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Analysis for a PRHRS Condensation Heat Exchanger of the SMART-P Plant

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1. Introduction

When an emergency such as the unavailability of feedwater or the loss of off-site power arises with SMART-P, the PRHRS passively removes the core decay heat via natural convection. The system is connected to the feedwater and steam pipes and consists of a heat exchanger submerged in a refueling water tank, a compensation tank, and check and isolation valves. The heat exchanger removes the heat from the reactor coolant system through a steam generator via condensation heat transfer to water in the refueling water tank. The compensating tank is pressurized using a nitrogen gas to make up the water volume change in the PRHRS. Before PRHRS operation, nitrogen may be dissolved in the cooling water of the PRHRS. Therefore, during PRHRS operation, nitrogen gas might be generated due to evaporation in the steam generator, which will act as a noncondensable gas in the condensation heat exchanger. The main objective of the present study was to assess the design of a PRHRS condensation heat exchanger (PRHRS HX) by investigating its heat transfer characteristics.

2. The results of modeling

A theoretical model using a heat and mass transfer analogy was developed to investigate the effects of noncondensable gases on the heat transfer coefficient of steam condensing inside a vertical tube. The Nusselt and Sherwood numbers in the gas phase were modified to incorporate the effects of condensate film roughness, suction, and developing flow. [4]

Also, a simple model using empirical correlations was also developed. Table I gives empirical correlations proposed by previous studies.

Authors	Empirical correlations
Vierow & Schrock [1]	$f = h_{\exp} / h_{Nu} = f_1 \cdot f_2 = (1 + a\,\mathrm{Re}_{mix}^{b}) \cdot (1 - cW_{nc}^{d})$
Siddique *et al.* [2]	$Nu(x) = C\,\mathrm{Re}_{mix}^{a} \left(\frac{W_{nc,w} - W_{nc,b}}{W_{nc,w}} \right)^{b} Ja^{c} Sc^{d}$
Kuhn *et al.* [3]	$f = h_{\exp} / h_{Nu} = f_{1,shear} \cdot f_{1,other} \cdot f_2 = \frac{\delta_{shear}}{\delta_{Nu}} \cdot (1 + a\,\mathrm{Re}_f) \cdot (1 - bW_{nc}^{c})$
Lee & Kim [5]	$f_d = h_{\exp,mix} / h_{Nu} = \tau_g^{*a} (1 - 0.964 W_{nc}^{b})$

Table I. The summary of empirical correlations

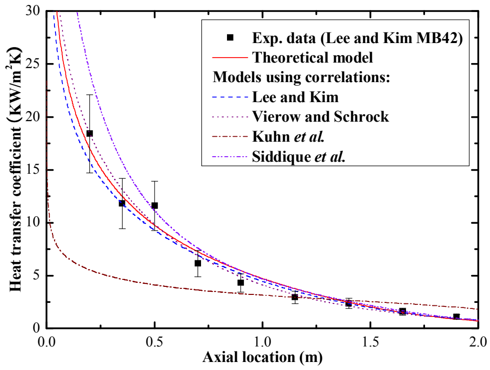

Figure 1. Model comparison for MB42 (ID=13mm, Remix,in=33494, W_{N2},in=10.2 %, P=0.105 MPa)

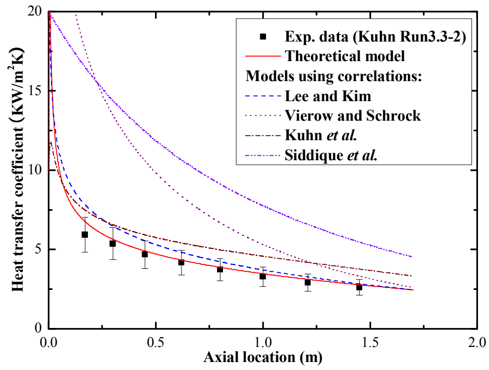

Figure 2. Model comparison for and Run 3.3-2 (ID=47.5mm, Remix,in=37537, W_{air},in=10.2 %, P=0.199 MPa)

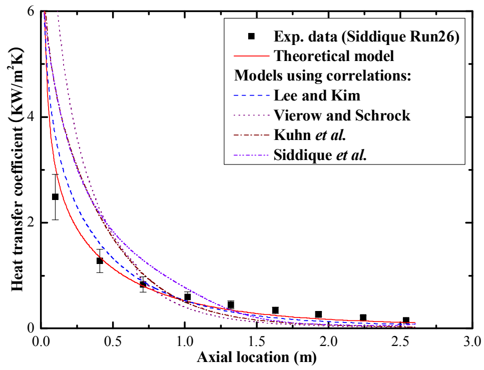

Figure 3. Model comparison for Run 26 (ID=46mm, Remix,in=15139, W_{air},in =22.4 %, P=0.233 MPa)

Figures 1-4 present the modeling results for the data obtained for various experimental conditions, including tube diameter, air or nitrogen as the noncondensable gas, the inlet mixture Reynolds number, the inlet noncondensable gas mass fraction, and system pressure. The theoretical model and the simple model using Lee and Kim's correlation predicted various sets of experimental data well, and their results were very similar. Specially, Fig. 4 shows that Lee and Kim's correlation can be useful to evaluate condensation heat transfer for high pressure steam/noncondensable gas mixture even though it was developed in low pressure conditions. On the other hand, it is shown that simple models using the other correlations have some limitation to be used for various conditions.

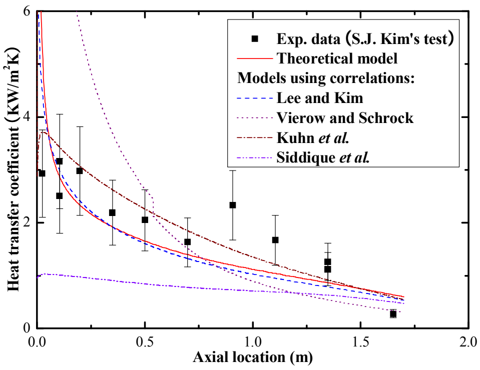

Figure 4. Model comparison for S.J. Kim data (ID=46.2mm, Remix,in=42112, W_{air},in =26 %, P=2.9 MPa)

3. Assessment of PRHRS heat exchanger

In real situation, the inlet steam should be condensed completely inside condenser tubes, and then a small amount of nitrogen will be accumulated above the completely condensation position. The effects of noncondensable nitrogen gas in real situation are less severe than that in mixture bypass situation. In this study, therefore, the theoretical model was used to assess the PRHRS HX conservatively. Based on the available design data, the tube inner diameter, outer diameter, and length were selected as 13 mm, 18mm, and 1.2 m, respectively. The inlet steam flow rate, system pressure and pool temperature were set to be 2.96 g/s, 3.5 MPa, and 100 ℃, respectively.

At first, condensation heat transfer rate ratio was defined as the theoretical heat transfer rate to latent heat transfer rate (= $\dot{m}_s i_{fg}$) ratio and completely condensation position was the location where the ratio is 1. Figure 5 shows the performance of PRHRS HX is enough until inlet nitrogen mass fraction 0.65. Figure 6 shows the condensation will be finished near 0.5 m in real situation. Figure 7 shows PRHRS HX will be sufficiently used in wide range of system pressure.

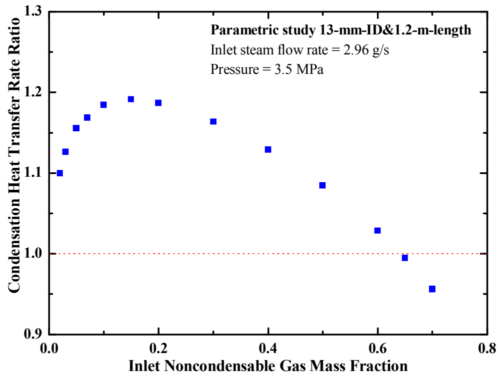

Figure 5. PRHRS HX for various inlet W_{N2}

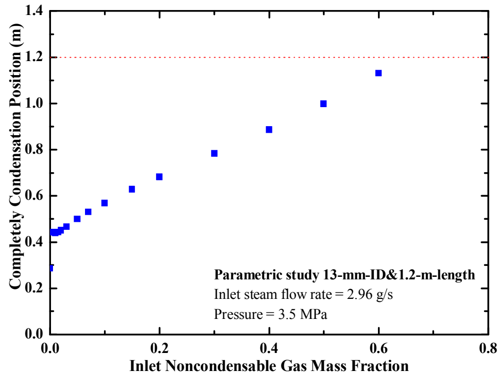

Figure 6. The position of completely condensation

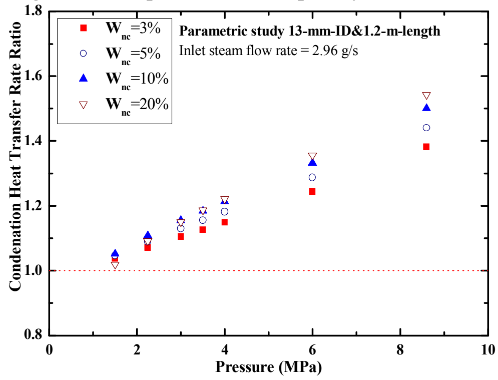

Figure 7 PRHRS HX for various system pressures

4. Conclusion

The theoretical model and the simple model using Lee and Kim's correlation predicted the experimental data well, regardless of the condenser tube diameter and the system pressure. In the assessment of PRHRS HX using the theoretical model, it was judged that the designed PRHRS HX could remove the core decay heat in reactor during the period of serious accidents.

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