Investigation of flow boiling heat transfer as passive containment cooling system

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1. Introduction

In 2011, severe accident of nuclear power plant (NPP) was occurred in Fukushima and radioactive materials were emitted [1]. In particular, because of Station Black Out (SBO) caused by tsunami and earthquake, safety system for cooling the core and containment building was not worked. After that, to prevent an accident like Fukushima, Passive Cooling System (PCS) which is worked without electrical power had been attracted. Many PCSs like passive decay heat removal system (PDHR), passive safety injection system (PSI) and passive containment cooling system (PCCS) were designed conceptually and the PCCS had been investigated mostly because it is very simple system [2]. The PCCS is consisted passive containment cooling tank (PCCT), passive containment cooling heat exchanger (PCCX) and connecting line. As removing residual heat of containment building by the PCCX, the temperature of fluid in the PCCX is increased, in addition the fluid is circulated passively because of density difference of fluid between the PCCX and downcomer. From now, most of research of PCCS were focused on the condensation heat transfer at the outside of the PCCX and single-phase heat transfer at the inside of the PCCX. However, at some research, it has been reported that boiling phenomena occurred at the inside of the PCCX [3]. In this study, the flow characteristic of the PCCS only focused on boiling phenomena inside the PCCX was analyzed, finally heat transfer coefficient (HTC) is compared with Chen's correlation.

2. Experimental facility

The experimental apparatus is composed with the PCCT, downcomer, horizontal inlet, test section and

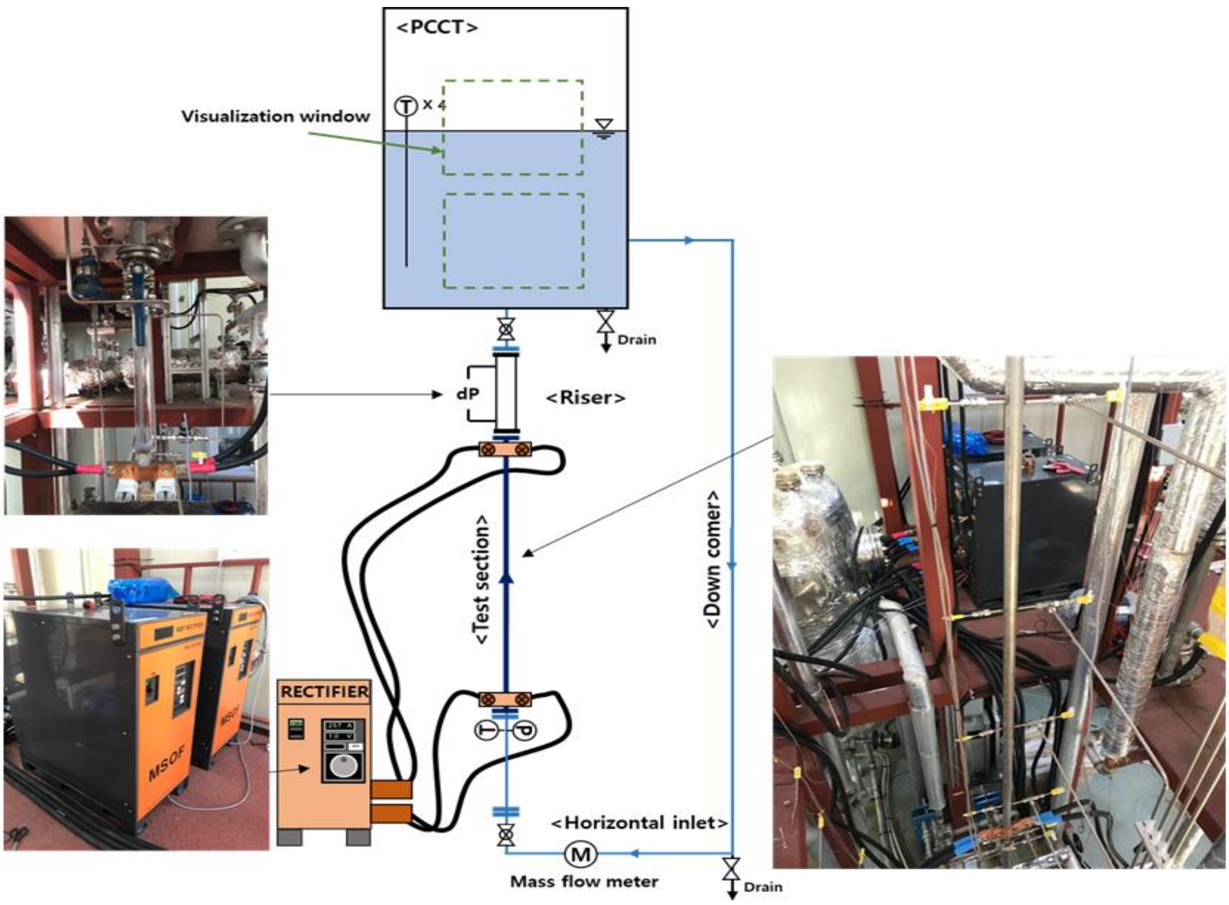

Fig. 1 Schematic of experimental apparatus

riser. Total height from horizontal inlet to top of the PCCT is 5.9 m and the working fluid is filled up to 5.1 m. De-ionized water (DI water) is used as working fluid to prevent corrosion at the test section. All of component is made by stainless-steel except visualization window which is installed front and back side of the PCCT and riser. Polycarbonate (PC) is used as material for visualization window and riser to visualization of two-phase flow and electrical insulant. The test section has 2.25 m of height and heated up by DC power supply. The inner diameter of test section and riser is 0.0233 and 0.024 m. The fluid and wall temperature were measured at the five points of the test section with equal spacing. The pressure was measured at inlet and outlet of test section and Coriolis flow meter was installed at the horizontal inlet to measure total mass flow rate. The schematic of the experimental apparatus can be shown by Fig. 1.

3. Test results

As Table. 1 showed, the heat flux is the only experimental parameter. Five heat flux cases were decided as 15.5, 30.4, 42.9, 53.1 and 58.5 kW/m^2. Water is filled as 5.1 m to fix the system pressure and the apparatus is open system. The inlet temperature set from 95 – 99 ℃ which is similar with saturation temperature to analyze boiling heat transfer phenomena. As increasing heat flux, the boiling phenomena was enhanced, and instability is occurred. In this study, single-phase flow, two-phase flow with instability and steady two-phase flow were showed according to heat flux.

Experimental parameter	**Value**
System pressure	1.5 bar
Inlet temperature	95 – 99 ℃
Heat flux	15.5 – 58.5 kW/m^2

Table. 1 Experimental condition

3.1 Mass flow rate

Fig. 2 presented the mass flow rate by time under various heat flux condition. In 15.5 kW/m^2 case, flow instability was not occurred because boiling was not existed. As value of heat flux is increased, the mass flow rate is fluctuated from 0.1 to 0.45 kg/s which is called flow instability and period of fluctuation is decreased because more and more vapor which is main factor at increase the flow rate is generated. The amplitude of fluctuation is similar at all cases. In 58.5 kW/m^2 case, the flow instability phenomena are disappeared because steady two-phase flow is induced. The flow instability phenomena can be divided as three steps. First, the incubation period, because fluid temperature in the test section is not high to generate the vapor, the mass flow rate is equal during few seconds. Few seconds later, reaching the condition for generating vapor, many vapor is generated by boiling and flashing at the test section and riser, respectively. Because density difference between test section & riser and down comer is increased, the mass flow rate is

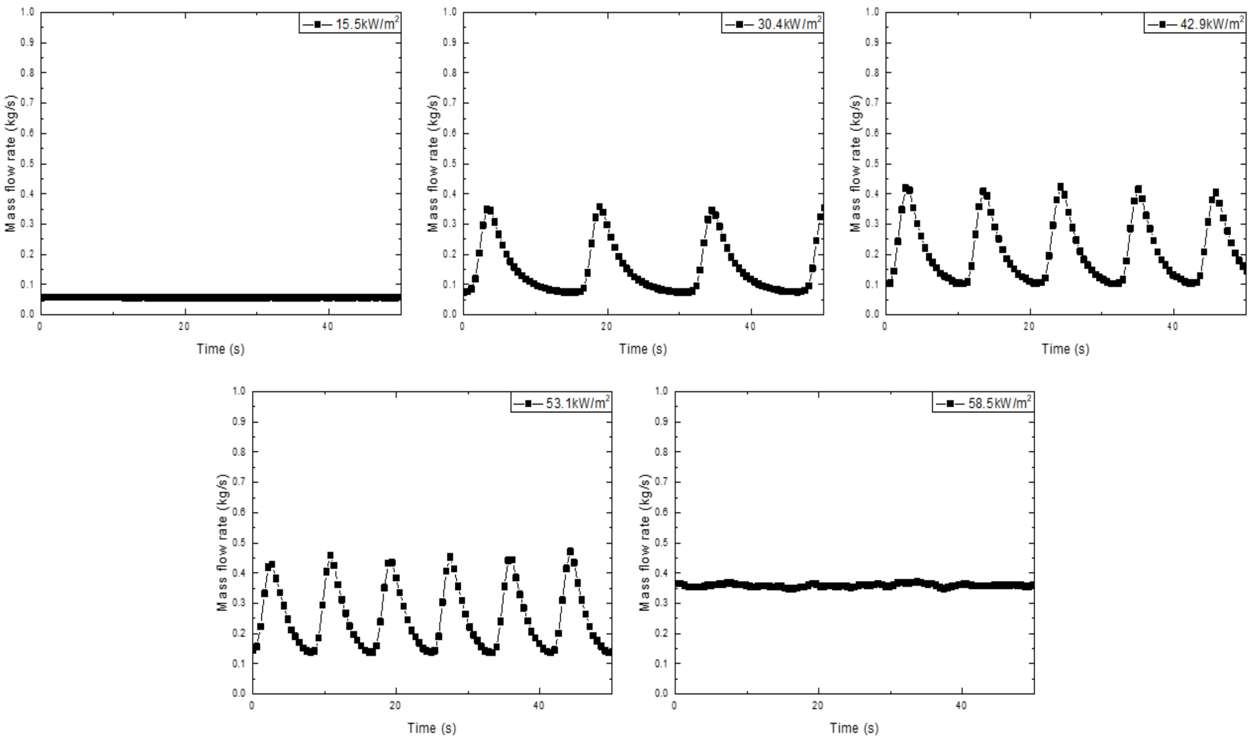

Fig. 2 Mass flow rate under various heat flux condition

increased dramatically. This period is named as flashing dominant period. Finally, through cold working fluid flow into the test section, the boiling and flashing phenomena are disappeared, and the mass flow rate is decreased. This period is named as flow decrease period. As heat flux increased, the incubation period is shorted, finally steady two-phase flow is induced.

3.2 Visualization

To help a clearer understanding of instability, the visualization data at the riser is presented. As shown in the Fig.3, only two-case of visualization data (42.9, 58.5 kW/m^2) are presented as representative for instability and steady two-phase flow. The fig. 3 presented a one period of fluctuation. In the case of 42.9 kW/m^2, the vapor generated by boiling flowed upward direction from the test section. As fluid flowing upward, the flashing phenomenon is occurred because the local pressure is decreased, and then the whole of riser is occupied by vapor. The total mass flow rate is increased because of density difference between riser and down comer and the flashing is persisted during few seconds. In addition, because of high mass flow rate, the boiling and flashing phenomenon is stopped by flowing cold working fluid into the test section. As a result, only liquid phase fluid occupied the whole of vertical upward line. In the case of 58.5 kW/m^2, two-phase flow is flowed, continuously.

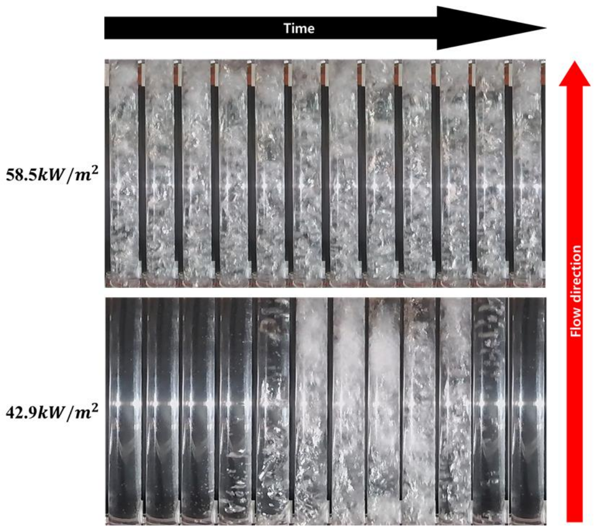

Fig. 3 Visualization data at the riser

3.3 Heat transfer coefficient

The experimental heat transfer coefficient (HTC) is compared with Chen's flow boiling heat transfer correlation. Although the experimental results contained the instability phenomena because there is not exist the correlation for natural circulation flow boiling with instability, the results were compared with Chen's correlation which is most used for flow boiling heat transfer. In addition, the experimental data was recorded during 30 minutes with 10 s time steps to calculate average value. The experimental HTC was calculated by Eq. 2. As mentioned before, wall and fluid temperature at the test section is measured at the five points. Therefore, when the calculate the experimental result, five local HTC were averaged.

$$h = \frac{Q}{A(T_w - T_b)} \quad \text{(Eq. 1)}$$

Chen's used the addictive model as shown in Eq. 2 [4].

$$h_{chen} = Fh_{mac} + Sh_{mic} \quad \text{(Eq. 2)}$$

F and S present the enhancement and suppression factor, respectively. In this study, F is assumed as 1 because fluid temperature is under the saturated temperature. Macro heat transfer coefficient and micro heat transfer coefficient is used from Dittus-boelter equation (Eq. 3) and Zuber's pool boiling model (Eq. 4), respectively.

$$h_{mac} = 0.023\mathrm{Re}_l^{0.8}\,\mathrm{Pr}_l^{0.4}\frac{\lambda_l}{d} \quad \text{(Eq. 3)}$$

$$h_{mic} = 0.00122\frac{\lambda_l^{0.79}C_{p,l}^{0.45}\rho_l^{0.49}}{\sigma^{0.5}\mu_l^{0.29}H_{fg}^{0.24}\rho_g^{0.24}}\Delta T_{sat}^{0.24}\Delta P_{sat}^{0.75} \quad \text{(Eq. 4)}$$

The Fig. 4 shows the results.

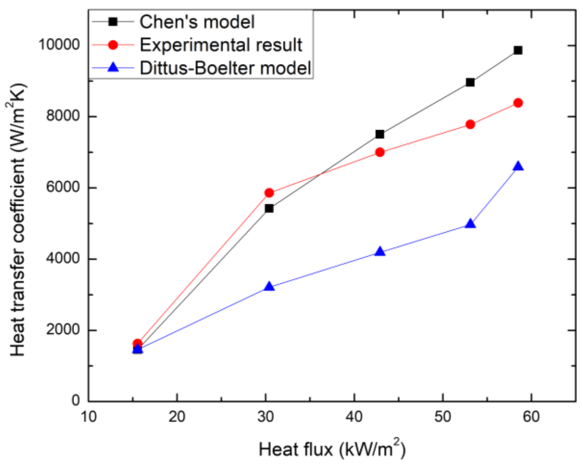

Fig. 4 Comparing the heat transfer coefficient with Chen's and Dittus-Boelter model

The results showed experimental results higher than single-phase flow heat transfer model (Dittus-Boelter model), but lower than two-phase flow boiling heat transfer model (Chen's correlation). The experimental result shows higher than single-phase forced convective heat transfer model (Dittus-Boelter) and good well with

Chen's model. However, increasing the heat flux condition, experimental results show some difference with Chen's model. This is thought to be the effect of an increase in flow rate due to an increase in vapor generated by flashing, however more experimental studies are needed.

4. Conclusions

In this study, the experimental apparatus to investigate two-phase natural circulation loop as passive containment cooling system was designed and presented flow phenomena as total mass flow rate and visualization data. According to the results, there are possibility of occurring instability phenomena, in addition, steady-two-phase flow under certain heat flux condition. Finally, the heat transfer coefficient was compared with general correlation for forced single-, two-phase flow heat transfer coefficient. Although the experiment was a passive system, the result showed higher heat transfer coefficient than force system with single-phase. However, increasing heat flux condition, the results show some difference with Chen's correlation. It might be the effect of the quality, mass flow rate, subcooling, however, more research are needed.

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REFERENCES

[1] Hirose, Katsumi. "2011 Fukushima Dai-ichi nuclear power plant accident: summary of regional radioactive deposition monitoring results." Journal of environmental radioactivity 111 (2012): 13-17.

[2] Chang, Soon Heung, Sang Ho Kim, and Jae Young Choi. "Design of integrated passive safety system (IPSS) for ultimate passive safety of nuclear power plants." Nuclear engineering and design 260 (2013): 104-120.

[3] Liu, Haiyang, N. E. Todreas, and M. J. Driscoll. "An experimental investigation of a passive cooling unit for nuclear plant containment." Nuclear engineering and design 199.3 (2000): 243-255.

[4] Chen, John C. "Correlation for boiling heat transfer to saturated fluids in convective flow." Industrial & engineering chemistry process design and development, 5(3), 322-329.