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EQUIVALENT f AND j FACTORS FOR CONDENSATION INSIDE HORIZONTAL SMOOTH AND FINNED TUBES

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ABSTRACT

For condensation inside horizontal smooth and finned tubes, the equivalent f and j factors can be employed to correlate the pressure drop and heat transfer performance, respectively. They are empirically found to be $f_{eq}=10^{-8}Re_{eq}^{-0.2}$ and $j_{eq}=0.045\ Re_{eq}^{-0.2}$ where Re_{eq} is the equivalent Reynolds number.

It is well known that the pressure drop and heat transfer performance may be expressed in dimensionless form as the Fanning friction coefficient f and Colburn's j factor. For turbulent flows inside tubes the f and j factors are empirically determined to be

$$f = 0.046\ Re^{-0.2} \qquad \text{and} \qquad j = f/2 \tag{1}$$

respectively, where Re denotes the Reynolds number. The so-called "goodness factor, i.e. j/f, takes the maximum value of 1/2 for long tubes.

In the case of condensation of refrigerant vapors inside smooth [1-4] and finned [2,3] tubes, the Nusselt number was employed for heat transfer correlation:

$$Nu = C\ Re_{eq}^{\ 0.8}\ Pr_{\ell}^{\ 1/3} \tag{2}$$

Here, C is an empirical constant equal to 0.05 [1], 0.0265 [4], or $0.02\ P_o^{-0.65}$ [2,3] where P_o is the ratio of the saturation pressure P_{sat} to the critical pressure of the fluid, P_c. Pr_{ℓ} is the Prandtl number for the liquid phase. Re_{eq} is the equivalent Reynolds number defined as

$$Re_{eq} = Re_{\ell} + Re_v(\mu_v/\mu_{\ell})(\rho_{\ell}/\rho_v)^{1/2} = D\ G_{eq}/\mu_{\ell} \tag{3}$$

in which μ_v and μ_{ℓ} are the vapor and liquid viscosities, and ρ_v and ρ_{ℓ} are the vapor and liquid densities, respectively. Re_v and Re_{ℓ} are evaluated as though each of the vapor and liquid flows were taking up the entire tube cross section. The characteristic length D is the inside diameter for the smooth tube and two times the hydraulic diameter for the internally finned tube [2,3]. G_{eq} is the equivalent mass velocity defined as

$$G_{eq} = \bar{G}_\ell + \bar{G}_v(\rho_\ell/\rho_v)^{1/2} \tag{4}$$

wherein G_{eq} is the equivalent liquid mass velocity (considering the total flow as an entirely liquid flow, Ref. 4) and $\bar{G}_\ell$ and $\bar{G}_v$ are the average mass velocities of the liquid and vapor, respectively. Several schemes have been proposed for correlating or predicting pressure drop. Elaborate calculations are required to identify the flow pattern using a flow regime map and its change along the tube [2,3,5,6]. It is a well-known fact that flow regime maps such as the Baker plot have a wide range of deviation. Different empirical equations are then employed for different flow patterns to determine the corresponding pressure drop. Since temperature affects the physical properties of the fluids and thus their flow velocity and pattern, a digital computer is usually employed for the pressure drop calculations. For a designer, the task is laborious and complicated.

In this paper, an attempt is shown to correlate the pressure drop and heat transfer performance for condensation of refrigerants inside smooth as well as finned tubes by using the equivalent f and j factors as functions of the equivalent Reynolds number in a manner analogous to single-phase flow. One defines

$$f_{eq} = \Delta P/(2G_{eq}{}^2 L/\rho_\ell D) \quad \text{and} \quad j_{eq} = Nu/(Re_{eq}Pr_\ell{}^{1/3}) \tag{5}$$

wherein L is the tube length for condensation. All fluid properties are those of the condensate, evaluated at the average film temperature. It should be noted that equation (5) may be reduced to those for single-phase flow.

In References [2,3], a total of 48 tests were conducted for condensation of Freon 12 in a smooth tube (7.75 mm ID) and two internally finned tubes (150% finned tube with 7.75 mm ID and 6 axial straight fins of 1.016 mm height and 0.889 mm thickness; 275% finned tube with 10.92 mm ID and 10 fins of 2.794 mm height and 0.508 mm thickness). The tubes are 6.4 m in length, mounted horizontally. The predominant flow patterns are dispersed, annular and slug flows. The test data range from P_{sat} = 95 psig to 295 psig, equivalent to $P_o{}^{-0.65}$ from 3.00 to 1.53. Using the average value of $P_o{}^{-0.65}$, i.e. 2.25, one gets 0.045 for $C = 0.02\ P_o{}^{-0.65}$ in equation (2). Then, equation (2) can be rewritten as

$$j_{eq} = 0.045\ Re_{eq}^{-0.2} \tag{6}$$

This equation can correlate the heat transfer data for condensation inside both the smooth and finned tubes within ± 30 percent as demonstrated in Refs. [2,3] through the use of equation (3). If the Cavallini-Zecchin's equation which is developed for smooth tubes and lower P_{sat} (100 to 150 psig) were employed the constant in equation (6) would have been 0.05.

Pressure-drop test data of References [2, 3] have been correlated in the form of f_{eq} versus Re_{eq} as shown in Fig 1. All test data fall within ± 50 percent of the equation

$$f_{eq} = 10^{-8}\ Re_{eq}^{-0.2} \tag{7}$$

In view of the complicated physical phenomena taking place in the two-phase flow, particularly inside the finned tubes, the extent of data scattering, although large compared to the single-phase flow case, is acceptable for condenser design considering the simplicity in the use of the equation.

As a corollary, the "goodness" factor, j_{eq}/f_{eq}, is obtained from equations (6) and (7) to be 4.5×10^6, seven orders of magnitude higher than that for the single-phase flow case. This may be taken as an indication of how much more effective condensation is in transferring heat compared to forced convection at the same expense in the pumping power.

Acknowledgment

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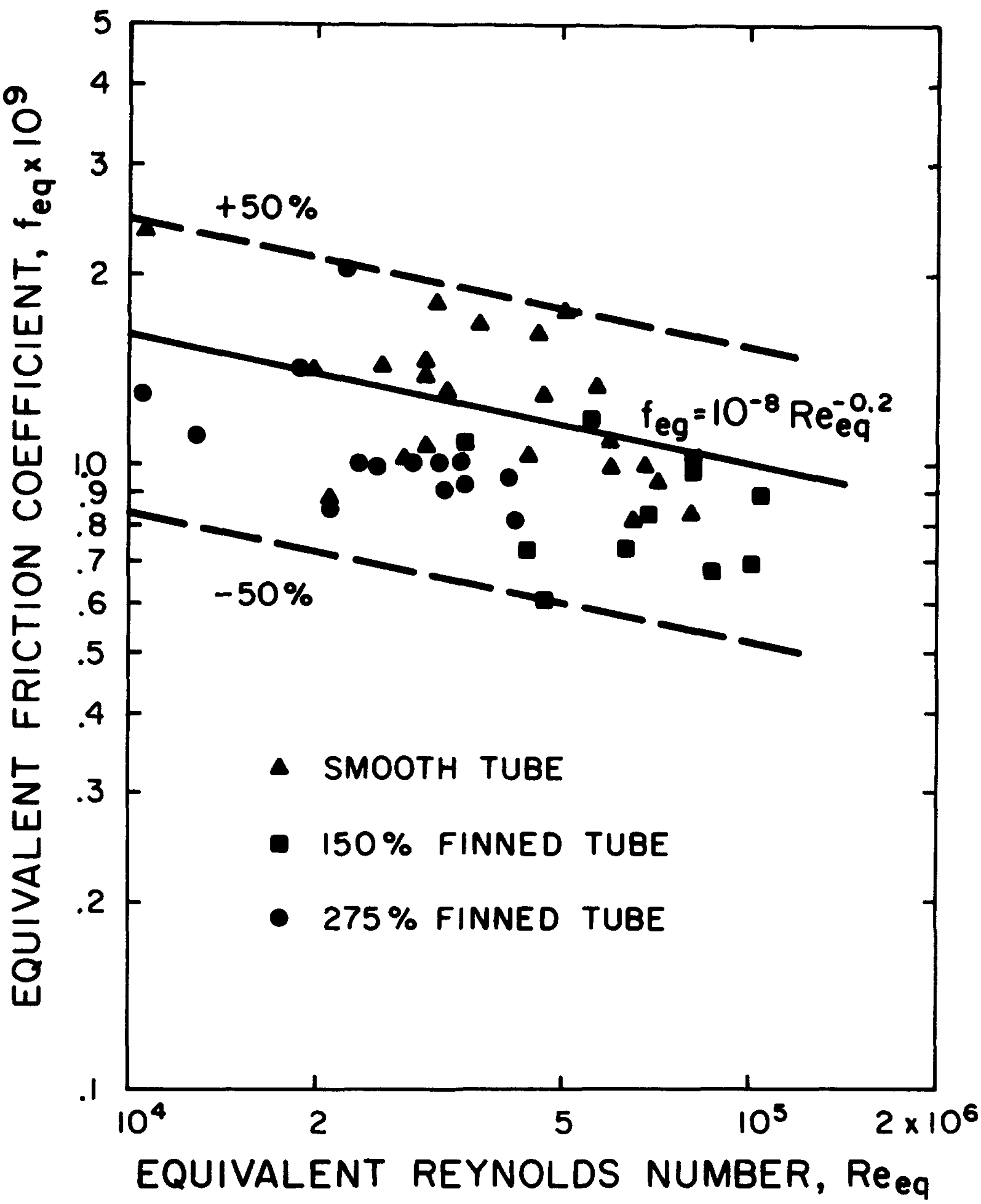

FIG. 1

Correlation of friction drop data for condensation inside smooth and finned tubes [2,3]