5.6. Pressure Drop

The total pressure, ΔP_t, across a system consists of three components: (a) a static pressure difference, ΔP_s, due to the density and elevation of the fluid, (b) a pressure differential, ΔP_m, due to the change of momentum, and (c) a pressure differential due to frictional losses, ΔP_f. That is

$$\Delta P_t = \Delta P_s + \Delta P_m + \Delta P_f \tag{5.46}$$

In a boiling system we are dealing with a vapor-liquid mixture and, in the evaporating zone, the relative quantity of liquid and vapor are changing. Therefore, these component pressure differentials must be determined for the two-phase mixture existing at each point and then integrated over the system.

The two-phase flow adds many complications to the calculation of pressure drop. As shown in Figure 5.6 the flow pattern can vary substantially from inlet to outlet. Although both the liquid and vapor are traveling together in the same direction they usually travel at different speeds as a result of slippage between them. The local flow pattern and flow rates can fluctuate resulting in a fluctuating pressure drop. Thus the ability to calculate the pressure drop is much poorer than for a single phase system. In spite of hundreds of researches on two-phase flows a ± 30% accuracy of a predicted pressure drop is considered excellent, a ± 50% a very good prediction, and a ± 100% error is very probable. Therefore, any vaporizer design should incorporate enough of a safety factor to allow for the uncertainties in calculating pressure drops and the corresponding flow rates as well as the potential effect on heat transfer coefficients.

5.6.1. Tube-Side Pressure Drop

The method of calculations given below is based on the Lockhart-Martinelli analysis which is a separated flow model; i.e., the flow rates of the vapor and liquid are based on the same pressure gradient. This seems to be the best current general model in the literature, although proprietary improvements have been made.

(a) Static Head Loss.

The static head loss is very important in vertical units when the heat flux is low and when in the bubble flow regime. Here

$$\Delta P_s = \frac{g}{g_c} \int \rho_{tp} \, dH \sin\theta \tag{5.47}$$

for vertical units $\sin\theta = 1$. ρ_{tp} can vary with height, H, and is also affected by slip. Here

$$\rho_{tp} = R_v \rho_v + (1 - R_v)\rho_\ell \tag{5.48}$$

and where the volume fraction of vapor is based on the Martinelli relationship

$$R_v = 1 - 1/\Phi_{\ell tt} = 1 - R_\ell \tag{5.49}$$

where $\Phi_{\vartheta tt}$, is defined in (c).

(b) Momentum Head Loss.

The momentum loss is easily determined from the inlet and outlet conditions for either each incremental step or on the overall system.

$$\Delta P_m = +\frac{G_t^2}{g_c}\left\{\left[\frac{(1-x)^2}{\rho_\ell(1-R_v)}+\frac{x^2}{\rho_v R_v}\right]_2-\left[\frac{(1-x)^2}{\rho_\ell(1-R_v)}+\frac{x^2}{\rho_v R_v}\right]_1\right\} \quad (5.50)$$

where x is local weight fraction of vapor.

(c) Friction Head Loss.

The friction head loss equations are in two forms either liquid or vapor based. Both will give the same result (both phases turbulent) but the liquid form is better when Re_ℓ > 4000 and vapor form for Re_ℓ < 4000. The single phase pressure drops are

$$\Delta P_\ell = 4 f_\ell (L/d_i) G_t^2 (1-x)^2 (1/2 g_c \rho_\ell) \quad (5.51)$$

$$\Delta P_v = 4 f_v (L/d_i) G_t^2 x^2 (1/2 g_c \rho_v) \quad (5.52)$$

and the two-phase pressure drops are

$$\Delta P_f = \Phi_{\ell tt}^2 \Delta P_\ell \quad (5.53)$$

$$\Delta P_f = \Phi_{vtt}^2 \Delta P_v \quad (5.54)$$

Here

$$\Phi_{\ell tt}^2 = 1 + 20/x_{tt} + 1/(x_{tt})^2 \quad (5.55)$$

$$\Phi_{vtt}^2 = 1 + 20 x_{tt} + 1/(x_{tt})^2 \quad (5.56)$$

where

$$x_{tt} = \left(\frac{1-x}{x}\right)\left(\frac{\rho_v}{\rho_\ell}\right)^{0.57}\left(\frac{\mu_\ell}{\mu_v}\right)^{0.11} \quad (5.29)$$

All of the above equations are applied in a stepwise manner along the tube and the final overall pressure drop is the sum of the drops across each step.

In a thermosyphon reboiler the above calculated pressure drop must match the available driving head which is total available head minus the sum of the recirculating liquid line frictional and momentum losses.

5.6.2. Shell-Side Pressure Drop

The calculation of pressure drop for two-phase flow across the tube bundles is done about the same as for flow inside tubes. However, there is much less data for these flows especially in the high liquid fraction ratios en countered in boiling. Most of the experimental data is in the high vapor fraction region as in condensers.

Ishihara et al. (56) reviewed the available data and correlations (57, 58, 59, 60) for shell-side flow and concluded that these correlations well represented the author's data but occasionally failed when compared against all the data. Ishihara et al. proposed that the Martinelli separated flow method be used and these equations are given below. Figure 5.32 shows the data compared to this method. The agreement is good in the high vapor fraction region but scatters more in the low vapor fraction region. Further improvements are claimed by the authors but are proprietary and unpublished.

The static head and momentum losses are calculated as in the above equations; however, the mass velocity, G_t, in equation 5.50 is based on the minimum flow area between the tubes.

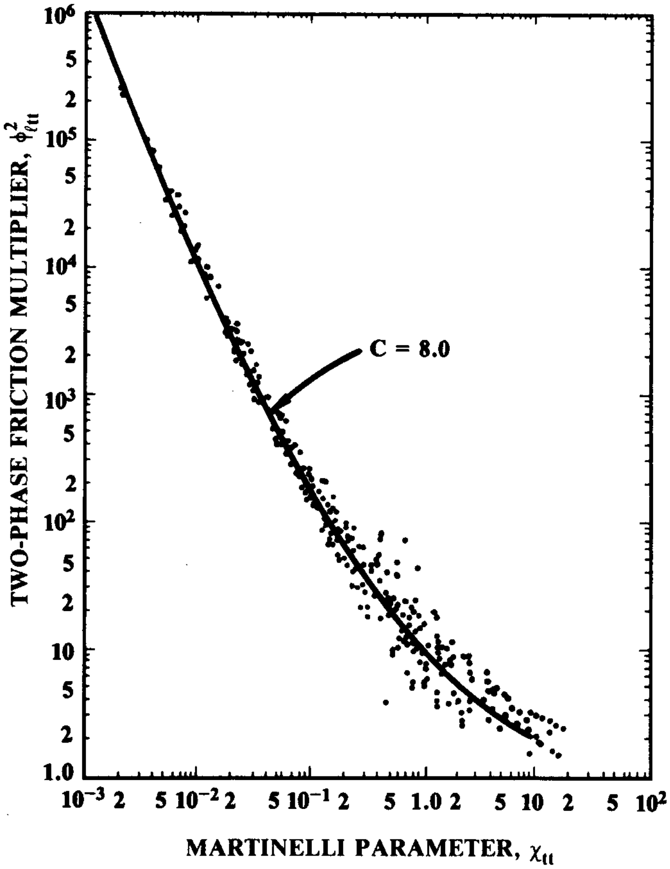

Fig. 5.32 Martinelli parameters for shell-side pressure drop data [56].

The friction head loss equations are those for flow across tube banks where the maximum mass velocity is based on the minimum flow area between the tubes, hence

$$\Delta P_\ell = 4 f_\ell N\, G^2_{t\max} (1-x)^2 (1/2 g_c \rho_\ell) \tag{5.58}$$

$$\Delta P_v = 4 f_v N\, G^2_{t\max} x^2 (1/2 g_c \rho_v) \tag{5.59}$$

and

$$\Phi^2_{\ell tt} = 1 + 8/x_{tt} + (x_{tt})^2 \tag{5.60}$$

$$\Phi^2_{vtt} = 1 + 8 x_{tt} + (x_{tt})^2 \tag{5.61}$$

Equations 5.53, 5.54, and 5.29 are unchanged.

The above equations can be used to develop circulation models for shell-side boiling. In a kettle reboiler with a cylindrical tube bundle, additional problems arise as to how to consider the flow through the bundle as both the height and flow area varies as one proceeds vertically through the bundle. There are also problems in how to calculate the downleg flow in the area between the shell and bundle outside diameter. A further complication is an allowance for a lower density due to some bubble entrainment in the recirculation stream. All these problems need further investigation plus some data on low vapor fraction two-phase flow pressure drops before shell-side circulation prediction methods can be useful.

Fair and Klip (61) proposed a shell-side circulation model and included the effect of flow across bundles of varying width and depth. They used the Grant and Chisholm (62) correlation equations. The analysis appears promising but needs to be compared to a wider range of reboiler designs together with a need for specific experiments to attempt circulation measurements in kettle reboilers.