Investigation of Natural Circulation Characteristics in PCCS (Passive Containment Cooling System)

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1. Introduction

Conceptual design of an advanced nuclear power plant under development in Korea, i-POWER (Innovative Passive Optimized Worldwide Economical Reactor), includes a PCCS (Passive Containment Cooling System) to depressurize and cool down a reactor containment building during any design-basis accident. Cooling mechanism of PCCS is a condensation heat transfer outside a vertical heat exchanger tube bundle and natural circulation inside the tube and a large water pool of PCCT (Passive Condensation Cooling Tank) as shown in Fig. 1 [1]. To validate a cooling performance and evaluate the condensation heat transfer characteristics of the PCCS heat exchanger, a separate effect test facility has been designed and constructed in KAERI (Korea Atomic Energy Research Institute) using a prototypic single bare heat exchanger tube [2]. From the test result in the previous research, the heat removal capability of PCCS was quantitatively evaluated considering the effect of a non-condensable gas concentration, a total mixture pressure, and a wall subcooling [3].

Since a driving force of PCCS is a natural circulation, two-phase flow instability inside the cooling pipe can be observed when the fluid is sufficiently heated up to make a phase change. This study focused on an experimental investigation of the natural circulation characteristics in PCCS. Using the separate effect test facility of PCCS, major thermal hydraulic parameters related to the flow instability were measured and investigated.

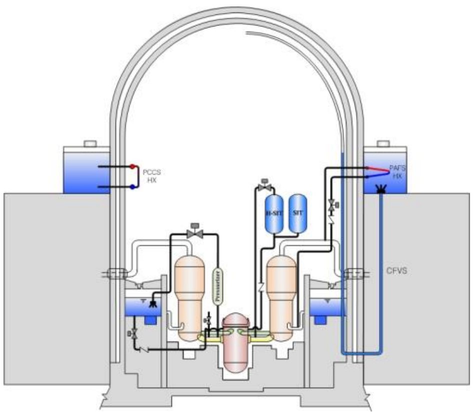

Fig. 1 Concept of PCCS heat exchanger in i-POWER [1]

2. Test Facility

A separate effect test facility was constructed to evaluate the heat removal capacity of the PCCS heat exchanger and the flow instability. The test facility is composed of a containment simulation vessel (CSV), a PCCT, a vertical heat exchanger tube, a circulation pump, flow control valves, piping, and their supporting structures as shown in Fig. 2 [2]. A single bare heat exchanger tube with an equivalent diameter, a thickness, and a length as the prototype PCCS heat exchanger design was installed in the CSV. The CSV was designed to have sufficient volume to simulate the actual conditions of a prototype reactor containment building. In the test facility, the natural circulation pipe connected the heat exchanger inlet and outlet to the PCCT water pool, where a position of a return-water line nozzle at the PCCT wall could be varied by adjusting valves.

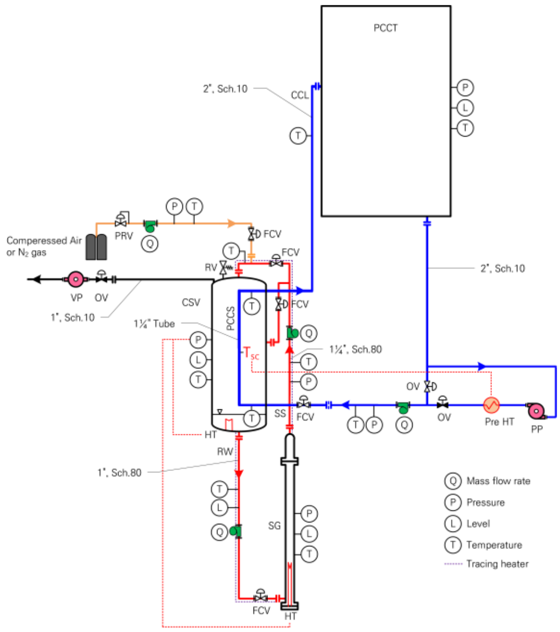

Fig. 2 Layout of PCCS Test Facility [2]

3. Test Result

To investigate the natural circulation characteristics of PCCS, two kinds of test conditions were considered in this study depending on an elevation of the return water line nozzle. As shown in Table I, the return water line nozzle from an outlet of the PCCS heat exchanger was connected above the water level of the PCCT in P05-L03B test, and under the water level in P05-L03C test, respectively. Atmospheric air was initially occupied in the CSV and electrical heaters in the CSV water pool were controlled to generate the steam and maintain a total pressure of the steam-air mixture as 0.5 MPa.

Table I: Problem Description

No	Case	CSV Pressure (MPa)	PCCT water level (m)	Return-water Line level (m)
1	P05-L03B	0.5	6.8	7.05
2	P05-L03C	0.5	6.8	5.4

Figs. 3 and 4 showed a natural circulation flow rate measured at the heat exchanger inlet and fluid temperatures in the cooling pipeline in case of the P05-L03B test, respectively. The result presented that a periodic peak of the flow rate was observed with a cycle of about 300 seconds, and natural circulation flow showed several intermittent peaks within the cycle. Due to a limitation in the flow meter, a negative flow could not be measured. A higher flow rate induced a smaller temperature difference between inlet and outlet of the PCCS heat exchanger, so that a subcooling degree in the outlet pipe of the heat exchanger increased and a collapsed water level in the return-water line was reduced. Since the return-water line nozzle in this test was located higher than the water level of the PCCT, a continuous natural circulation could not be maintained in an open loop condition and the flow rate was steeply diminished. It made an increase of the fluid enthalpy from the heat transfer at the heat exchanger, which could resume a two-phase natural circulation flow in the loop by a flashing in the return water line. This cyclic behavior can be considered as two-phase flow instability by the density-wave oscillation.

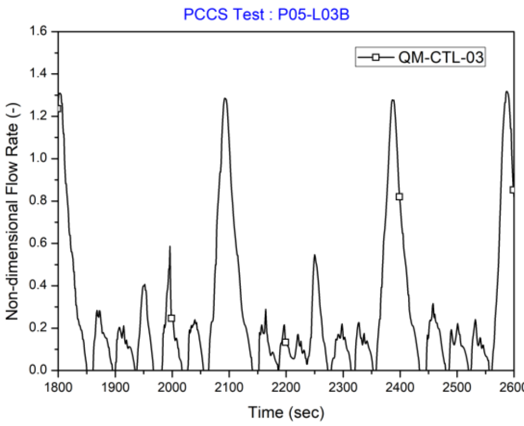

Fig. 3. Flow rate of the heat exchanger inlet in P05-L03B test

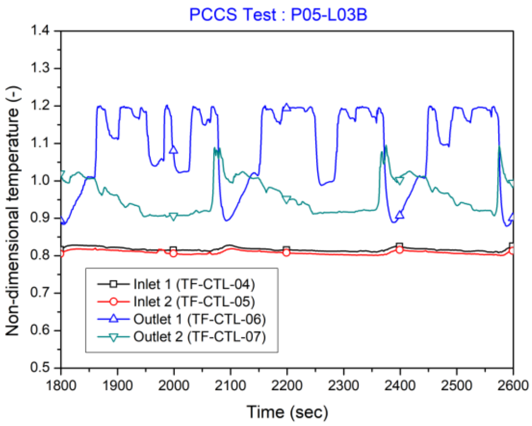

Fig. 4. Fluid temperature of the natural circulation loop in P05-L03B test

The P05-L03C test was performed by changing a location of the return-water line nozzle to the point lower than the PCCT water level. In this case, a static head could be maintained in the return-water line due to a higher level of the water pool, so that an unstable behavior of the natural circulation was mitigated as shown in Fig. 5. Even though a periodic peak of the flow rate was observed within a cycle of about 300 seconds by a flashing in the return-water line, a continuous flow rate was maintained during the whole transient without termination of a natural circulation. This behavior also affected the fluid temperature transient as shown in Fig. 6, where the temperature difference between the heat exchanger inlet and outlet decreased rather than that of the P05-L03B test. It can be concluded from the present test results that a position of the return-water line nozzle of the PCCT can significantly affect the behavior of the two-phase flow instability in the cooling pipe.

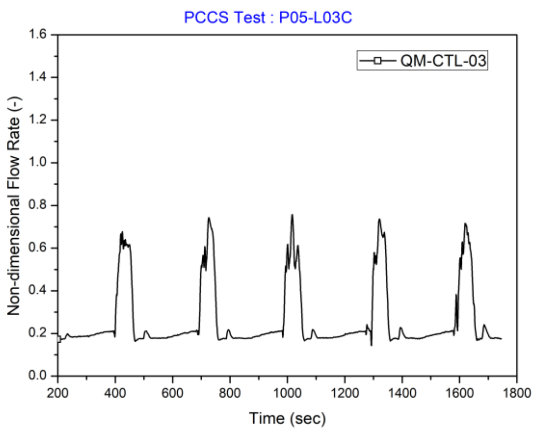

Fig. 5. Flow rate of the heat exchanger inlet in P05-L03C test

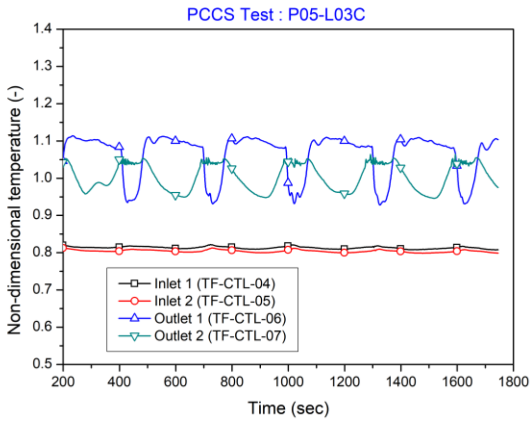

Fig. 6. Fluid temperature of the natural circulation loop in P05-L03C test

3. Conclusions

Two-phase flow instability in PCCS was experimentally investigated by utilizing the separate effect test facility with a single tube heat exchanger. At a constant pressure and temperature condition of the steam-air mixture, oscillation of the flow rate was observed according to variation of the natural circulation driving force and the flashing in the return-water line. The cyclic behavior of the natural circulation flow rate and the fluid temperature of the cooling pipe can be interpreted as a density wave oscillation. And this instability was mitigated when the water pool level was higher than the return water nozzle due to a larger static head and subcooling degree. In the future, the instability will be simulated in a more realistic manner with installing bundle tubes inside the CSV. Also, the present experimental result for the flow instability will be utilized to validate prediction capability of a thermal hydraulic system analysis code for an accident analysis with PCCS.

ACKNOWLEDGMENTS

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