Flow Instability Inside Passive Containment Cooling System and Mitigation Strategies

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1. Introduction

Several design basis accidents such as loss of coolant accident (LOCA) and main steam line break (MSLB) could threaten the integrity of containment building by increasing containment temperature and pressure. Although containment spray systems (CSS) are installed for the depressurization of containment against the accidents, iPower nuclear power plant requires passive safety system design to provide for malfunction of CSS. Therefore, passive containment cooling system (PCCS), which consists of passive containment cooling tank (PCCT), heat exchanger modules, and connection pipelines, is under development.

The natural circulation behavior of the PCCS is an important hydraulic phenomenon for the guarantee of decay heat removal capacity, required to satisfy the safety acceptance criteria. Especially, flow instabilities have been reported for multi-channel heat exchangers operating with natural circulation [1-3]. Flow instability could threaten the structural integrity and enlarge the performance uncertainty of the system. Therefore, the effects of design parameters on natural circulation flow rate and flow instability must be analyzed to evade uncertainty of system securing enough cooling performance.

In this study, the flow behaviors of iPOWER PCCS according to various operating conditions and design parameters (elevation of returning pipeline) were analyzed by MARS-KS code to observe the flow instability phenomenon inside the system. The analysis results provide physical insight on possible flow instability and its mitigation strategies, that would be a crucial information on designing natural circulation-based multi-channel heat exchanging system.

2. Simulation Conditions

In this section, MARS model of iPOWER PCCS design and boundary conditions for flow behavior analysis are demonstrated.

2.1 Hydraulic Model

Hydraulic model, which simulates the iPOWER PCCS, is drawn in Fig. 1. PCCT is divided into two vertical pipe components with junctions at each elevation to simulate the natural convection of coolant inside the PCCT. In a single PCCT volume, liquid and atmosphere volumes were divided. Time dependent volumes were connected to each PCCT volume as atmosphere boundary conditions. Initially, total volumes below the PCCT water level were filled with coolant. Supplying and returning pipelines were modeled, considering the design information in horizontal and vertical pipe components with form loss coefficients at curved positions. Heat exchange tubes of a module were merged as a single pipe component with conservation of flow area and application of appropriate inlet and outlet pressure loss coefficients. The surface area of the heat exchanger tubes was conserved through heat structure modeling. Therefore, 8 pipes simulate 8 heat exchanger modules. Throttling nozzles and module headers are modeled with single volumes. Combination of horizontal pipe and branch components represent the hydraulic volume for common headers to consider the pressure drops according to distances between each heat exchanger module, inlet, and outlet of heat exchanger tray. The heat exchangers had constant heat flux boundary conditions and rest hydraulic volumes were insulated.

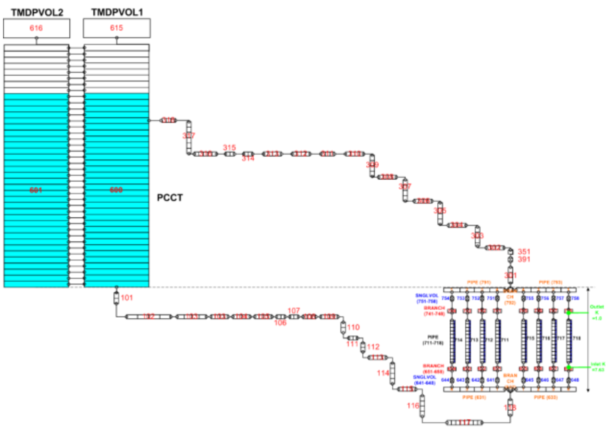

Fig. 1. MARS nodalization for iPOWER PCCS.

2.2 Boundary Conditions

For the analysis of flow behaviors of iPOWER PCCS during LBLOCA condition, several representative boundary conditions were determined. Three parameters of PCCT water levels, inlet coolant temperatures, and heat fluxes were varied. Initially coolant temperature was assumed as 50 °C. As the heat exchanger between PCCS and reactor coolant in gas phase proceeds, the

PCCS coolant temperature will increase. After the coolant temperature reaches the saturation temperature, the PCCT level will be decreased. Additionally, the mass and energy leaked to containment will be decreased with accident progress. Therefore, heat transfer rate to PCCS decreases.

Table I Boundary conditions for the observation of PCCS flow behaviors

Case #	Heat [MW]	PCCT level [m]	Coolant temperature [℃]
1	2, 4, 6, 8 (1.241 ~ 4.965 kW/m^2)	16	50
2		16	70
3		16	90
4		16	99
5		14	99
6		12	99
7		10	99
8		8	99
9		6	99

Based on the predicted approximate behaviors of PCCS parameters in LOCA condition, nine boundary conditions were determined as summarized in Table 1. For each boundary condition, flow behaviors inside PCCS were analyzed with hydraulic model shown in Fig. 1.

3. Results and Discussion

MARS analysis results on natural circulation behavior inside the PCCS according to boundary conditions and designs (elevation of returning pipeline) are demonstrated in this section.

3.1 Flow Behaviors

The natural circulation flow rates of PCCS having returning pipeline, which is connected to 15m-PCCT elevation, are plotted in Fig. 2. The plotted dots indicate the average flow rates for 5,000 sec each boundary condition, and deviation bars mean the amplitude of flow oscillation. The system mass flow rate decreases as the PCCT level decreases because the height difference between thermal centers (PCCT and heat exchanger) decreases. Additionally, coolant flow rate decreases as the loaded heat flux decreases, because the reduction of temperature difference between inlet and outlet of heat exchanger results in reduction of buoyancy force.

When the inlet subcooling is relatively high, stable natural circulations are achieved. The formation of stable natural circulation indicates constant heat removal through the system could be achieved at corresponding boundary condition. However, as the PCCT level decreases, flow oscillations (flow instability) are observed. The decrease of heat flux on heat exchanger tube results in the magnification of boundary conditions showing the flow instability. It would be related to the effect of reduced buoyancy force. This tendency indicates that PCCS has high possibility of flow instability under long-term cooling condition of LOCA.

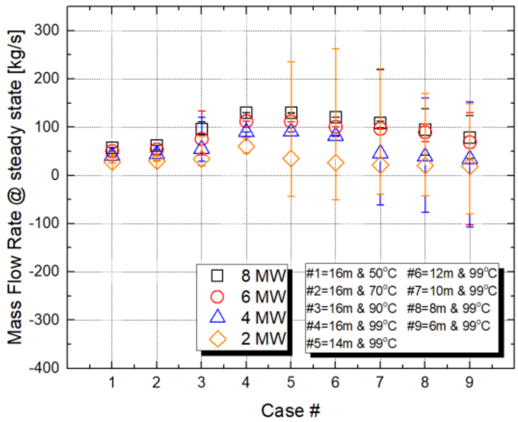

Fig. 2. PCCS mass flow rates according to boundary conditions (elevation of returning pipeline=15m)

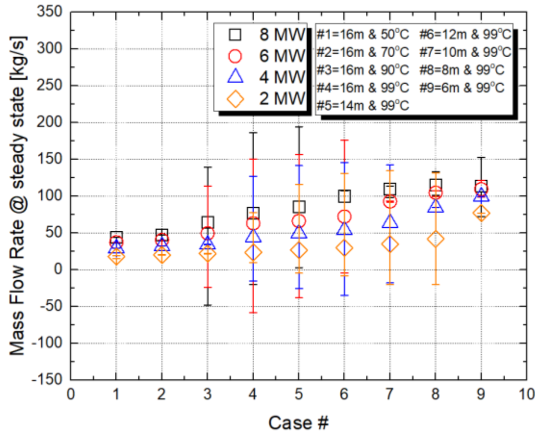

Fig. 3. PCCS mass flow rates according to boundary conditions (elevation of returning pipeline=6m)

As a design study of PCCS, the effect of elevation of returning pipeline on systematic flow behavior was analyzed. The flow behaviors of PCCS having 6m-height returning pipeline with boundary conditions presented in Table 1 is shown in Fig. 3. The total length of returning pipeline was adjusted to be equal to 15m-height case by extending the length of horizontal pipeline. Installation of returning pipeline far from initial water level showed different flow behaviors compared to that of PCCS having 15m-height returning pipeline (Fig. 2).

At most of boundary conditions, system mass flow rate was proportional to elevation of returning pipeline because due to the larger height difference between thermal centers. The mass flow rate was inversely proportional to PCCT water level due to decreased hydrostatic head on returning pipe with constant height difference between thermal centers. Furthermore, the flow instability was occurred at wider range of boundary condition. Therefore, PCCS with returning line of higher elevation (close to PCCT level) has better performance in terms of flow stability and heat exchanger temperature.

3.2 Flow Instability Mechanisms

The flow oscillations were observed wide range of boundary conditions according to PCCT designs. The flow instability could threaten the integrity of system structures and increase the uncertainty of cooling performance. Thus, flow instability mechanisms must be identified to establish mitigation strategies against the phenomenon.

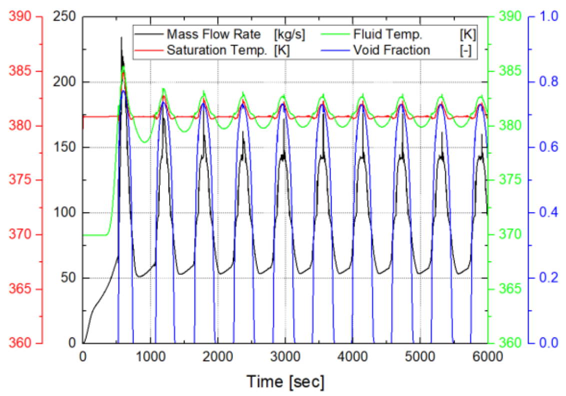

Fig. 4. Variation of void fraction, saturation temperature, coolant temperature, and mass flow rate at 8m-elevation returning pipeline (Q=8MW, case #7).

Fig. 4 plotted the void fraction, saturation temperature, coolant temperature, and mass flow rate when the PCCS having 15m-height returning pipeline showed flow oscillation. The coolant temperature at the heat exchanger outlet was lower than saturation temperature. However, the decrease of the hydrostatic pressure accompanied with the increase of elevation induced the flashing. The flashing at the returning pipeline reduced pressure head, consequently, mass flow rate increased. The increase of mass flow rate reduced outlet temperature of heat exchanger, void fraction at the returning pipeline due to flashing decreased, and mass flow rate was decreased. This cycle occurred repetitively, and flashing-induced flow instability has been frequently observed in the heat exchanger with unheated riser [4-6].

The decrease of returning pipeline elevation also affected the flow instability mechanism. As shown in Fig. 5, the boiling was occurred at the heat exchanger tube. Low mass flow rate results from low height difference between thermal centers caused boiling. In general, when the heat exchanger is divided into boiling part and non-boiling part, the density difference influences on pressure propagation velocity and perturbation of parameters related to the two-phase flow [7-9]. The difference in propagation velocity causes flow oscillation, which is defined as density wave oscillation (DWO). Therefore, the DWO, caused by boiling at heat exchanger, with relatively low fluctuation amplitude was observed. In the PCCS, bubbles generated from heat exchanger tubes was accumulated at the outlet of common header. When the void fraction become higher than certain point, the buoyancy force overcome the pressure head, excursion of mass flow rate was observed.

Through the analysis on flow instability mechanisms according to PCCS designs, it was confirmed that flashing at returning pipeline (unheated riser) and boiling at heat exchanger could cause the flow oscillation.

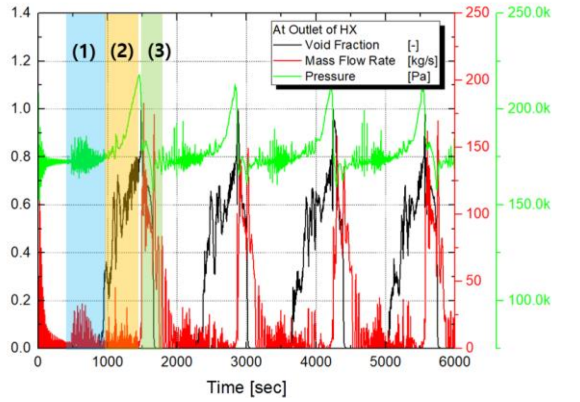

Fig. 5. Variation of void fraction, pressure, and mass flow rate at heat exchanger outlet (Q=8MW, case #3).

3.3 Flow Instability Mitigations

It was observed that flashing and boiling at unheated riser and heat exchanger causes flow instability of PCCS. Based on the observed flow instability mechanisms, the mitigation strategies could be established. In previous literatures, flashing-induced instability was attempted to mitigate through increasing flow resistance in pipeline using orifices.

The flow instability plane, which consists of inlet subcooling number and phase change number, is general criteria, designing the heat exchangers [4]. Artificial increase of heat exchanger inlet flow resistance showed the reduction of unstable region in flow instability plane was observed in Fig. 6 (red area is unstable region for original design, and green one is unstable region for PCCS with increased flow resistance) because the increase of flow resistance reduces the change of momentum, if the buoyancy force is constant as expressed in Eqn. (1). Consequently, the amplitude of flow oscillation would be decreased, and flow instability could be mitigated.

$$\sum_k L_k \frac{\partial \left(G_m\right)_k}{\partial t} = \Delta P_B - \Delta P_f \qquad (1)$$

The density wave oscillation-type flow instability has been mitigated by increasing the system pressure [7-9]. As shown in Fig. 7, the increase of system pressure through the higher PCCT water level reduced the unstable conditions. Although the increased boiling temperature at heat exchanger mitigated the phase change rate, the increased of pressure head at returning pipeline reduced the system flow rate. Thus, the effect of system pressure on the reduction of unstable region in flow instability map is not large.

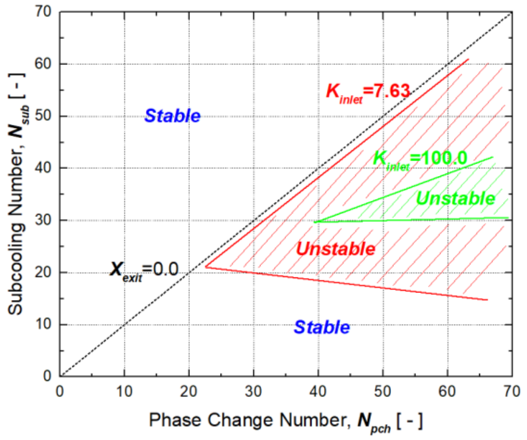

Fig. 6. Flow instability plane for PCCS and unstable regions according to inlet loss coefficients.

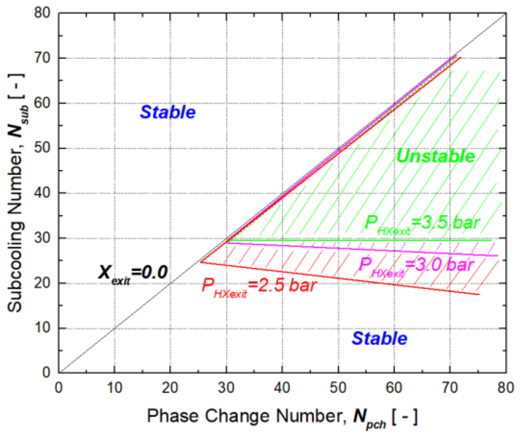

Fig. 7. Flow instability plane for PCCS and unstable regions according to system pressures.

The increase of flow resistance and system pressures mitigated the flow instability of PCCS. However, the mitigation strategies could induce reduction of system flow rate and increase of heat exchanger temperature, that would be a negative effect on heat removal rate in temperature boundary conditions. Hence, further study deducing the optimal design, which includes narrow range of flow instability condition and high mass flow rate, must be conducted.

4. Conclusions

Natural circulation behaviors of iPOWER PCCS under various operating conditions and designs were analyzed by MARS-KS code to observe the effects of design parameters on system flow rate and flow instability. According to elevations of returning pipeline, the flow behaviors were varied because height difference between thermal centers, PCCT and heat exchanger, and pressure head at returning pipeline is different. In terms of stability of natural circulation and heat exchanger temperature, higher elevation of returning pipeline is recommended. Flashing at returning pipeline and boiling at heat exchanger were the cause of flow instability in PCCS. Additional analyses for flow instability indicated that the increase of flow resistance and system pressure could mitigate the flow instability by reducing the momentum change and increasing boiling temperature.

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