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SUBJECT: A Method of Correlating Experimental Fluid Friction
Data for Square Array Tubular Heat Exchangers

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SUMMARY

An analytical method of correlating fluid friction data for flow parallel to square array cylindrical tubes in rectangular cross-sectional flow channels has been devised. Using this technique, the experimental values for friction factors and Reynolds moduli are multiplied by correlation terms which yield new friction factors and Reynolds moduli that pertain to the core region of the tube bundle excluding the wall effects. Model configurations with different numbers of tubes and different tube bundle to shell wall spacing can thus be correlated by converting the data to those which would apply to an infinite array tube bundle.

NOMENCLATURE

- a = cross-sectional flow area of channel, ft^2
 B = constant in $f = B N_{\text{Re}}^{-C}$
 C = constant in $f = B N_{\text{Re}}^{-C}$
 d = hydraulic diameter ($4a/p$), ft
 D = tube diameter, ft
 f = friction factor defined by $f = \frac{\Delta P}{\frac{L}{d} \frac{\rho u^2}{2g_c}}$
 g_c = gravitational conversion factor = $4.170 \times 10^8 \text{ lb}_m\text{-ft}/\text{lb}_f\text{-hr}^2$
 L = channel length, ft
 n = number of channels
 N_x = number of tubes in a horizontal row
 N_y = number of tubes in a vertical row
 N_{Re} = Reynolds modulus defined by $N_{\text{Re}} = \frac{u d}{\nu}$
 s = tube spacing, wall to wall, ft . (assumed to be the same in both x and y directions)
 s' = tube to shell wall spacing, ft . (assumed to be the same in both x and y directions)
 s_1 = s/D
 s_2 = s'/D
 u = mean fluid velocity, ft/hr
 p = wetted perimeter, ft
 ΔP = pressure drop through channels, lb_f/ft^2
 ν = kinematic viscosity, ft^2/hr
 ρ = fluid density, lb_m/ft^3
 q = volumetric flow rate, ft^3/hr

Subscripts

- 1: central channels
 2: side channels
 3: corner channels
 e: total or experimental

INTRODUCTION

In obtaining experimental fluid friction data for flow parallel to square array cylindrical tubes in rectangular cross-sectional flow channels, it is customary to use a mean velocity determined by dividing the total volumetric flow by the total cross-sectional flow area and to use the hydraulic diameter which is based on the total wetted perimeter. However, in the heat exchanger shell, there are side and corner flow channels which will contribute to the data thus obtained. Since the effect of these peripheral channels will be different for different numbers of tubes and/or tube to shell wall spacing, this effect should be considered in the general correlation of data. The smaller the number of tubes in the heat exchanger, the greater will be the effect of the peripheral channels; for example, if the bundle consists of a five by five array of twenty-five tubes, there will be twenty peripheral channels and only sixteen central core channels.

By making use of the continuity equation and the hydraulic diameter correlation concept for flow channels of different configurations, two correlation factors are evolved which yield new friction factors and Reynolds moduli that pertain to the core region of the tube bundle and exclude the effects caused by flow adjacent to the shell wall of the heat exchanger.

ANALYSIS OF SYSTEM

The fluid actually flows through three distinct types of channels as shown in Figure 1: (1) those in the core of the tube bundle, (2) those

Fig. 1. Cross Section of Tube Bundle Showing the Three Types of Flow Channels.

adjacent to the shell wall, and (3) those at the corners of the tube bundle. If the hydraulic diameters of these channels are not the same, for a given pressure drop, each will have a different mean fluid velocity and hence a different Reynolds modulus and friction factor. This analysis is based upon the assumption that fully developed turbulent flow is established, hence the equation $f = B N_{Re}^{-C}$ applies to all three types of channels with the same values for the constants B and C. It is then possible to interpret the experimental data in terms of the fluid friction characteristics for a single central flow channel or, the so-called infinite array.

The following equations for the flow cross-sectional area, wetted perimeter and hydraulic diameter apply to the three types of flow channels.

$$a_1 = D^2 \left[(S_1 + 1)^2 - \frac{\pi}{4} \right] \text{-----} (1)$$

$$P_1 = \pi D \text{-----} (2)$$

$$d_1 = D \left[\frac{4(S_1 + 1)^2 - \pi}{\pi} \right] \text{-----} (3)$$

$$a_2 = D^2 \left[(S_1 + 1)(S_2 + \frac{1}{2}) - \frac{\pi}{8} \right] \text{-----} (4)$$

$$P_2 = D(S_1 + 1 + \frac{\pi}{2}) \text{-----} (5)$$

$$d_2 = D \left[\frac{4(S_1 + 1)(S_2 + \frac{1}{2}) - \frac{\pi}{2}}{S_1 + 1 + \frac{\pi}{2}} \right] \text{-----} (6)$$

$$a_3 = D^2 \left[(S_2 + \frac{1}{2})^2 - \frac{\pi}{16} \right] \text{-----} (7)$$

$$P_3 = D(2 S_2 + 1 + \frac{\pi}{4}) \text{-----} (8)$$

$$d_3 = D \left[\frac{4(S_2 + \frac{1}{2})^2 - \frac{\pi}{4}}{2 S_2 + 1 + \frac{\pi}{4}} \right] \text{-----} (9)$$

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For the experimental data, which are taken for all channels as a group, the following equations apply:

$$a_e = D^2 \left[(N_x + N_x S_1 - S_1 + 2S_2)(N_y + N_y S_1 - S_1 + 2S_2) - \frac{N_x N_y \pi}{4} \right] \quad (10)$$

$$p_e = D \left[2(N_x + N_y + N_x S_1 + N_y S_1 - 2S_1 + 4S_2) + N_x N_y \pi \right] \quad (11)$$

$$d_e = D \left[\frac{4(N_x + N_x S_1 - S_1 + 2S_2)(N_y + N_y S_1 - S_1 + 2S_2) - N_x N_y \pi}{2(N_x + N_y + N_x S_1 + N_y S_1 - 2S_1 + 4S_2) + N_x N_y \pi} \right] \quad (12)$$

By summing the quantities for the individual channels, it can be demonstrated that

$$a_e = n_1 a_1 + n_2 a_2 + n_3 a_3 \quad (13)$$

$$p_e = n_1 p_1 + n_2 p_2 + n_3 p_3 \quad (14)$$

$$d_e = \frac{4(n_1 a_1 + n_2 a_2 + n_3 a_3)}{n_1 p_1 + n_2 p_2 + n_3 p_3} \quad (15)$$

and by definition

$$n_1 = (N_x - 1)(N_y - 1) \quad (16)$$

$$n_2 = 2(N_x + N_y - 2) \quad (17)$$

$$n_3 = 4 \quad (18)$$

The experimental friction factor and Reynolds modulus are obtained from

$$f_e = \frac{\Delta P}{\frac{L}{d_e} \frac{\rho u_e^2}{2g_c}} \quad (19)$$

and

$$N_{Re_e} = \frac{u_e d_e}{\nu} \quad (20)$$

and for a central flow channel

$$f_1 = \frac{\Delta P}{\frac{L}{d_1} \frac{\rho u_1^2}{2g_c}} \quad (21)$$

and

$$N_{Re_1} = \frac{u_1 d_1}{\nu} \quad (22)$$

From these equations,

$$\frac{f_1}{f_e} = \frac{d_1}{d_e} \left(\frac{u_e}{u_1} \right)^2 \quad (23)$$

and

$$\frac{N_{Re_1}}{N_{Re_e}} = \frac{d_1/d_e}{u_e/u_1} \quad (24)$$

These are the factors by which the experimental friction factors and Reynolds moduli may be multiplied to obtain the friction characteristics of a central flow channel. The hydraulic diameters d_1 and d_e are obtained from equations (3) and (12) and the relationship between u_e and u_1 is obtained by the following method. The experimental mean fluid velocity, u_e , is obtained by dividing the total quantity flow, q_e , by the total cross-sectional flow area, then

$$q_e = n_1 q_1 + n_2 q_2 + n_3 q_3 \quad \text{or}$$

$$u_e a_e = n_1 u_1 a_1 + n_2 u_2 a_2 + n_3 u_3 a_3$$

Therefore

$$\frac{u_e}{u_1} = \frac{n_1 a_1}{a_e} + \frac{n_2 a_2}{a_e} \left(\frac{u_2}{u_1} \right) + \frac{n_3 a_3}{a_e} \left(\frac{u_3}{u_1} \right) \quad (25)$$

$$\text{Since } f \sim N_{Re}^{-C} = \frac{\nu^C}{u^C d^C}$$

$$\Delta P = \frac{L}{d_1} \frac{\nu^C}{u_1^C d_1^C} \frac{\rho u_1^2}{2g_c} = \frac{L}{d_2} \frac{\nu^C}{u_2^C d_2^C} = \frac{L}{d_3} \frac{\nu^C}{u_3^C d_3^C} \frac{\rho u_3^2}{2g_c} \quad \text{or}$$

$$\frac{u_2}{u_1} = \left(\frac{d_2}{d_1} \right)^{\frac{1+C}{2-C}} \quad \text{-----} \quad (26)$$

and

$$\frac{u_3}{u_1} = \left(\frac{d_3}{d_1} \right)^{\frac{1+C}{2-C}} \quad \text{-----} \quad (27)$$

By using these equations, the correlation factors f_1/f_e and N_{Re_1}/N_{Re_e} can be determined for a given configuration and assumption for C . It is possible to express these correlation factors in terms of N_x , N_y , S_1 and S_2 ; but as these equations are long and complicated it is simpler to work in steps with the individual equations as stated.

DISCUSSION

This analysis should be useful in the general correlation of fluid friction data from square array heat exchangers of different configurations. There are three main points that should be emphasized:

1. Fully developed turbulent flow should exist at all times. Unless turbulent flow exists, the results of this analysis will be in error since for laminar flow, the friction characteristics are dependent upon the shape of the cross-sectional flow area and the use of the hydraulic diameter as a correlating term for different shapes is invalid.

2. For a given configuration, the hydraulic diameters of the three different types of channels should not have widely differing values. It is recommended that in the design of a model configuration, the shell be designed so that the hydraulic diameter of the side flow channels will be the same as that of the central flow channels. Under this condition, the effect of these correlation factors will be a minimum being controlled only by the small effect of the four corner flow channels.

3. The value for C should be judiciously chosen, i.e., it should correspond to the slope of the original f vs. N_{Re} curve when plotted logarithmically.