Development of a New Correlation for Condensation Heat Transfer Coefficient inside a Vertical Tube in the Presence of Noncondensable Gas

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1. Introduction

Even a small amount of noncondensable gas can reduce the condensation heat transfer considerably. In the condenser tube, the condensate flows as an annular liquid film adjacent to the tube wall, while the vapor/noncondensable gas mixture flows in the core region. Consequently, the noncondensable gas layer that forms adjacent to the liquid/gas interface reduces the heat transfer capability. Several correlations were developed to evaluate steam condensation heat transfer with noncondensable gas in a vertical condenser tube. In this study, two empirical correlations proposed by Vierow and Schrock [1] and Kuhn [3] are considered and a new correlation is developed to improve the accuracy of prediction. In these correlations, the local heat transfer coefficient is simply expressed in the form of a "degradation factor," defined as the ratio of the experimental heat transfer coefficient to a reference heat transfer coefficient.

2. Evaluation of the previous correlations

Here, brief descriptions for the previous correlations are following as:

Vierow and Schrock [1] : from 22 mm ID tube

$$f = \frac{h_{\exp}}{h_{Nu}} = f_1 \cdot f_2 = (1 + a\,\mathrm{Re}_{mix}^{b}) \cdot (1 - cW_{nc}^{d}) \quad (1)$$

Kuhn [3] : from 47.5 mm ID tube

$$f = \frac{h_{\exp}}{h_{Nu}} = f_1 \cdot f_2 = f_{1,shear} \cdot f_{1,other} \cdot f_2$$
$$= \frac{\delta_{Nu}}{\delta_{shear}} \cdot (1 + a\,\mathrm{Re}_f) \cdot (1 - bW_{nc}^{c}) \quad (2)$$

where f is degradation factor, and f_1 and f_2 are including the effects of interfacial shear stress and noncondensable gas, respectively.

The heat transfer coefficients calculated using two empirical correlations are compared with Lee and Kim [4]'s data obtained from a steam condensation experiment with nitrogen inside a 13-mm-ID vertical tube. Figure 1 shows that the correlation of Vierow and Schrock [1] predicts well the data, while the correlation of Kuhn [2] very under-predicts them. Figure 2 shows that the first correlation is acceptable for the smaller-diameter condenser tube. However, the agreements of each correlation with experimental data are reversed when condenser tube diameter is large, as shown in Fig. 3. Predictions using two correlations are showing a large difference because the data relative to each correlation were obtained with the different designs of the test sections. Specially, the diameters of condenser tubes were different. Therefore, it needs to develop a new correlation which can be useful to evaluate condensation heat transfer coefficient inside a vertical tube with noncondensable gas irrespective of the condenser tube diameter.

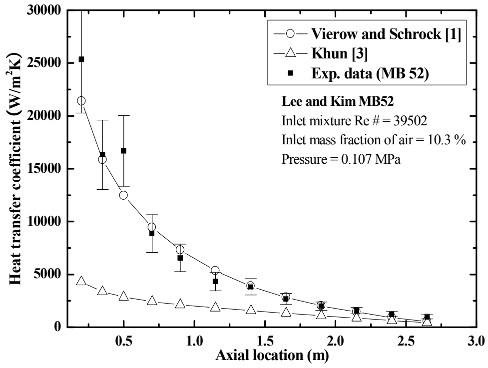

Figure 1. Comparison of empirical correlations for small tube

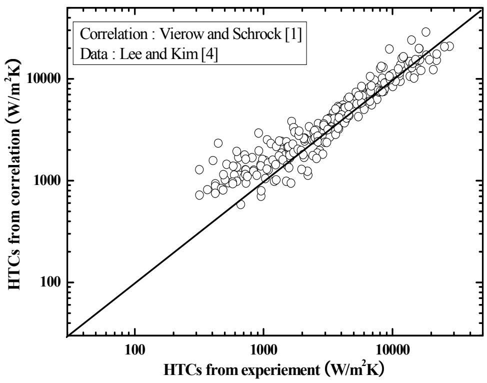

Figure 2. Comparison of experimental HTCs with Vierow and Schrock's correlation

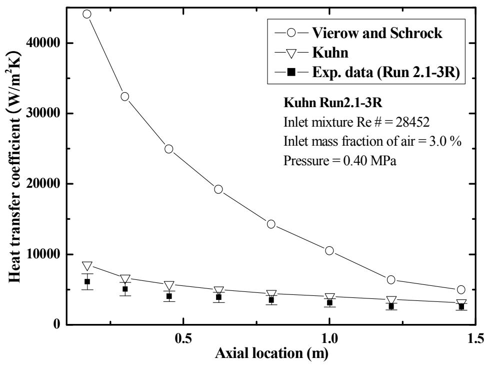

Figure 3. Comparison of empirical correlations for large tube

3. Development of a new correlation

The degradation factor method is used to correlate Lee and Kim's data because of its simplicity. The effect of interfacial shear stress is not considered using Reynolds number, but using dimensionless shear stress τ_g^*. The factor for pure steam condensation heat transfer is correlated against dimensionless shear stress as shown in Fig. 4, and given by

$$f_{pure} = h_{\exp,pure} / h_{Nu} = 0.8247 \tau_g^{*0.3124} . \qquad (4)$$

The correlation for the effect of noncondensable gas is accomplished by plotting the data set in the form $(1 - f_{\exp} / \tau_g^{*0.3124})$ versus W_{nc} as shown in Fig. 5. Then, the final form of new correlation is given by

$$f_d = h_{\exp,mix} / h_{Nu} = \tau_g^{*0.3124} (1 - 0.964 W_{nc}^{0.402}) . \qquad (5)$$

Figure 6 shows that the agreement of present correlation for Lee and Kim's data is good like Vierow and Schrock's correlation. In addition, the predictions of it are also acceptable for larger condenser tubes as shown in Fig. 7. Consequently, present correlation can be useful to evaluate condensation heat transfer of steam/noncondensable gas mixture irrespective of the condenser tube diameter.

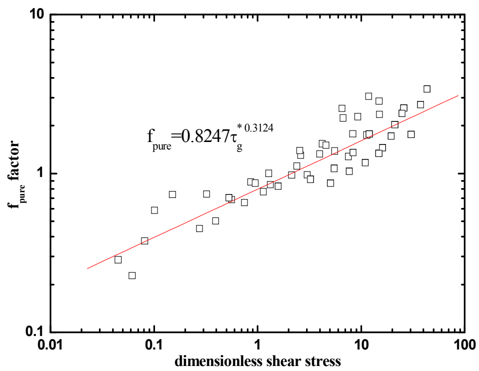

Figure 4. Factor for pure steam condensation heat transfer

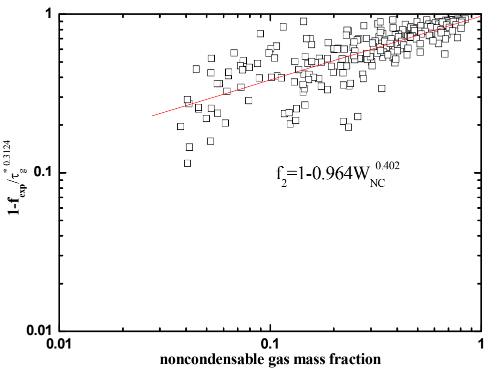

Figure 5. Factor for the effect of noncondensable gas

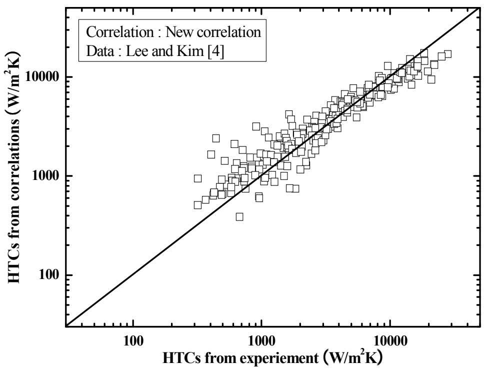

Figure 6. Comparison of experimental HTCs with present correlation

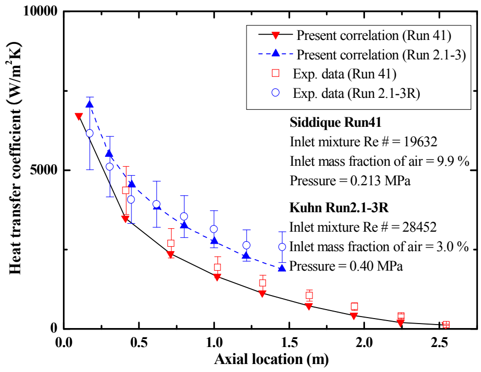

Figure 7. Comparison of present correlation for large tube

4. Conclusion

Two empirical correlations showed their limits. The correlation of Vierow and Schrock [1] is only acceptable for smaller-diameter condenser tubes, and that of Kuhn is only reasonable for larger-diameter condenser tubes. On the other hand, the newly developed correlation is good to calculate heat transfer coefficients of steam condensation in the presence of noncondensable gas regardless of the diameter of condenser tube.

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