Experiments on Heat Transfer Performance Assessment of Multi-Pod Heat Pipe in presence of Non-condensable gas

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1. Introduction

Multi-Pod Heat Pipe (MPHP) is a new safety concept in which Two-Phase Closed Thermosyphon (TPCT) that makes heat exchange without separate external power supply using the phase change of working fluid is applicable to Passive Containment Cooling System (PCCS)[1]. The previous study [2] explored the temperature and pressure variation of MPHP. To assess the heat transfer performance of MPHP, further experiment was conducted by increasing the capacity of heater. In addition, when MPHP is applied to nuclear power plant, there will be lots of Pipes of Boiling region to remove decay heat of $18MW_t$ [1]. Such array of pipes will lead to a higher weight fraction of air, non-condensable gas, at the center of pipe assembly. In this study, experiments on the effect of heat transfer inhibition on non-condensable gas were conducted by increasing injection heat up to 10~25kW as well as injecting a certain amount of air.

2. Experimental method

2.1 Experimental facility design

As a result of the previous study [2], the assessment of the heat transfer performance of MPHP required an additional increase in the heater capacity. The existing experimental equipment was installed with two heaters with the capacity of 5kW. In this study, two heaters of 15kW were equipped by increasing the heat range, and the below pressure tank was newly produced.

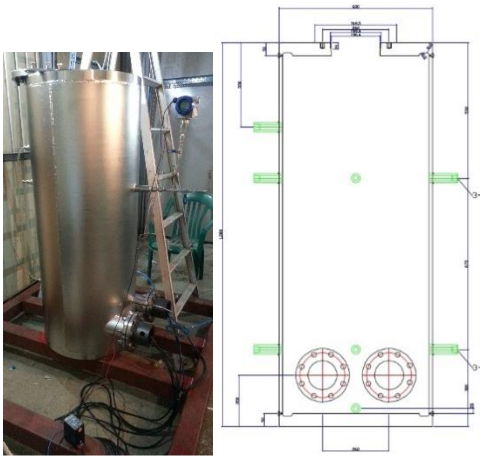


Fig. 1. Pressure tank with the capacity of 30kW

Since the newly produced pressure tank could keep a higher heat than the existing one, it was designed to increase the internal volume and hold rising pressure depending on the temperature.

Table I: The specification of pressure tank

Material	Stainless-steel 310
Diameter(m)	0.6
Height(m)	1.5
Volume(m^3)	2.55
Design pressure(MPa)	0.1

In heat pipe assembly, experiments were conducted by using the conventional designed and produced MPHP.

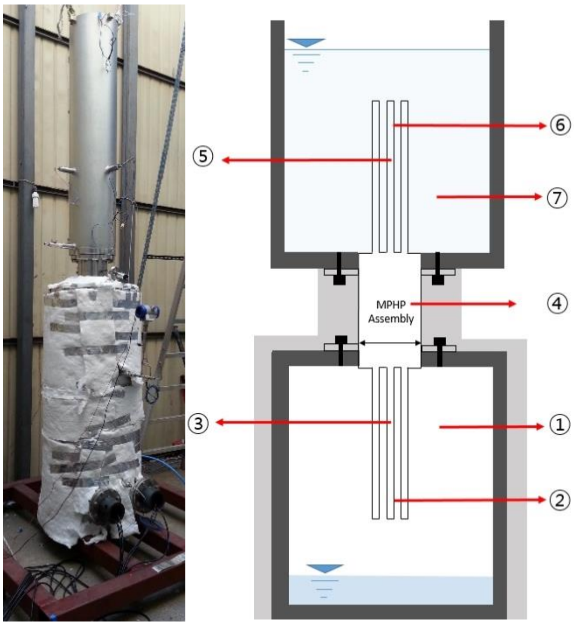


Fig. 2. The overall experimental facility and the measuring part of temperature and pressure

The measuring part of temperature and pressure for the heat transfer performance was shown in Table Ⅱ. The temperature and pressure of the inside of pressure tank were measured. Also, the temperature of the outer wall and inside of MPHP and the coolant was measured.

Table Ⅱ: The experimental matrix

Point	①	②	③	④	⑤	⑥	⑦
Variable	T_h, P_h	T_{wbo}	T_b	T_a	T_c	T_{wco}	T_{cold}

The air was injected through shut-off valve of pressure tank by using air compressor. The specification of air compressor is as follows.

Table Ⅲ: The specification of air compressor

Model	Flow rate	Range
AS680-T10	120L/min	0.55-0.8MPa

2.2 Experimental matrix

The conditions for initial experiment are shown in Table Ⅱ. The power of 10kW, 15kW, 20kW and 25kW was injected by a volume change in 5kW within the power range. To identify the effect of heat transfer inhibition of non-condensable gas in each input power, the experiment was conducted by injecting the amount of air differently.

Table Ⅳ: The experimental matrix

Test-ID	Input(kW)	Initial absolute pressure(MPa)	The predicted air fraction in steady state(w/o)
10-n1	10	0.1	0.4
10-n2		0.14	0.45
10-n3		0.21	0.5
15-n1	15	0.1	0.35
15-n2		0.15	0.4
15-n3		0.22	0.45
20-n1	20	0.1	0.3
20-n2		0.16	0.35
20-n3		0.27	0.4
25-n1	25	0.1	0.25
25-n2		0.18	0.3
25-n3		0.29	0.35

The range of input power was determined by Boiling Limitation (BL), a major limit of TPCT, and Counter Current Flow Limitation (CCFL). As mentioned earlier, TPCT is operated by the reduction from phase change of working fluid within an enclosed pipe. Accordingly, the main limits to TPCT were BL, in which dry-out occurs due to excess heat flux and the occurrence of CCFL between vapor phase and liquid phase due to phase change of working fluid [3]. The equations for BL (1) and CCFL (2) are as follows [4].

$$\dot{Q}_{max} = A_{rad} h_{fg} \rho_v^{0.5} [g\sigma(\rho_l - \rho_v)]^{1/4} Ku_{BL} \quad (1)$$
$$Ku_{BL} = 0.16[1 - \exp(-D_i/L_b)(\rho_l/\rho_v)^{0.13}$$

$$\dot{Q}_{max} = Ku_{CCFL} A_{axi} h_{fg} [g\sigma(\rho_l - \rho_v)]^{1/4} [1 + (\rho_l/\rho_v)^{0.25}]^{-2} \quad (2)$$

$$Ku_{CCFL} = (\rho_l/\rho_v)^{0.14} tanh^2 Bo^{1/4}$$
$$Bo = d\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2}$$

The results of the equations (1) and (2) are shown in Fig. 3.

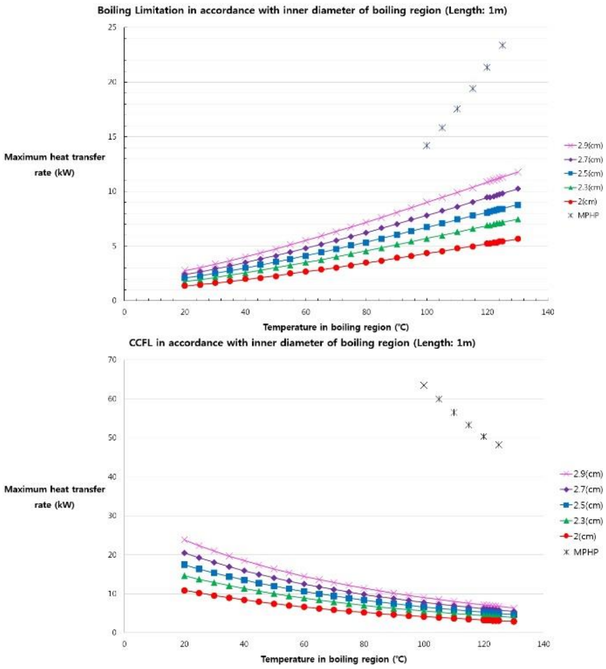


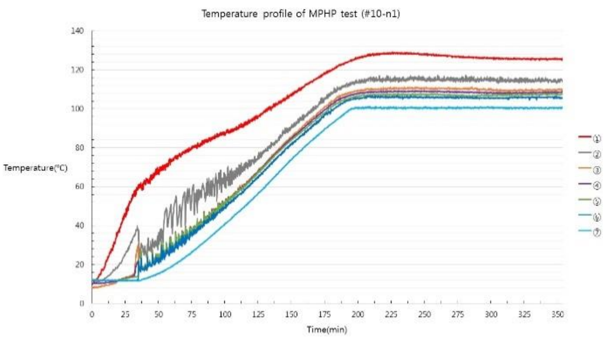
Fig. 3. The Boiling Limitation and Counter Current Flow Limitation in TPCT

Based on the results of data [5] of MPHP used in this experiment, while the operation range of BL was 14~25kW in boiling region with 2.9 cm in inner diameter and 1m in length, the operation range of CCFL was 45~60kW.
Considering that MPHP was run at 100~125℃ in the steady state and the above result indicated the result when there was one pipe, the conclusion was that BL and CCFL were unlikely occur when the experiment was conducted within the maximum of 25kW.

3. Experimental Result

3.1 Temperature and pressure profile

As mentioned earlier, the experiment was carried out by adjusting power and air input differently. As a result, in the case of test 10-n1~n3, the changes in temperature and pressure are shown in Fig. 3~5.



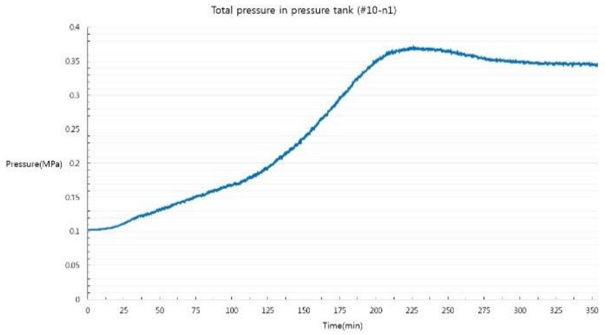


Fig. 4. Temperature and pressure profiles at test number 10-n1.

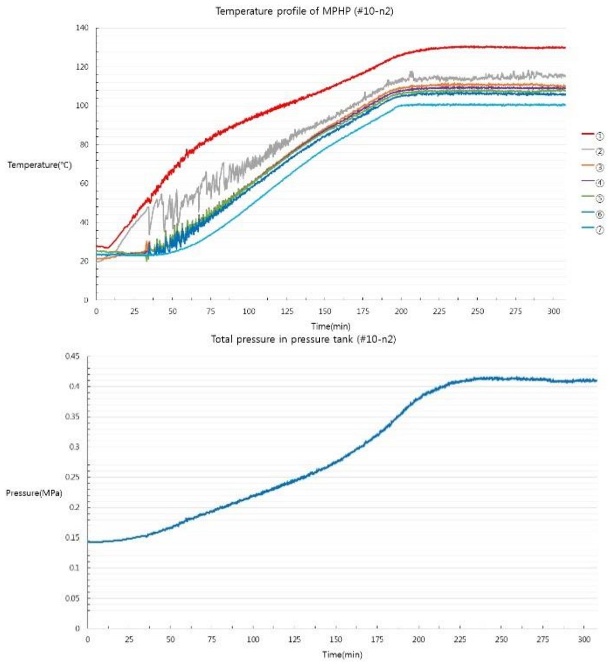


Fig. 5. Temperature and pressure profiles at test number 10-n2

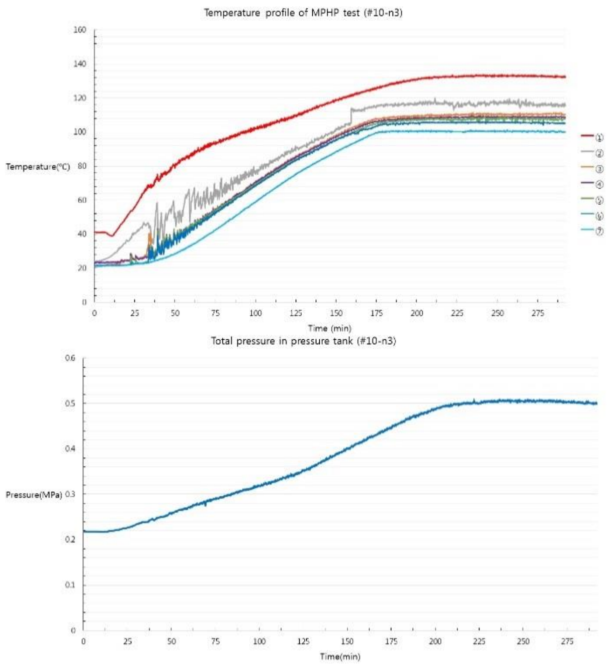


Fig. 6. Temperature and pressure profiles at test number 10-n3

The results of the experiment up to 10~25kW indicated the temperature and pressure profiles shown in Fig. 3~5. In test 25-n3, the inner pressure of pressure tank was not in the steady state due to MPHP, continuing to increase. Thus the experiment was forcibly finished and the temperature and pressure profile are as follows.

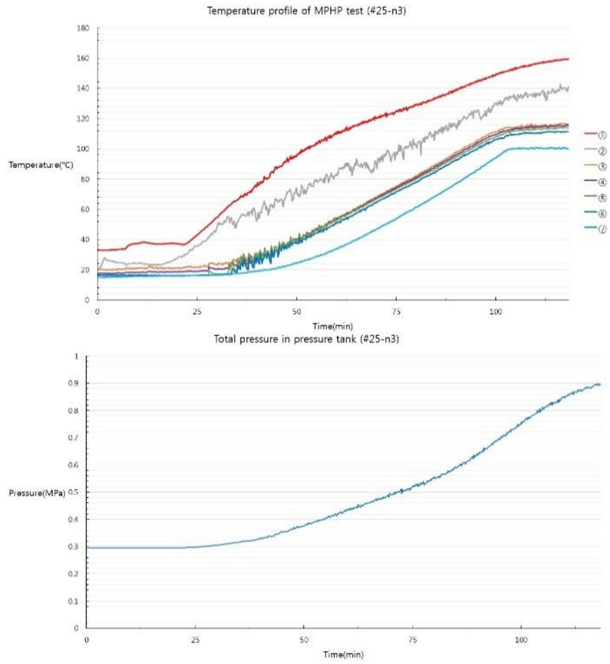


Fig. 7. Temperature and pressure profiles at test 25-n3

This was a result from the inhibition of heat, which should have been transmitted from the inner pressure tank to MPHP due to a rising air input.

In addition, after observing the temperature of the outer wall of vapor inserted inside pressure tank, there was a sharp rise in temperature, contrary to expectations that there was a rapid change in the inner temperature of pressure tank by air. This can be shown in Fig. 8 and Fig. 9.

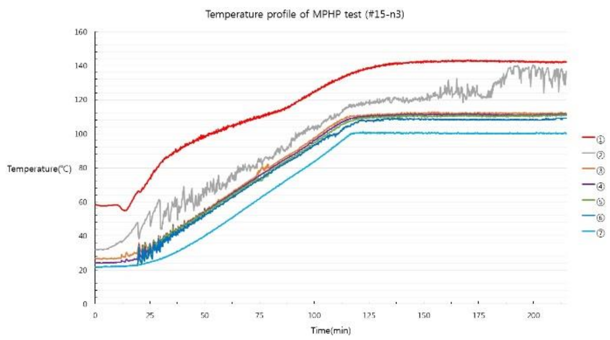


Fig. 8. Temperature profile at test 15-n3

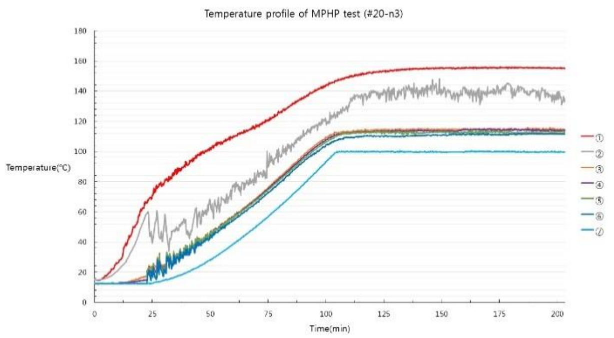


Fig. 9. Temperature profile at test 20-n3

The previous experiments and correlations [5] and [6] showed that a higher air weight fraction led to a lower heat transfer coefficient, when injecting a certain amount of heat. A stable heat and a lower heat transfer coefficient should lead to a sharp increase in temperature. However, like Fig. 8-9, the reason for a rise in wall temperature was that working fluid was not equally distributed to 7 boiling regions in one adiabatic region so that this led to dry-out and the temperature of outer wall would rise.

3.2 Heat transfer coefficient in each region

Based on the data of the previous experiment, the heat transfer coefficient of each area is as follows. In the case of test 15-n3 where dry-out was expected to occur, the measurement was done by calculating the average temperature of the steady state before a sharp rise in wall temperature. This study made a comparison between the estimated heat transfer coefficients and heat transfer correlations determined by the previous study [7].

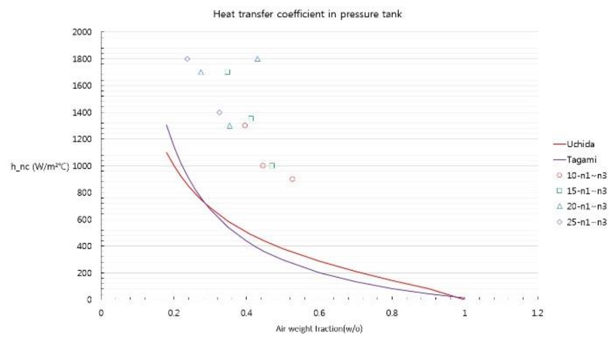


Fig. 8. Heat transfer coefficient in pressure tank

Table Ⅴ: Air weight fraction and heat transfer coefficient in pressure tank

Test-ID	W_{nc}(w/o)	h_{nc}(W/m^2℃)
10-n1	0.395	1300
10-n2	0.446	1000
10-n3	0.527	900
15-n1	0.348	1700
15-n2	0.413	1350
15-n3	0.468	1000
20-n1	0.275	1700
20-n2	0.35	1300
20-n3	0.43	1800
25-n1	0.237	1800
25-n2	0.325	1400

As expected, heat transfer coefficient of the inner pressure tank reduced as air weight fraction rose. Making a comparison between Uchida correlation and Tagami correlation indicated higher figures. This shows that since Uchida and Tagami correlations were developed for nuclear accident analysis, they were conservative [5] and [6].

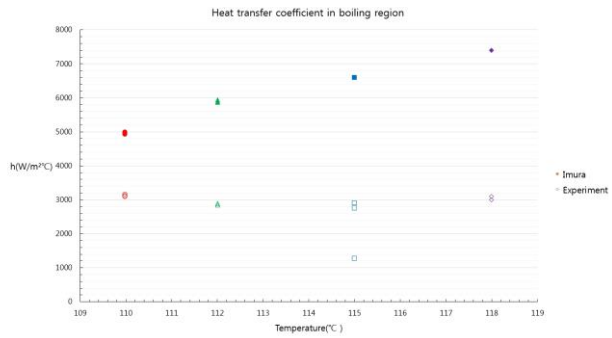


Fig. 9. Heat transfer coefficient in boiling region

When compared with Imura correlation [7], heat transfer coefficient in the evaporating part had a regular value depending on heat. This can be found in the following equation.

$$h_b = \dot{Q}_i / \{A_i(T_{wbi} - T_b)\} \quad (3)$$
$$T_{wbi} = T_{wbo} - \{\dot{Q}_i ln(r_o/r_i)\}/2\pi k L_b$$

Since the temperature on inner wall of the evaporating part was impossible to measure due to the characteristics of TPCT, calculation was done by the data of inner wall temperate. This indicated that a higher heat led to a sharp rise in the temperature of outer wall rather than a rise in the temperature of boiling region. Thus, the temperature of inner wall dramatically rose, compared with a rise in the temperature of boiling region.

Table Ⅵ: Temperature on inner wall and boiling region

Test-ID		T_b	T_{wbi}-T_b	h_b(W/m^2℃)
10	n1	110	5	3100
	n2		5	3150
	n3		5	3080
15	n1	112	8	2900
	n2		8	2850
	n3		8	2850
20	n1	115	11	2750
	n2		10	2900
	n3		24	1250
25	n1	118	12.7	3000
	n2		12.3	3100

Therefore, an increasing heat led to a gradual increase in temperature variation, so there was no significant change in heat transfer coefficient.

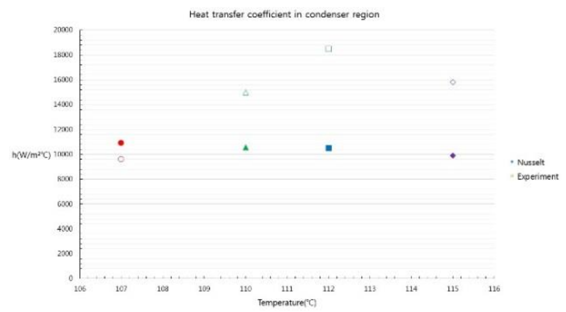


Fig. 10. Heat transfer coefficient in condenser region

Table Ⅶ: Heat transfer coefficient and Temperature difference between inner and inner wall on condenser region

Test-ID	T_C-T_{wci}	h_C(W/m^2°C)
10-n1~n3	1.6	9600
15-n1~n3	1.5	15000
20-n1~n3	1.6	18500
25-n1~n3	2.4	15800

Heat transfer coefficient in condenser region rose depending on a rising heat.

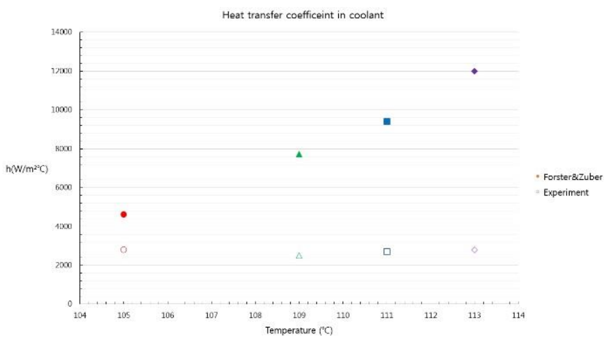


Fig. 11. Heat transfer coefficient in coolant tank

Heat transfer coefficient arising from temperature difference between outer wall on condenser region and coolant is shown in Table Ⅷ.

Table Ⅷ: Heat transfer coefficient and temperature difference between outer wall on condenser region and coolant

Test-ID	T_{wco}-T_{cold}	h_{Cold}(W/m^2°C)
10-n1~n3	5.3	2800
15-n1~n3	8.87	2500
20-n1~n3	11.12	2700
25-n1~n3	13.3	2800

3.3 Overall heat transfer rate

The substitution of heat transfer coefficient with temperature difference in MPHP indicated overall heat transfer rate, a goal for the study.

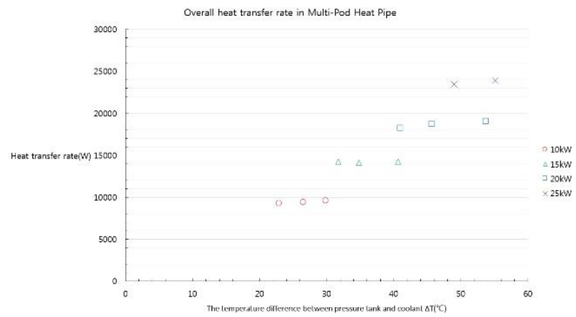
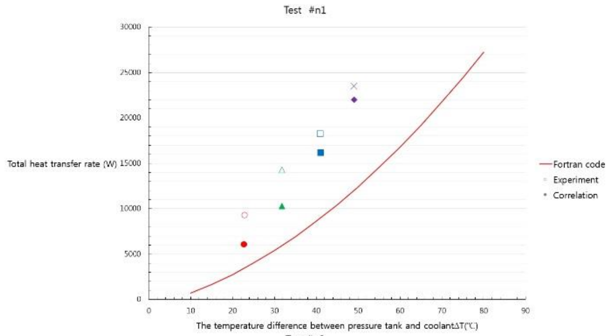


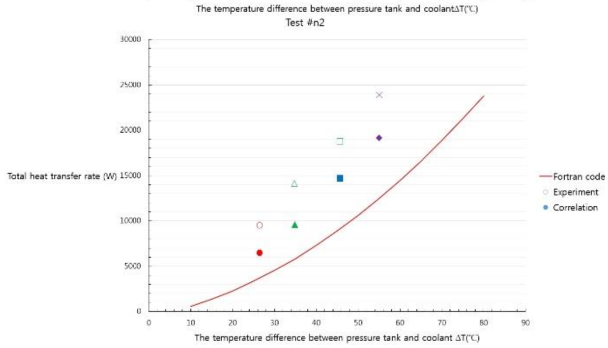
Fig. 12. Overall heat transfer rate in MPHP

Table Ⅸ: Overall heat transfer rate in MPHP experiment

Test-ID	T_h-T_{Cold}-ΔT_{bc}	Q (W)
10-n1	22.8	9290
10-n2	26.5	9485
10-n3	30	9590
15-n1	31.75	14280
15-n2	34.8	14140
15-n3	40.6	14240
20-n1	41	18270
20-n2	45.68	18800
20-n3	53.7	19060
25-n1	49	23500
25-n2	55.1	23880

The experiment showed that a higher temperature of inner pressure tank led to an increase in the total heat. Since there was a difference between the results of heat transfer coefficient and the heat transfer correlation determined in the previous study, the comparison was made to check whether there are any differences in overall heat transfer rate.





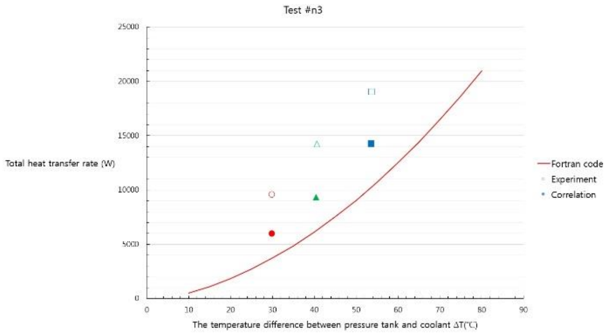


Fig. 13. Comparison between experimental result, correlation result and fortran calculation

As shown in Fig. 13, there was a difference of 3000~4000W in overall heat transfer rate substituted with heat transfer coefficient that was calculated in heat transfer correlation. In addition, this study made a comparison between the equation for overall heat transfer rate in the previous study [7] and the result of calculation program with fortran code. There was a wide gap, and the actual MPHP assembly was 30cm in length of adiabatic region so that there was no difference between boiling region and condenser region. Thus, there was a difference in overall heat transfer rate.

4. Conclusions

As a result of this experiment, conclusions are as follows.

(1) In the case of MPHP assembly with the same length of 1m of Boiling region and condenser region, it is possible to remove heat up to about 20kW.
(2) Applying nuclear power plant for the equal distribution of working fluid requires considerations.
(3) To apply nuclear power plant, further research is needed through computer simulation of heat transfer rate depending on the number of pipe.

NOMENCLATURE

A_{rad}: Radial area ($= \pi D_i L_b$)
A_{axi}: Axial area ($= 0.25\pi D_i^2$)
Ku: kutateladze number
h_{fg}: Latent heat (J/kg)
$\dot{Q}$: Heat transfer rate (W)
ρ: Density (kg/m^3)
D: Diameter (m)
L: Length (m)
W: weight fraction (w/o)
g: Gravity (=9.8m/s^2)
Bo: Bond number
h: Heat transfer coefficient (W/m^2℃)
ΔT: Temperature difference (℃)

Subscript

h: Inner pressure tank
wbo: Outer wall of boiling region
wbi: Inner wall of boiling region
b: Boiling region
a: Adiabatic region
c: Condenser region
bc: Boiling region and condensation region
nc: non-condensable gas
wco: Outer wall of condenser region
cold: Coolant
i: inner
l: liquid
v: vapor
BL: Boiling Limitation
CCFL: Counter Current Flow Limitation

REFERENCES

[1] J. S. Park, S.N. Kim, “Design of Passive Containment Cooling System of PWR using Multi-pod Heat Pipe”, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May.17-18, 2012
[2] G. H. Nam, S.N. Kim, “Experimental Study on the Passive Containment Cooling System of PWR using Multi-Pod Heat Pipe”, Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, Oct.24-25, 2013
[3] Hussain H. Ahmad, Anwar A. Yousif, “Comparison between a Heat Pipe and a Thermosyphon Performance with Variable Evaporator Length”, Al-Rafidain Engineering, Vol.21, No. 2, 2013
[4] Balkrishna Mehta, Sameer Khandekar, “Two-Phase Closed Thermosyphon with nanofluids”, 14th International Heat Pipe Conference (14th IHPC), Brazil, 2007
[5] J.C. de la Rosa, A. Escriva, “Review on condensation on the containment structures”, Journal of Nuclear Energy, Vol.51, pp.32-66, 2009
[6] P.F. Peterson, “Theoretical basis for the Uchida correlation for condensation in reactor containments”, Journal of Nuclear Engineering and Design, Vol.162, pp.301-306, 1996
[7] G.H. Nam, J.S. Park, S.N. Kim, “Heat Transfer Modes and their coefficients for a Passive Containment Cooling System of PWR using a Multi-Pod Heat Pipe”, Transactions of the Korean Nuclear Society Spring Meeting, Gwangju, Korea, May.30-31, 2013