Experimental study of post-dryout with R-134a upward flow in smooth tube

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1. Introduction

The post-dryout region in the tube is characterized by two-phase flow which transports liquid droplets in a continuous vapor flow, terminating in the superheated single-phase region. Significant thermal non-equilibrium between the liquid and vapor phases is usually present in the dispersed flow film boiling (DFFB) regime, except for the high mass velocities. Water cooled reactors generally operate with significant margin to dryout (burn-out condition). However, it is necessary to demonstrate fuel rod cladding temperatures within an allowable temperature range for certain postulated accidents. The numerous experiments and theoretical researches on post-dryout heat transfer have been conducted. The experimental work of heat transfer in the post-dryout region of R-113 upward high quality flow in a uniformly heated tube was performed by T. Ueda et al. [1]. A large number of correlations have been developed for the heat transfer in DFFB regime [2-6]. This study focuses on the parameter effects and the development of correlation in the post-dryout heat transfer of tube.

2. Test Data Reduction

The inside tube wall temperatures were calculated from local heat generation and heat conduction through the wall:

$$T_{wi} = T_{wo} - \frac{q_Z d_{in}}{2k_w}\left(\frac{1}{2} - \frac{d_{in}^2}{d_{out}^2 - d_{in}^2}\ln\frac{d_{out}}{d_{in}}\right)$$

The average heat flux (q_E) of the test section was calculated:

$$q_E = \frac{EI}{\pi d_{in} L_H}$$

Since the tube resistance varied with the tube wall temperature, the heat generated in the tube was locally calculated in consideration of the variation of tube resistance by tube wall temperature. The resistance of carbon steel (SA192) was calculated as a function of temperature, thus the heat flux was not uniform along the direct heated test section. The local heat flux (q_Z) is calculated:

$$q_Z = q_E(R_Z / R_{REF})$$

where, R_Z is the carbon steel resistance at temperature of segment (Z), and R_{REF} is the carbon steel resistance at average tube temperature. The average tube temperature was calculated by summing the product of each segment temperature and segment length and then dividing by tube length.

3. Experimental Results and Discussion

Fig. 1 is the typical example of wall superheated temperature at the inside tube surface in the post-dryout region of smooth tube as a function of equilibrium quality. It shows the pressure effect on the wall temperature. The wall temperature is decreased as the pressure increases at the mass flux of 290 kg/m^2-sec, however the wall temperatures are not affected by the pressure at the mass flux of 700 kg/m^2-sec. These can be explained in terms of a change in density ratio of R-134a. The density ratio (ρ_l / ρ_g) of R-134a sharply decreases with increasing pressure and it causes void fraction to decrease. The decrease of void fraction results in lower vapor superheat, hence low thermal non-equilibrium and better convective heat transfer from the wall. This effect is dominant with decreasing mass flux since the thermal non-equilibrium becomes significant and the void fraction larger. The other competing mechanism with increasing pressure is to decrease of vapor velocity by the decrease of density ratio, and it results in the decrease of convection heat transfer in DFFB region. However, the improvement of the heat transfer in DFFB regime with increasing pressure is mainly attributed to the lower thermal non-equilibrium between vapor and entrained droplets. Thus, the latter mechanism is less effective than the former mechanism. Fig. 1 also shows the critical point moves to lower qualities as the pressure increases.

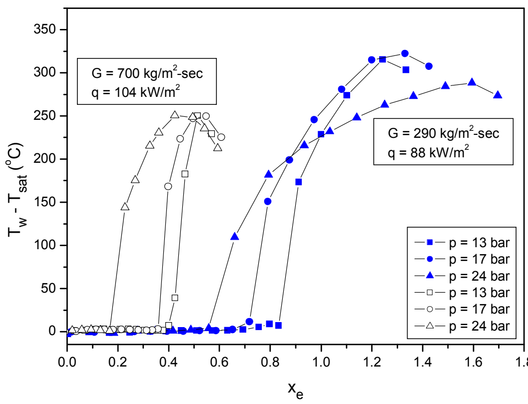

Figure 1. Wall temperature distribution with quality in smooth tube at 13, 17 and 24 bar

4. Correlation of post-dryout heat transfer

In non-equilibrium model (Chen et al. (CSO) [6], Groenveld-Delrome [4], Saha [5]), the actual quality and the vapor temperature are calculated and the post-dryout heat transfer coefficient is calculated based on the difference of wall and superheated vapor temperatures, while the heat transfer coefficient in equilibrium model (Dougall-Rosenhow [2], Condie-Benngston [3]) is calculated based on the difference of wall and saturated vapor temperatures. The empirical correlation on smooth tube is developed with the experiment results, which the heat transfer coefficient was calculated based on the saturated vapor temperature and the inside tube wall temperature. The predicted wall superheat by the obtained correlation is shown in Fig. 2 with CSO correlation results and it agrees well with the prediction by CSO correlation. The following is the correlation obtained here with the present experiment results for the smooth tube.

$$Nu_S = 0.2935 \frac{x_c^{0.568}\left\{\mathrm{Re}_v\left[x_e + \frac{\rho_v}{\rho_l}(1-x_e)\right]\right\}^{0.645}\mathrm{Pr}_{vf}^{0.854}}{x_e^{0.715}\left(1+\frac{dzchf}{d}\right)^{0.088}}$$

The 923 data points were used for statistical fit and the empirical correlation was obtained from regression analysis. The correlation obtained for smooth tube predicts the wall temperature in the post-dryout region with the average error of -2.0% for data used in its development. The present correlation includes parameters of $\mathrm{Re}_v, \mathrm{Pr}_{vf}$ which are thought to be important in DFFB heat transfer, and x_e accounting for the local variation of the heat flux, and x_c, $1+\frac{dzchf}{d}$ accounting for the influence of critical point hydraulics and distance from the critical point.

3. Conclusion

The experiments for post-dryout heat transfer using R-134a in the smooth tube were performed. The wall temperature is dependent on mass flux and pressure, and the tube wall temperature is decreasing with increasing pressure. The empirical thermal equilibrium correlation for heat transfer in the post-dryout region of smooth tube was presented at the relatively high quality conditions. The correlation presented for smooth tube has the regression fit with the average error of -2.0% for data used in its development. This research provides an insight into the post-dryout heat transfer of smooth tube through new correlation presented for post-dryout heat transfer. For the accurate prediction of wall temperature in the post-dryout region, it is necessary to supplement the correlations obtained here by considering a thermal non-equilibrium at high quality condition with direct measurement of the vapor superheat.

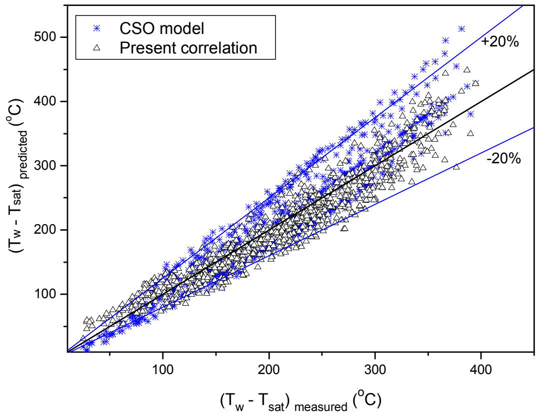

Figure 2. Measured vs. predicted wall superheat in a smooth tube by CSO [6] and present correlation

REFERENCES

[1] T. Ueda, H. Tanaka and Y. Koizumi, Dryout of liquid film in high quality R-113 upflow in a heated tube, in Proceedings of the 6th International Heat and Transfer Conference, paper No. FB-26, Toronto, 1978.

[2] R.S. Dougall and W.M. Rohsenow, Film boiling on the inside of vertical tubes with upward flow of the fluid at low qualities, MIT report No. 9079-26, Massachusetts Institute of Technology, 1963.

[3] K.G. Condie, S.J. Bengston and S.L. Richlein, Measurement of axially varying non-equilibrium in post-critical heat flux boiling in a vertical tube, NUREG/CR-3362, U.S. Nuclear Regulatory Commission, 1983.

[4] D.C. Groenveld and G.G.J. Delorme, Prediction of thermal non-equilibrium in the post-dryout regime, Nuclear Engineering and Design, Vol. 36, p. 17, 1976.

[5] P. Saha, A non-equilibrium heat transfer model for dispersed droplet post- dryout regime, International Journal of Heat Mass Transfer, Vol. 23, p. 483, 1980.

[6] J.C. Chen, F.T. Ozkaynak and R.K. Sundaram, Vapor heat transfer in post-CHF region including the effect of thermodynamic non-equilibrium, Nuclear Engineering and Design, Vol. 51, p. 143, 1979.