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Condensation Heat Transfer on a Vertical Tube with Non-Condensable Gas

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1. Introduction

After Fukushima accident, containment integrity was re-emphasized to prevent a large release of radioactive materials to the environment following a postulated accident. Korea Hydro and Nuclear Power Company Ltd. (KHNP) has developed a passive containment cooling system (PCCS) to substitute an active containment spray system for innovative power reactor (iPOWER). The PCCS of iPOWER adopted vertical heat exchangers located in the containment as shown in Fig. 1. When postulated accident comes, an external condensation occurs at the outer surface of the heat exchangers, and heat is transferred to the passive containment cooling tanks (PCCT). Over the last decades, many researcher performed the external condensation test with non-condensable gas [1, 2]. According to the previous studies, heat transfer coefficients (HTCs) of condensation are affected by several factors, such as curvature effect (radius of heat exchangers), wall subcooling degree, and pressure. Hence, the test results are deviated with each other since geometry of the test sections and test conditions are different with each other.

In this paper, we performed the external condensation test for a single circular tube, which was same with the prototype of the PCCS in iPOWER. The test conditions were determined to cover the expected operating conditions of the PCCS following a postulated accident. The condensation HTCs were plotted using various factors, and the test results were suggested with a comparison of the other test results.

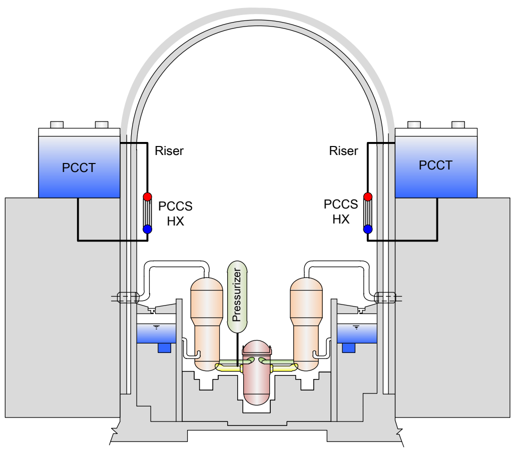


Fig. 1. Concept of PCCS HX in containment [3].

2. Test Methodology

2.1 Test Facility

As shown in Fig. 2, the test facility, called a small test loop for reactor containment natural convection and condensation (ATRON), is designed considering the prototype of PCCS. The containment simulated vessel had 1/20 scale of the prototype using the modified linear scaling law [4]. To simulate the accident condition in LOCA case, steam generator provided steam into the containment. The steam injected into the water located in the bottom of the containment to minimize a convective flow effect by the velocity of the injected steam. Height of the single tube is reduced as 1m from the 6m height of the prototype.

In this study, we obtained the HTCs for a tube, thus a forced convective flow condition was maintained as a steady-state condition using a pump.

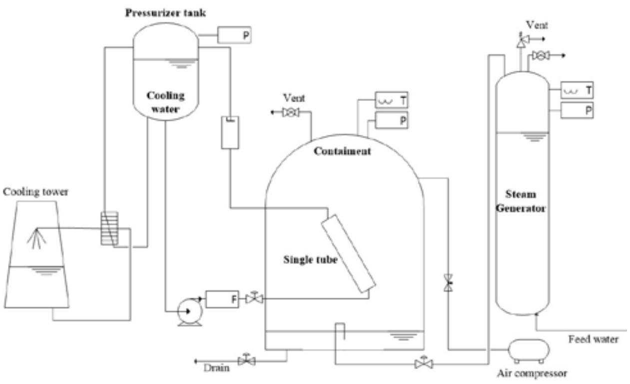


Fig. 2. Schematic diagram of test facility.

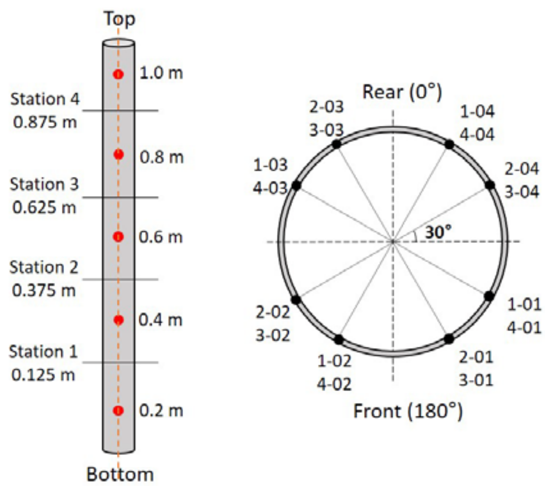


Fig. 3. Thermocouple arrangement for the tube.

As shown in Fig. 3, five K-type thermocouples are installed along the centerline of the tube to measure the heat transfer rate of the tube. 16 K-type thermocouples are installed in the tube surface to measure the wall temperature of the tube. Average temperature using 72 K-type thermocouples in the containment and containment pressure are used to calculate the air mass fraction inside the containment.

2.2. Test facility

Table I describes the test matrix. The pressures, air mass fractions, and wall subcooling degree are selected to cover the expected operating condition following LOCA condition.

Table I. Single Tube Test Matrix

Variables	Values
Pressure(bar.A)	2, 3, 4, 5
Air mass fraction	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8
Wall subcooling(°C)	5, 10, 20, 30, 40, 50, 60

3. Results and Discussion

3.1 Heat transfer coefficient of single tube

The heat transfer coefficient of single tube can be calculated as:

$$HTC = \frac{\dot{m}c_p(T_{out}-T_{in})}{A(T_{bulk}-T_{wall})} \quad (1)$$

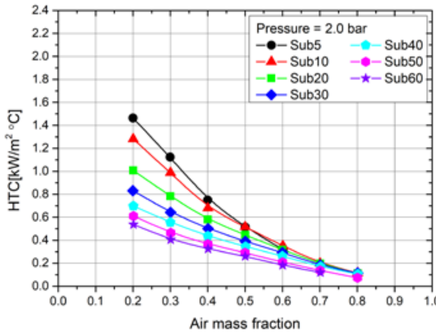
where, $\dot{m}$ is the mass flow rate, c_p is the specific heat, T_{out} is the temperature of tube outlet, T_{in} is the temperature of tube inlet, A is the tube surface area, T_{bulk} is the average bulk temperature inside the containment, T_{wall} is the average wall termpature of tube.

3.2 Non-condensable gas and Wall subcooling effects

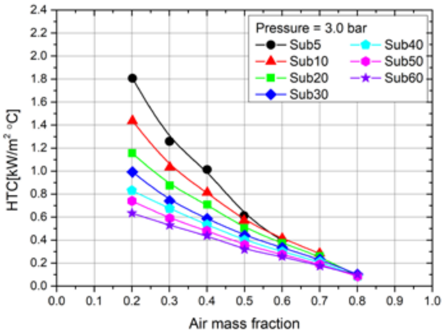
Figure 4(a)-(d) present HTCs of the single tube according to the air mass fractions and wall subcoolings for each pressure. HTCs of the vertical tube decreased as the air mass fraction decreased. For the same wall subcooling, HTC decreased as the air mass fraction increased because the condensation heat transfer impaired due to the lack of presence of steam near the tube wall.

Considering the pressure effect, the higher pressure condition had a higher HTCs as the steam enthalpy in case of the higher pressure condition was higher than the lower pressure condition. Therefore, the heat transfer rate and the HTCs are enhanced.

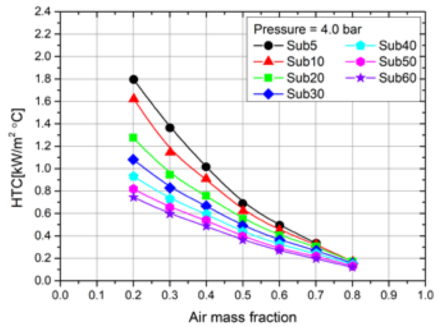
In regard of wall subcooling, the HTCs decreased as the wall subcooling increased. This was because the lower wall subcooling condition had higher steam concentration near the boundary layer of the tube compared to the higher wall subcooling condition. Therefore, the HTC in the lower wall subcooling case became higher than the opposite case. In contrast, the wall subcooling effect became negligible in the high air mass fraction cases.



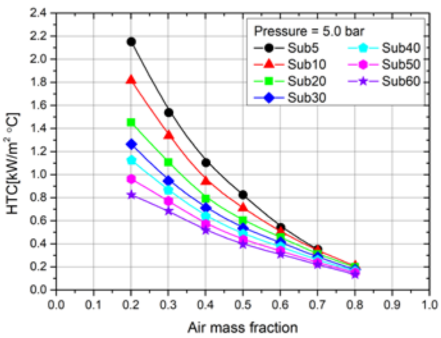
(a) 2 bar



(b) 3 bar



(c) 4 bar



(d) 5 bar

Fig. 4. HTC according to the air mass fraction.

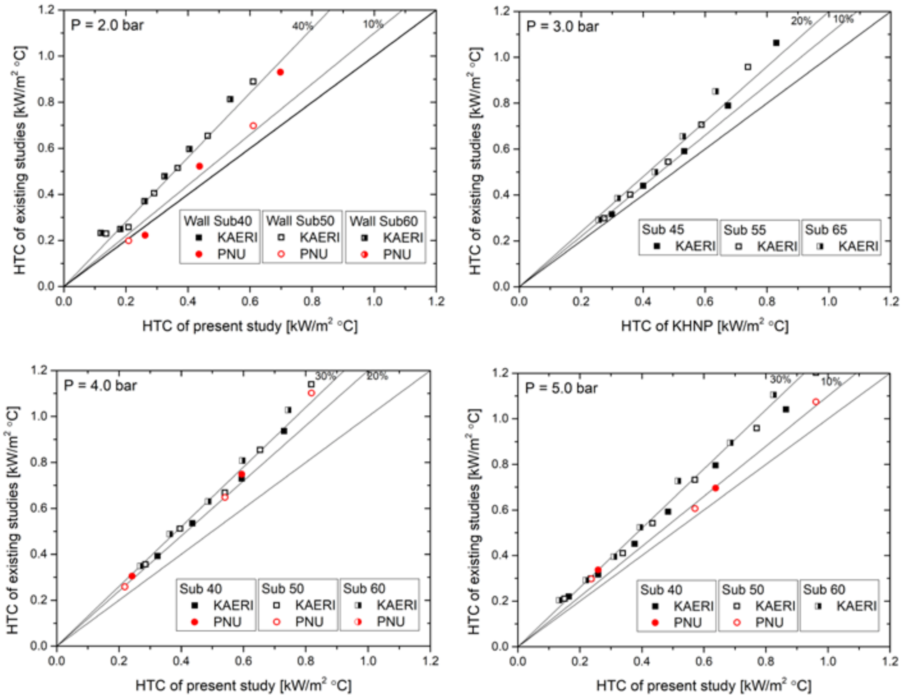


Fig. 5. Comparison of HTC between inclined and vertical tube.

3.3 Comparison of test data for previous studies

Fig. 5(a)-(d) present the comparison of the HTCs between present study and previous studies. The results of the previous studies were higher than the results of present study. KAERI conducted 5m height of the prototype tube test and PNU performed 1.28m height of tube test.

The deviation between our test data and the PNU's test data were within 20% and the deviation from KAERI were within 40%.

During the test, condensate flowed down from the top of tube surface to the bottom of tube. For the longer tube, the velocity of the condensation on the tube surface was accelerated by gravity, thus mixing near the concentration boundary layer became higher than the short length of the tube. The higher mixing near the concentration boundary layer induced higher steam concentration in the boundary layer, and this effect stimulated the heat transfer rate. Based on the comparison results, it seems that the mixing enhancement resulted the higher HTCs in the longer tube case. This effect will be evaluated in further study.

4. Conclusion

The single tube condensation test was conducted to obtain the heat transfer coefficient of the prototype tube. The test conditions were determined to cover the expected operating condition following a postulated accident condition. The higher pressure condition induced the higher HTCs and the high steam mass fraction condition enhanced the HTCs. The lower wall subcooling condition maintained the higher steam concentration near the concentration boundary layer, and this induced the higher HTCs.

The length effect can be observed in our test data comparing with the previous data. It seems that the mixing near the concentration boundary layer was more activated in the longer tube case, and this increased the HTCs.

ACKNOWLEDGMENT

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