24th International Conference on Nuclear Engineering (ICONE24), Jun. 26-30, 2016, Charlotte, North Carolina.

[5] M. Mochizuki, R. Singh, T. Nguyen and T. Nguyen, “Heat pipe based passive emergency core cooling system for safe shutdown of nuclear power reactor”, Applied Thermal Engineering, Volume 73, 2014, pp. 699-706.

[6] M. Mochizuki, T. Nguyen, K. Mashiko, Y. Saito, R. Singh, T. Nguyen and V. Wuttijumnong, “Prevention possibility of nuclear power reactor meltdown by use of heat pipes for passive cooling of spent fuel”, Frontiers in Heat Pipes, Volume 4, No. 1, 2013, pp. 1-6.

[7] J. H. Choi, C. H. Lim, H. D. Kim, “Design and operation characteristics of fork-end heat pipe for application to passive cooling of spent fuel pool”, International Conference on Nuclear and Renewable Energy Resources, 2018, Jeju, Korea.