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A CORRELATION OF SUBCOOLED-BOILING PRESSURE DROP FOR LOW-PRESSURE WATER FLOWING IN TUBES WITH CONSTANT HEAT FLUX

by James R. Stone
Lewis Research Center
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TECHNICAL PAPER proposed for presentation at
1970 Heat Transfer and Fluid Mechanics Institute
Naval Postgraduate School, Monterey, California, June 10-12, 1970

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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James R. Stone*

E-5468

ABSTRACT

A one-dimensional-flow model is developed which relates the pressure drop for subcooled boiling inside straight, circular tubes with constant heat flux to parameters generally known (physical properties, heat flux, mass velocity, and geometry), and one unknown variable, the net fraction of heat added to the fluid which goes into vaporization. The basic equations of change are applied to a differential control volume. It is assumed that a modified single-phase friction factor may be used. Thus, an equation for the local pressure gradient is obtained, dependent only on known quantities and the vaporization-rate parameter. This equation is then integrated for constant heat flux, physical properties, and vaporization-rate parameter. The overall pressure drop is thus obtained as a function of known quantities and the effective mean value of the vaporization-rate parameter. The method of correlation is to determine mean values of this vaporization-rate parameter from experimental pressure drop data and then correlate this parameter as a function of test variables

The effects of non-equilibrium void fraction on pressure drop are adequately approximated to give a satisfactory correlation of the pressure-drop data. However, since the mean vaporization rate parameter is really a lumped pressure-drop parameter, based on several simplifying assumptions, this correlation should not be used to predict void fraction. The correlation is based on data for water at pressures from 17 to 400 psia, mass velocities from 0.61×10^6 to 10.4×10^6 lbm/(hr)(ft^2), and heat fluxes from 0.13×10^6 to 3.45×10^6 Btu/(hr)(ft^2). Calculations based on this correlation are simplified since no independent prediction of void fractions or experimental void-fraction data are required in order to predict the pressure drop.

INTRODUCTION

This analysis deals with the pressure drop during subcooled boiling at low pressures in straight circular tubes with constant heat flux. Subcooled boiling generates vapor within a fluid whose bulk temperature is below its saturation temperature. Thus, when a cold liquid contacts a sufficiently hot surface, vapor forms at the hot wall, and some of it condenses in the cold liquid stream. The resulting increased volume and velocity of the stream produces both a higher heat transfer coefficient and a pressure drop often several times greater than that for all-liquid flow.

Knowledge of pressure drop in subcooled boiling is important in the design of compact power systems with high-heat-flux boilers and direct-boiling nuclear reactors. The pressure drop must be known to determine local saturation temperatures and pumping power

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requirements. A better understanding of the subcooled-boiling regime also contributes to the understanding of boiling dynamics.

The problem of subcooled-boiling pressure drop is a particular area of the more general problem of pressure drop in two-phase flow, which has been the subject of numerous experiments and correlations. A comprehensive review of these studies is presented by Tong [1]. In order to apply such two-phase pressure-drop correlations to subcooled boiling, it is necessary that the vapor fraction be known. Since this is not generally known, especially at low pressures, most existing correlations of subcooled boiling pressure-drop data have been made on a purely empirical basis, and the extent of their validity is unknown. Three of the typical correlations are: Reynolds [2] for pressures from 45 to 100 psia, Owens and Schrock [3] for 50 to 400 psia, and Mendler, et al. [4] for 800 to 2150 psia. Thom, et al. [5] have recently developed a relation for the mean density of water in subcooled boiling at 750 to 1000 psia; this relation and Thom's earlier two-phase pressure-drop correlation [6] were used successfully to calculate subcooled-boiling pressure drop. Although this approach is more basic than the preceding correlations [2, 3, 4], the results may be limited to high pressures.

The differences in form of the various subcooled-boiling pressure-drop correlations and the fact that some data, such as those of Jeglic, Stone, and Gray [7], do not agree well with any of these correlations indicate that there is some uncertainty about the proper method of analyzing the data. Thus, it is desirable to develop equations which will allow the correlation of data over a wide range of test conditions. The purpose of this study is to produce a broadly applicable, but minimally complicated, correlation of subcooled-boiling pressure drop for low-pressure water flowing in tubes with constant heat flux. One of the available void-fraction predictions, e.g. [8, 9, 10], could be used, but this would greatly increase the complexity of the analytical formulation. However, the pressure-drop formulation must take into account the effects of void fraction, in order to give a satisfactory correlation of the pressure-drop data. This is done by determining a mean vaporization-rate parameter from the pressure-drop data to account for the phase non-equilibrium. Data are correlated for water at pressures from 17 to 400 psia, mass velocities from 0.61×10^6 to 10.4×10^6 lbm/(hr)(ft^2), heat fluxes from 0.13×10^6 to 3.45×10^6 Btu/(hr)(ft^2), tube diameters from 0.118 to 0.375 inch, and tube length-to-diameter ratios from 25 to 127.

DERIVATION OF CORRELATING EQUATIONS

The basic equations of change for homogeneous two-phase flow (mean gas velocity equal to mean liquid velocity) are applied to the differential control volume shown in Fig. 1. The void fraction is formulated in terms of the mean local velocity. This velocity is then related to the heat balance by means of a vaporization-rate parameter γ, which is the net fraction of the heat added through the wall that goes into vaporization. The resultant expressions for velocity and void fraction are substituted in the pressure-gradient equation, giving a relation which is a function of known variables, γ, and the two-phase friction factor, f_{TP}. The pressure-gradient equation is then integrated, assuming heat flux, physical properties, f_{TP}, and γ are constant. Assuming a simple relation for the effective mean two-phase friction factor, $\bar{f}_{TP}$, the overall pressure drop is obtained as a function of known variables and the effective mean value of the vaporization-rate parameter, $\bar{\gamma}$. The method of correlation is to determine effective mean values of the vaporization-rate parameter $\bar{\gamma}$ from experimental pressure-drop data and then correlate $\bar{\gamma}$ as a function of known parameters.

Continuity Equation

The continuity equation is used to obtain a relationship between the local average void fraction and the local average velocity. The continuity equation for steady two-phase flow may be written as follows:

$$d(v_g \rho_g A_g + v_l \rho_l A_l) = 0 \tag{1}$$

Introducing the assumptions of equal average phase velocities, i.e. $v_g = v_l = v$, and constant densities, and defining the average void fraction $\alpha = A_g/A$, there results:

$$\frac{d\alpha}{dv} = \frac{\rho_l - \alpha(\rho_l - \rho_g)}{v(\rho_l - \rho_g)} \tag{2}$$

Noting that the density of the liquid is much greater than that of the gas, Eq. (2) simplifies to:

$$\frac{d\alpha}{dv} = \frac{1 - \alpha}{v} \tag{3}$$

Separating variables and integrating, noting that at $\alpha = 0$, $v = G/\rho_l$, yields

$$\alpha = 1 - G/\rho_l v \tag{4}$$

Vapor Generation Equation

In this section the local mean velocity is related to the heat balance by means of the vaporization-rate parameter. As heat is added to a fluid flowing in the subcooled-boiling regime, an amount of fluid per unit time dW_v is vaporizing at the hot wall, and an amount dW_c is condensing in the subcooled stream; thus the net rate of vaporization in the control volume, $dW_v - dW_c$, is equal to $d(\rho_g v A_g)$. From the continuity equation (Eq. (4)), the net vaporization rate is given by

$$A\ d(\rho_g v \alpha) = \frac{\pi D^2}{4} \rho_g dv \tag{5}$$

The maximum rate of vapor formation is given by the rate of heat input, π Dq dz, divided by the enthalpy of vaporization λ. The ratio of the actual net rate of vaporization to the maximum is given by the expression:

$$\gamma = \frac{D\lambda\rho_g}{4q}\frac{dv}{dz} \tag{6}$$

By rearranging Eq. (6), the rate of change of velocity with distance may be obtained as follows:

$$\frac{dv}{dz} = \frac{4q\gamma}{D\lambda\rho_g} \tag{7}$$

Bowring [8] reports that the fraction of heat going into vaporization is essentially constant. But Levy [9] indicates that this is not the case and instead proposes an exponential variation of γ with heat-balance quality. This relationship is then shown by Kroeger and Zuber [10] to be an approximation. For simplicity in the present formulation, a mean, or lumped, value will be used. Thus, assuming that γ is constant, Eq. (7) may be integrated, noting that $v = G/\rho_l$ at $z = L_o$ (the inception of boiling). Thus v is obtained as a function of z.

$$v = \frac{G}{\rho_l} + \frac{4q\gamma}{D\lambda\rho_g}(z - L_o) \tag{8}$$

Momentum Equation

A momentum balance about the differential volume yields the following:

$$d\left(\frac{\rho_g A_g v^2}{g_c} + \frac{\rho_l A_l v^2}{g_c}\right) = -F\rho_l A_l\left(\frac{g}{g_c}\right)dz - A\,dP - \pi D\tau\,dz \tag{9}$$

where F is an orientation factor equal to the cosine of the angle between the $+z$ axis and the gravity vector. Again assuming constant densities, and making use of the continuity equation (Eq. (4)), the momentum equation may be simplified to yield the following equation for the pressure gradient:

$$-\frac{dP}{dz} = \frac{4\tau}{D} + \frac{G}{g_c}\frac{dv}{dz} + F\left(\frac{g}{g_c}\right)\rho_l(1 - \alpha) \tag{10}$$

Two-Phase Friction Factor

The two-phase friction factor is defined, by analogy to the single-phase (Fanning) friction factor, as the ratio of twice the shear stress to the total momentum flux or the resistive force divided by surface area times dynamic pressure:

$$f_{tp} = \frac{2\tau g_c}{\left(\rho_l A_l v^2 + \rho_g A_g v^2\right)/A} \tag{11}$$

Noting that ρ_g/ρ_l is much less than unity, and using Eq. (8), the frictional pressure drop term may be written

$$\frac{4\tau}{D} \cong \frac{2f_{tp}}{Dg_c}(Gv + \rho_g v^2) \tag{12}$$

The pressure gradient may now be obtained in terms of known parameters and γ, substituting Eqs. (4), (8), and (12) in Eq. (10), assuming $1 + (\rho_g/\rho_l) = 1$ and $1 + 2(\rho_g/\rho_l) = 1$.

$$-\left(\frac{dP}{dz}\right) = \frac{4\gamma}{D}\left(\frac{q}{G\lambda}\right)\left(\frac{G^2}{\rho_g g_c}\right) + \frac{2f_{tp}G^2}{D\rho_g g_c}\left[\left(\frac{\rho_g}{\rho_l}\right) + 4\gamma\left(\frac{q}{G\lambda}\right)\left(\frac{z - L_o}{D}\right) + 16\gamma^2\left(\frac{q}{G\lambda}\right)^2\left(\frac{z - L_o}{D}\right)^2\right] + \frac{F\left(\frac{g}{g_c}\right)\rho_l}{1 + 4\gamma\left(\frac{q}{G\lambda}\right)\left(\frac{\rho_l}{\rho_g}\right)\left(\frac{z - L_o}{D}\right)} \quad (13)$$

Integrated Pressure Drop Equation

The pressure gradient equation may be integrated assuming γ and f_{tp} are constant (as well as q, G, D and properties). Integrating from $z = L_o$ to $z = L$, and defining $L_b = L - L_o$, the following equation for the pressure drop is obtained.

$$\Delta P_b = \left[4\bar{\gamma}\left(\frac{q}{G\lambda}\right) + 2\bar{f}_{tp}\left(\frac{\rho_g}{\rho_l}\right)\right]\left(\frac{G^2}{\rho_g g_c}\right)\left(\frac{L_b}{D}\right) + 4\bar{\gamma}\bar{f}_{tp}\left(\frac{q}{G\lambda}\right)\left(\frac{G^2}{\rho_g g_c}\right)\left(\frac{L_b}{D}\right)^2 + \frac{32}{3}\left(\bar{\gamma}^2\bar{f}_{tp}\right)\left(\frac{q}{G\lambda}\right)^2\left(\frac{G^2}{\rho_g g_c}\right)\left(\frac{L_b}{D}\right)^3 + F\left(\frac{g}{g_c}\right)\rho_l L_b\left\{\frac{\ln\left[1 + 4\bar{\gamma}\left(\frac{q}{G\lambda}\right)\left(\frac{\rho_l}{\rho_g}\right)\left(\frac{L_b}{D}\right)\right]}{4\bar{\gamma}\left(\frac{q}{G\lambda}\right)\left(\frac{\rho_l}{\rho_g}\right)\left(\frac{L_b}{D}\right)}\right\} \quad (14)$$

The bars are written over γ and f_{tp} to indicate that these are effective mean values. Equation (14) may be nondimensionalized as follows. The dimensionless group, $q/G\lambda$, is commonly called the boiling number and is denoted in the remainder of this report by N_b.

$$\frac{\Delta P_b}{(G^2/\rho_g g_c)} = \left[4\bar{\gamma}N_b + 2\bar{f}_{tp}\left(\frac{\rho_g}{\rho_l}\right)\right]\left(\frac{L_b}{D}\right) + 4\bar{\gamma}\bar{f}_{tp}N_b\left(\frac{L_b}{D}\right)^2 + \frac{32}{3}\,\bar{\gamma}^2\bar{f}_{tp}N_b^2\left(\frac{L_b}{D}\right)^3 + F\left[\frac{\rho_l L_b(g/g_c)}{G^2/\rho_g g_c}\right]\left\{\frac{\ln\left[1 + 4\bar{\gamma}N_b\left(\frac{\rho_l}{\rho_g}\right)\left(\frac{L_b}{D}\right)\right]}{4\bar{\gamma}N_b\left(\frac{\rho_l}{\rho_g}\right)\left(\frac{L_b}{D}\right)}\right\} \quad (15)$$

Evaluation of Vaporization Rate Parameter

In order to make use of the model presented herein to calculate pressure drops, the mean vaporization-rate parameter $\bar{\gamma}$ must be known for the conditions of interest. To develop a means of predicting $\bar{\gamma}$, the data of Reynolds [2] and Jeglic, Stone, and Gray [7] are examined. For the purpose of evaluating $\bar{\gamma}$ from pressure drop data, Eq. (15) must be solved for $\bar{\gamma}$. To get this solution in closed form, a series approximation for the logarithmic term is used. Although this introduces some inaccuracy, the gravitational pressure drop term is small compared with the inertial and frictional term, so that little error in $\bar{\gamma}$ is introduced by this approximation. Thus, Eq. (15) may be rewritten as a quadratic in $\bar{\gamma}$ and solved as follows:

$$\bar{\gamma} = \sqrt{\left(\frac{b}{2a}\right)^2 + \frac{c}{a}} - \frac{b}{2a} \tag{16}$$

where

$$a = \frac{32}{3}\,\bar{f}_{tp}N_b^2\left(\frac{L_b}{D}\right)^3 + \frac{4}{3}\,FN_b^2\left(\frac{L_b}{D}\right)^2\left[\frac{\rho_l L_b(g/g_c)}{G^2/\rho_g g_c}\right] \tag{16a}$$

$$b = 4N_b\left(\frac{L_b}{D}\right) + 4\bar{f}_{tp}N_b\left(\frac{L_b}{D}\right)^2 - 2FN_b\left(\frac{\rho_l}{\rho_g}\right)\left(\frac{L_b}{D}\right)\left[\frac{\rho_l L_b(g/g_c)}{G^2/\rho_g g_c}\right] \tag{16b}$$

$$c = \frac{\Delta P_b}{(G^2/\rho_g g_c)} - 2\bar{f}_{tp}\left(\frac{\rho_g}{\rho_l}\right)\left(\frac{L_b}{D}\right) - F\left[\frac{\rho_l L_b(g/g_c)}{G^2/\rho_g g_c}\right] \tag{16c}$$

In order to solve for $\bar{\gamma}$ from Eq. (16), $\bar{f}_{tp}$ must be known. Thom [6] found that the two-phase friction factor is not greatly different from the liquid-phase friction factor at low vapor qualities. Therefore, a simple relation of the type, $f_{tp} \propto Re_l^{-0.2}$, is chosen. Several trials indicate that the following relation applies.

$$\bar{f}_{tp} = 0.020\ Re_l^{-0.2} \tag{17}$$

Higher values of the coefficient multiplying $Re_l^{-0.2}$ yield increased scatter in $\bar{\gamma}$ values calculated from experimental data. The difference of this equation from a standard single-phase correlation may well be due to the combined effects of the definitions and simplifying assumptions used.

RESULTS AND DISCUSSION

The subcooled-boiling pressure-drop data of Reynolds [2], and Jeglic, Stone, and Gray [7] are now examined. The experimental pressure-drop data yield mean values of the vaporization-rate parameter $\bar{\gamma}$ from Eq. (16). As noted by Kroeger and Zuber [10], the point of boiling initiation is quite important, and no widely applicable means is available to determine L_o. Therefore, the only data used herein are those for which are given either L_o [2] or the wall-temperature distribution, from which L_o may be estimated [7]. Whether this L_o indicates the first surface bubble nucleation or the point of the first bubble departure is uncertain.

The mean vaporization-rate parameter is correlated as a function of known variables. Finally, as a check, the correlation obtained is used to predict the pressure drop, and this calculated pressure drop is then compared with experimental data. This is done for the data [2,7] used in obtaining this correlation and also for the data of Owens and Schrock [3].

Correlation of Mean Vaporization-Rate Parameter

Figure 2 shows the mean vaporization-rate parameter $\bar{\gamma}$ plotted against subcooling number N_{sc} for various values of boiling number N_b over a wide range of test variables at an exit pressure of 100 psia [2,7]. It can be seen that $\bar{\gamma}$ decreases with increasing N_{sc} for constant N_b Also, $\bar{\gamma}$ increases with increasing N_b at constant N_{sc}. No effects of heat flux or mass velocity, except as accounted for in N_b, are seen, nor are there any effects of geometry not accounted for in the equations. The data for a given pressure may be reduced to a single curve by plotting $\bar{\gamma}$ against $N_{sc}N_b^{-0.7}$, as shown for 100 psia data [2,7] in Fig. 3. To account for the effect of pressure, $\bar{\gamma}$ is plotted against $N_{sc}N_b^{-0.7}(\rho_l/\rho_g)^{0.5}$ in Fig. 4; data for very low pressure drops are not shown on this figure since there is considerable scatter in such data. It should be noted that N_{sc} is based on heat-balance enthalpies. As has been previously observed [8,9,10], liquid temperatures in the subcooled-boiling regime are less than a heat balance would indicate; thus, establishment of limiting behavior can only be approximate. In the limit as $N_{sc} \rightarrow 0$, $\bar{\gamma}$ is assumed to approach 1.0; so the following simple equation yielding this limit is used:

$$\gamma = \left[\frac{1}{1 + 0.0145\ N_{sc}N_b^{-0.7}(\rho_l/\rho_g)^{0.5}}\right]^2 \qquad (18)$$

No attempt is made to establish limiting behavior at low $\bar{\gamma}$. This would require predicting the inception of boiling and is beyond the scope of this report.

Comparison of Experimental and Calculated Pressure Drops

Pressure drops, calculated from Eq. (15) with $\bar{f}_{tp}$ from Eq. (17) and $\bar{\gamma}$ from Eq. (18), are compared with experimental data in Fig. 5, where $(\Delta P_b)_{Exp}$ is plotted against $(\Delta P_b)_{Cal}$. The data used to obtain the correlation and some lower pressure-drop data [2,7] are shown in Figs. 5(a) and (b). Figure 5(a) shows data for water boiling in a 0.375-inch-diameter tube at pressures from 45 to 100 psia with mass velocities from 1.56×10^6 to 2.34×10^6 lbm/(hr)(ft^2) and heat fluxes from 0.13×10^6 to 0.30×10^6 Btu/(hr)(ft^2) [2]. Perhaps more importantly, the boiling number N_b ranges from 0.060×10^{-3} to 0.22×10^{-3}. All the data agree within ±30 percent ±0.1 psi. (The absolute value is included in the scatter band description since the low ΔP_b data are difficult to measure accurately.) Figure 5(b) shows data for water boiling in 0.23-inch-diameter tubes at pressure from 17 to 100 psia with mass velocities from 1.04×10^6 to 10.4×10^6 lbm/(hr)(ft^2) and heat fluxes from 0.52×10^6 to 3.45×10^6 Btu/(hr)(ft^2) [7]; N_b ranges from 0.22×10^{-3} to 1.56×10^{-3}. 96 Percent of the data agree within ±30 percent ±0.5 psi. As a further check of the correlation, the data of

Owens and Schrock [3], not used in developing the correlation, are shown in Fig. 5(c) for N_b ranging from 0.17×10^{-3} to 0.87×10^{-3}. These data are for water boiling in 0.1181-inch- and 0.1824-inch-diameter tubes at pressure from 50 to 400 psia with mass velocities from 0.61×10^6 to 3.9×10^6 lbm/(hr)(ft^2) and heat fluxes from 0.21×10^6 to 1.27×10^6 Btu/(hr)(ft^2). 98 Percent of the data agree within ±30 percent ±0.25 psi. It should be noted, for comparisons regarding scatter, that Reynolds [2] correlated his data within ±20 percent and that Owens and Schrock [3] correlated their data within +27 to -31 percent. Therefore, considering the wider range of test variables, especially boiling number and pressure, the data scatter obtained with this model is considered acceptable. Thus, the nonequilibrium homogeneous-flow model presented herein is, at least effectively, valid over the ranges of variables given above.

SUMMARY OF RESULTS

A one-dimensional, nonequilibrium, homogeneous-flow model is developed herein which relates the pressure drop in subcooled boiling inside tubes with constant heat flux to variables generally known (physical properties, mass velocity, heat flux, and geometry) and one unknown variable, the net fraction of the heat added that goes into vaporizing liquid. This variable is referred to herein as the vaporization-rate parameter. A correlation of the mean value of the vaporization-rate parameter is presented. The data correlated are for water at pressures from 17 to 400 psia, mass velocities from 0.61×10^6 to 10.4×10^6 lbm/(hr)(ft^2), and heat fluxes from 0.13×10^6 to 3.45×10^6 Btu/(hr)(ft^2); the boiling number, defined as heat flux divided by the quantity, mass velocity times latent heat of vaporization, ranges from 0.06×10^{-3} to 1.56×10^{-3}. The effects of void fraction are lumped in the vaporization-rate parameter. Therefore, this model should not be used to predict void fraction explicitly. Calculations based on this correlation are simplified since no independent prediction of void fractions or experimental void-fraction data are required in order to predict pressure drop.

NOMENCLATURE

A	cross-sectional area for flow, in.^{2}
a	parameter defined in Eq. (16a), dimensionless
b	parameter defined in Eq. (16b), dimensionless
c	parameter defined in Eq. (16c), dimensionless
D	tube inside diameter, in.
F	orientation factor, dimensionless
f	friction factor, dimensionless
G	mass velocity, lbm/(sec)(in.^{2})
g	acceleration due to gravity, in./sec^2
g_c	conversion factor, 386 (lbm)(in.)/(lbf)(sec^2)
h	enthalpy, Btu/lbm
L	length, in.
N_b	boiling number, $q/G\lambda$, dimensionless
N_{sc}	subcooling number, $[h_{sl} - (h_o + h_e)/2]/\lambda$, dimensionless
P	pressure, psia
q	heat flux, Btu/(sec)(in.^{2})
Re_l	liquid Reynolds number, DG/μ_l, dimensionless

v	velocity, in./sec
W	rate of phase change, lbm/sec
z	axial distance along boiler tube, in.
α	void fraction, A_g/A, dimensionless
γ	vaporization rate parameter, dimensionless
Δ	difference, value at inception of boiling minus value at tube exit
λ	enthalpy of vaporization, Btu/lbm
μ	viscosity, lbm/(in.)(sec)
ρ	density, lb/in.^{3}
τ	shear stress at wall, psi

Subscripts:

b	boiling
Cal	calculated
c	condensing
Exp	experimental
e	tube exit
g	gas phase
l	liquid phase
o	inception of boiling
s	value at saturation temperature
tp	two-phase
v	vaporizing

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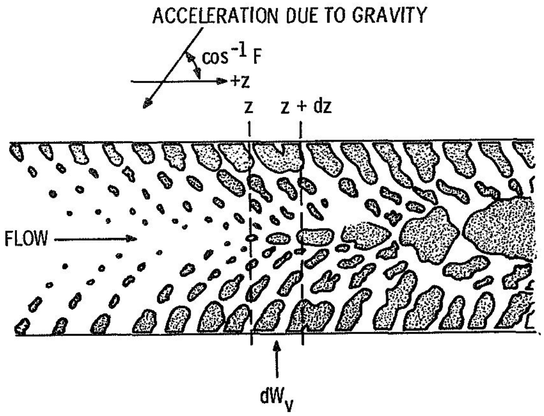


Figure 1. - Differential control volume for subcooled boiling flow.

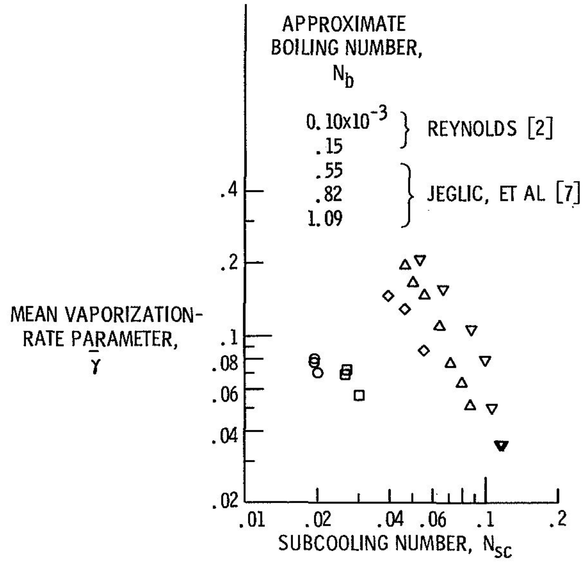


Figure 2. - Mean vaporization-rate parameter as a function of subcooling number for various boiling numbers; exit pressure, ~100 psia.

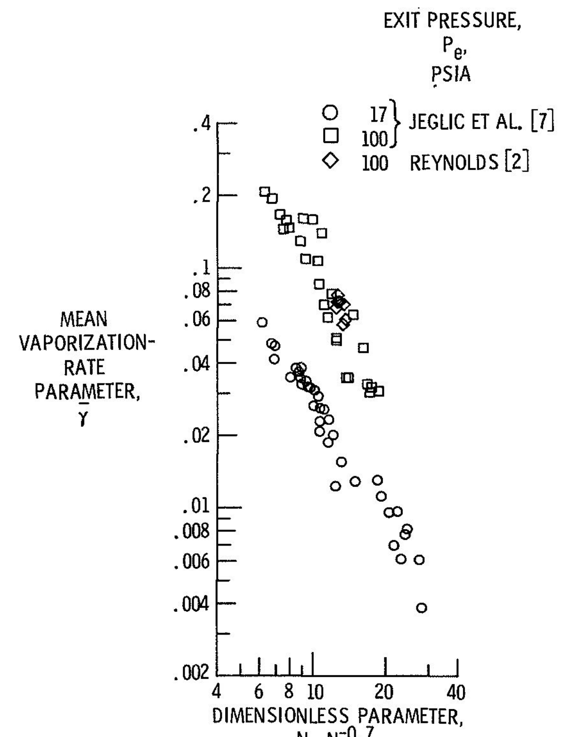


Figure 3. - Mean vaporization-rate parameter as a function of dimensionless parameter $N_{sc}N_b^{-0.7}$ for exit pressures of 17 and 100 psia.

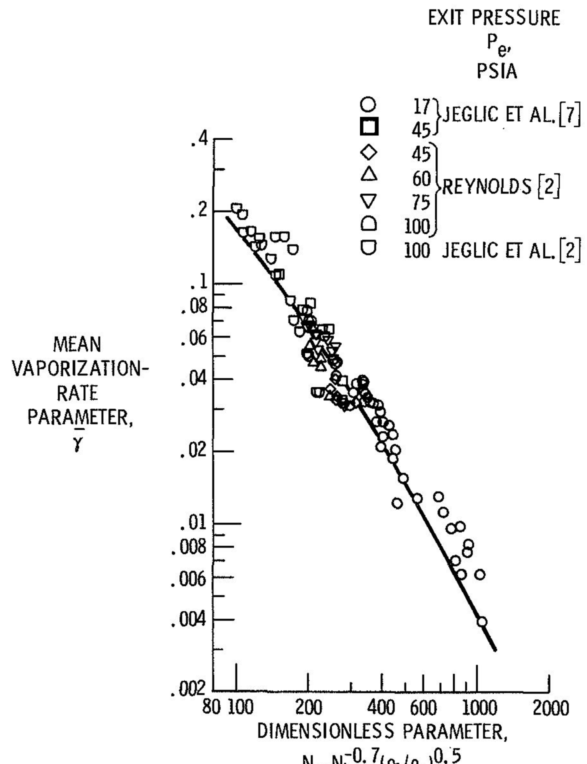
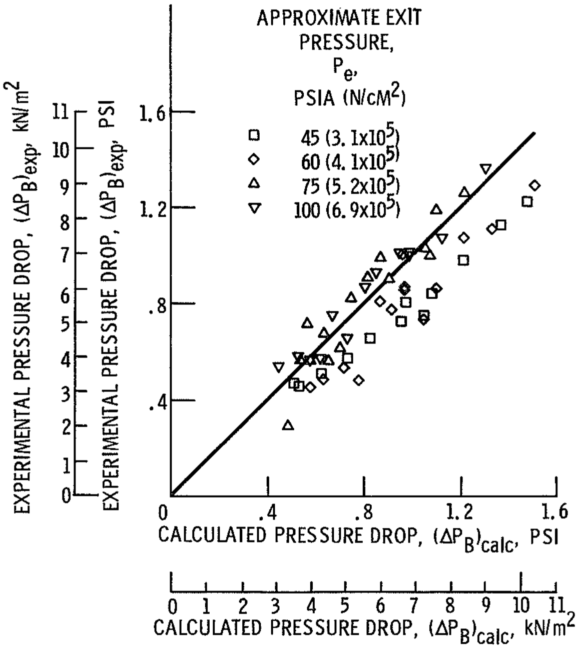


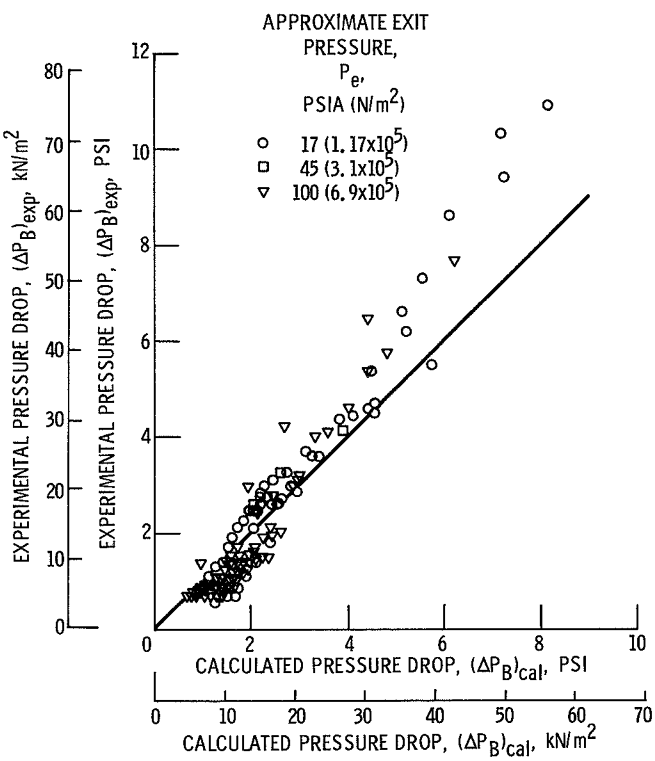
Figure 4. - Mean vaporization-rate parameter as a function of dimensionless parameter, $N_{sc}N^{-0.7}(\rho_l/\rho_g)^{0.5}$.

E-5468



(A) DATA OF REYNOLDS (REF. 2).

Figure 5. - Comparison of experimental and calculated pressure drops.



(B) DATA OF JEGLIC, STONE, AND GRAY (REF. 7).

Figure 5. - Continued.

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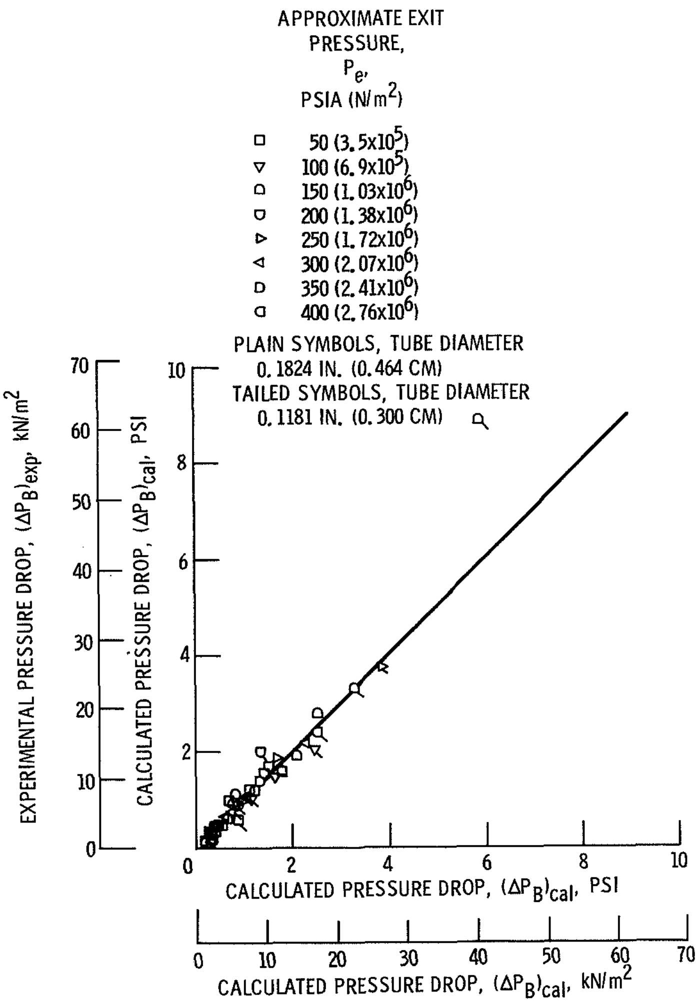

(C) DATA OF OWENS AND SCHROCK (REF. 3).

Figure 5. - Concluded.