Effects of Air Injection on Condensation-Induced Pressure Shock and Critical Heat Flux of Inclined Downward-Facing Heater

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1. Introduction

In order to meet the European Utility Requirements (EUR), a core catcher system, an ex-vessel corium cooling system applicable for the EU-APR1400 was proposed and under development. The core catcher system is one of safety components to mitigate severe accidents when molten corium is released from reactor vessel to the containment cavity. To remove decay heat generated from the molten corium, the core catcher system is supplied with cooling water from the Internal Reactor Water Storage Tank as shown in Fig. 1. The heat transferred to the water drives natural circulation flow through the narrow and inclined channel. As the decay heat of molten corium is sufficiently strong to induce boiling, the core catcher system may experience pressure transition by repetitive boiling and condensation and even departure from nucleate boiling (DNB). To ensure the integrity of core catcher system, it is necessary to investigate aforementioned effects and provide an engineered solution to prevent it from the thermal attack.

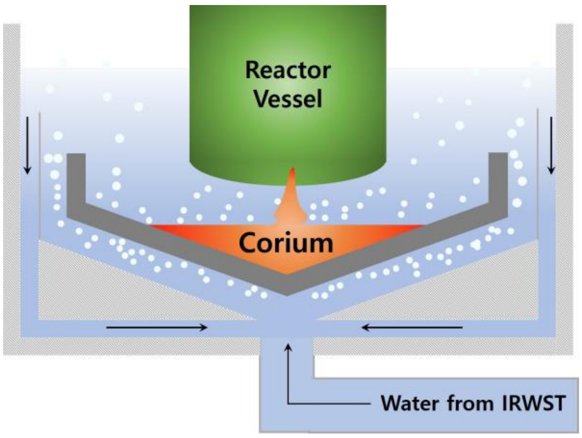

Fig. 1. A conceptual design of core catcher system deployed in EU-APR1400.

The principle of pressure shock in the core catcher system is depicted in Fig. 2. Water flows through the 10° inclined channel and is heated by the decay heat of the molten corium. After some distance along the heated surface, nucleate boiling is initiated, which generates small bubbles near the surface. The steam bubbles are then coalesced into a larger bubble. As the enlarged bubble departs from the heated section where corium exist, subcooled water in the vicinity of the bubble rapidly condenses the bubble. As the volume of water and steam with same mass shows large difference, the rapid condensation may induce pressure shock.

DNB is one of the most important phenomena in terms of thermal safety margin. In boiling situation, dry patches, dry interface between the surface, and the bubble can be created on the heater surface. The hotter the surface temperature, the more dry patches appear on the heated surface. As the bubbles merge together and form a vapor film on the heated surface, it degrades heat transfer process. At this point, the temperature of the surface rises extremely rapidly and the surface may experience serious mechanical damage. This phenomenon is defined as the DNB and the limiting heat flux is usually known as critical heat flux (CHF). In the core catcher system, the CHF is expected to occur at the end of the heated surface marked as region (a) in Fig. 2 as it will have the highest surface temperature along the heated section.

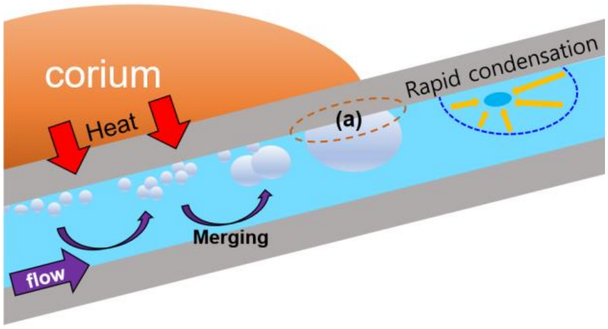

Fig. 2. Steam bubble behavior in core catcher system.

Jeong investigated the boiling heat transfer characteristics in the core catcher system of EU-APR1400 [1-3]. Bubble condensation induced pressure shock (BCIPS) was introduced as one of the factors that can influence the bubble dynamics and boiling heat transfer surrounding heated surface. Depending on the condition, the magnitude of pressure shock becomes greater although the mechanism to produce pressure shocks is similar. It is called condensation induced water hammer (CIWH). In this case, the pressure shocks, whose peak pressure is larger than yield strength of pipelines, can be generated.

Liang and Griffith [4] and Griffith [5] investigated non-condensable gas effect on chugging phenomenon, which is a kind of CIWH. The analytical model suggested showed that the presence of non-condensable gas can suppress the chugging effect. In addition, from an experiment of steam and air injection into subcooled water, it was found that mere 1% injection of air reduced the chugging considerably.

Inspired by the previous research in our lab, the objective of this study is to experimentally investigate the feasibility of air injection to reduce BCIPS in the core catcher system. The air injection system was established and connected to the previous experimental facility fabricated by Jeong [1-3]. In addition, we also focused on the characteristic change in boiling heat transfer and CHF depending on air injection.

2. Experimental Setup

The main components of the loop are shown in Fig. 3. To simulate core catcher system, the channel was inclined by 10° upward from the horizon. The height of the channel was determined as 30 mm. The heater of test section is made of a copper block, whose length and width are 216 mm and 108.5 mm, respectively. More details of the test section are explained in Ref. [1]. A DC power supply was employed to generate heat. The preheater and surge tank were installed to adjust the water temperature at the inlet. Helically coiled tube, through which cold water flows, is installed inside the surge tank to cool down the water. The air injecting system was located at the channel between test section and preheater located 1 meter away from the test section.

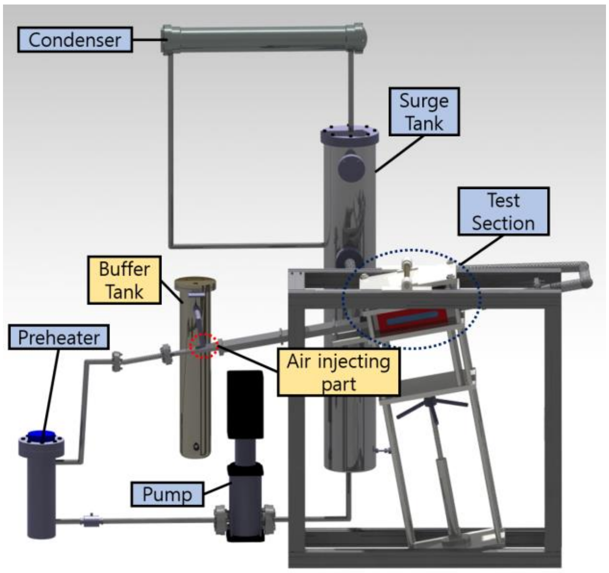

Fig. 3. 3D drawing of the downward-facing water boiling loop with air injector.

The air injection was carefully controlled using mass flow controller (MFC) and other components in Fig. 4. The buffer tank was first pressurized with air compressor to desired injection pressure. The digitally controlled MFC starts injection when the pressure reaches desired setup.

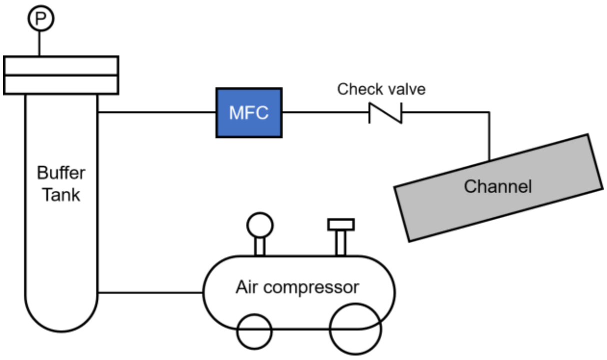

Fig. 4. The components of the air injector.

To maintain equal surface condition in every test, the rust and foreign substance on the heater surface were removed by hydrochloric acid (35wt. %). Moreover, the heater surface was polished with sandpapers of 400 grits and rinsed in DI water. The buffer tank was pressurized only up to 3 bar by the air compressor due to the operating limit allowable for the MFC. Deionized water was used for all experiments. Mass flux, water subcooling, and pressure in the loop were set as 40 kg/m^2·sec, 20 K, and 1 bar, respectively. The effects of air injection and the amount of injected air on pressure peak and CHF were compared with the case without air injection. Investigated air injection flow rates were 1, 5, 10, and 15 liters per minute (LPM).

The pressure peaks were recorded at the heat flux of 300 to 350 kW/m^2 and 350 to 400 kW/m^2 for 100 seconds for several times. At the same time, the behaviors of bubbles in test section were captured by using a high-speed camera. A CHF was judged to occur when the temperature of the heater surface continued to show increasing trend. The experiments were repeated 3 times for each case to check reproducibility.

3. Results and Discussion

Figure 5 shows the comparison of bubble behavior at heat flux of 350 to 400 kW/m^2 with and without air injection. In Fig. 5(a), in the case of non-air injection, the steam bubble was rapidly condensed and the flow reversal was observed. However, in the case of air injection (10 LPM) in the Fig. 5(b), such phenomena were not shown.

In addition, in the air injection case, maximum peak pressure of 16 kPa was observed, which is smaller than that (120 kPa) of non-air injection case. The reduction of the pressure shock could be attributed to decrease in steam condensation. Given the presence of the mixture gas consists of non-condensable gas and steam, if condensation occurs, the non-condensable gas will be left behind and forms a gas layer at the interface between the bubble and water. Steam partial pressure and the interface temperature decrease due to the gas layer. Consequently, it degrades the condensation heat transfer [2].

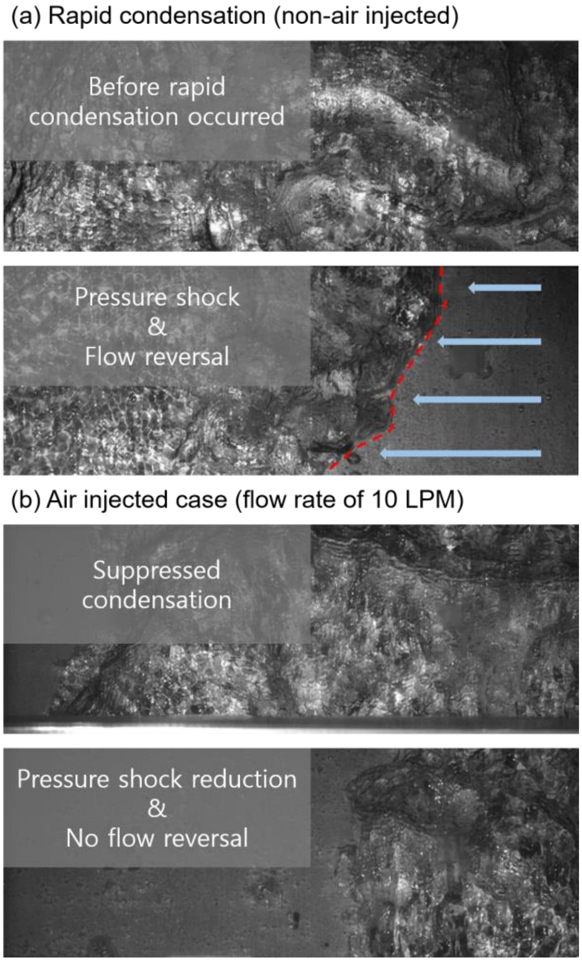

Fig. 5. The behavior of steam bubble at the heat flux 350-400 kW/m^2. (a) non-air injection; (b) injected air flow rate at 10 LPM.

The number of pressure peaks is counted and classified by the range of the heat flux and the pressure in Fig. 6. For air injection at 1 LPM, the number of pressure peaks in a range from 15 to 20 kPa increased than the case of non-air injection. However, because no pressure peaks exceeding 30 kPa, which can damage the system, were observed, it is reasonable to conclude that air injection has positive effect on reducing pressure induced incidents. Moreover, pressure peaks of 20 kPa disappear in the case of 5 and 10 LPM air injection. The number of pressure peaks of 15 to 20 kPa also decreased remarkably. No pressure peak was observed in case of 15 LPM case. Therefore, it can be clearly concluded that air injection significantly affects the pressure peaks depending on its amount.

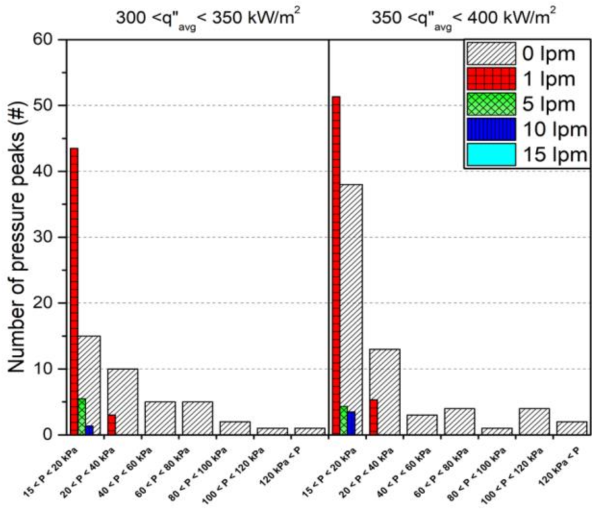

Fig. 6. Influence of injected air flow rate on number of pressure peak in each range.

The boiling curve up to CHF for the investigated cases is shown in Fig. 7. When air is injected, the departure of steam bubbles from the heater surface and fluid turbulence increases. Consequently, the heat transfer performance of air injection cases is more efficient than the case without air injection below 150 kW/m^2. Nevertheless, the trend is reversed at the high heat flux region. In high heat flux condition, a heating surface delivers more vigorous heat to the coolant. Accordingly, steam bubble production is much faster than in the low heat flux region. As the steam and air exhibit extremely lower heat transfer coefficient than liquid water, the additional production of vapor adversely affects the heat removal from the surface to the fluids in the channel. That is the reason that the heat transfer decreases when the air was injected. The effect of air injection on the CHF is shown in Fig. 8. It also decreased by 10% from 470 kW/m^2. However, the heat transfer including the CHF was not monotonically related to air flow rate.

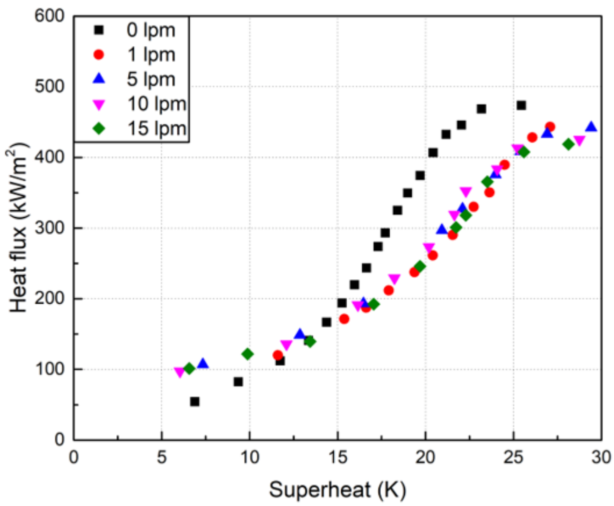

Fig. 7. Influence of injected air flow rate on the heat flux with wall superheat.

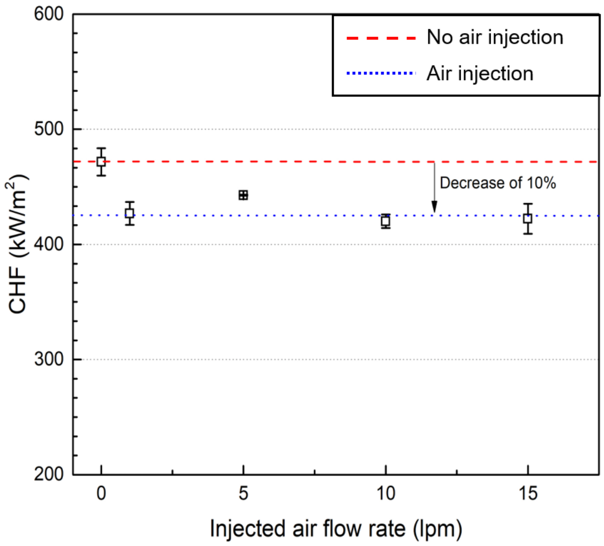

Fig. 8. Influence of injected air flow rate on CHF.

4. Summary and Conclusion

In present study, the effects of air injection on CIPS and DNB were investigated with a 10° inclined downward-facing heater. The major outcomes from this study can be summarized as follows:

- In the non-air injection case, pressure shock and flow reversal were observed due to occurrence of the rapid condensation. However, the phenomena were not observed when air was injected because non-condensable gas formed an additional thermal resistance layer against condensation heat transfer.
- The number of pressure peaks were reduced remarkably due to the air injection. For air flow rate at 1 LPM, although the number of small pressure peaks of 15 to 20 kPa increased, peak pressure over 30 kPa was vanished. The smaller pressure shock also was reduced as the amount of air injection increased. Especially, in the case of 15 LPM, no pressure peak was observed.
- At the low heat flux up to 150 kW/m^2, the heat transfer performance was enhanced as the air injection caused the fluid turbulence and faster bubble departure from heating surface. However, it was reduced due to increased steam generation in high heat flux condition.
- The CHF was reduced from 470 kW/m^2 to 420-440 kW/m^2. If the thermal safety margin is sufficiently secured, the air injection method introduced in this paper is expected to provide a solution against the pressure shock such as CIWH.

Acknowledgments

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