

Conceptual Validation Tests on Forced Convection Condensation using SISTA

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1. Introduction

One of small modular pressurized water integral-type reactors SMART [1] selected newly developed passive safety design concept—containment pressure and radioactivity suppression system (CPRSS) [2]. When design basis accidents (DBAs), such as small break loss-of-coolant-accident (SBLOCA) or main steam line break (MSLB), it removes steam and radioactive material ejected into low containment area (LCA).

CPRSS includes a vertical condenser (CHX: CPRSS heat exchanger) submerged in an emergency cooldown tank (ECT) as an ultimate heat sink. The heat exchanger is operated by forced convection condensation in presence of non-condensable gas under initial transient condition. Therefore, it is important to understand the condensation in a submerged vertical pipe under air-steam mixture conditions.

In this study, a separate effect test was performed to verify the performance of a vertical condensation pipe with an inner diameter of 17.5 mm. Air/steam mixture temperature and heat transfer coefficients (HTC) inside the pipe were locally measured and effects of inlet steam mass flux, inlet air mass fraction and temperature distribution of cooling water in ECT were investigated.

2. Experimental Setup

The SMART IRWST separate effect test apparatus (SISTA) was constructed based on Ishii's scaling law (1:5,000 volume scale) to simulate main components of CPRSS such as LCA, ECT, CHX, and so on [2]. Fig. 1 shows the components for the forced convection test and once through flow path of SISTA facility. The steam from the steam generator was supplied to CHX via LCA and air from the air compressor was injected before the test section. The steam flow rate was measured using a Coriolis mass flow meter (CMFS010) with accuracy of $\pm 0.05\%$. Air was measured with a thermal mass flow meter (TLF-23) which was calibrated with a Coriolis mass flow meter under air flow conditions.

CHX test section was made of SUS pipe of 1/2 inch 10 SCH. (17.5 mm id. and 2.1 mm thick). The test section was installed at 110 mm from the center line of ECT filled with water at a level of 1.75 m. The entrance area of the test section, 1.9 m above from the ECT bottom, was insulated with a double pipe. The heat transfer length of the test section was 1.75 m corresponding to the ECT water level, and five measuring points were installed at 375 mm intervals.

The outer wall temperature was measured with a 0.5 mm sheathed TC installed in the pipe wall groove, and the fluid temperature inside the pipe was measured with thermocouples which traverse radially with 13 points. The thermocouples for the ECT temperature were installed along the center line of the ECT at the same height as the measuring position.

Local heat flux was calculated by condensate rate.

$$q'' = \frac{m_{s_{i+1}} - m_{s_i}}{0.0175\pi\Delta L} h_{fg} \quad (1)$$

Here, the local steam flow rate was calculated from the local air mass fraction.

$$m_s = m_a \left[\frac{(1 - w_a)}{w_a} \right] \quad (2)$$

Local air mass fraction was calculated by measured temperature and pressure with an ideal gas assumption.

$$w_a = 1 - \frac{P_s}{1.61P_t - 0.61P_s} \quad (3)$$

Local steam quality was calculated as follow.

$$x = m_s / m_{s_{in}} \quad (4)$$

Finally, heat transfer coefficient was obtained as follow.

$$h = q'' / (T_{sat} - T_{wi}) \quad (5)$$

The experiment was conducted under 1 bar in the test section. The inlet air mass flux ($G_{s_{in}}$) and inlet air mass fraction ($w_{a_{in}}$) ranged 5–10 kg/m²s and 0.1–0.4, respectively.

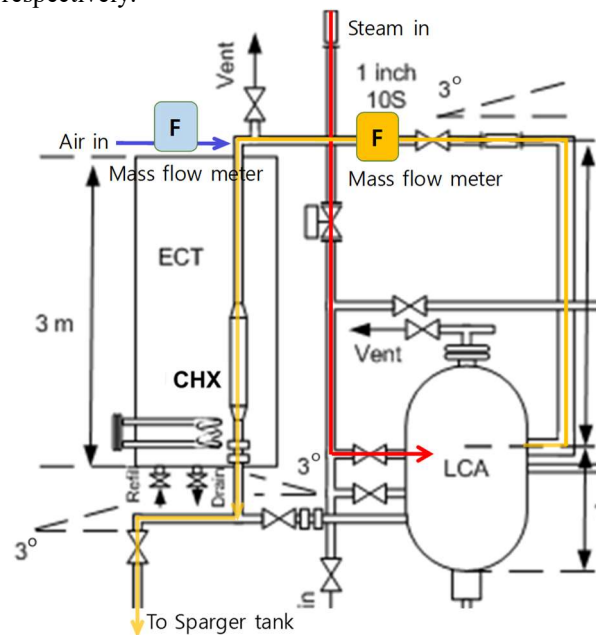


Fig. 1. Schematics of SISTA test facility and flow path for the forced convection condensation

3. Results and Discussion

2.1 Local Temperature

Fig. 2 shows the temperature distribution of the air/steam mixture inside the test section under an inlet steam mass flux of $5 \text{ kg/m}^2\text{s}$ and an inlet air mass fraction of 0.2. The temperature has a lower value toward the wall. This is due to the accumulation of non-condensable air near the walls. As it goes to the downstream, the saturation temperature decreases as the steam partial pressure decreases, and the non-uniform distribution near the wall surface becomes more significant. Fig. 3 shows the temperature distribution of the mixture, inner wall, and ECT along the axial direction.

2.2 Heat Transfer Coefficients

Fig. 4 shows the distribution of heat transfer coefficients with respect to the steam quality. The heat transfer coefficient increases as the inlet steam mass flow rate increases. This is because the thermal resistance decreases as the condensate film becomes thin due to the interfacial shear force [3]. In addition, as the steam velocity increases, the turbulent mixing effect hinders the formation of an air layer formed near the wall [4]. On the other hand, when the inlet air mass fraction increases, the heat transfer coefficient decreases by preventing the steam from contacting the wall.

2.3 Effects of ECT Temperature Distribution

The ECT with vertical pipe heat exchanger has a thermal stratification as time goes on. Fig. 5 shows two conditions of the ECT temperature distribution. Fig. 6 shows the distribution of local heat flux in the axial direction. When the ECT thermal stratification is small, the heat flux decreases from the inlet to the outlet. This is because the condensate film becomes thick and the air mass fraction increases as condensation occurs along the pipe. However, when the ECT thermal stratification is significant, the temperature difference between the steam and the coolant is small at the inlet region, leading to the lower heat flux.

Fig. 7 shows the local heat transfer coefficient with respect to the steam quality in different cooling conditions. The steam quality of the data is low under the low ECT temperatures. The heat transfer coefficient distributions of the two conditions are smoothly coupled, which means that the local heat transfer coefficient mainly depends on the steam quality regardless of the temperature distribution of the ECT.

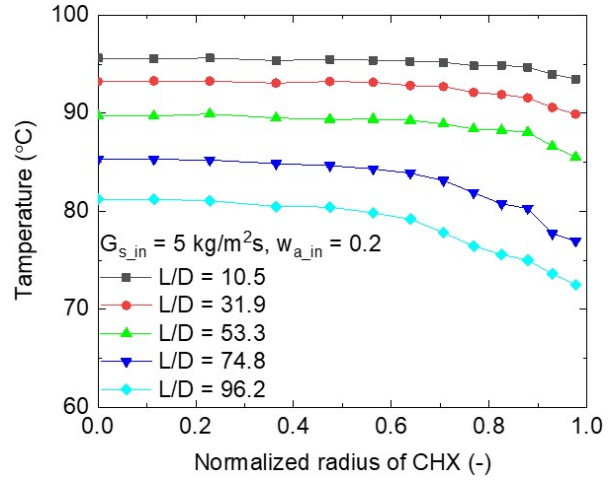


Fig. 2. Temperature distribution of air/steam mixture along the radius

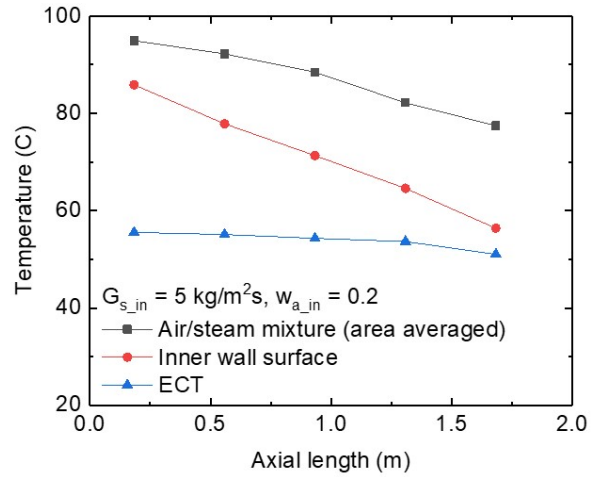


Fig. 3. Temperature distribution along the pipe axis

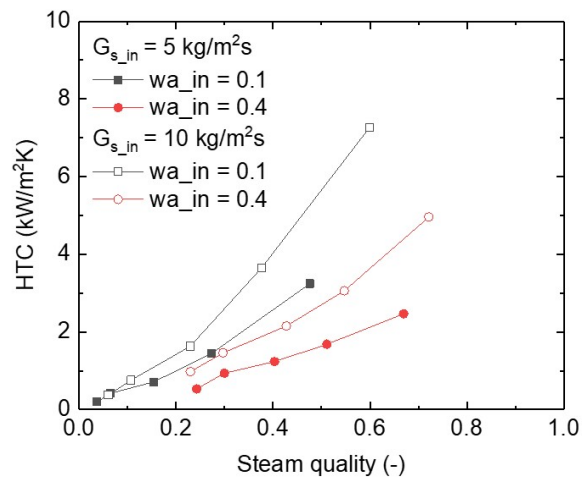


Fig. 4. Heat transfer coefficient with respect to the steam quality in different inlet steam mass flux and inlet air mass fraction

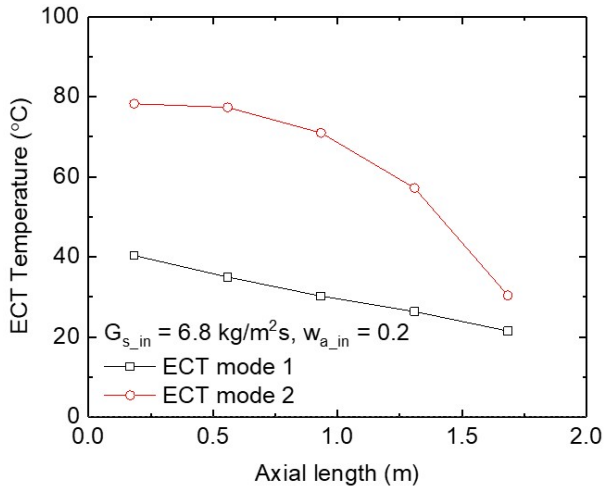


Fig. 5. Temperature distribution of cooling water in ECT

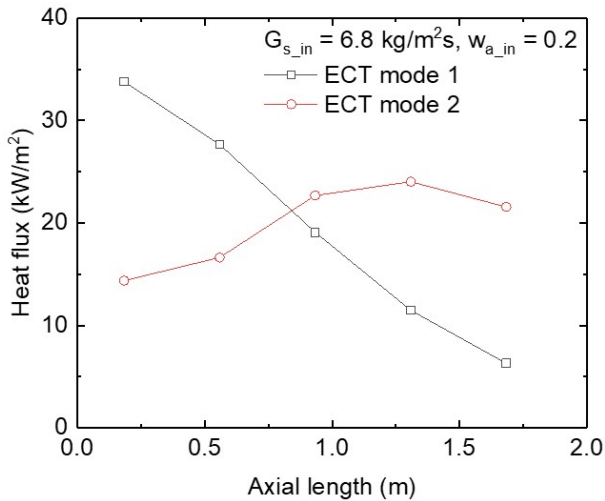


Fig. 6. Heat flux distribution under different ECT temperature condition

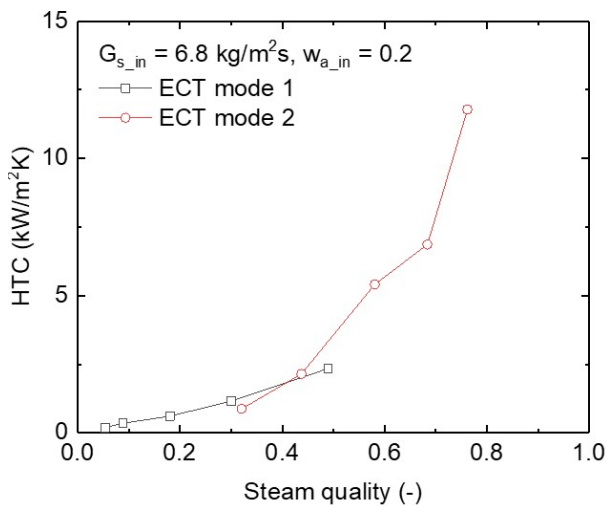


Fig. 7. Heat transfer coefficient with respect to the steam under different ECT temperature condition

4. Conclusions

In order to investigate the heat transfer characteristic of CHX in CPRSS, an in-tube condensation heat transfer experiment was conducted under air/steam mixture condition in a vertical pipe with an inner diameter of 17.5 mm. From the local temperature distribution of the mixture inside the pipe, it was confirmed that the air mass fraction was increased near the wall surface to inhibit condensation heat transfer. The local heat transfer coefficient decreases as the steam mass flux decreases and the air mass fraction increases. In addition, the distribution of heat flux varied greatly depending on the temperature distribution of the ECT cooling water, while the distribution of heat transfer coefficient with respect to the steam quality was not significantly affected.

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