An experimental study on the condensation of steam-air mixture of a vertical single tube

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1. Introduction

iPOWER which is being developed by KHNP is planning to adopt passive containment cooling system (PCCS). PCCS is being applied to the advanced reactors in which AP1000, AES-2006, CAP1400 are included. When DBA comes, PCCS suppresses the containment temperature and pressure by releasing energy into atmosphere through the heat exchangers installed in the containment building, Fig. 1 shows the operating principle of PCCS. First, the density difference of coolant inside the loop is occurred due to the heat transferred from high temperature steam in the containment and then the natural circulation is formed. Finally, heat is removed passively because of the natural circulation.

Heat removal performance data of a single tube is necessary in order to design PCCS. As summarized in table Ⅰ, a lot of researchers tried to measure the heat removal performance in the vertical single tube [1]~[5] . However, there are large deviations between the experiment results. It might be resulted from the difference of tube diameter, size of a pressure vessel and the range of wall subcooling in each studies. Therefore, a KHNP's design specification [5] was considered and experiments were conducted in various test conditions in this study.

2. Experimental Apparatus

A small-sized PCCS experimental apparatus, a small scale test loop for reactor-containment natural convection and condensation (ATRON), is installed in central research institute of KHNP. The purpose of experiments is summarized below;

(1) Measurement of thermal performance in a single tube.
(2) Measurement of thermal performance in bundle tubes.
(3) Visualization of steam flow inside a pressure vessel.

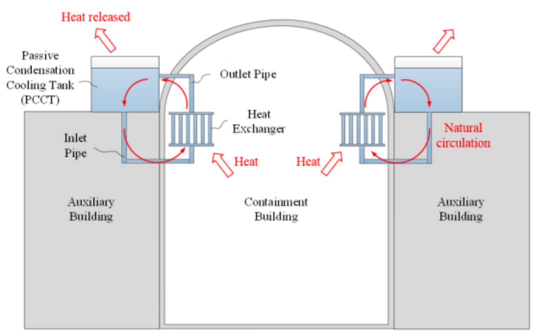


Fig. 1. A concept of PCCS

Table Ⅰ. Specification of test apparatus on several studies

	Tube Outer diameter	Height of pressure vessel	Shape of pressure vessel
Dehbi[1]	38.0 mm	5.0 m	Cylinder type
Kawakubo[2]	10.0 mm (I.D.)	2.7 m	
Su[3]	38.0 mm	3.5 m	
Lee[4]	40.0 mm	2.0 m	
Ha[5] (KHNP)	31.8 mm	3.9 m	Dome type

In this paper, a portion of part (1) is handled.

2.1 Description of test facility

A schematic view of experimental apparatus is indicated in Fig 2. ATRON is consist of a containment-simulated pressure vessel, a steam supply system, a pure water generation system, a pressure tank and a single tube etc. The scale ratios of a pressure vessel compared to the actual containment is one-twentieth in length and one-eight thousands in volume. The pressure vessel was designed in slab type in order to make measuring steam bulk flow and analysis by the system analysis codes like RELAP, GOTHIC easy. A single tube which plays a role as a heat exchanger is one meter long. The outer diameter and the inner diameter are 0.0318 meter and 0.0257 meter, respectively. Forced circulating flow condition inside a circulation loop is maintained by a pump. Heat absorbed in the circulating loop passes through the cooling system and is finally removed into the circulating water system which functions as a heatsink. Specifications of main experimental equipment are summarized in table Ⅱ.

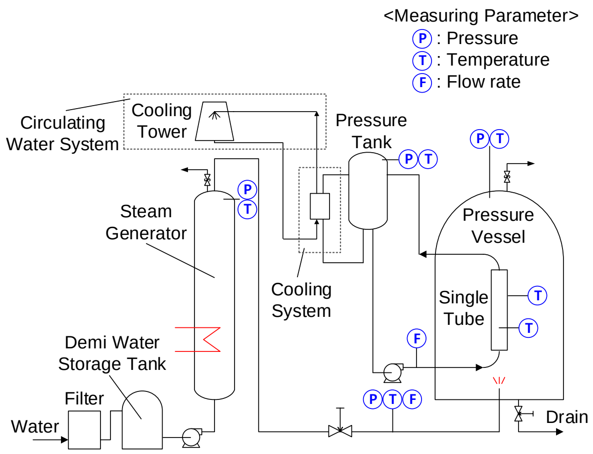


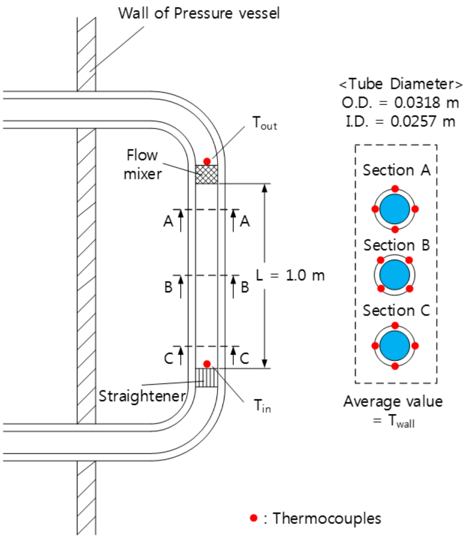
Fig. 2 Schematic view of the experimental apparatus

Table Ⅱ. Details of the experimental apparatus

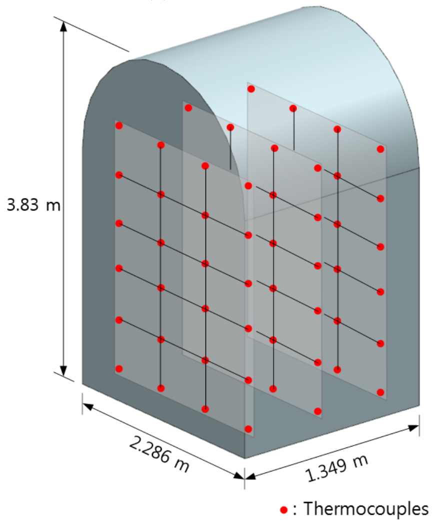
	Item	Unit	Value
Pressure vessel	Design pressure	bar	7.0
	Design temperature	℃	180
	Material	-	Carbon steel (SS304-coated)
Single tube	Length	m	1.0
	Diameter (outer/inner)	m	0.0318 / 0.0257
	Material	-	Stainless steel

2.2 Measurements

Major measurement variables of which measuring points are indicated in Fig. 2 and Fig. 3 are temperature, pressure and flow rate. Temperatures in the single tube and the pressure vessel were measured locally. Space-averaged value of all local values were used to calculate thermal performance.



(a) Test section



(b) Locations of thermocouples inside of the pressure vessel

Fig. 3. Details about main test apparatus

Table Ⅲ. Test matrix

Condition	Value
Air mass fraction	0.5
Wall subcooling	10℃ ~ 60℃
Total pressure	2 bar, 3 bar, 4 bar

2.3 Test matrix

Table Ⅲ indicates the test matrix. Tests were conducted in the condition that the value of air mass fraction is fixed to 0.5. Wall subcooling, which means the difference between tube wall temperature and bulk temperature in the pressure vessel, was changed thereby controlling the coolant flow rate inside the single tube. Also, total pressure in the vessel was controlled by regulating the amount of steam and compressed air which were injected to the vessel.

3. Experiment Result

3.1 Thermal performance

Thermal performance can be evaluated by two indicators, which are heat removal rate and heat transfer coefficient (HTC). They are calculated using the following equations.

$$Q_{removal} = \dot{m} \times c_p \times (T_{out} - T_{in}) \qquad \text{Eq. (1)}$$

$$HTC = \frac{Q}{A_S \times \Delta T_{sub}} \qquad \text{Eq. (2)}$$

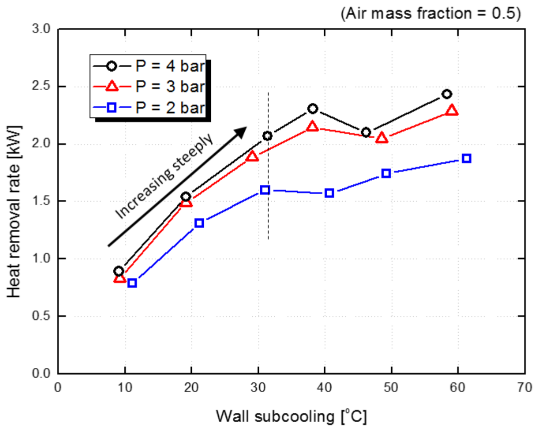
(where $\Delta T_{sub} = T_{bulk} - T_{wall}$)

The values of each variables used in Eq. (1), Eq. (2) were time-averaged value during 20 minutes in the steady state condition.

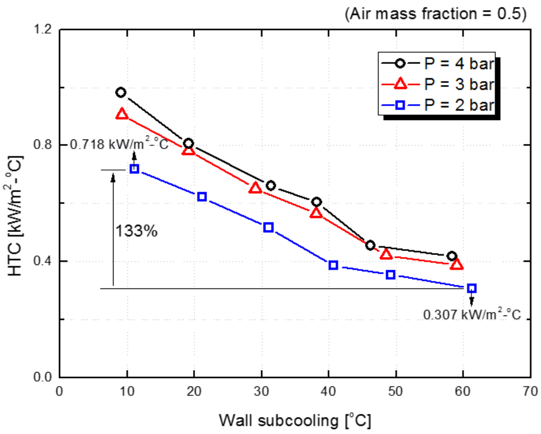
3.2 Effect of Subcooling

Experimental results about the effect of wall subcooling is summarized in Fig. 4. As shown in Fig. 4(a), it is confirmed that heat removal rate was increased as wall subcooling grows. In the range from 10℃ to 30℃ of wall subcooling, heat removal rate increased steeply in accordance with the increase of wall subcooling, but it can be known that a rate of increasing of heat removal rate is decreased in the region higher than 40℃.

Fig. 4(b) indicates the changes of HTC according to the rise of wall subcooling. In contrast to heat removal rate, HTC is decreased as wall subcooling is increased. In the condition of total pressure 2 bar, maximum value of HTC was measured when wall subcooling is minimum, and minimum value was measured when the value of wall subcooling is the highest. The highest value of HTC was 0.718 kW/㎡-℃ which is as high as 233% of minimum value, 0.307 kW/㎡-℃. Additionally, it can be

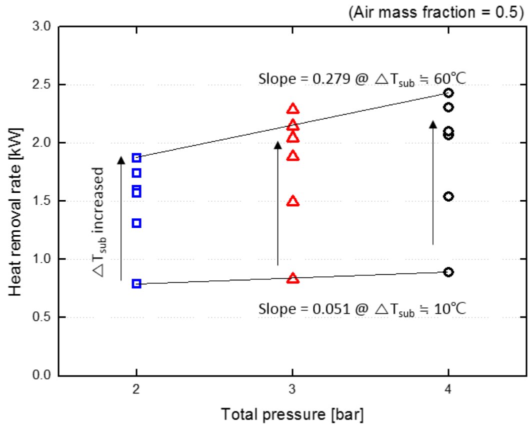


(a) Heat removal rate

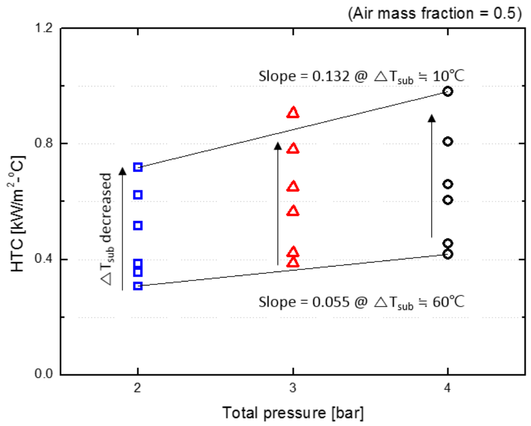


(b) Heat transfer coefficient

Fig. 4. Thermal performance according to various wall subcooling



(a) Heat removal rate



(b) Heat transfer coefficient

Fig. 6. Thermal performance in accordance with total pressure

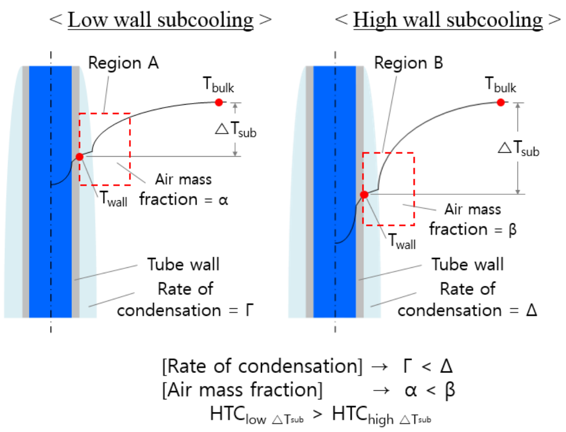


Fig. 5. Comparison of air mass fraction in different wall subcooling conditions

confirmed that high HTC values are measured in the condition of low wall subcooling, and the same tendency is observed in the condition of 3 bar and 4 bar each.

Fig. 5 explains the tendency that high HTC is measured in low wall subcooling condition. In the condition of high wall subcooling, the rate of condensation (Δ) on the wall in local region (B) is higher than in the low wall subcooling condition (Γ, A) because the wall temperature in the high wall subcooling condition is lower than another condition. Higher condensation rate (Δ) makes a quantity of steam reduced locally, finally, air mass fraction in local region near the wall (β) is increased. A higher value of air mass fraction means there exists more non-condensable gases in the local region. In Conclusion, a lower value of HTC is measured in high wall subcooling condition.

3.3 Effect of Pressure

As confirmed by Fig. 4, both heat removal rate and HTC were increased as total pressure was grown. Rearraging the independent value of graphs in Fig. 4 to the total pressure, Fig. 4 is converted to Fig. 6. Curves in the graph in Fig. 6 were drawn by connecting 2 points, respectively, which are the result in the conditions of pressure 2, 4 bar and wall subcooling 10, 60℃. In Fig. 6(b), the value of slope were increased as the value of wall subcooling was decreased. In other words, it is confirmed that HTC is affected by pressure in the condition of low wall subcooling more than in the condition of high wall subcooling. On the contrary, heat removal rate is influenced by pressure in the condition of high wall subcooling much more.

4. Conclusions

In this paper, thermal performance of PCCS was measured using containment-simulated pressure vessel. From the experimental results, it is known that wall subcooling affects negative effect to HTC and total pressure in the pressure vessel affects positive effect to HTC. In addition, it is concluded that HTC is influenced by total pressure more in the condition of low wall subcooling. In the future, the effects of air mass fraction, tube position (length) and inclination angle are planned to be investigated through the additional experiments.

Acknowledgement

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Nomenclature

A	area	m^2
c_p	Specific heat	kJ/kg-^oC
HTC	Heat transfer coefficient	kW/m^2-^oC
L	Length	m
$\dot{m}$	Mass flow rate	kg/s
P	Pressure	bar
Q	Hear rate	kW
T	Temperature	^oC

<Subscripts>

bulk	average value of the specified space
in	inlet
out	outlet
removal	removal
s	surface
sub	subcooling
wall	wall

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