Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2017

Experimental Study on Heat Transfer Characteristics of a Multi-Pod Heat Pipe for Passive Cooling of Spent Fuel Pool

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1. Introduction

After Fukushima accident, long term cooling of spent fuel pool(SFP) during a station black-out(SBO) accident became one of key issues related to nuclear safety. Necessity of passive cooling systems for SFP has been continuously risen. Heat pipe is a device which effectively transfers heat via convection only using natural motive forces such as gravity and capillary force. Hence, it is suitable as a main component of the passive cooling system of SFP. Some studies for application of heat pipes for passive cooling of decay heat in reactor core and SFP have been reported. In China, Ye et al. [1] and Wang et al. [2] performed CFD analysis and experiments for passive SFP cooling system using loop-type thermosyphon heat pipe. In Japan, Mochizuki et al. [3] suggested flexible thermosyphon for SFP. In Korea, Jeong et al. [4] and Kim and Bang [5] proposed the concept of a hybrid heat pipe with a control rod for passive in-core cooling system.

In this study, a multi-pod heat pipe(MPHP) is proposed to design a passive cooling system of SFP during a SBO accident using surrounding air as the ultimate heat sink. Figure 1 shows the proposed design concept of the MPHP, which has tremendously extended heat transfer area in the air-cooled condenser part due to very small thermal capacity and heat transfer coefficient of air, relative to the water-heated evaporator part. The unique design features of the proposed MPHP, including the parallel-type condenser and the manifold header, has extremely large scale compared with conventional heat pipe in order to apply system scale. Therefore it could have different operation features and heat transfer characteristic. In this work, the heat transfer characteristics of the MPHP is experimentally investigated by varying heat source temperature as an independent variable.

2. Experimental Method

Figure 2 is the manufactured MPHP. It is made of copper. The evaporator is 1-m long with 19.05-mm outer diameter and 0.8-mm thickness. The condenser is 1-m long with 12.7-mm outer diameter and 0.8-mm thickness. The circular fins are attached on the condenser tube, which has height of 9.65-mm and thickness of 0.5-mm. The number of fins per each condenser tube is 300. The 12-condenser tubes are connected to the manifold header. The header plays a role in gathering condensed working fluid in the condenser tubes. The condenser tubes and the header have 7° inclination to insure the easy return of condensate to the evaporator part.

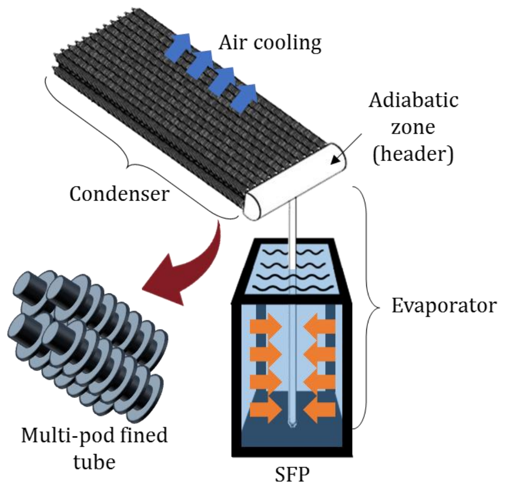


Figure 1 Concept of MPHP for passive cooling of spent fuel pool

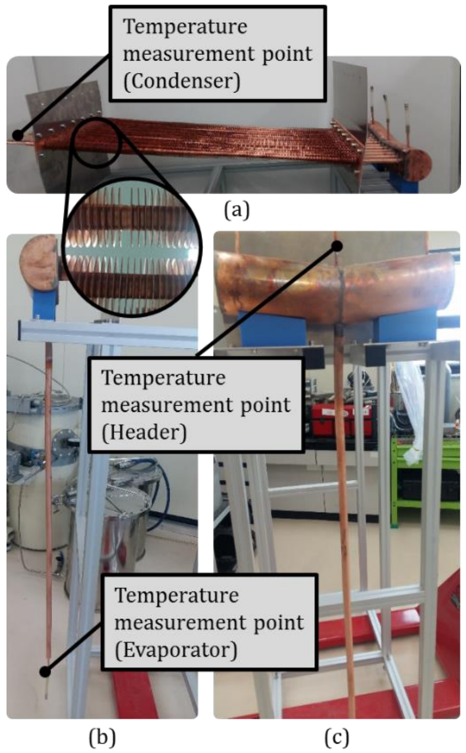
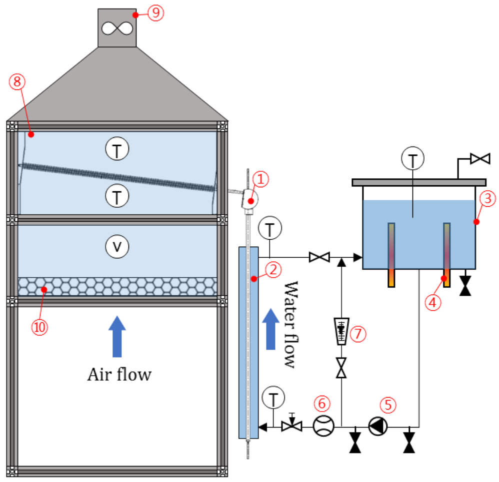


Figure 2 Manufactured MPHP test sample and measurement points; (a) top view of condenser; (b) side view of evaporator and heard; (c) front view of evaporator and header



① MPHP ② Water jacket ③ Heating chamber ④ Heater
⑤ Pump ⑥ Flow meter ⑦ Rota-meter ⑧ Air duct
⑨ Fan ⑩ Honeycomb straightener

Figure 3 Schematic of the test facility

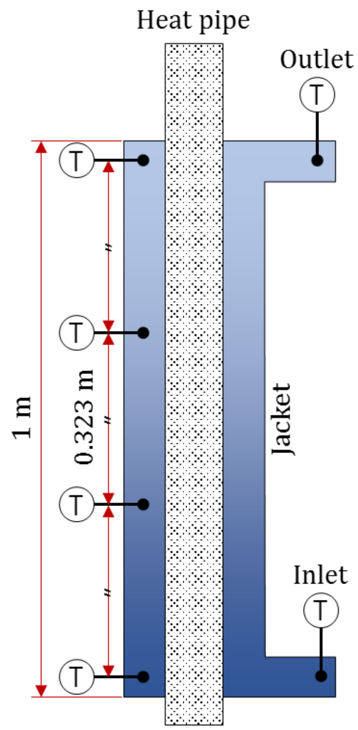


Figure 4 Schematic of the heating jacket and evaporator with temperature measurement points

The working fluid is water. The inside of MPHP maintains high vacuum to boil water at low temperature. The initial filling height of water is 1.2 m, which is 120% relative to the volume of the evaporator tube.

Figure 3 shows the schematic of the MPHP thermal-performance test facility, which is composed of two main parts: a water-heating loop and an air-cooling duct. The water heating loop supplies thermal energy to the MPHP as a heat source. The evaporator tube is inserted into an annular jacket with the heated circulating water in the range of 60-100 ℃, which corresponds to the operating condition of SFP during SBO. The air duct cools down the MPHP with convective air flow under atmospheric condition. The air flow with a desired flow rate is generated with a fan and straightened due to honeycomb straighteners at the inlet of the duct.

Figure 4 shows temperature measurement points in the loop of circulating water. Inlet and outlet temperatures of the hot water are measured by 1/10 Din class RTD. Also four T-type thermocouples are embedded in the jacket.

The heat transfer rate of MPHP is calculated by the calorimetry method,

$$q = \rho_l Q c_{p,l} \left(T_{in} - T_{out} \right) \tag{1}$$

where ρ_l and $c_{p,l}$ are density and heat capacity of water, respectively. The inlet and outlet temperatures of the hot water are denoted by T_{in} and T_{out}, respectively. Q is the volumetric flow rate.

3. Results and Discussion

3.1 Start-up of MPHP

In classical heat pipe theory, it has ‘start-up’ period. Likewise, start-up period was observed experimentally in MPHP which is represented in figure 5. The huge temperature difference is occurred between evaporator and header. It is larger than saturation temperature difference from hydrostatic pressure head of initial working fluid level. It means thermodynamic state of evaporator side is superheated liquid. After few times, extreme transition of temperature is occurred. The onset of nucleate boiling is appeared at this point. The vapor is generated in bottom of evaporator and it could entirely fill cross-sectional area of evaporator. Then, the vapor lift up above liquid to the header. Finally, the evaporator temperature drop down due to decrease of hydrostatic pressure head difference, also the temperature of header side increase due to the energy transfer by vapor. This dynamic phenomenon is call as ‘geyser boiling’ also it is the triggering signal of start-up.

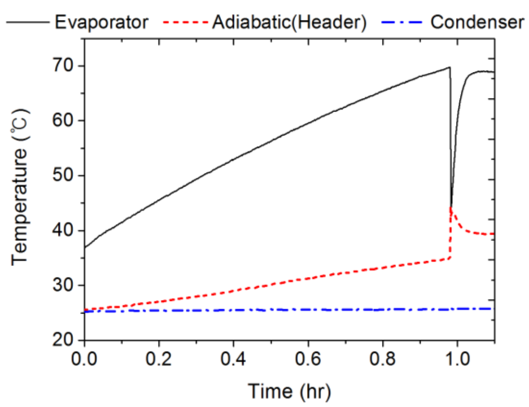


Figure 5 Temperature history for start-up period of the MPHP test sample

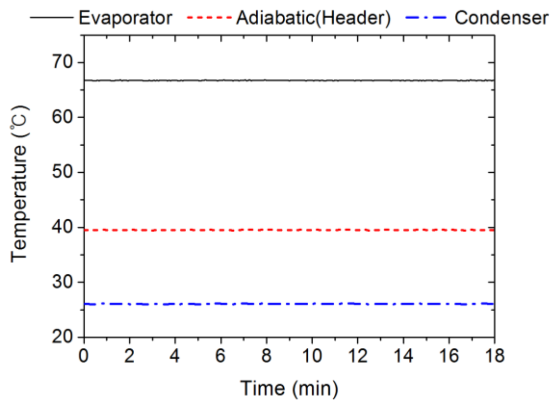


Figure 6 Working fluid temperature during pre-heating status at heat source temp. of 66.7 ℃

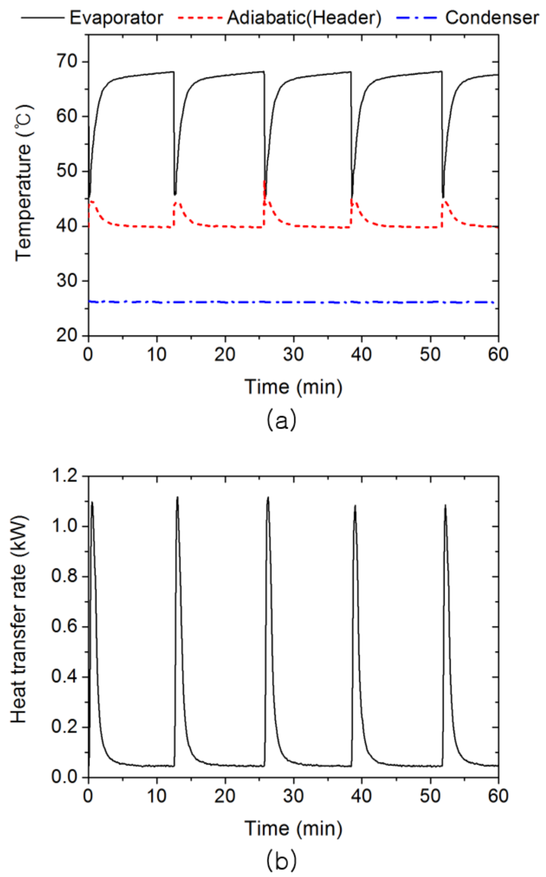


Figure 7 Geyser boiling status at heat source temp. of 67.6 ℃; (a) temperature history of working fluid; (b) heat transfer rate

3.2 Operation status

In this section, the heat transfer characteristic is introduced with operation status. The operation status could be classified four steps: *pre-heating – geyser boiling – pool boiling – evaporation on liquid-film.*

Figure 6 shows the trend of working fluid temperature during the pre-heating status. Those are stable due to without phase change phenomenon. Also heat transfer rate is really low, that is 31 W.

Figures 7 and 8 show the geyser boiling status. Tian et al. [6] and Sarmasti et al. [7] reported experimental study of geyser boiling. The tendency of temperature history is similar with their results in present study. The heat transfer rate extremely increase when geyser boiling occurred. This is due to phase change as well as instantaneously generated flow. The frequency of geyser boiling is affected by heat source temperature. It's reduced with increases of heat source temperature.

Figure 9 shows the pool boiling status. The temperature difference between evaporator and header is similar with saturation temperature difference from hydrostatic pressure head of initial working fluid level. It means that all liquid pool might be saturation condition. Moreover, the geyser boiling is intermittently occurred. It seems like similar with slug regime of flow boiling.

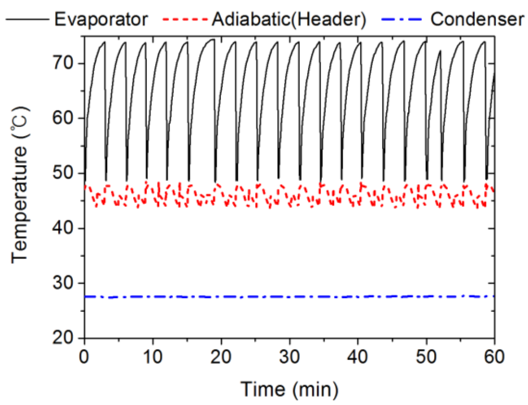


Figure 8 Working fluid temperature during geyser boiling status at heat source temp. of 74.9 ℃

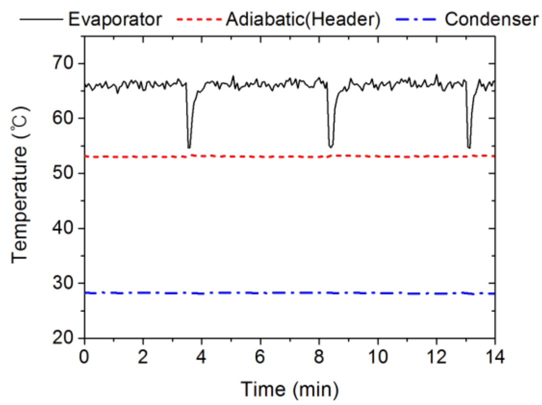


Figure 9 Working fluid temperature during pool boiling status at heat source temp. of 82.8 ℃

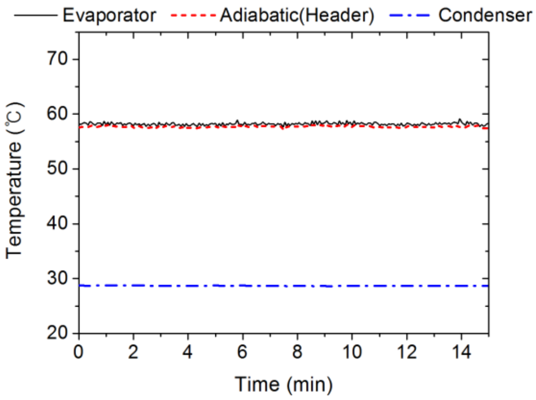


Figure 10 Working fluid temperature during evaporation on liquid-film status at heat source temp. of 98.3 ℃

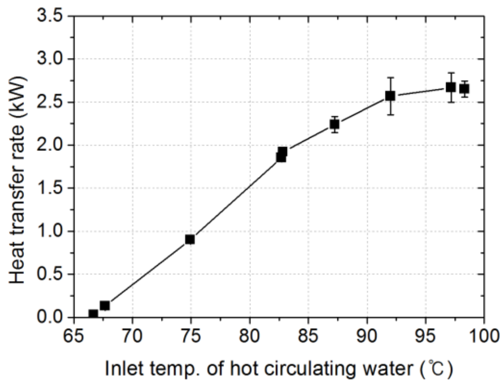


Figure 11 Average heat transfer rate of the MPHP with varying heat source temperature (Circulating water velocity: 0.71 m/s; Air velocity: 0.5 m/s)

Figure 10 shows the evaporation on liquid-film status. The temperature of evaporator and header are almost same thus, there is no hydrostatic pressure head along the evaporator. Then, the condensate could be fell down with shape of liquid-film on the evaporator wall and it's vaporized immediately. Thus, it seems like similar with shape of annular flow.

3.3 Effect of Heat Source Temperature

Figure 11 shows the effect of heat source temperature on the heat transfer rate of the MPHP. The heat transfer rate was increased according to increase of heat source temperature. The measurement uncertainty in the present study ranges from 2% to 104% at the lowest heat transfer rate.

Geyser boiling appears under 80℃ while pool boiling is observed in the temperature range from 80 to 95℃. Then, liquid-film evaporation is found over 95℃. Thus, the heat transfer rate seems to be closely related to the observed boiling regime inside the evaporator tube.

4. Conclusions

In this study, heat transfer characteristics of the multi-pod heat pipe as a key component to design a passive cooling system of spent fuel pool in preparation for a station black-out accident of a PWR were experimentally investigated. The main findings from this study are following:

- MPHP has start-up process for operation. Also, geyser boiling phenomenon is the triggering of start-up process.
- The heat transfer rate is increased with increase of heat source temperature. It is, also, related with operation status. Especially, in the geyser boiling status, the average heat transfer rate is relatively small, even though very high heat transfer rate is instantaneously reveled when geyser boiling occurred. Because the poor heat transfer rate is found during super-heating of liquid.
- MPHP has four operation status, those are *pre-heating*, *geyser boiling*, *pool boiling* and *evaporation on liquid-film*. Especially, geyser boiling status has relatively low heat transfer capacity, also it has instability feature. Therefore it have to be excluded when designing normal operation condition for passive cooling system of spent fuel pool during station black-out accident.

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