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Counter-Current Experiments for the Direct Contact Condensation of Pure Steam on a Stratified Liquid in a Horizontal Pipe

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1. Introduction

Direct contact condensation is very important in a LWR (Light Water Reactor) safety analysis and other industrial applications. There have been a lot of theoretical and experimental researches on a horizontal in-channel condensation using a rectangular channel, while there is very few experimental data on an in-tube condensation. The objectives of the present study are to evaluate a condensation heat transfer in a counter-current steam-water flow in a horizontal circular pipe and to compare the experimental data with the co-current data.

2. Experimental Works

The direct-contact condensation experimental facility used for the present study has been described in a previous literature [1]. The present test matrix included 12 tests for the counter-current experiments. The test section is slightly inclined and thus the experimental condition is comparable to the test cases of Chu [2].

To evaluate the averaged values of the temperature and velocity at each vertical position from the bottom, the temperature and velocity profiles are measured. The local heat transfer coefficient is calculated by using the gradient of the bulk temperature profile along the flow direction. The local liquid Nusselt number is also calculated.

3. Results and Discussion

The present experimental conditions of the counter-current flow lie in the stratified flow region and on the interface between the stratified and wavy flow regions.

3.1 Local Water Temperature and Velocity

Figures 1 shows a typical profile of the local water temperature measured at three locations of 0.441, 0.895, and 1.349 m downstream from the water inlet for the typical test case of CT001. The inlet water temperature was 41^{o}C, and the inlet Reynolds numbers of the water and steam were 3994 and 6823, respectively.

The liquid region can be classified into three regions in a vertical direction; the water layer close to the bottom (bottom region), the water layer close to the steam-water interface (interface region) and the in-between (transition region). For the case of CT001, in the bottom region ($y^* < 0.6$) the local water temperature remains constant. The local water temperatures are almost constant along the flow direction in the bottom layer, while they increase along the flow direction in the transition region ($0.6 < y^* < 0.8$) and then they rise sharply to a saturation temperature in the interface region ($y^* > 0.8$). The regional boundaries between the bottom and transition regions and between the transition and interface regions are deeper in the counter-current cases than in the co-current cases.

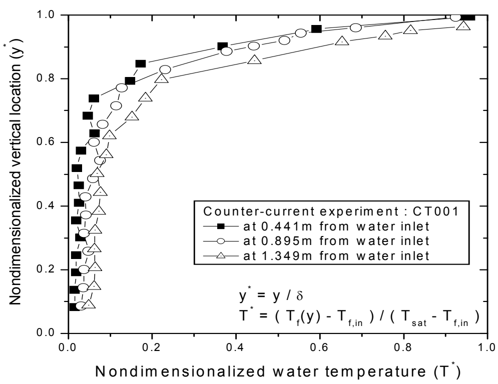

Figure 1. Profiles of the Local Water Temperature for the Counter-Current Flow Tests

The temperature distribution in the counter-current flow is different from that in the co-current flow. The water bulk temperature in the bottom region is almost constant, which implies that a condensation occurs in the steam-water interface region and it does not affect the bottom region. The affected interface region is wider due to the counter-current motion of the steam and the liquid and their mixing.

3.2 Local Liquid Nusselt Number

The effects of the inlet liquid and steam Reynolds numbers on the local Nusselt number for a similar inlet steam and liquid Reynolds numbers, respectively, are investigated. The local liquid Nusselt number decreases along the flow direction of the steam. It is higher with a higher inlet liquid and steam Reynolds numbers.

3.3 Comparison of the Heat Transfer Characteristics with the Co-Current Experimental Data

The test cases of CO001 and CT010 are selected to compare the heat transfer characteristics between the co-current and counter-current flow cases. It should be noted that the degrees of the inclination angle both of the co-current and counter-current condensation experiment are 2.1^o and about 0.3^o (slightly inclined), respectively. Although the inlet flow rates are similar, the Reynolds numbers are different because the film thickness and thus its hydraulic diameter have different values. The water layer is thinner in the co-current case than in the counter-current case. It is caused by the higher inclination angle and a sweeping of the water by the co-current steam. The liquid hydraulic diameter in the co-current case of CO001 is about half of that in the counter-current case of CT010. Thus the influence region of a heat transfer through the water layer is deeper and the liquid-side heat transfer rate is higher in the co-current case than in the counter-current case. In the bottom layer, the local temperature is changed more along the flow direction in the co-current case than in the counter-current case.

The logarithmic heat transfer coefficients of CO001 and CT010 are 2492.9 and 1065.7 $W/m^2 \cdot K$, respectively, and the logarithmic Nusselt numbers of CO001 and CT010 are 49.3 and 32.3, respectively. The overall heat transfer characteristics are better in the co-current flow than in the counter-current flow with the same injection flow rates of steam and water.

Figure 2 shows a comparison of the local Nusselt number between the co-current and counter-current flows. The local values are also higher in the co-current flow than in the counter-current flow. The local Nusselt number is higher at the steam inlet for both the co-current and counter-current flow cases.

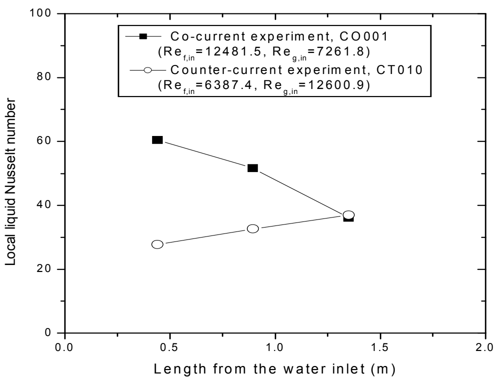

Figure 2. Comparison of the Local Nusselt Number between Co-Current and Counter-Current Flows

3.4 Assessment of the Previous Correlations

Figure 3 shows a comparison of the Nusselt numbers estimated from the experimental data with those calculated from four existing correlations. Kim[3]'s correlation with the Froude number overestimates the experimental Nusselt numbers with a standard deviation of 132.5%, and the other three correlations of Chu et al.[2]'s, Segev et al.[4]'s, and Kim[3]'s with the Reynolds number deviate with standard deviations of 15.6%, 29.7%, and 31.7%, respectively. The correlations obtained by Segev et al.[4] and Kim[3] are based on a rectangular flow channel and a very shallow water layer thickness. However, the correlation obtained by Chu et al. [2] is based on the experimental data obtained by using a circular pipe with a diameter of 8.4 cm and its prediction over the present experimental data is comparatively accurate.

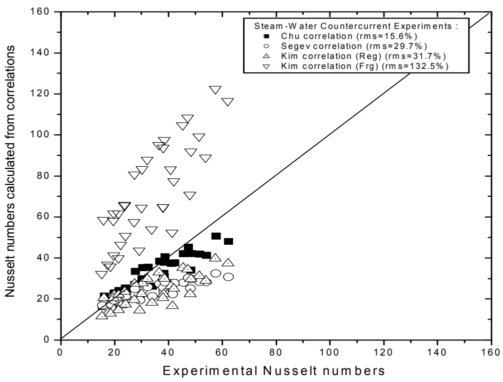

Figure 3. Comparison of Nusselt numbers Estimated from the Counter-Current Experimental Data with Those Calculated from the Existing Correlations

4. Conclusion

Several experiments were performed to obtain reliable data on the interfacial condensation phenomena for the counter-current flows in a horizontal circular pipe. The following conclusions have been reached:

1. The overall heat transfer characteristics are better in the co-current flow than in the counter-current flow with the same injection flow rates of the steam and the water.
2. Comparisons of the present experimental data of the counter-current flow with four existing correlations showed that Chu[2]'s correlation is better than the other correlations.

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