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Effect of exit restriction on the two-phase natural circulation flow as PCCS

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1. Introduction

Since natural circulation flow systems have the advantage that electric force for driving is not required, efforts are being made to apply it to the system in various fields. In particular, one of the most important issues in natural circulation flow accompanied by two-phase flow is the flow instability phenomenon. The phenomenon of flow instability has been studied by various researchers since the 1960s, and in particular, research has been continuously conducted to identify it in the field of nuclear power [1-4]. In particular, they focused on the flow instability phenomenon that occurs in the boiling water reactor (BWR), which is different from the natural circulation conditions because it was performed under forced convection conditions. Recently, as the importance of reactor safety has been emphasized, research on a natural circulation system has been actively conducted. However, the analysis is ambiguous as studies on natural circulation flows with two-phase flows have not yet been clearly proved. This study is an experimental study to analyze two-phase natural circulation flow accompanied by boiling, and the experimental facility is designed by considering the passive containment cooling system as an application. In order to help understand the two-phase natural circulation flow phenomenon, the flow phenomenon is analyzed by considering the thermal boundary and exit restriction as experimental parameters.

2. Experimental facility

Fig. 1 shows overall schematic of experimental facility for investigating two-phase natural circulation flow. The facility is mainly consisted with pressurized loop (PL, red line) and natural circulation loop (NCL, blue line). The PL is designed to make the temperature thermal boundary condition using hot water. There are pre-heaters for heating the fluid, pressurized vessel for heat transfer with the NCL, heat exchanger for preventing the cavitation at the pump, auxiliary pressurized vessel for maintaining the temperature, pump for driving the fluid and mini pressurized vessel for responding volume change of fluid. Temperature of the fluid in the PL is controlled by PID controller from 120 to 150℃. To prevent the boiling phenomena in the PL, the loop is pressurized up to 8bar considering the safety coefficient. The range of temperature and pressure is referred from design value of containment building.

The NCL is designed to simulate the two-phase

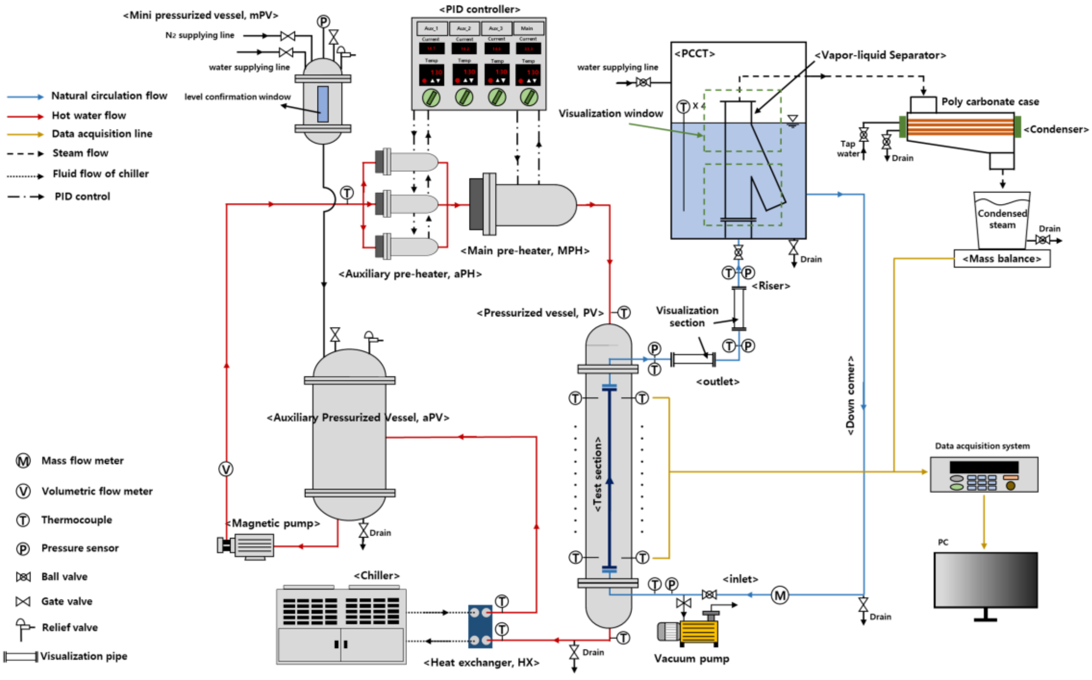

Fig. 1 Schematic of experimental facility

natural circulation flow as passive containment cooling system (PCCS). Deionized water (DI-water) is used as working fluid for preventing the corrosion and it flow through the passive containment cooling tank (PCCT), down comer, inlet, heat removal line (test section & two bending parts), horizontal outlet, riser and PCCT. Total height of the facility is 6.0m and the working fluid is filled up to 5.1m. Temperature of the working fluid is set as saturated condition (98℃) cause inlet subcooling effect is not concerned in this experiment. System pressure is considered as atmospheric condition. There are visualization sections for watching the two-phase flow phenomenon at the horizontal outlet, riser and PCCT. Visualization sections are made of quartz glass tube and polycarbonate (PC) plate located at the horizontal outlet, riser and PCCT, respectively. Except visualization sections, all of experimental facility line are made of stainless steel with 42.6mm of diameter. The heat is transferred from the pressurized vessel of PL to the heat removal line of NCL by temperature boundary condition. To measure the fluid and wall temperature, seventeen and fifteen K-type thermocouples are installed at the pressurized vessel and test section, respectively. Test section has 38.3mm of diameter and 2.35m of height. Although two-bending parts of heat removal line receive the heat from the pressurized vessel, experimental data are measured only at the test section. In addition, fluid temperature and pressure are measured inlet/outlet of the heat removal line and riser. Total mass flow rate is measured at the inlet by Coriolis flow meter. For investigating the effect of exit form loss, a ball valve is located at the end of the riser. The exit form loss is controlled by the degree of the ball valve from 0 to 45°. The form loss coefficient according to 0, 15, 30 and 45 degrees was calculated as 0.05, 4.35, 6.42 and 22.5, respectively [5]. Table 2 shows the experimental cases. The temperature value in the table. 1 represents the fluid temperature at the PL that served as a thermal boundary condition.

Degree Case	0°	15°	30°	45°
119.6℃	T1_0	T1_15	T1_30	T1_45
128.9℃	T2_0	T2_15	T2_30	T2_45
135.2℃	T3_0	T3_15	T3_30	T3_45
140.2℃	T4_0	T4_15	T4_30	T4_45
146.6℃	T5_0	T5_15	T5_30	T5_45
151.8℃	T6_0	T6_15	T6_30	T6_45

Table. 1 Description of experimental cases

3. Results and Discussion

3.1 Effect of temperature boundary

Fig. 2 shows trend of total mass flow rate according to temperature boundary condition. In fig. 2 (a), which is lowest temperature boundary condition, the flow instability phenomenon cannot occur because it is a low thermal boundary condition to generate vapor. However, according to temperature boundary conditions increasing, the flow instability phenomenon occurred because of vapor which is induced by boiling and flashing, mainly [6]. In addition, according to the flow instability phenomenon is enhanced, the maximum and minimum mass flow rate is increased.

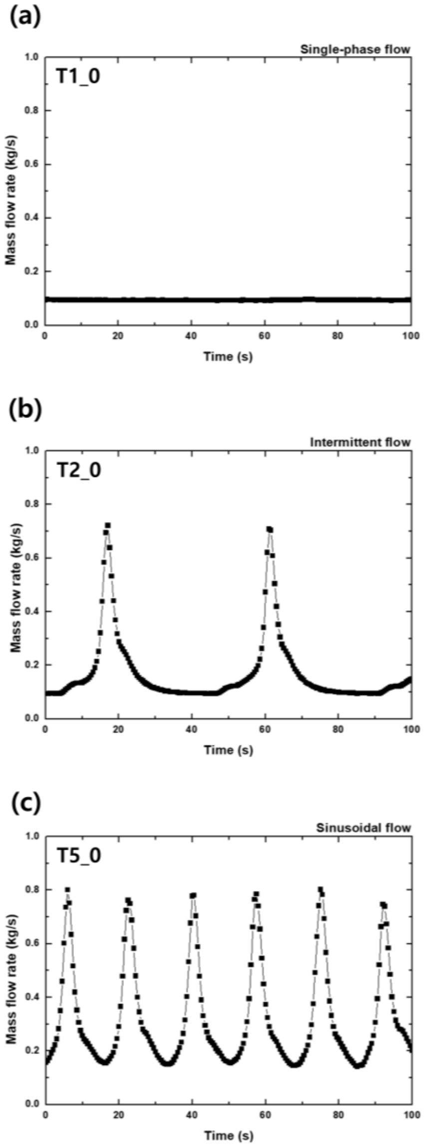

Fig. 2 Trend of mass flow rate according to temperature boundary condition; (a) T1_0, (b) T2_0, (c) T5_0

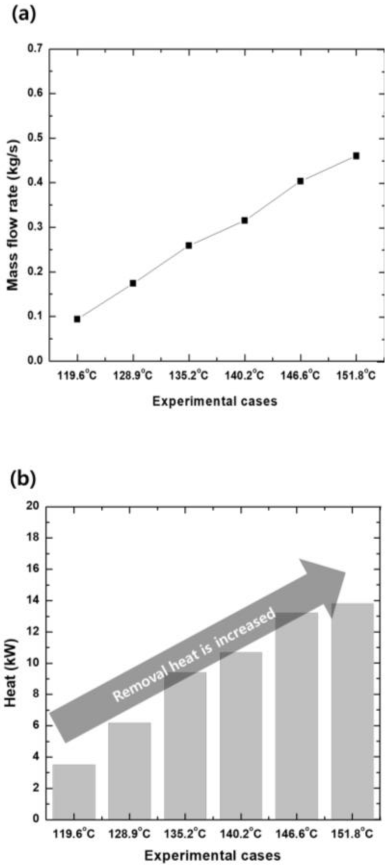

Fig. 3 Trend of mass flow rate and heat removal rate according to temperature boundary condition; (a) average mass flow rate, (b) heat removal rate

Fig. 3 presents the average total mass flow rate (fig. 3 (a)) and removal heat rate from PL to NCL (fig. 3 (b)). As above mentioned, since the flow instability phenomenon intensifies, the average mass flow rate increases as the temperature boundary condition increases. This causes an increase in heat transfer performance. As can be seen fig. 3 (b), the heat removal rate of NCL is increased as temperature boundary condition increases. Although the heat transfer performance may increase as the boiling phenomenon intensifies, an analysis for this will be performed later.

3.2 Effect of exit restriction

In order to, confirm the effect of the structural difference of the experiment facility on the flow, an experiment is conducted to analyze the effect of exit restriction using the ball valve served as orifice installed in the riser. To control the exit restriction, the degree of ball valve is changed as 0, 15, 30 and 45 degree. However, in the case of 0 to 30 degrees, there is no particular difference in the experimental results, so 0- and 45-degree cases are compared representatively.

Fig. 4 present the trend of total mass flow rate according to temperature boundary condition under different exit restriction. The increase in exit restriction does not affect the presence or absence of flow instability under same temperature boundary condition. However, a large exit restriction resulted in stabilizing the system. Comparing fig. 4 (b) and (e), the maximum and minimum total mass flow rates are relatively low in the large exit restriction case. As a result, the magnitude of the flow amplitude is small when the exit restriction is large, which is more evident when comparing fig. (c) and (f). This trend is observed not only in total mass flow rate but also in fluid temperature and wall temperature.

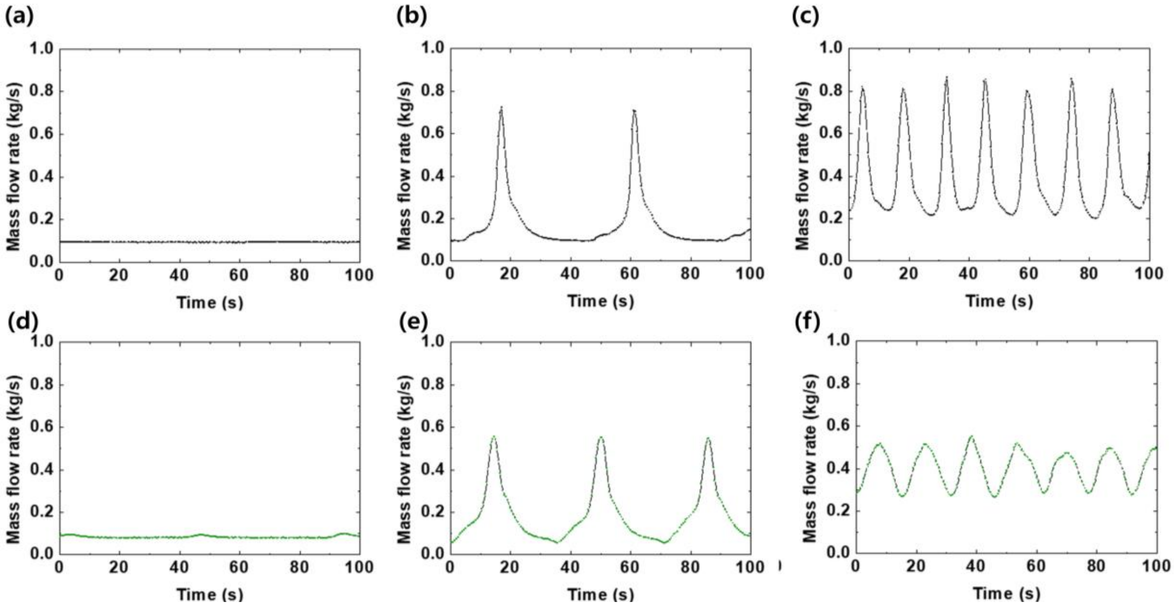

Fig. 4 Trend of total mass flow rate according to temperature boundary condition under different exit restriction; (a) T1_0, (b) T2_0, (c) T5_0, (d) T1_45, (e) T2_45, (f) T5_45

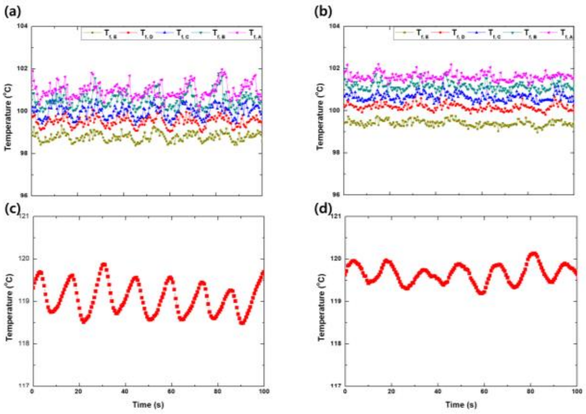

Fig. 5 Trend of fluid and wall temperature under different exit restriction; (a),(c) T5_0, (b),(d) T5_45

Fig. 5 shows trend of the fluid and wall temperature under different exit restriction. In addition, it shows that when the exit restriction is large, both the fluid temperature ((a), (b)) and the wall temperature ((c), (d)) have small amplitudes, so that a more stable system can be operated. This is contrary to previous studies that the system becomes unstable when the exit restriction is large [7].

In addition, the system does not show a significant difference in heat removal rate despite the large exit restriction. Fig. 6 shows the heat removal rate from PL to NCL according to temperature boundary (from T1 to T6) condition under different exit restriction (black – 0 degree, red-45 degree). As in the case of 0 degree, even at large exit restrictions, heat removal increased as the temperature boundary condition increased. However, in all cases, there is no significant difference in heat removal rate. The maximum difference is 4.14%. As a results, the high exit restriction showed the effect of stabilizing the system without reducing the amount of heat removal rate. As mentioned earlier, this is a result contrary to previous studies, and there are various cases, but additional analysis is required.

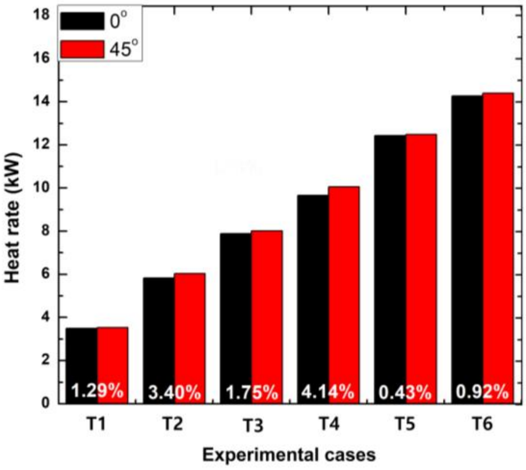

Fig. 6 Heat removal rate according to temperature boundary condition under difference exit restriction; black-0degree, red-45degree

4. Conclusions

In this study, the effect of thermal boundary and exit restriction on flow phenomenon is analyzed using an two-phase natural circulation experimental facility simulated PCCS. As the thermal boundary conditions increase, the total mass flow rate increases linearly, resulting in high heat removal rate. As the exit restriction increased, the amplitude of the flow decreased and the system is stabilized. In addition, although the system is stabilized due to large exit restriction, the heat removal rate does not show a significant difference with low exit restriction case.

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