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

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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 ($Q_{h}exp(t/u)$, $t=10$, 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 ($\delta=0.3$, 0.4 and 0.5 mm) with surface roughness ($R_{a}=0.40$ to 0.78 m) 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, $t$, 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 ($\Delta T_{l}=\text{constant}$) and $20$ to $64$ K lower than the values derived from these correlations at a fixed heat flux ($q^{*}=\text{constant}$).

Influence of $u$, $d$, $L/d$, $\mu/\mu_{w}$, $Pr$ 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, $\Delta T_{l}$, 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 $\Delta T_{l}$ ranging from $40$ to $120$ K.

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

The influence of $L/d$ on $h$ is checked for the $\Delta T_{l}$ of $40$, $80$ and $120$ K. The $h$ for each $\Delta T_{l}$ 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 $\mu/\mu_{w}$, where $\mu$ is the viscosity of the fluid at its main stream temperature and $\mu_{w}$ is its viscosity at the temperature of the tube wall. The exponent, $n$, of $\mu_{w}$ 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 $\Delta T_{l}$ from $5$ to $140$ K.

The values of $[Nu_{d}/Re_{d}^{0.85}](\mu/\mu_{0.14})$ 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 $\Delta T_{l}=40$, $80$, $100$ 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 ($\Delta T_{l}=5$ to $140$ K) are plotted on log $[Nu_{d}/Pr^{0.85}](\mu/\mu_{w}^{0.14})$ versus log ($Re_{d}$) graph in Figure 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 $\mu/\mu_{w}$ clarified in this work [5].

\[
Nu_{d} = 0.02 Re_{d}^{0.85} Pr^{0.4} \left( \frac{L}{d} \right)^{-0.08} \left( \frac{\mu}{\mu_{w}} \right)^{0.14}
\]  

(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 ($\Delta T_{l}=5$ 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