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Concentric Annular Thermosyphon for Passive Cooling System of Spent Fuel Pool

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Abstract

Since the Fukushima accident, safety issues about spent fuel pools(SFP) have been raised. Current cooling systems of SFP are vulnerable to an accident such as a blackout. Hence, lots of attempts to develop passive cooling systems of SFP have been made, and heat pipes can be used effectively to develop a new passive cooling system of SFP. An annular thermosyphon is similar to a conventional heat pipe except that the cross section of the pipe is annular instead of circular. The heat transfer area and heat transfer coefficient of the evaporator section of the annular thermosyphon can be increased significantly without increasing the outer diameter of a pipe. In this study, a new passive cooling system of SFP with the annular thermosyphon was designed, and experiments were conducted to optimize the thermal performance of the thermosyphon. Using R-134a as working fluid, we measured the temperatures of the evaporator section and the condenser section of the heat pipe by changing the charging ratio and the air velocity. And We measured heat transfer rate of heat pipe at the emergency cases. The result of experiments shows that the optimal charging ratio is 65%, and that heat transfer rate increases as air velocity and water temperature increases. The narrower clearance, the better thermal performance.

Key words : Spent fuel pool, Passive cooling system, Concentric annular thermosyphon

Ⅰ. Introduction

When fuel in a nuclear reactor is spent, or no longer usable, it is removed from the reactor core and replaced with fresh fuel. The spent nuclear fuels are still highly radioactive and continue to generate significant heat for decades. Hence, every nuclear plant has a spent fuel pool(SFP) to store the spent nuclear fuels. The spent nuclear fuels are submerged in the water of SFP, and the water is continuously circulated to draw heat away from the spent fuels and keep them at a safe temperature.

Since the Fukushima accident, safety issues about spent fuel pools have been raised. Because current cooling systems of SFP are vulnerable to an accident such as a malfunction or blackout, lots of

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attempts to develop passive cooling systems of SFP have been made.

A heat pipe is an efficient heat transfer device which can transfer heat at a low temperature difference through phase change of the working fluid. Due to this feature, heat pipes can be used effectively to develop a new passive cooling system of SFP. Therefore, there have been lots of studies that have tried to apply heat pipes to the passive cooling system of SFP.

Mochizuki et al planned a completely passive cooling system using a loop heat pipe to cool the residual heat of nuclear reactor in case of an emergency involving a loss of power(Mochizuki et al., 2012). Ye Cheng et al designed and simulated heat pipe of passive cooling system of SFP, and confirmed possibility of heat pipe application to the passive cooling system of SFP(Ye Cheng et al., 2013). Hanyang Cu et al set up a large scale loop heat pipe test facility to study the heat transfer characteristics(Hanyang Cu et al., 2014). Xiaowei Li et al numerically investigated the flow of water of SFP and the heat transfer characteristics of two-phase loop heat pipes(Xiaowei Li et al., 2015).

There are lots of preceding researches to apply heat pipes to the passive cooling system of SFP. However, these researches are all about wickless heat pipes and thus there are no researches about an annular thermosypon.

An annular thermosyphon is similar to the conventional heat pipe except that the cross section of the pipe is annular instead of circular. Its surface for heat transfer can be increased significantly without increasing the outer diameter of pipe. Hence, applying an annular thermosyphon to the SFP passive cooling system is more efficient(Nouri-Borujerdi, M.Layeghi., 2005). This paper designs a loop-type concentric annular thermosyphon for the passive cooling system of SFP by referring the preceding researches, and studies thermal performance of the thermosyphon with charging ratios, air velocities ,water temperatures and clearance of annular space.

Ⅱ. Passive Cooling System Of SFP

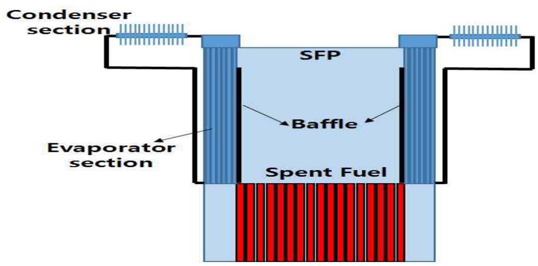
Taking into account the storage capacity of spent fuel and representatives, we selected a SFP of Hanul plant Unit 3 in Korea as the SFP to apply passive cooling system using loop-type annular thermosyphon, because it's Korea standard nuclear power plant.

<Table 1> shows the specifications of the SFP of Hanul plant unit 3.

<Table 1> The specification of the SFP of Hanul plant unit 3

Specification	Value
SFP width	10.44m
SFP length	8.64m
SFP height	12.64m
Water level	12.04m
Air temperature	10~40°C
Air humidity	70~90%
Rack height	4.72m

Referring to the suggestions from the precedent studies, we designed a passive cooling system using the thermosyphon like [Fig. 1].



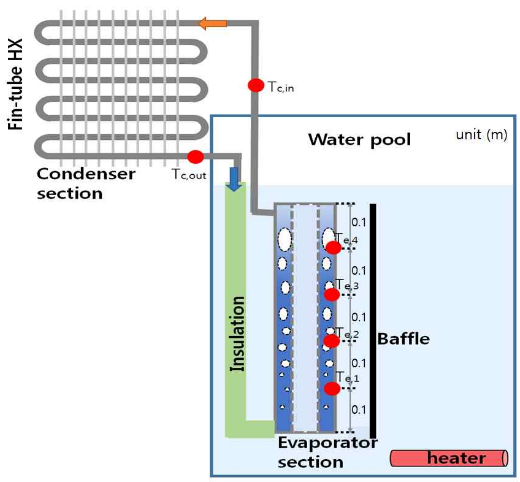
[Fig. 1] Schematic of SFP passive cooling system for nuclear power plant

The evaporator section of the heat pipe is located on the edge of the SFP upper section. The condenser section is a fin-tube heat exchanger which is exposed to the air. Also, there is a baffle to make the uniform flow of water circulation.

Ⅲ. Experimental Set Up And Method

[Fig. 2] shows the schematic of the experimental set up. SFP and spent fuel were substituted with the water pool and the heater respectively. The specification of the water pool is shown on <Table 2>. According to the SFP cooling criterion of Korea standard nuclear power plant design specification, the maximum temperature of water is 48.9°C in normal operation. So we chose R-134a as a working fluid and manufactured an annular thermosyphon like as a specification of <Table 3> and [Fig 7]. The condenser section is a fin-tube heat exchanger, and the specification is shown on <Table 4>.

We measured the temperatures of the evaporator section and the condenser section through T-type thermocouples and a data logger, and measured input powers through a power meter with a regulator. Then, we calculated heat transfer coefficients with equation (1) and equation (2).



[Fig. 2] Schematic of experimental set up

<Table 2> Specification of water pool

Specification	Value
Width	0.4m
Length	0.4m
Height	0.8m
Water level	0.7m
Material	ABS resin

<Table 3> Specification of evaporator section

Specification	Value
Material	Copper
Working fluid	R-134a
Length	500mm
O.D. of outer tube	22.22mm
I.D. of inner tube	11.1mm

<Table 4> Specification of fin tube heat exchanger of condenser section

Specification	Value
Tube O.D.	7.3mm
Tube length	5780mm
Tube material	Copper
Fin height	12mm
Fin thickness	0.25mm
Fin material	Al plate

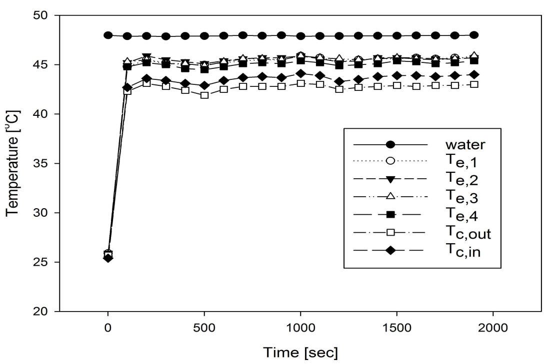
$$h_e = \frac{q_e}{T_e - T_{sat}} [W/m^2℃] \quad (1)$$

$$h_{air} = \frac{Q}{A_c(T_c - T_{air})} [W/m^2℃] \quad (2)$$

The experiments were conducted indoor at 25(±1)°C and the temperature of water was 48(±0.3)°C.

Ⅳ. Results And Consideration

[Fig. 3] shows the temperature profiles of the annular thermosyphon which is running at the temperature of 48°C and the charging ratio of 65%. The temperatures of the evaporator section are 45~46°C which are lower than the water temperature. That is because the working fluid in the evaporator section draws heat from the water through the tube wall, and it is boiling. The temperatures of the condenser section inlet are 43~44°C. The temperatures of the condenser section outlet are 42~43°C which are 1~2°C lower than the inlet temperature. Heat transfer rate through the thermosyphon is 83.12W, and heat transfer coefficient is 928.15W/m^2·°C. The cooling load of SFP of Hannul plant unit 3 is 4MW(Seol et al., 2013).

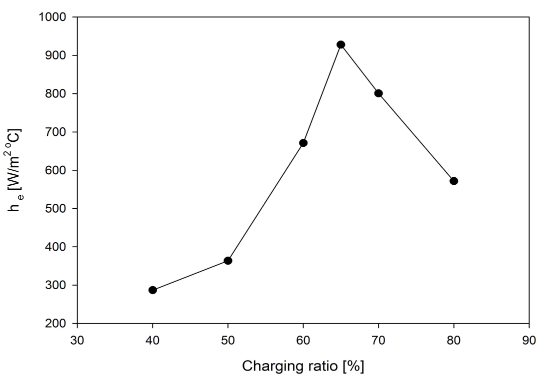


[Fig. 3] Temperature profiles of loop-type annular thermosyphon

The reduction model of water pool in this study contains one-ten-thousandth of the amount of water of the original water pool, which means that the cooling load of the model water pool is 0.4kW. Therefore, if there are five loop-type annular thermosyphons, it can have the capacity to handle the cooling load. If an actual size thermosyphon (Outer tube O.D.:66.67mm, inner tube I.D.:32.8mm, height:7m)apply to SFP, 1661 thermosyphons can remove 4MW in total from SFP.

1. Effect of charging ratio

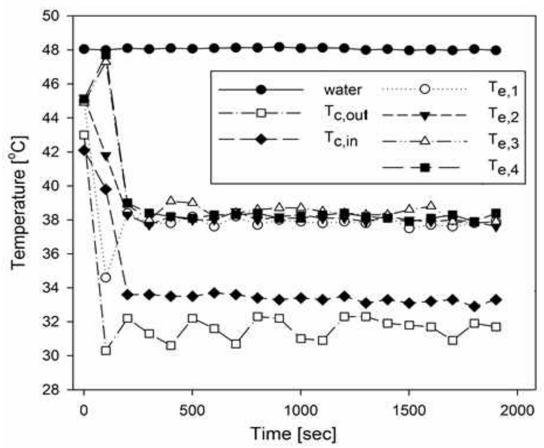
[Fig. 4] is the graph showing variations of heat transfer coefficient(h_e) with charging ratio. Charging ratio is defined as the volumetric ratio of liquefied working fluid to the whole loop-type annular thermosyphon. When the charging ratio was 20%, it was too small to operate well. When the charging ratio was 30%, the thermosyphon operated for about 10minutes at first, but after that, it didn't work well. When the charging ratio is 30~65%, the more the charging ratio increases, the more heat transfer coefficient increases. That's because the amount of the liquefied working fluid in evaporator section increases with an increase of the charging ratio. However, heat transfer coefficient decrease quickly over 65% of charging ratio. Because excessive amount of liquefied working fluid increases the area of the single phase fluid region which results in the decrease of heat transfer. So, the optimal charging ratio is 65% of the thermosyphon inner volume.



[Fig. 4] Heat transfer coefficients of evaporator section according to charging ratio

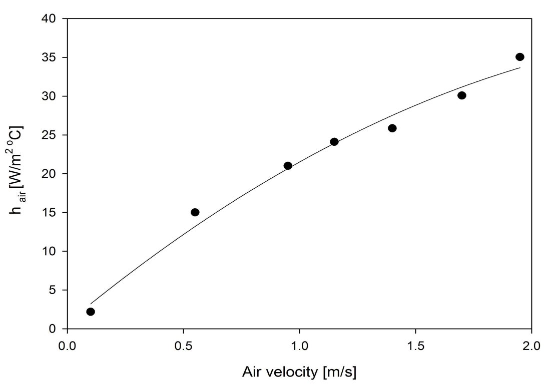
2. Effect of air velocity

[Fig. 5] shows the temperature profiles of the annular thermosyphon which is running at an air velocity of 1.4m/s and the charging ratio of 65%. The temperatures of the evaporator section are 37~39°C. The temperature of the condenser section inlet is about 33.5°C, and the temperatures of the condenser section outlet are 30~33°C. The temperatures of the thermosyphon are lower than those for the natural convection in the condenser section. That's because the more working fluid at the condenser section is condensed and returns to evaporator section.



[Fig. 5] Temperature profiles of concentric annular thermosyphon at forced convection condition

[Fig. 6] is the graphs showing the variation of average temperatures of the condenser section, heat transfer rates, and heat transfer coefficients with air velocity. As the air velocity increases, the temperature of the condenser section decreases. And both the heat transfer rate and the heat transfer coefficient of air increase with air velocity. When air velocity is 1m/s, the heat transfer rate is 330W which is 4.13 times higher than that of natural convection and, its heat transfer coefficient is 21.03W/m^{2}·°C. Also, when air velocity is 2m/s, the heat transfer rate is 445W which is 5.56 times higher than that of natural convection, and its heat transfer coefficient is 35.06W/m^{2}·°C. Therefore, when air velocity is 1m/s, two thermosyphons can remove 660W which is more than the cooling road of 400W. Therefore, when air velocity is 1m/s, two thermosyphons can remove 660W which is more than the cooling road of 400W. When air velocity is 2m/s, only one thermosyphon can remove cooling road. These experiment results show that this passive cooling system using the thermosyphon can replace the present cooling system. At the normal operation state, with other power such as fan, this cooling system can be worked more effectively.



[Fig. 6] Effects of air velocity on h_{air}

3. Effect of water temperature

According to the system design of SFP(OPR-1000), the maximum temperature of water of SFP in emergency is 60.0°C. Even in the case of malfunctioning of an active cooling system, temperature of water should be under 82.2°C. So we conducted this experiment under natural convection state to find out how much thermosyphon draws heat from SFP in an emergency state such as a black out or a short circuit.

<Table 5> shows that the heat transfer rate increases as the temperature of water increases. This result indicates that this cooling system using a loop-type annular thermosyphon can be operated passively well without other power.

<Table 5> Heat transfer rate according to water temperature

Temperature of water [°C]	**Q** [W]
48	83.12
60	165.83
82	264.22

4. Effect of clearance of annular space

[Fig. 7] and <Table 6> show each experiment cases for effects of clearance of annular space.

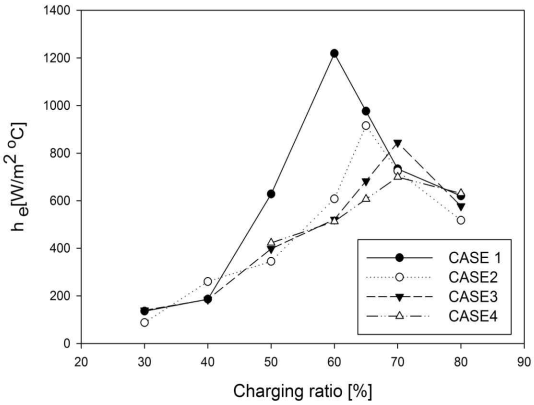
Case1 Case2 Case3 Case4

[Fig. 7] Plane view of annular space of evaporator section

<Table 6> Specifications of each cases

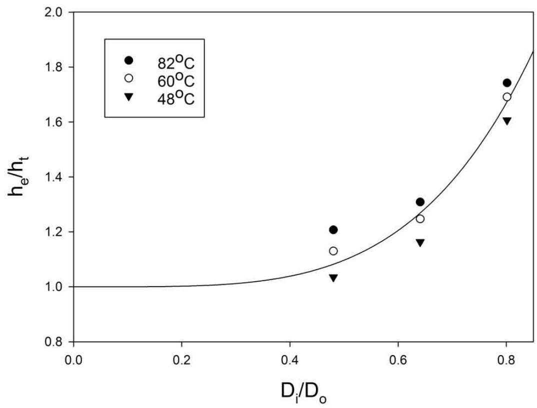
	O.D.[mm]	**I.D.**[mm]	**Clearance**[mm]
Case1	22.22	14.08	1.97
Case2	22.22	11.1	3.56
Case3	22.22	7.92	5.15
Case4	22.22	-	(thermosyphon)

[Fig. 8] shows the heat transfer coefficient of evaporator according to the clearance in each case. The narrower clearance, the better thermal performance. The narrower clearance, means a larger heat transfer area. That is, as the heat transfer area is widened, more bubbles are generated in the narrower annular space, thereby improving the thermal performance of the heat pipe.



[Fig. 8] Variation of heat transfer coefficient with charging ratio and clearance

[Fig. 9] shows the heat transfer coefficient ratio to the thermosyphon and annular heat pipes(h_e/h_t) according to diameter ratio(D_i/D_o). When the diameter ratio is 0, it means conventional a thermosyphon. Closer to 1, means clearance become narrow.



[Fig. 9] Ratio of heat transfer coefficient between thermosyphon and annular heat pipe (h_e/h_t) according to diameter ratio(D_i/D_o)

Based on the results, correlation is derived as follows.

$$\frac{h_e}{h_t} = 1 + (\frac{D_i}{D_o})^4 \quad (3)$$

When the nuclear boiling is dominant, heat transfer coefficient of thermosyphon is expressed by result of experiment.

$$h_t = \frac{113.72q^{0.25}}{(T_e - T_{sat})} \quad (4)$$

Substituting (4) into (3), the evaporation heat transfer coefficient is derived as follow.

$$h_e = \frac{113.72q^{0.25}}{(T_e - T_{sat})}\left[1 + (\frac{D_i}{D_o})^4\right] \quad (5)$$

The predicted value is within ±10% of the experimental value.

Ⅴ. Conclusions

In this research, we designed a passive cooling system using the loop-type annular heat pipe and conducted various experiments to find out the thermal performance of the thermosyphon.

The optimal charging ratio is 65% of the whole volume of the loop type thermosyphon.

At this charging ratio, the evaporator section which is submerged in hot water can be packed with the liquefied working fluid.

At natural convection in condenser section, this thermosyphon can remove 83.12W from the water pool. So, five thermosyphons can remove 415.6W which is more than cooling load 400W.

If the air velocity at condenser section is increased, both the heat transfer rate of heat pipe and the heat transfer coefficient of air are much larger than those for the natural convection. This result indicates that this cooling system with other power such as fan can be worked more effectively at the normal operation state.

Heat transfer rate of the heat pipe increases, as water temperature increases. At 60°C in a state of emergency, a thermosyphon can remove 165.83W and two thermosyphons can cope with the cooling load. The narrower clearance, the better thermal performance. Therefore, the passive cooling system using a loop type annular thermosyphon can remove the cooling load of SFP.

Nomenclature

A : *area (m^2)*
h : *heat transfer coefficient (W/m^2 ℃)*
Q : *heat transfer rate (W)*
q : *heat flux (W/m^2)*
T : *temperature (℃)*

Subscripts

air : *air*
c : *condenser section*
e : *evaporator section*
in : *inlet*
out : *outlet*
sat : *saturation*
t : *thermosyphon*

References

A Nouri-Borujerdi, M.Layeghi(2005), A review of concentric annular heat pipes, Heat transfer engineering 26, 45~58, Taylor and Francis Inc. (10.1080/01457630590950934)

Mochizuki M, Singh R, Nguyen T, Nguyen T, Sugihara S, Mashiko K, Saito Y and Wuttijumnong, V(2012), Nuclear reactor must need heat pipe for cooling, Front. Heat Pipes (FHP) 2, 1~5. (10.5098/fhp.v2.3.3001)

Seol GW, Yoon DH, Kim JH, and Shin BS(2013), Detailed analysis for cooling performance of spent fuel pool and heat removal performance of passive condensation cooling tank, Korea institute of nuclear safety, RR-1019

Wen Fu, Xiaowei Li, Xinxin Wu, and Zhengming Zhang(2015), Investigation of a long term passive cooling system using two-phase thermosyphon loops for the nuclear reactor spent fuel pool, Annals of Nuclear Energy 82, 346~356. (10.1016/j.anucene.2015.05.026)

Xiong ZQ, Gu HY, Wang ML and Cheng Y(2014), The thermal performance of a loop-type heat pipe for passively removing residual heat from spent fuel pool. Annals of Nuclear Energy 280, 262~268. (10.1016/j.nucengdes.2014.09.022)

Ye C, Zheng MG, Wang ML, Zhang RH and Xiong ZQ (2013). The design and simulation of a new spent fuel pool passive cooling system. Annals of Nuclear Energy 58, 124~131. (10.1016/j.anucene.2013.03.007)

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