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Heat Transfer

Fifth Edition

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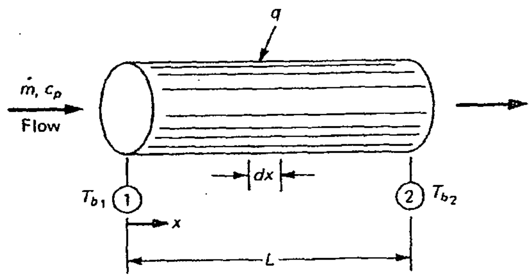
Fig. 6-1 *Total heat transfer in terms of bulk-temperature difference.*



plicated problems may sometimes be solved analytically, but the solutions, when possible, are very tedious. For design and engineering purposes, empirical correlations are usually of greatest practical utility. In this section we present some of the more important and useful empirical relations and point out their limitations.

First let us give some further consideration to the bulk-temperature concept which is important in all heat-transfer problems involving flow inside closed channels. In Chap. 5 we noted that the bulk temperature represents energy average or "mixing cup" conditions. Thus, for the tube flow depicted in Fig. 6-1 the total energy added can be expressed in terms of a bulk-temperature difference by

$$q = \dot{m} c_p (T_{b_2} - T_{b_1}) \qquad \dot{m} = \rho v A \tag{6-1}$$

provided c_p is reasonably constant over the length. In some differential length dx the heat added dq can be expressed either in terms of a bulk-temperature difference or in terms of the heat-transfer coefficient

$$dq = \dot{m} c_p dT_b = h(2\pi r)\, dx\, (T_w - T_b) \tag{6-2}$$

where T_w and T_b are the wall and bulk temperatures at the particular location. The total heat transfer can also be expressed as

$$q = hA(T_w - T_b)_{av} \tag{6-3}$$

where A is the total surface area for heat transfer. Because both T_w and T_b can vary along the length of the tube, a suitable averaging process must be adopted for use with Eq. (6-3). In this chapter most of our attention will be focused on methods for determining h, the convection heat-transfer coefficient. Chapter 10 will discuss different methods for taking proper account of temperature variations in heat exchangers.

For fully developed turbulent flow in smooth tubes the following relation is recommended by Dittus and Boelter [1]:

$$\mathrm{Nu}_d = 0.023\, \mathrm{Re}_d^{0.8}\, \mathrm{Pr}^n \tag{6-4}$$

The properties in this equation are evaluated at the fluid bulk temperature, and the exponent n has the following values:

This may be restructured as

$$\bar{h}^{3/4} = C\left[\frac{\rho(\rho-\rho_v)gk^3}{\mu^2}\frac{\mu P}{4\dot{m}}\frac{4\sin\phi\, A/P}{L}\right]^{1/4}$$

and we may solve for $\bar{h}$ as

$$\bar{h} = C^{4/3}\left[\frac{\rho(\rho-\rho_v)gk^3}{\mu^2}\frac{\mu P}{4\dot{m}}\frac{4\sin\phi\, A/P}{L}\right]^{1/3} \tag{9-23}$$

We now define a new dimensionless group, the *condensation number* Co, as

$$\mathrm{Co} = \bar{h}\left[\frac{\mu^2}{k^3\rho(\rho-\rho_v)g}\right]^{1/3} \tag{9-24}$$

so that Eq. (9-23) can be expressed in the form

$$\mathrm{Co} = C^{4/3}\left(\frac{4\sin\phi\, A/P}{L}\right)^{1/3}\mathrm{Re}_f^{-1/3} \tag{9-25}$$

For a vertical plate $A/PL = 1.0$, and we obtain, using the constant from Eq. (9-10),

$$\mathrm{Co} = 1.47\,\mathrm{Re}_f^{-1/3} \qquad \text{for } \mathrm{Re}_f < 1800 \tag{9-26}$$

For a horizontal cylinder $A/PL = \pi$ and

$$\mathrm{Co} = 1.514\,\mathrm{Re}_f^{-1/3} \qquad \text{for } \mathrm{Re}_f < 1800 \tag{9-27}$$

When turbulence is encountered in the film, an empirical correlation by Kirkbride [2] may be used:

$$\mathrm{Co} = 0.0077\,\mathrm{Re}_f^{0.4} \qquad \text{for } \mathrm{Re}_f > 1800 \tag{9-28}$$

9-4 Film condensation inside horizontal tubes

Our discussion of film condensation so far has been limited to *exterior surfaces,* where the vapor and liquid condensate flows are not restricted by some overall flow-channel dimensions. Condensation inside tubes is of considerable practical interest because of applications to condensers in refrigeration and air-conditioning systems, but unfortunately these phenomena are quite complicated and not amenable to a simple analytical treatment. The overall flow rate of vapor strongly influences the heat-transfer rate in the forced convection-condensation system, and this in turn is influenced by the rate of liquid accumulation on the walls. Because of the complicated flow phenomena involved we shall present only two empirical relations for heat transfer and refer to reader to Rohsenow [37] for more complete information.

Chato [38] obtained the following expression for condensation of refrigerants at low vapor velocities inside horizontal tubes:

$$\bar{h} = 0.555\left[\frac{\rho(\rho-\rho_v)gk^3h'_{fg}}{\mu d(T_g - T_w)}\right]^{1/4} \tag{9-29}$$