§6. Turbulent Heat Transfer for Heating of Water in a Short Vertical Tube

Hata, K. (Inst. of Advanced Energy, Kyoto Univ.),
Noda, N.

The accurate expression for calculation in turbulent heat transfer is necessary to clarify the onset of subcooled nucleate boiling, subcooled boiling heat transfer and DNB (departure from nucleate boiling), whose knowledge is important to discuss the mechanisms of subcooled flow boiling critical heat flux in a short vertical tube [1-4]. The turbulent heat transfer coefficients for the flow velocities (u=4.0 to 21 m/s), the inlet liquid temperatures (T_{in}=296.5 to 353.4 K), the inlet pressures (P_{in}=810 to 1014 kPa) and the increasing heat inputs ($Q_0 \exp(t/\tau)$, τ=10, 20 and 33.3 s) are systematically measured by the experimental water loop. The Platinum test tubes of test tube inner diameters (d=3, 6 and 9 mm), heated lengths (L=32.7 to 100 mm), ratios of heated length to inner diameter (L/d=5.51 to 33.3) and wall thicknesses (δ=0.3, 0.4 and 0.5 mm) with surface roughness (Ra=0.40 to 0.78 μm) are used in this work [5].

Turbulent Heat Transfer

Figure 1 shows the typical examples of the turbulent heat transfer curves for Platinum test tube of d=3 mm, L=32.7 mm and L/d=10.9 with the exponential period, τ, of around 33.3 s at u=13.3 m/s. The experimental data are compared with the values derived from other workers' correlations. The experimental data for d=3 mm at the high heat flux point are 17.6 to 53.8 % higher than the values derived from these correlations at a fixed temperature difference between heater inner surface temperature and average bulk liquid temperature (ΔT_L=constant) and 20 to 64 K lower than the values derived from these correlations at a fixed heat flux (q=constant).

Influence of u, d, L/d, μ/μ_w, Pr and Re_d

Figure 2 shows the influence of the flow velocity on the turbulent heat transfer coefficient, h, for the inner diameter of 3 mm, the heated length of 66.5 mm and the L/d of 22.2. The h for the flow velocities of 4.0, 6.9, 9.9, 13.3, 17 and 21 m/s were shown versus the flow velocity with the temperature differences between the heater inner surface temperature and the average bulk liquid temperature, ΔT_L, of 40, 80 and 120 K. The h for six different flow velocities becomes linearly higher with an increase in the flow velocity. The slope, n, on the log-log graph kept almost constant about 0.85 with the ΔT_L ranging from 40 to 120 K.

The effect of the inner diameter on the h was represented versus d with ΔT_L as a parameter. The h for each ΔT_L is almost proportional to $d^{-0.15}$ in the range of the ΔT_L from 40 to 120 K.

The influence of L/d on h is checked for the ΔT_L of 40, 80 and 120 K. The h for each ΔT_L becomes linearly lower with an increase in the L/d with a similar slope, n, of -0.08.

The viscosity gradient of the fluid in the tube is taken into account by means of the ratio of μ/μ_w, where μ is the viscosity of the fluid at its main stream temperature and μ_w is its viscosity at the temperature of the tube wall. The exponent, n, of μ/μ_w is almost taken as 0.14 in the expression for the turbulent heat transfer coefficient, h, for the inner diameter of 6 mm, the heated length of 69.6 mm and the L/d of 11.6 in the range of the ΔT_L from 5 to 140 K.

The values of $[Nu_d/Re_d^{0.85}/(\mu/\mu_w)^{0.14}]$ become linearly higher with the increase in the Prandtl number, Pr. The slope, n, of the curve on the log-log graph is almost constant about 0.4 similar to the experimental data for ΔT_L=40, 80, 100 and 120 K.

All the data for wide ranges of test tube inner diameters (d=3, 6 and 9 mm), heated lengths (L=32.7 to 100 mm), L/d=5.51 to 33.3, inlet liquid temperatures (T_{in}=296 to 353 K), flow velocities (u=4.0 to 21 m/s) and temperature differences between heater inner surface temperature and average bulk liquid temperature (ΔT_L=5 to 140 K) are plotted on log $[Nu_d/Pr^{0.4}/(L/d)^{-0.08}/(\mu/\mu_w)^{0.14}]$ versus log (Re_d) graph in Fig. 3 to determine the final value of the exponent, n, for the Reynolds number, Re_d. The final value of n was also given 0.85 as the best-fitted one based on the experimental data in this work.

Correlation

The turbulent heat transfer correlation is derived as follows based on the effects of Re_d, Pr, L/d and μ/μ_w clarified in this work [5].

$$Nu_d = 0.02\, Re_d^{0.85}\, Pr^{0.4} \left(\frac{L}{d}\right)^{-0.08} \left(\frac{\mu}{\mu_w}\right)^{0.14} \qquad (1)$$

Most of the data are within 15 % difference of Eq. (1) for wide range of the temperature difference between heater inner surface temperature and average bulk liquid temperature (ΔT_L=5 to 140 K) with d=3, 6 and 9 mm, L=32.7 to 100 mm and u=4.0 to 21 m/s.

Reference

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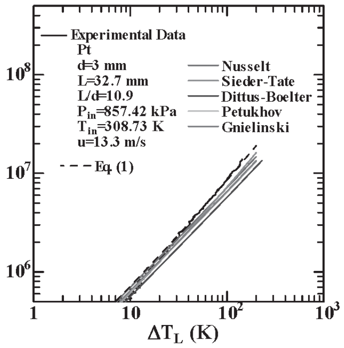

Fig. 1 q vs. ΔT_L for d=3 mm, L=32.7 mm and u=13.3 m/s at P_{in}=857 kPa.

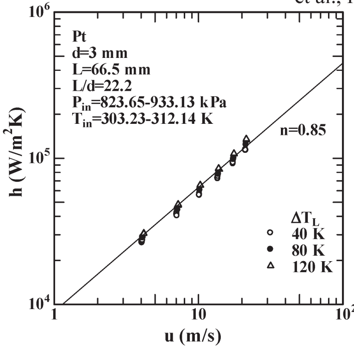

Fig. 2 h vs. u for d=3 mm and L=66.5 mm with the ΔT_L of 40, 80 and 120 K.

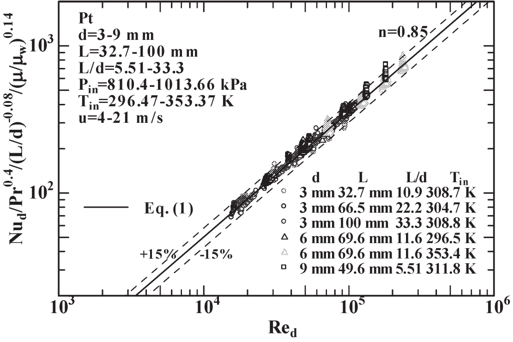

Fig. 3 $Nu_d/Pr^{0.4}/(L/d)^{-0.08}/(\mu/\mu_w)^{0.14}$ vs. Re_d for d=3, 6 and 9 mm with u=4 to 21 m/s.