TECHNICAL NOTE

Two-phase vertical upflow through tube banks with bypass lanes

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Equations are developed for predicting the pressure gradient during the upward flow of two-phase mixtures through tube banks with bypass lanes at the walls of the duct. Satisfactory agreement is demonstrated with experiment

Key words: *tube heat exchangers, two phase flow, bypass effects*

In many industrial processes fluid flows across banks of tubes in ducts. It is important in these circumstances to allow for, or to eliminate by the use of sealing strips, bypass effects; there is a tendency for the fluid to flow more quickly along the smooth duct wall, thereby reducing flow through the bank of tubes.

This problem can be important in two-phase flow for an additional reason; one of the phases may flow preferentially along the wall, altering the composition within the tube bank. If, for example, the bank is being used to boil a liquid it is obviously undesirable that the liquid should be flowing along the duct wall.

Polley and Grant[1] obtained good agreement with experimental data for vertical upflow through banks with bypass lanes with the following assumptions:

- the pressure drop through bank and bypass are the same;
- the liquid and gas distribute themselves to give minimum pressure drop.

They found on this basis that the minimum pressure drop was obtained either when the bypass flow was almost all liquid, or almost all gas. As a result of experimental observations they concluded that the 'almost all liquid' situation was that which occurred in practice. On this basis they were able to predict the observed pressure drop to within ±20%.

Barbe and Roger[2] observed that their experimental data were well represented using whichever is the greater of:

$$-\mathrm{D}p = g\rho_L \tag{1}$$

and:

$$\mathrm{D}p = \mathrm{D}p_{FL} + 2\sqrt{\mathrm{D}p_{FL}\mathrm{D}p_{FG}} + \mathrm{D}p_{FC} \tag{2}$$

No model was proposed to support these relationships. These equations do not satisfactorily predict the Polley and Grant[1] data at higher mass velocities.

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This note develops equations similar to those of Barbe and Roger[2], and develops equations for determining the error, with increasing mass flow rate, in using these equations. The basic assumption used here is that, at lower mass dryness fractions, the bypass will only contain liquid.

Basic relationships

On the basis that the liquid phase will occupy the bypass in vertical upflow, and that the pressure drop is the same in each flow path:

$$\mathrm{D}p = \mathrm{D}p_{FLb} - g\rho_L \tag{3}$$

where $\mathrm{D}p_{FLb}$ is the pressure gradient due to friction and form drag in the bypass. At lower flow rates this can be approximated by Eq (1).

With decreasing liquid content of the flow, that is with increasing dryness fraction, a point will be reached where no liquid flows through the bank. In

Notation

A	Minimum flow cross-section over bank and bypass
A_b	Minimum flow cross-section in bypass
C	Blasius coefficient for bank with bypass
C_b	Blasius coefficient for bypass
C_i	Blasius coefficient with no bypass
$\mathrm{D}p$	Static pressure gradient:
$\mathrm{D}p_{FG}$	due to friction when gas flows alone
$\mathrm{D}p_{FL}$	due to friction when liquid flows alone
$\mathrm{D}p_{FLb}$	due to friction when liquid only flows through bypass
g	Gravitational acceleration
G	mass flow rate
n	Blasius exponent
X	Lockhart–Martinelli parameter
ρ_L	Liquid density

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that case the static pressure gradient through the bank is:

$$\mathrm{D}p = \mathrm{D}p_{FG}\left(\frac{A}{A-A_b}\right)^{2-n}\frac{C_i}{C} \tag{4}$$

where A is the total flow cross-section and A_b that in the bypass. $\mathrm{D}p_{FG}$ is the pressure gradient if the gas flows alone, C_i is the Blasius coefficient for the tube bank with no by-pass lane, C the coefficient with a by-pass lane, and n the Blasius exponent. The exponent is assumed the same in both banks. The gravitational force on the gas is neglected.

With further increase in mass dryness fraction the gradient will approach:

$$\mathrm{D}p = \mathrm{D}p_{FG} \tag{5}$$

Comparison with experiment

Barbe and Roger[2] tested an in-line tube bank, 3 rows wide and 2.5 m long, with air–water and propane (56%)–ethane (44%) mixtures. The tubes were 6.9 mm in diameter on a 1.5 pitch diameter ratio. The ratio $A/(A-A_b)$ is understood to be 1.5.

Figs 1 and 2 compare the data with Eqs (1) and (5), as a plot of $\mathrm{D}p/\mathrm{D}p_{FL}$ to a base of the Lockhart–Martinelli parameter X. Except at the highest mass flow rate of 208 kg/(m^2 s) the agreement with experiment is satisfactory. Eqs (1) and (2) gave[2] a rather similar agreement with experiment.

It is evident that the transition from Eq (1) to Eq (5) occurs at:

$$-\mathrm{D}p_G = g\rho_L \tag{6}$$

Where gas pressure gradient exceeds $g\rho_L$, Eq (5) is applicable.

Correction for by-pass friction

Where C_b is the Blasius coefficient with bypass, the relationship between the various coefficients can be readily shown to be[3,4]:

$$\frac{C_b}{C} = \frac{N}{N_b}\left[\frac{A_b}{A} + \left(1-\frac{A_b}{A}\right)\left(\frac{C_b}{C_i}\frac{N}{N_b}\right)^{1/(2-n)}\right]^{2-n} \tag{7}$$

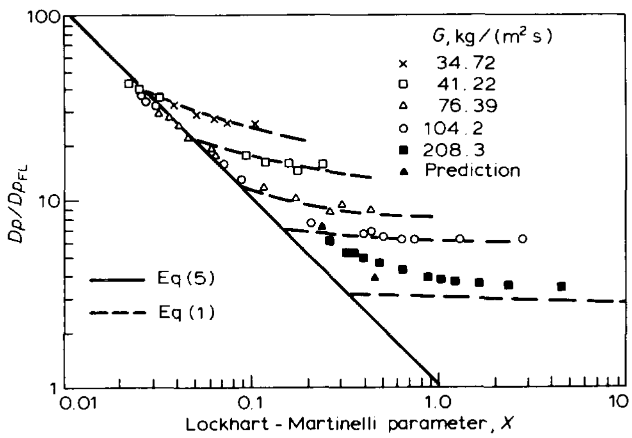

Fig 1 $\mathrm{D}p/\mathrm{D}p_{FL}$ to base of the Lockhart–Martinelli parameter for an air–water mixture at a pressure of 1 bar

The number of restrictions in the bypass, N_b, may differ from the number of restrictions in the tube bank for a staggered arrangement. At the condition where Eq (4) applies, the bypass friction pressure gradient is:

$$\mathrm{D}p_{FLb} = \mathrm{D}p_{FL}\left(\frac{A}{A_b}\right)^{2-n}\frac{C_b}{C} \tag{8}$$

Hence from Eqs (3) and (8)

$$-\frac{\mathrm{D}p}{g\rho_L} = 1 - \frac{\mathrm{D}p_{FL}}{g\rho_L}\left(\frac{A}{A_b}\right)^{2-n}\frac{C_b}{C} \tag{9}$$

Combining Eqs (4) and (9) and re-arranging gives the value of X at which Eq (9) applies:

$$\frac{1}{X^2} = \frac{\mathrm{D}p_{FG}}{\mathrm{D}p_{FL}} = -\frac{g\rho_L}{\mathrm{D}p_{FL}}\left(1-\frac{A_b}{A}\right)^{2-n}\frac{C}{C_i} + \left(\frac{A}{A_b}-1\right)^{2-n}\frac{C_b}{C_i} \tag{10}$$

Table 1 shows values predicted using these equations; a specimen calculation is given in the appendix. The third column in the table is a measure of the error introduced by neglecting bypass friction. It is only at

Table 1 Correction for bypass friction

G, kg/(m^2 s)	$\frac{g\rho_L}{\mathrm{D}p_{FL}}$	$-\frac{\mathrm{D}p}{g\rho_L}$ Eq (9)	X Eq (10)
AIR–WATER	From Fig 1		
208	3.1	1.488	0.4341
104	7.0	1.096	0.2241
76	10.0	1.007	0.1605
47	19.0	1.013	0.0859
35	30.0	1.005	0.0546
PROPANE–ETHANE	From Fig 2		
114	3.5	1.383	0.3988
81	6.0	1.130	0.2574
47	15.0	1.021	0.1083

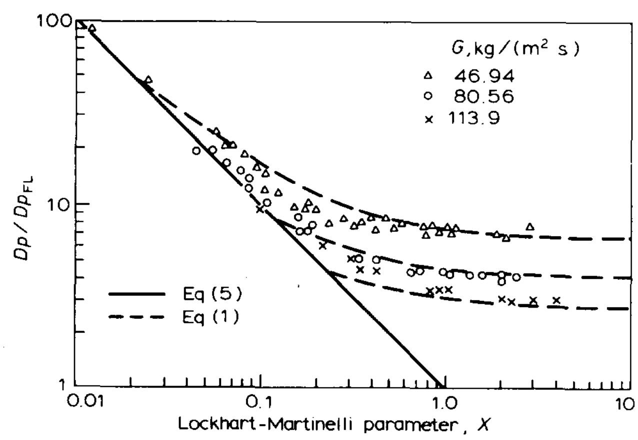

Fig 2 $\mathrm{D}p/\mathrm{D}p_{FL}$ for a propane–ethane mixture the two highest mass velocities that friction in the bypass is important; this is entirely consistent with the data in Fig 1.

In the case of the two highest mass velocities the predicted values are shown in Fig 1. At the lower mass velocities the predicted points are, for practical purposes, on the curve given by Eq (1). Thus it appears that this procedure is adequate in assessing when bypass friction is significant.

Conclusions

A simple method for predicting pressure gradient in vertical two-phase flow across tube banks, at low mass velocities, with bypass lanes has been developed and compared with experiment. The greater of the pressure gradients given by Eqs (1) and (5) should be used.

Eqs (9) and (10) can be used to determine the upper value of mass velocity that can be used for a given accuracy of prediction.

At higher mass velocities the Polley–Grant method is recommended.

References

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Appendix

The procedure to estimate the Lockhart–Martinelli parameter at the point where all the liquid is flowing in the bypass, with no gas in that flow path is now demonstrated. The mass velocity is 208 kg/m^2 s.

From Fig 1, taking as an approximation the value where Eqs (1) and (5) intersect:

$$\left(-\frac{g\rho_L}{Dp_{FL}}\right)^{1/2}=3.1$$

Also:

$$\frac{A_b}{A}=\frac{1}{3}$$

Assuming[3] $C_b/C_i=0.5$ and $n=0.2$ then using Eq (7):

$$\frac{C_b}{C}=\left[\frac{1}{3}+\left(1-\frac{1}{3}\right)(0.5)^{1/1.8}\right]^{1.8}=0.6496$$

Using Eq (9):

$$-\frac{Dp}{g\rho_L}=1+\frac{1}{3.1^2}\times 3^{1.8}\times 0.6496=1.488$$

The corresponding value of X is obtained using Eq (10). First:

$$\frac{C}{C_i}=\frac{C}{C_b}\cdot\frac{C_b}{C_i}=\frac{0.5}{0.6496}=0.7697$$

Hence from Eq (10):

$$X=1/[3.1^2(1-\tfrac{1}{3})^{1.8}0.7697+3.1^{1.8}\times 0.5]^{0.5}=0.4341$$

At this value of X the ratio $(-g\rho_L/Dp_{FL})^{1/2}$ is only marginally less than assumed above.

At a mass velocity of 104 kg/m^2 s:

$$\left(-\frac{g\rho_L}{Dp_{FL}}\right)^{1/2}=7$$

Hence, again using Eq (9):

$$-\frac{Dp}{g\rho_L}=1+\frac{1}{7^2}\times 3^{1.8}\times 0.6476=1.096$$

and, using Eq (10), the corresponding value of X is:

$$X=1/[7^2\times(1-\tfrac{1}{3})^{1.8}0.7697+(3-1)^{1.8}\times 0.5]^{0.5}$$
$$=0.2241$$