Role of Surface Tension and Tube Diameter in Film Condensation on Horizontal Tubes

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The Nusselt equation for film condensation has been used successfully to correlate heat transfer data for a number of systems. However, in the case of condensation on the outside of horizontal cylinders the data for various substances and for different pipe diameters do not appear to be adequately handled by the Nusselt equation alone. As a consequence different values of the constant 1.2 in Equation (1) are usually obtained for each individual case (*1*).

$$h_{Nu}\left(\frac{\mu_f^2}{k_f^3\,\rho_f^2 g_c}\right)^{1/3} = 1.2\ N_{Re_f}^{-1/3} \qquad (1)$$

where

$$N_{Re_f} = 2\Gamma'/\mu_f$$

It appears that most of the deviation is due to the thickening of the film and droplet breakoff which occur along the bottom of the pipe. Silver has developed a correction for resistance at the liquid-vapor interface involving molecular capture of gas molecules by the liquid. This correction is only important at very low pressures (*10*).

The processes which take place at the bottom of the pipe depend upon the surface tension and density of the liquid and on the pipe diameter. The relationships involved are the same as those used in the drop weight and pendant drop methods for measuring surface tension (*2*). The force available to support the weight of the drop is given by surface tension force times the circumference of the supporting area.

Since the complete description of the problem is complex, it was decided to resort to a dimensional analysis approach for the purposes of correlating heat transfer data. In view of the fact that the Nusselt equation adequately handles all but a region near the bottom of the pipe, only a dimensionless correction factor to be applied to the Nusselt equation was sought. The dimensionless group obtained in this manner was the Ohnesorge number N_{Oh}, which is used in atomization. The proposed correlation is of the form

$$\frac{h_m}{h_{Nu}} = A\ N_{Oh}^{B} \qquad (2)$$

where

$$N_{Oh} = \mu/(\rho g_c D\,\sigma)^{1/2}$$

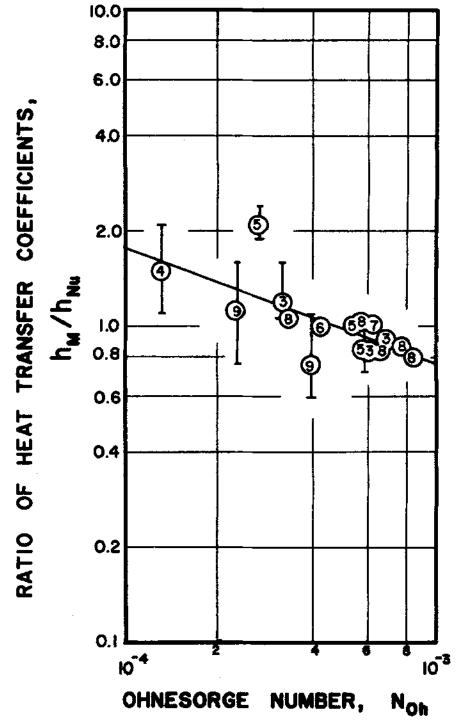

Fig. 1. Effect of Ohnesorge number.

The data of various observers who condensed pure saturated vapors outside single horizontal tubes are summarized in Figure 1 and Table 1. For clarity only the range of observed values of h_m/h_{Nu} is given. In most cases where only a few points are reported, the circle covers the observed range. In several instances the range is quite wide and the circle is located at the mean value. The values of h_m/h_{Nu} presented in Table 1 were calculated from the data presented in the references cited. In several instances the values of h_m/h_{Nu} differ from those given in reference *1*.

The data in Figure 1 indicate that h_m/h_{Nu} may be correlated in terms of the Ohnesorge number, evaluated at the film temperature, as suggested by Equation (1). The least squares fit is given by

$$\frac{h_m}{h_{Nu}} = 0.057\ N_{Oh}{}^{-0.373} \qquad (3)$$

As shown in Figure 1, Equation (3) correlates the data of a number of different substances and different pipe diameters. It provides a means of accounting for the processes which occur at the bottom of the pipe. Thus the gen-

TABLE 1. CONDENSATION HEAT TRANSFER COEFFICIENTS

Vapor	$\frac{h_m}{h_{Nu}}$	$N_{Oh_f}\times 10^4$ (mean)	Diameter, in.	Reference
Steam	1.0 to 1.6	3.20	0.675	*3*
Steam	1.1 to 2.1	1.33	3.0	*4*
Steam	1.9 to 2.4	2.65	0.84	*5*
Steam	0.7 to 1.9	2.25	1.125	*9*
Benzene	0.8 to 0.9	6.00	0.675	*3*
Benzene	0.8 to 1.2	4.15	1.31	*6*
Benzene	0.9 to 1.1	5.25	0.84	*5*
Benzene	1.0 to 1.1	6.10	0.625	*7*
Tetrachloromethane	0.9	6.90	0.675	*3*
Toluene	0.7 to 1.0	5.75	0.84	*5*
Toluene	0.6 to 1.1	4.00	1.125	*9*
Methanol	1.06	5.65	2.0	*8*
Ethanol	1.02	3.30	2.0	*8*
Propanol	0.87	7.75	2.0	*8*
Butanol	0.85	8.30	2.0	*8*
i-Propanol	0.7 to 0.9	6.85	2.0	*8*

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eral correlation of heat transfer data for condensation of pure substances on horizontal pipes is given by the combination of Equations (1) and (3).

$$h_m \left(\frac{\mu_f^2}{k_f^3 \rho_f^2 g_c}\right)^{1/3} = 0.069 \; N_{Oh_f}^{-0.373} \; N_{Re_f}^{-1/3}$$

This relation contains the Nusselt analysis and the corrections for the effects of surface tension and pipe diameter which are important at the bottom of the pipe.

NOTATION

A = least squares curve fit constant
B = least squares curve fit constant
D = pipe diameter
g_c = gravitational constant
h_m = observed mean heat transfer coefficient
h_{Nu} = Nusselt's mean heat transfer coefficient
k = thermal conductivity
N_{Oh} = Ohnesorge number, $\mu/(\rho g_c D \sigma)^{1/2}$
N_{Re} = Reynolds number

Greek Letters

Γ' = mass rate of flow of condensate
μ = viscosity
ρ = density
σ = surface tension

Superscript

f = physical property evaluated at film temperature

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Distillation in Packed Columns: The Relationship Between HTU and Packed Height

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HTU (or HETP) in packed distillation columns has been found to vary with packed height. The explanations that have been given are improper evaluation of end effects (*1*); phase channeling, that is, a small portion of the liquid flows down through the bed without any appreciable mass transfer between the phases (*2*); or the variation of mass transfer area with packed bed height (*3*).

It is the purpose of this communication to show quantitatively that longitudinal mixing (back mixing) of the phases is an important factor that determines the relation between HTU and packed height in the case where end effects have been evaluated properly and the liquid is distributed evenly ensuring uniform mass transfer area throughout the bed.

LONGITUDINAL MIXING MODEL

The model used to derive the relationship between HTU and packed height is the model developed by Miyauchi and Vermeulen (*4*) for two-phase flow operations. In this model the longitudinal mixing in each phase is characterized by a single parameter: the eddy dispersion coefficient.

The basic differential equations can be derived from steady state material balance for a differential element of the bed height dz.

For the gas phase

$$D_y \frac{d^2y}{dz^2} - G_M \frac{dy}{dz} - K_g a\,(y^* - y) = 0 \qquad (1a)$$

and for the liquid phase

$$D_x \frac{d^2x}{dz^2} + L_m \frac{dx}{dz} + K_g a\,(y^* - y) = 0 \qquad (1b)$$

$K_g a$ is the point mass transfer coefficient and its value is assumed to be constant throughout the bed.

The boundary conditions are

$$z = 0 \;:\; G_M y_B = G_M\, y - D_y \frac{dy}{dz} \qquad (2a)$$

$$\frac{dx}{dz} = 0 \qquad (2b)$$

$$z = 1 \;:\; L_M\, x_D = L_M\, x + D_x \frac{dx}{dz} \qquad (2c)$$

$$\frac{dy}{dz} = 0 \qquad (2d)$$