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

Hata, K. (Inst. of Advanced Energy, Kyoto Univ.), Shirai, Y. (Dept. of Energy Sci. and Tech., Kyoto Univ.), Masuzaki, S.

The accurate expression for calculation in transient turbulent heat transfer is necessary to clarify the onset of subcooled nucleate boiling, subcooled boiling heat transfer and DNB (departure from nucleate boiling) in transient operation mode for a nuclear fusion facility.

For many years we have systematically measured the steady state turbulent heat transfer coefficients. The influence of Reynolds number (Re_d), Prandtl number (Pr), dynamic viscosity (μ_l) and L_{eff}/d on the steady state turbulent heat transfer was investigated into details, and the widely and precisely predictable correlation of the steady state turbulent heat transfer for heating of water in a short vertical tube was given based on the experimental data [1].

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

Figure 1 shows the typical example of the transient turbulent heat transfer curve for Pt test tube of d=6 mm and L_{eff}=59.2 mm with the exponential period, τ, of 28.2 ms at the flow velocity, u, of around 3.98 m/s. The experimental data were compared with the values derived from Eq. (1). The experimental data at the boiling initiation point are 44.1 % higher than the value derived from Eq. (1) with u=3.98 m/s at a fixed temperature difference between heater inner surface temperature and liquid bulk mean temperature ($\Delta T_L=(T_s-T_L)$=constant), and 62.7 K lower than the value derived from Eq. (1) at a fixed heat flux (q=constant).

Figure 2 shows the influence of the exponential periods, τ, on the transient turbulent heat transfer coefficient, h, for the inner diameters of 3 and 6 mm, the effective lengths of 56.7 and 59.2 mm and the L_{eff}/d of 18.9 and 9.87. The h for the flow velocity, u, of 4.0 m/s on d=3 mm inner diameter and those for the u of 4.0, 6.9, 9.9 and 13.3 m/s on d=6 mm inner diameter were shown versus the exponential period with the temperature differences between the heater inner surface temperature and the average bulk liquid temperature, ΔT_L, of 40, 80, 100 and 120 K. The h for eleven to twelve different exponential periods are almost constant down to the τ of around 125 ms with a decrease in the exponential period from around 30 s. And those become gradually higher with a decrease in the exponential period. For power transient experiments, the rate of increasing heat input is very high. It takes time to form the fully developed temperature profile in the test tube because the test tube has some heat capacity. Then the temperature profile in the thermal boundary layer on the test tube surface grows. Namely, it is explained to be as a result of the time lag of the formation of the transient turbulent heat transfer for the increasing rate of the heat input.

The ratios of transient turbulent heat transfer data for wide exponential period (478 points) to the corresponding values calculated by the steady state turbulent heat transfer correlation, Eq. (1), are shown versus the non-dimensional exponential period, $p^*=\tau u/\{\sigma/g/(\rho_l-\rho_g)\}^{0.5}$, in Fig. 3. The ratios are almost constant for the non-dimensional exponential period greater than around 300 and equivalent to unity, and it becomes gradually higher with the decrease in non-dimensional exponential period from around 300. And the value of the transient turbulent heat transfer almost becomes two times as large as the steady state one at the non-dimensional exponential period of 16.59. The transient turbulent heat transfer correlation for the wide range of exponentially increasing heat inputs ($Q_0 \exp(t/\tau)$, τ=18.6 ms to 25.7 s) is derived as follows based on the effect of the non-dimensional exponential period clarified in this work [2].

$$Nu_d = 0.02\, Re_d^{0.85}\, Pr^{0.4} \left(\frac{L_{eff}}{d}\right)^{-0.08} \left(\frac{\mu_l}{\mu_w}\right)^{0.14} \left(1+9.46\, p^{*-0.8}\right) \qquad (2)$$

The ratios of the transient turbulent heat transfer data for d=3 and 6 mm, L_{eff}=56.7 and 59.2 mm, L_{eff}/d=18.9 and 9.87 and τ=18.6 ms to 25.7 s to the values calculated from the transient turbulent heat transfer correlation, Eq. (2), are shown versus the non-dimensional exponential period, p^*, with the inlet liquid temperatures, T_{in} of 296.93 to 304.81 K at the inlet pressures, P_{in}, of 794.39 to 858.27 kPa in Fig. 3. This correlation can describe not only the transient turbulent heat transfer data (422 points) for d=6 mm but also those for d=3 mm (56 points) obtained in this work under the wide ranges of the non-dimensional exponential periods (p^*=20.6 to 1.30×10^5) and the flow velocities (u=4.0 to 13.3 m/s) at 140.99 K$\le\Delta T_{sub,in}\le$147.36 K within ±15 % difference as shown in Fig. 3.

1) Hata, K., and Noda, N., *Journal of Power and Energy Systems*, **2**, No. 1 (2008) 318-329.

2) Hata, K., et al., *Journal of Power and Energy Systems*, **5**, No. 3 (2011) 414-428.

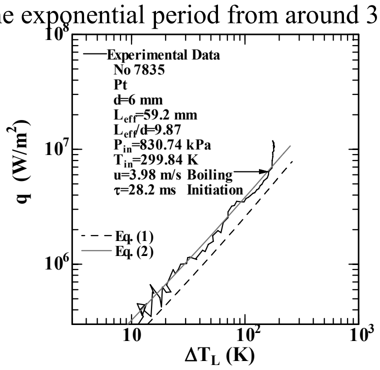

Fig. 1 Relationship between q and ΔT_L for Pt test tube of d=6 mm and L_{eff}=59.2 mm with τ=28.2 ms at u=3.98 m/s and P_{in}=831 kPa

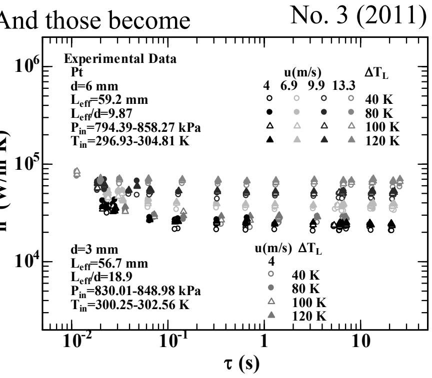

Fig. 2 h vs. τ for d=3 and 6 mm, and L_{eff}=56.7 and 59.2 mm with ΔT_L=40, 80, 100 and 120 K at u=4, 6.9, 9.9 and 13.3 m/s

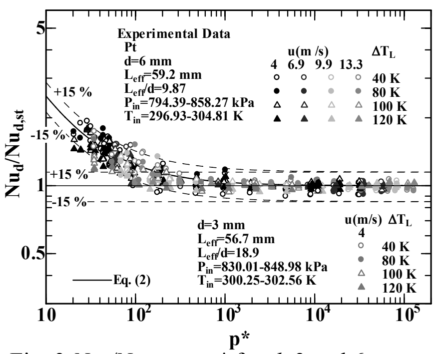

Fig. 3 $Nu_d/Nu_{d,st}$ vs. p^* for d=3 and 6 mm, and L_{eff}=56.7 and 59.2 mm with ΔT_L=40, 80, 100 and 120 K at u=4, 6.9, 9.9 and 13.3 m/s