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SUBCOOLED BOILING PRESSURE DROP WITH WATER AT LOW PRESSURE

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Abstract—Results are presented for an experimental study of pressure drop with subcooled boiling of water at pressures below 100 p.s.i.a. in horizontal round tubes of diameter less than 0·2 in. Test conditions were comparable to those required for the cooling of high power density systems. A correlation is presented in graphical form which satisfactorily accounts for variations in velocity, pressure, and inlet temperature. The correlation is in good agreement with the limited data reported by other investigators for similar conditions. Application of the data to diagnosis of system stability is noted.

NOMENCLATURE

- c, specific heat at constant pressure, [Btu/lbm°F];
- D, tube diameter [in.];
- f, friction factor, $= \Delta PD/2L\rho V^2$;
- G, mass velocity;
- h, single-phase heat-transfer coefficient [Btu/hr ft^2°F];
- k, thermal conductivity;
- L, heated and pressure-tap length [in.];
- Nu, Nusselt number, $= hD/k$;
- P, pressure [lbf/in.^{2} abs.];
- ΔP, overall pressure drop;
- Pr, Prandtl number, $= c\mu/k$;
- q'', heat flux [Btu/hft^2];
- Re, Reynolds number, $= GD/\mu$;
- T, temperature, [°F];
- V, velocity;
- w, mass flow rate [lbm/h];
- x, distance along tube;
- α, exponent of viscosity ratio;
- μ, dynamic viscosity;
- ρ, density.

Subscripts

- a, adiabatic condition;
- b, denotes subcooled boiling;
- i, condition at test-section inlet;
- ib, denotes incipient boiling;
- nb, denotes nonboiling;
- o, condition at test-section outlet;
- s, saturation condition;
- x, condition at position x;
- w. condition at tube wall.

Fluid properties are evaluated at the bulk fluid temperature unless otherwise noted.

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INTRODUCTION

SUBCOOLED boiling is frequently the most practical mode of heat transfer for accommodating the high heat-transfer rates which must be dissipated in many systems. Subcooled boiling is encountered, for example, in the cooling of high-power electron tubes, accelerator targets, high-temperature pressure transducers, high-field electromagnets, and computer components. Numerous theoretical and experimental studies have established reliable predictions for wall temperatures and critical heat flux; however, relatively little success has been reported in the general correlation of pressure drop. The designer usually obtains pressure drop data directly from experiments; however, only a limited amount of data appears to have been reported for the high heat flux, low pressure conditions of interest in the applications mentioned above. This paper summarizes the results of an investigation of the pressure drop characteristics for subcooled boiling of water at less than 100 p.s.i.a. in tubes of less than 0·2 in. i.d.

TEST PROGRAM

The test sections consisted of various lengths of uniform-wall stainless steel or nickel tubes, fitted with power connections and instrumentation for monitoring static pressures and wall temperatures. As shown in Fig. 1, the pressure taps were constructed by brazing small stainless tubes to the outside of the test tube and drilling 0·013 in. holes through the wall. A strip of high temperature insulating material was used to reinforce the tap tubes. Insulated thermocouples were secured to the tube wall and the inner wall of the heated shield. During the initial testing, measurements were made with several test sections having six pressure taps and five wall thermocouples; however, in subsequent test runs, the temperature instrumentation was eliminated and only two pressure taps were used.

These test sections were installed in the horizontal position in a loop which circulated degassed and demineralized distilled water. A large pressure drop was maintained across a throttle valve directly upstream of the test section in order to eliminate system-induced flow instabilities. Direct-current electrical power was supplied to the test sections by a motor-generator facility.

The pressure level was recorded by Bourdon-type test gauges, and the incremental pressures were obtained from a bank of U-tube manometers. Local fluid temperatures were obtained by heat balance using the measured inlet water temperature. The measured wall temperatures were corrected by a solution to the heat conduction equation to obtain the heated surface temperature.

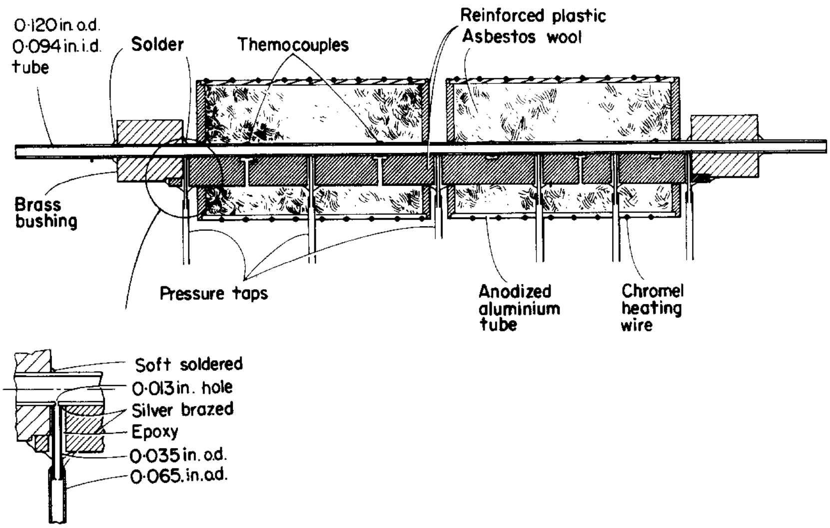

FIG. 1. Details of test-section construction.

Data were taken for the following range of conditions: $D = 0{\cdot}062 - 0{\cdot}198$ in., $L/D = 24 - 195$, $P_o = 30$–80 p.s.i.a., $V_i = 5$–60 ft/s, $T_i = 50$–145°F, and $q'' = 0$–$5{\cdot}5 \times 10^6$ Btu/hft^2. The data were generally obtained by setting pressure and flow conditions, and increasing the heat flux to just below the estimated critical heat flux or to the point where saturated exit conditions were reached. A detailed presentation of the data as well as further information on the experimental procedure is given in [1, 2].

DISCUSSION OF RESULTS

General behavior of data

Typical pressure profiles are given in Fig. 2 for a wide range of heat fluxes. The pressure gradient decreases from the isothermal value at low heat fluxes due to the effect of radial property variation on the single-phase friction factor. Once boiling is initiated, there is a general increase in pressure gradient, particularly near the exit of the test section where the vapor volumetric fraction is large. Figure 3 illustrates the dependence of the overall pressure drop on heat flux, inlet velocity, inlet temperature, and exit pressure. Consider an individual curve for constant inlet velocity, inlet temperature, and exit pressure. As the heat flux is increased, the pressure drop decreases due to the decrease in friction factor, then increases when subcooled boiling becomes well established. The rate of increase is particularly large as the critical heat flux or saturated exit condition is approached. At high heat fluxes the pressure drop with subcooled boiling can be 10–20 times the adiabatic value.

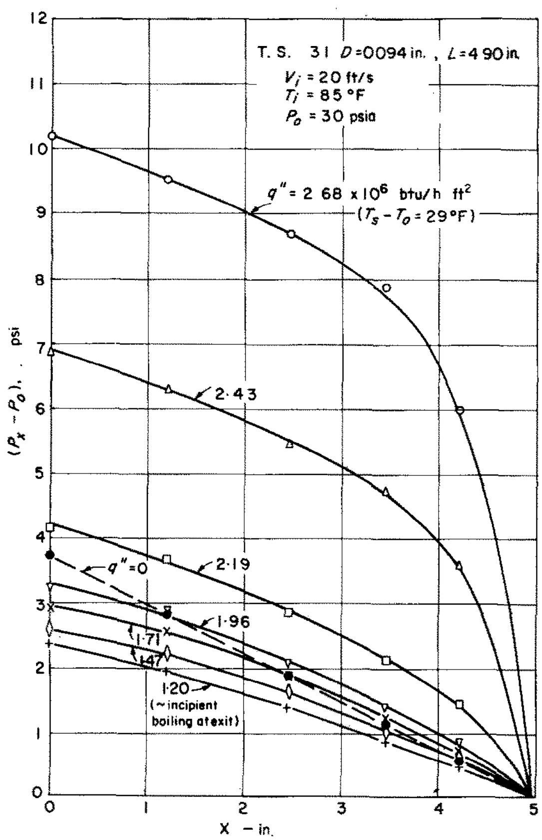

FIG. 2. Typical pressure profiles for single-phase and subcooled boiling conditions.

Determination of boiling length

One of the difficulties associated with the correlation of subcooled boiling pressure drop lies in determining with precision the point of incipient boiling within the channel. The most meaningful definition of incipient boiling would appear to be the point at which the friction factor increases above the diabatic single-phase value. This is analogous to the increase of the heat-transfer coefficient above the single-phase value; and corresponds to the beginning of the knee of the boiling curve. The following analytical prediction for incipient boiling was chosen since it was found to be accurate for the present test conditions [6]:

$$q''_{ib} = 15{\cdot}60\ P^{1{\cdot}156}(T_w - T_s)^{2{\cdot}30P^{-0{\cdot}0234}} \tag{1}$$

The nonboiling length can then be derived from heat balance considerations as

$$L_{nb} = [T_{w,ib} - T_i - q''/h]\,(wc/q''\pi D) \tag{2}$$

where h is obtained from the correlation of the present heat-transfer data

$$Nu/Pr^{0{\cdot}4} = 0{\cdot}0157\,Re^{0{\cdot}85}. \tag{3}$$

Due to the pressure gradient within the test section, an iterative procedure was generally required to find L_{nb}.

Data were taken to establish the appropriate correlation for non-boiling pressure drop. The isothermal data are shown in Fig. 4 to be in close agreement with the conventional smooth tube values. The wall-to-bulk viscosity ratio was chosen as the correlation parameter for the effect of heating. Figure 5 illustrates that a constant power, α, of the viscosity ratio is generally adequate for correlation; however, the value of α increases near the inlet region of the

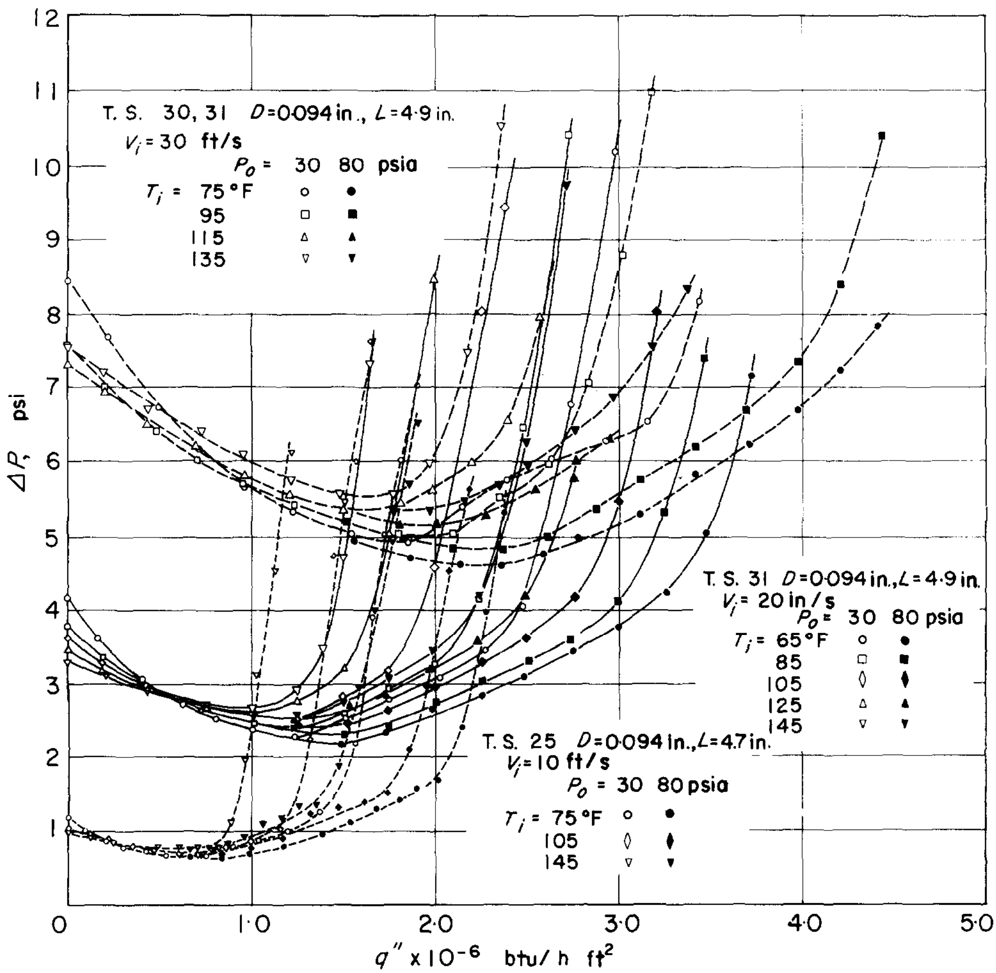

FIG. 3. Dependence of overall pressure drop on operating conditions.

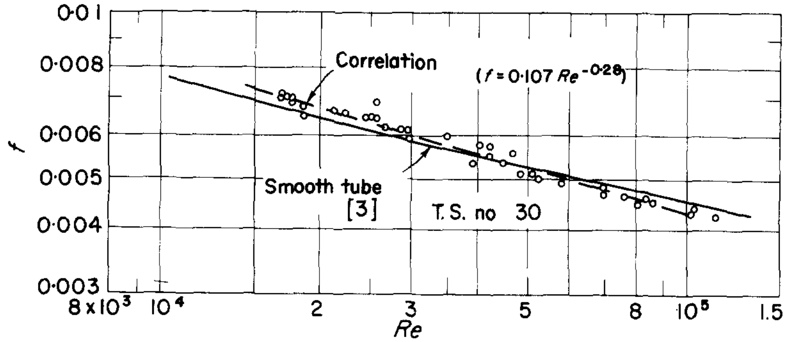

FIG. 4. Adiabatic friction factor correlation.

tube at high heat fluxes. As shown in Fig. 6, the value of α based on the over-all friction factor is relatively insensitive to velocity level. More recent experiments for fully-developed turbulent flow [4, 5] suggest that f/f_a is actually a more complex function of μ_W/μ, and also depends on Re. For the present conditions, the following simple relation was found to quite accurately represent the data:

$$f = 0{\cdot}107\, Re^{-0{\cdot}28}(\mu_W/\mu)^{0{\cdot}35}. \quad (4)$$

The nonboiling pressure drop was then calculated using L_{nb} and equation (4), where the properties were taken at the average wall and fluid temperatures in the nonboiling region. This result was then subtracted from the total measured pressure drop to obtain the desired ΔP_b. Due to the high heat fluxes considered, the majority of the pressure drop data were taken for conditions where boiling occurred essentially at the test-section inlet.

Presentation of boiling data

(a) *General considerations.* In general, the pressure drop for subcooled boiling has proved to be difficult to handle on a fundamental basis, and the literature consists largely of data tabulations or empirical correlations valid for narrow ranges of conditions. The reason for this difficulty can be seen by considering the various components of the pressure gradient:

$$\left(\frac{dP}{dx}\right)_{\text{total}} = \left(\frac{dP}{dx}\right)_{\text{friction}} + \left(\frac{dP}{dx}\right)_{\text{momentum}} + \left(\frac{dP}{dx}\right)_{\text{elevation}} \quad (5)$$

For inclined pipes, the elevation term can be readily evaluated from void fraction data. The momentum term can also be evaluated from void information, provided that some assumptions are made regarding the distribution and velocity of each phase. The friction term can be isolated

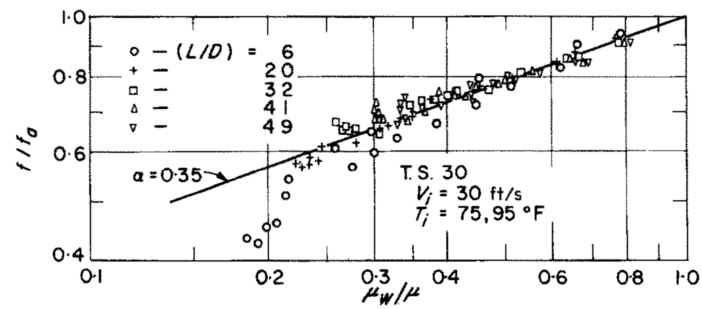

FIG. 5. Correlation of local single-phase diabatic friction factor with viscosity ratio.

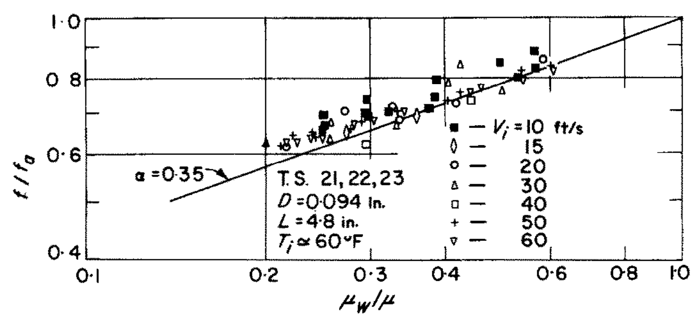

FIG. 6. Correlation of overall single-phase diabatic friction factor with viscosity ratio.

by subtracting the elevation and momentum terms from the measured total gradient, and correlated by a two-phase friction-factor multiplier similar to that used for bulk boiling. This approach has been used by Miller [7], Mendler *et al.* [8], and Sher and Green [9] to correlate subcooled boiling data for water at high pressure. The accuracy of the method is contingent upon reliable void fraction data which are still not abundant for subcooled boiling conditions.

Under certain conditions, the void fraction may be very small so that only the friction component is involved. Sabersky and Mulligan [10] and Jicha and Frank [11] found that data of this type could be reasonably well correlated by means of a simple analogy between heat transfer and friction. The Reynolds analogy was greatly in error when applied to the present local pressure gradients [1], due to the large acceleration component. Jordan and Leppert [19] found that the analogy was reasonably accurate when the pressure gradients were adjusted for acceleration effects. Their method of correlation would require extensive local void fraction information.

Several investigators have made detailed measurements of pressure gradients in uniformly heated tubes, and developed correlations for the total pressure gradient of the following form:

$$\frac{(\mathrm{d}P/\mathrm{d}x)_b}{(\mathrm{d}P/\mathrm{d}x)_{nb}} = f(L_b/L_{b,s}, q'', P, G). \qquad (6)$$

Owens and Schrock [12] achieved correlation in terms of only the length ratio while Reynolds [13] found that only length ratio and heat flux were important. However, Tarasova *et al.* [14, 15] demonstrated that correlation over a wide range of conditions requires consideration of all variables. Their design relation is an integrated form of equation (6) over the boiling length. These investigations were generally carried out at relatively high pressure and low heat flux.

This last approach is most appropriate for correlation of the present data; however, there are two major difficulties involved. First, the pressure drop is significant compared to the pressure level. This means that the pressure gradient will be linked in complex fashion to the boiling length and pressure level. Furthermore, the question arises as to which pressure should be used in evaluating $L_{b,s}$. Second, the reference nonboiling gradient is difficult to specify since the single-phase friction factor is a strong function of wall temperature for the high heat fluxes considered here. In view of these difficulties, it was deemed appropriate to adopt a scheme which correlated a number of the variables, yet which was readily useable for design purposes.

(b) *Correlation procedure.* The pressure drop data were correlated by plotting $\Delta P_b/\Delta P_{a,s}$ vs. $L_{b,s}$. The boiling pressure drop ΔP_b is the pressure drop over the length L_b, from the incipient boiling point to the exit of the heated section. The reference pressure drop $\Delta P_{a,s}$ is the pressure drop that would exist in a similar adiabatic tube with fluid temperature T_{ib} and length $L_{b,s}$. The reference length $L_{b,s}$ is the length which would be required to bring the fluid to the saturation condition corresponding to the pressure at the exit of the heated section. The length ratio $L_b/L_{b,s}$ can be regarded as an enthalpy rise or subcooling parameter. This parameter is identical to that used by other investigators; however, with a large pressure gradient the actual length of tube required to bring the flow to saturation conditions can be much less than $L_{b,s}$ based on the exit pressure. The ratio $\Delta P_b/\Delta P_{a,s}$ is essentially a two-phase multiplier which incorporates both friction and momentum effects. However, through the introduction of $L_{b,s}$ in the reference term, the ratio is forced to zero as $L_b/L_{b,s}$ approaches zero. This tends to compress the data near incipient boiling, which, if the usual $\Delta P_b/\Delta P_a$ were used, would reflect the large differences between adiabatic and diabatic friction factors. This is of little concern in the present study since data for high boiling heat fluxes are of primary interest.

Figures 7 and 8 present typical data plotted in terms of these correlating parameters. In all

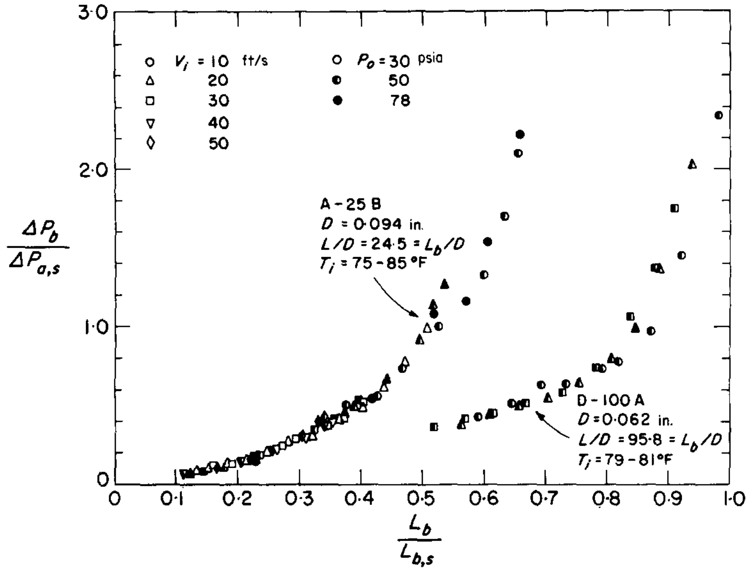

FIG. 7. Correlation of data for various velocities, pressures and inlet temperatures

cases the entire tube was calculated to be in subcooled boiling according to the criterion noted above. At low power levels the boiling intensity is moderate and the pressure drop is below that which would be predicted for adiabatic single-phase flow. At higher power the boiling is well established and there is a large increase in the pressure drop due to increased friction and production of large non-equilibrium voidage. For longer tubes the runs were terminated when saturated outlet conditions were reached, but for shorter tubes the highest data points are close to the critical heat flux condition. It is seen that this method of representation has promise since the data for a given tube can be represented by a single curve for a range of inlet velocity, pressure, and inlet temperature.

Best-fit curves for the entire test results are presented in Fig. 9. These curves can be generally grouped according to L_b/D with higher pressure drop being observed with lower L_b/D. This might be expected since the heat flux for a given $L_b/L_{b,s}$ increases with decreasing L_b/D. A secondary effect of diameter is obtained with the general trend being an increase in pressure drop with larger diameter pipes. This diameter effect appears to be related to changes in the phase distribution or flow pattern. Flow pattern studies of boiling water for similar conditions have indicated that high velocity transitions, bubbly to slug (or froth) and slug (or froth) to annular, occur at slightly higher exit subcoolings, or lower $L_b/L_{b,s}$, as the tube diameter is increased [16, 17]. This suggests that the void fraction is greater for the larger diameter tubes; consequently the momentum pressure drop and total pressure drop should be larger as the diameter is increased. Some caution must be exercised in extrapolating to larger tube sizes since it might be expected that above a certain diameter there is little change in the pressure drop.

The preceding discussion was concerned with data for which the entire tube was in boiling. It is also appropriate to discuss results for the case where incipient boiling occurred downstream of the tube entrance. Typical results are presented in Fig. 10 for a tube of $L/D = 195$, where the computed boiling lengths are indicated. For short $L_b/L_{b,s}$ the pressure drop ratios are somewhat higher than those observed with tubes with full length boiling. This is largely a

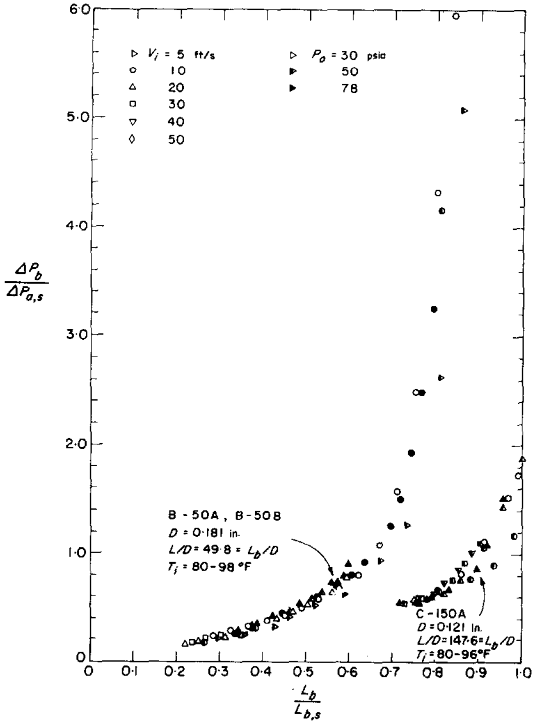

FIG. 8. Correlation of data for various velocities, pressures and inlet temperatures.

consequence of the adiabatic reference; for the same $L_b/L_{b,s}$ the long tube with partial boiling has a higher fluid bulk temperature than the short tube with total boiling. Consequently, $\Delta P_{a,s}$ is lower for the long tube and the ratio $\Delta P_b/\Delta P_{a,s}$ might be expected to be higher. This is of little consequence for design purposes, however, since these data lie in the region where the pressure drop is not particularly large. At higher heat fluxes the data are in reasonably good agreement with the previously obtained curves for shorter tubes. In any event, it appears that the pressure drop in any situation where there is partial boiling in the tube is not greatly different from the adiabatic single-phase value; thus, the curves presented in Fig. 9 can be regarded as design curves for most cases of practical significance.

COMPARISON WITH RESULTS OF OTHER INVESTIGATIONS

Ricque and Siboul [4] appear to be the only investigators who have reported low pressure data at high heat fluxes for horizontal tubes. An analysis of the tabulated data, using their experimental friction factors and heat-transfer coefficients, indicated that virtually all points were for boiling over the entire test section. The reduced data as presented in Fig. 11 are seen to be in excellent agreement with the present correlation curves for comparable geometrical conditions.

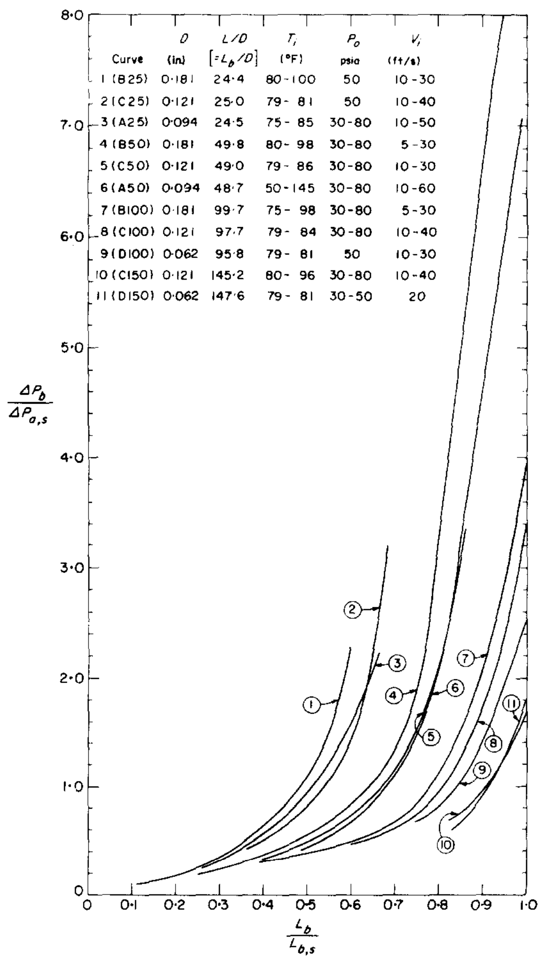

FIG. 9. Final correlation curves for present test data.

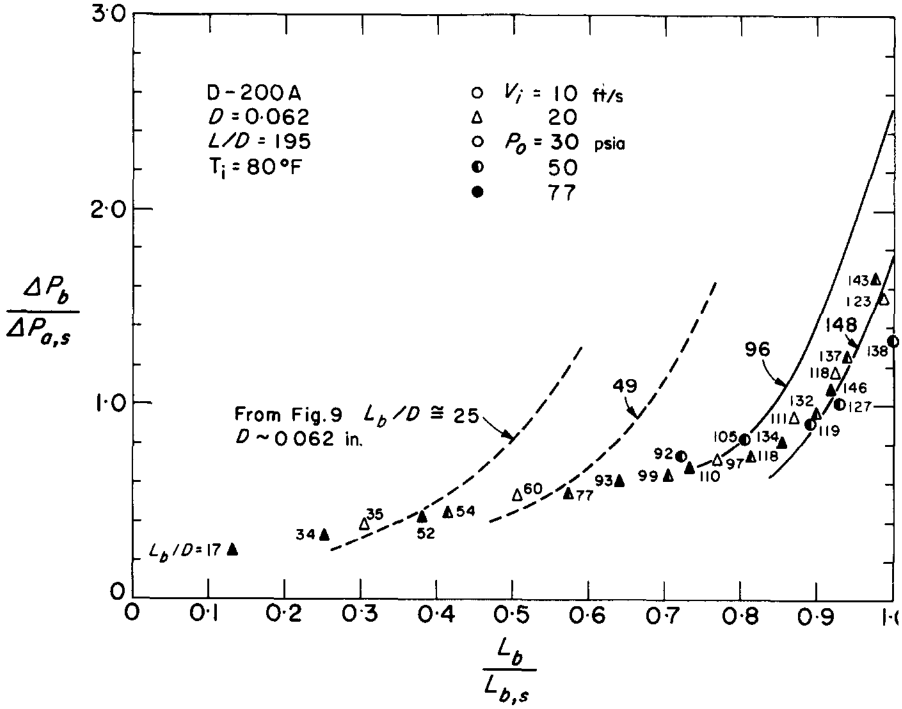

FIG. 10. Comparison of partial boiling results with correlation curves.

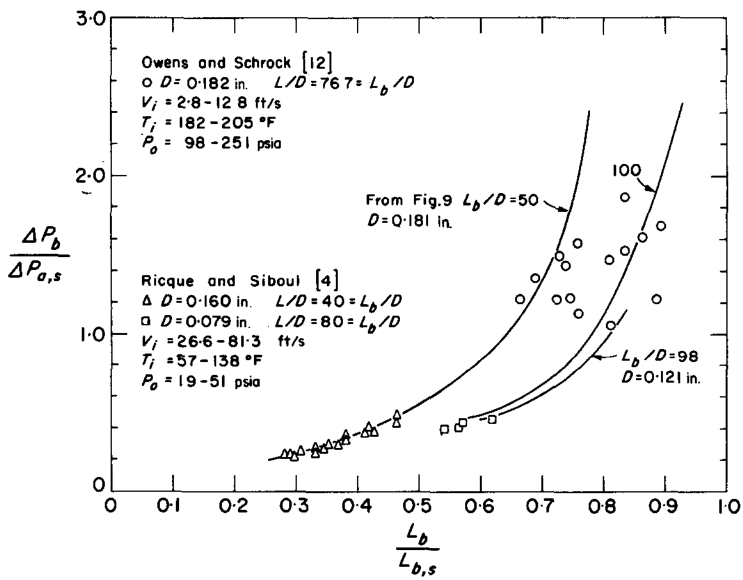

FIG. 11. Comparison of horizontal and vertical data with correlation curves.

Owens and Schrock [12] presented a comprehensive study of pressure gradients for subcooled boiling in small diameter vertical tubes. There is some difficulty in relating these data to the present correlation curves since there is no satisfactory means of correcting for the gravitational pressure drop. However, these data should still be useful for a general comparison; accordingly, they were reduced using the nonboiling relations recommended in the paper. As shown in Fig. 11, the data for the total pressure drop with established boiling over the entire test section are in general agreement with the present correlation curves. Reduction of ΔP_b by subtracting the gravity head would improve the agreement somewhat. This comparison suggests that the present correlating curves might be valid for pressures in excess of 100 p.s.i.a.

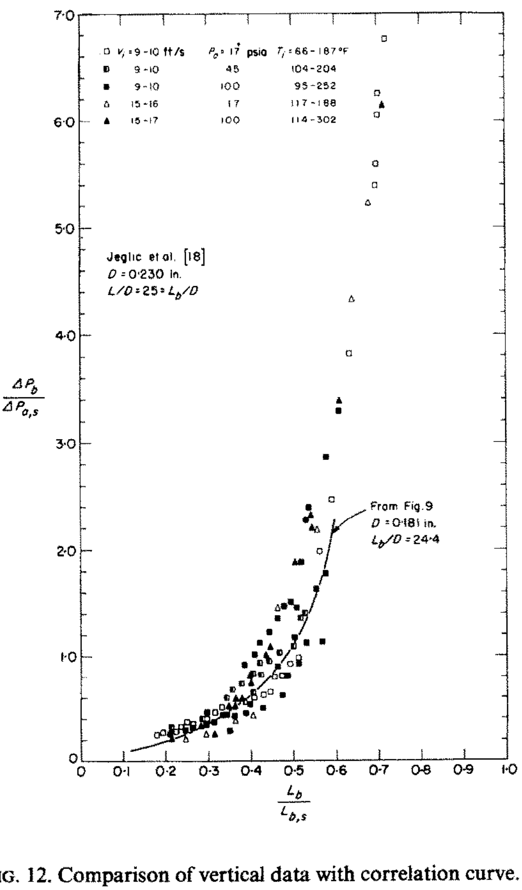

FIG. 12. Comparison of vertical data with correlation curve.

Jeglic *et al.* [18] reported overall pressure drop data for subcooled boiling in vertical tubes of somewhat larger diameter. Their tabulated data included a correction for the gravity head equal to the height of the liquid column. This correction overestimates the actual gravity term at higher heat flux; however, the data are still of interest for comparative purposes since they were taken for conditions similar to those of the present study. The data were reduced using appropriate friction and heat-transfer data for that study. As indicated in Fig. 12 the data are in reasonable agreement with the present correlation curve for a similar geometry. Some scatter at low $L_b/L_{b,s}$ would be expected due to the wide range of inlet temperatures considered by these investigators. In all probability, the general scatter would be considerably reduced by using the actual mean density in computing the gravity correction. This would tend to increase the pressure drop ratios by varying degrees depending on the operating conditions. However, the higher points would not be significantly affected since the gravity head is but a small part of the total pressure drop. These higher points are actually in rather good agreement with an extrapolation of the present curve. This would suggest that the effect of tube diameter becomes relatively unimportant at about 0·2 in.

CONCLUDING REMARKS

A large amount of pressure drop data for subcooled boiling of water at low pressure in small diameter tubes has been correlated in Fig. 9. The correlation curves are in good agreement with the limited data reported by other investigators for similar conditions. The correlation should be of particular interest in the design of cooling systems to accommodate high heat fluxes. Since the tubes in these applications are generally short, and the pressure drop is quite large, the gravitational component of the pressure drop can usually be neglected for inclined tubes. Thus the present data are also adequate for inclined tubes.

These data are also useful for examining the hydrodynamic stability of single or multiple channels with subcooled boiling. System-induced instability of either the excursive or oscillatory type may limit the heat flux to a value well below the stable critical heat flux, which can be very high for small diameter tubes [20]. It has been shown analytically and experimentally [21, 22] that both the parallel channel excursive instability and upstream compressible volume oscillatory instability are associated with a minimum in the pressure drop—flow rate curve for the cooling channel:

$$\frac{\partial \Delta P}{\partial w} = 0. \tag{7}$$

Low pressure systems have particularly distinct minima, thus stability is a common problem. The usual solution is to provide a flow restriction at the channel inlet so that the operating condition corresponds to a positive-sloping portion of the pressure drop—flow rate curve for the complete channel, restriction plus boiling section. Since the restriction represents a severe penalty in increased pressure head, it is necessary to have accurate pressure drop data for the boiling section so as to size the restriction properly. The present correlation is well suited for this purpose, and has given accurate predictions of instability thresholds [21, 22].

Finally, it is noted that these results are applicable only to straight, smooth tubes. In other situations, such as coiled tubes, rough tubes, or tubes with twisted tapes, the pressure drop characteristics can be expected to be markedly different. A preliminary report of subcooled boiling with tape-generated swirl flow is given in [2], and will be reported in more detail in the near future.

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Résumé—On présente des résultats pour une étude expérimentale de la chute de pression avec ébullition sous-refroidie de l'eau à des pressions inférieures à 6, 9 bars dans des tubes circulaires horizontaux dont le diamètre est inférieur à 5 mm. Les conditions d'essais étaient comparables à celles nécessaires pour le refroidissement des systèmes à densité de puissance élevée. On présente une corrélation sous forme graphique qui tient compte de façon satisfaisante des variations de vitesse, de pression et de température d'entrée. La corrélation est en bon accord avec les résultats limités exposés par d'autres chercheurs pour des conditions similaires. On donne une application des résultats au diagnostic de la stabilité du système.

Zusammenfassung—Es wurden Ergebnisse einer experimentellen Untersuchung des Druckabfalles bei unterkühltem Sieden von Wasser in waagerechten Rohren mit Durchmessern bis zu 5 mm bei Drücken unter 7 bar vorgelegt. Die Versuche stellten ähnliche Anforderungen, wie sie bei der Kühlung von Anlagen hoher Leistungsdichte auftreten. Eine Beziehung in Form einer graphischen Darstellung gibt in befriedigender Weise die Änderungen von Geschwindigkeit, Druck und Eintrittstemperatur wieder. Diese Beziehung stimmt mit der beschränkten Zahl von Daten, wie sie von anderer Seite veröffentlicht wurden, gut überein. Die Brauchbarkeit der angegebenen Werte für Stabilitätsuntersuchungen an einer Anlage wurde festgestellt.

Аннотация—Представлены результаты экспериментального изучения падения давления при кипении недогретой воды при давлениях ниже 100 psia в горизонтальных трубах диаметром менее 0,2 дюйма. Условия опыта соответствовали требованиям, предъявляемым к сильнонапряженным энергетическим системам охлаждения. Приводится график удовлетворительно учитывающий изменения скорости, давления, температуры на входе. Результаты хорошо совпадают с ограниченным количеством данных, полученных в аналогичных условиях другими исследователями. Отмечено, что результаты можно использовать для диагностики стабильности системы.