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A forced convection subcooled boiling model for nonuniform axial heat fluxes

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Abstract—The modeling of convective subcooled boiling of water flowing in round tubes subjected to nonuniform axial heat fluxes is described. The effects of different axial heat flux profiles are modeled using a local hypothesis; i.e. flow and thermal development are assumed to occur very rapidly in the subcooled boiling (SCB) flow regime. A computer code has been developed to predict the pressure drop, heat transfer coefficient and wall temperature for nonuniform axial heat fluxes, starting with a well-validated code for uniform axial heat fluxes. The predictions for some common nonuniform axial heat profiles are compared to the uniform heat flux case.

INTRODUCTION

THE MODELING of convective subcooled boiling (SCB) in round tubes is of considerable practical interest for the analysis and design of cooling systems, particularly for high heat flux situations such as those found in X-ray tubes, rocket engines, particle accelerators, fusion experiments and many other applications. Subcooled boiling is often desirable in these applications because the SCB heat transfer coefficient can be many times larger than that of single phase liquid (SPL) flows. As a result, SCB cooling systems are capable of removing the same amount of heat with lower flow rates and smaller pumps than SPL systems.

The axial heat flux profile on cooling tubes is normally not uniform in most applications. The shape of the heat flux profile significantly influences the two-phase SCB flow behavior and the resulting tube wall temperature and the critical heat flux (CHF). Consequently, there is a need to be able to accurately predict the *local* pressure, temperature, quality, void fraction and CHF of the subcooled two-phase flow with axially nonuniform heat fluxes in order to be able to select a cooling system design which operates in a safe regime far from the burnout condition. It is felt that a computer code which integrates the conditions along the tube is essential for this purpose, particularly at high heat fluxes where the flow properties tend to change very rapidly along the tube.

The most widely used method for estimating the SCB heat transfer and pressure drop is to use correlations. Virtually all these SCB correlations are based on experimental data for uniform axial heat fluxes. For example, the careful experiments by Owens and Schrock [1] and Dormer and Bergles [2] have been used by these researchers to produce empirical correlations to their data which are very useful for design purposes within the range of validity of each particular correlation.

In an effort to obtain accurate results for convective subcooled boiling of water in round tubes for a broader range of conditions, the computer code described in Hoffman and Kline [3] and Hoffman and Wong [4] was developed for uniform axial heat fluxes. The SCB-1A Code is the name given to the final code version ASCB53 described in detail in ref. [4]. This work was extended to microtubes with inner diameters of 1 mm or less in Hoffman and Stetson [5]. The SCB-1A computer code was validated using over a hundred experimental runs of Owens and Schrock [1] and of Dormer and Bergles [2] and has been found to be accurate to within about $\pm 20\%$. (See Appendix for range of validity.)

This paper describes the new SCB-2A Code which allows the calculation of the heat transfer and the pressure drop along a water-cooled tube for a wide variety of nonuniform axial heat flux profiles. It is assumed in the following that the reader is familiar with ref. [4], since this paper builds on the equations for the SCB-1A Code described in that paper. However, all the important equations in the model of ref. [4] are also summarized in the Appendix.

MODELING THE FLOW REGIME TRANSITIONS

Figure 1 shows a typical triangular-shape axial heat flux profile along the round tube. The flow conditions have been chosen such that the water enters the tube in the SPL (Single Phase Liquid) regime. The SCB regime which follows is divided into the highly subcooled PDB (Partially Developed Boiling) regime and the FDB (Fully Developed Boiling) regime for improved modeling of the physical phenomena. The PDB regime begins at ONB (Onset of Nucleate Boiling) when the wall superheat (i.e. the local wall temperature minus the local saturation temperature) reaches the value given by the Davis and Anderson

NOMENCLATURE

Acronyms

- BD — bubble departure point
- CHF — critical heat flux
- FDB — fully developed boiling regime
- OBB — onset of bulk boiling
- ONB — onset of nucleate boiling
- OSNVG — onset of significant net vapor generation (assumed the same as the BD point)
- PDB — partially developed boiling regime
- SBD — suppression of bubble departure point
- SCB — subcooled nucleate boiling regime
- SNB — suppression of nucleate boiling point
- SPL — single phase liquid regime.

Symbols

- C_o — radial void distribution parameter
- c_p — specific heat per unit mass
- D — inner diameter of tube
- f — Fanning friction factor
- g — acceleration of gravity
- G — mass flux
- h — heat transfer coefficient
- i — enthalpy
- k — thermal conductivity
- K_{red} — reduction factor for near-wall void fraction
- L — heated length of tube
- p — pressure
- Pe — Peclet number
- Pr — Prandtl number
- q'' — heat flux
- r — cavity radius
- Re — Reynolds number
- T — temperature
- ΔT_{SAT} — temperature difference, $T_w - T_{SAT}$
- ΔT_{SUB} — temperature difference, $T_{SAT} - T_f$
- u — velocity
- v — specific volume
- x' — nonequilibrium quality
- z — distance along tube from heated inlet
- Z^+, Z_f^+, Z_{mf}^+, Z_{mp}^+, Z_p^+ — nondimensional distances defined in the text and Appendix.

Greek symbols

- α' — nonequilibrium volumetric void fraction
- α_w — near-wall void fraction
- θ — tube inclination angle from horizontal
- μ — dynamic viscosity
- ρ — density
- σ — surface tension coefficient
- $(\phi_{fo})^2$ — two-phase friction multiplier.

Subscripts

- accel — acceleration
- b — bulk or mixed mean
- c — core-flow
- f — liquid or bulk mean liquid
- fo — liquid only
- fg — vapor minus liquid property
- fric — friction
- g — vapor
- grav — gravity
- h — heated
- i — inner
- in — inlet
- iso — isothermal
- SAT — saturation
- SUB — subcooling
- S–Z — Saha–Zuber
- w — wall.

ONB model [6] (see Appendix for equations). The PDB regime is the transition regime between the fully-developed SPL regime and the fully-developed subcooled nucleate boiling (FDB) regime. In the PDB regime, a thin near-wall bubble layer develops and grows in thickness as the wall and the bulk fluid temperatures increase. This creates a near-wall void fraction.

As the bulk temperature of the fluid increases, a point is reached where the local subcooling is small enough to allow bubbles to depart from the near-wall region and enter the core flow. This creates a volumetric void fraction. This point is defined as the OSNVG (Onset of Significant Net Vapor Generation) or more simply, as the BD (Bubble Departure) point. The Saha–Zuber correlation [7] is used to predict the subcooling at this point which is defined as the beginning of the FDB regime. (See Appendix for equations.) For the particular triangular-shaped heat flux profile shown in Fig. 1, the location of the BD point occurs before the peak heat flux is reached.

It should be noted that both the near-wall void fraction, α_w, in the PDB regime (and in the early part of the FDB regime) and the volumetric void fraction, α', in the FDB regime are due to a nonequilibrium phenomenon. This nonequilibrium effect is due to the temperature profile produced by the heat flux, and both voids would disappear (i.e. the vapor would condense) if the heat flux went to zero at some point along the tube. In many SCB models (but not the present one), the near-wall void fraction is assumed to be negligible and only the volumetric void fraction is considered.

After the peak heat flux point in Fig. 1 is passed,

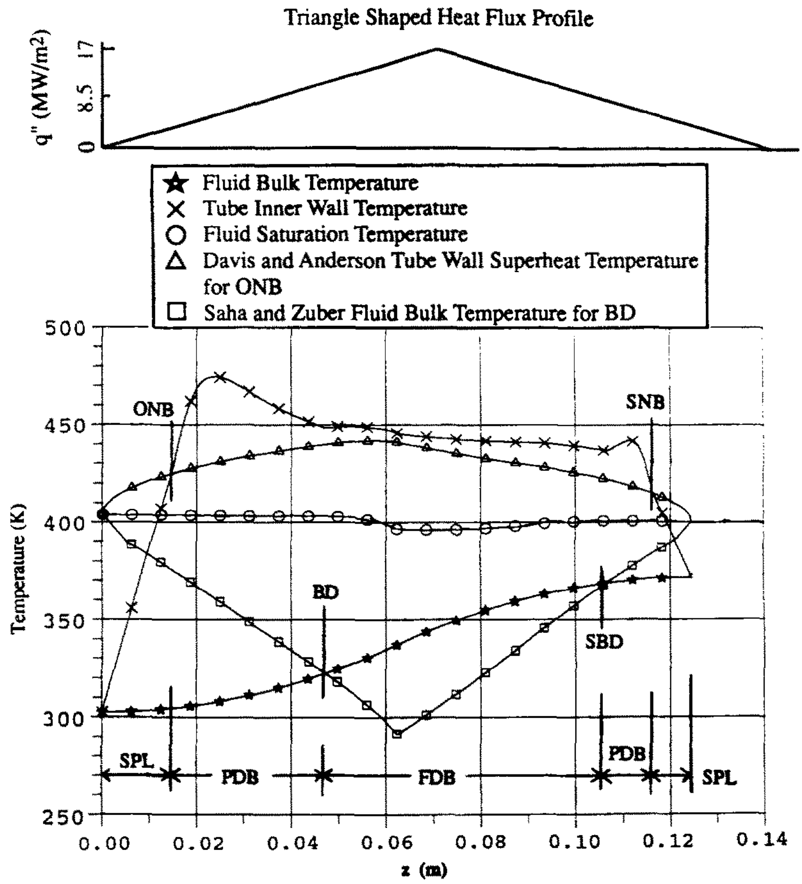


FIG. 1. The various key temperature profiles predicted by the SCB-2A Code for a triangular-shaped axial heat flux profile, showing the various transitions between regimes along the tube. The calculations were done for the following water inlet conditions and tube geometry: $\overline{q''} = 8.5 \times 10^6$ W m^{-2}, $G = 6071$ kg m^{-2} s^{-1}, $T_{b(in)} = 303$ K, $p_{in} = 2.75 \times 10^5$ Pa, $D_i = 2.39$ mm, $L_h = 0.1245$ m.

the bulk temperature continues to increase, but at a slower rate. The wall temperature, on the other hand, is actually decreasing due to the high heat transfer coefficients in the SCB regimes. The Saha–Zuber correlation predicts that the subcooling required for bubble departure also decreases as the heat flux decreases, as shown on Fig. 1. At the new transition point labelled SBD (Suppression of Bubble Departure) on Fig. 1, the actual local subcooling has fallen to the value predicted by the Saha–Zuber correlation. In our model, we assume that at this point, the flow transitions from the FDB regime back to the PDB regime.

As the heat flux continues to decrease toward zero along the tube, a point is reached where the local wall superheat decreases to the value predicted by the Davis and Anderson equation. At this second new transition point, labelled SNB (Suppression of Nucleate Boiling) on Fig. 1, it is assumed that all subcooled nucleate boiling ceases.

The two new transition points, SBD and SNB, have been introduced to model the new phenomena introduced by the axially *decreasing* heat flux in the flow direction. It can be seen that these models for the subcooled boiling flow regime transitions represent the limiting case of very rapid flow and thermal adjustments to the local heat flux condition. In this respect, our present model is a type of 'local hypothesis' model and implies that hysteresis effects are negligible. This local hypothesis model for convective SCB is given some support by the findings of Bergles and Rohsenow [8] with regard to the rapid transition from SPL to PDB, and by Tong (ref. [9, p. 144]) for the behavior of the critical heat flux (CHF) in SCB. However, a thorough validation of the local hypothesis using experimental data is still required.

HEAT TRANSFER COEFFICIENT MODEL IN THE PDB REGIME

The heat transfer coefficient for water in the SPL regime, h_{SPL}, is well established (see Appendix). Also in the FBD regime, many correlations have been proposed for the heat transfer coefficient (e.g. see [10]). For our work, we have chosen the Jens and Lottes correlation [11] for predicting the wall superheat, ΔT_{SAT}, in FDB since it appears to be accurate in the pressure range where most water cooling systems operate.

In the intermediate PDB regime, several empirical correlations have been proposed to give a smooth transition of the heat transfer coefficient between the SPL and FDB regimes and to match the limited PDB heat transfer data (e.g. Bergles and Rohsensow [8], Gungor and Winterton [12] and Kutateladze [13]). After trying many different forms, we have chosen a modified form of Kutateladze's empirical correlation to model the PDB regime (see Springsteen [14] for more details):

$$h_{\rm PDB} = [(1-Z^{+}_{\rm mp})^{m} h^{n}_{\rm SPL} + (Z^{+}_{\rm mp})^{m} h^{n}_{\rm FDB}]^{1/n} \qquad (1)$$

where the empirical nondimensional axial distance which was found to give smooth transitions at ONB and BD is:

$$Z^{+}_{\rm mp} = 0.5[1-\cos(\pi Z^{+}_{\rm p})]. \qquad (2)$$

This parameter is a function of the standard nondimensional distance between ONB and BD:

$$Z^{+}_{\rm p} = \frac{z - z_{\rm ONB}}{z_{\rm BD} - z_{\rm ONB}}. \qquad (3)$$

We have chosen $m = 1$ and $n = 2$ for the exponents. For this case, the results for the heat transfer coefficient and the wall temperature are plotted in Fig. 2 for a typical set of flow conditions and a uniform heat flux of 5×10^{6} W m^{-2}. Note that the flow experiences all three flow regimes (SPL, PDB and FDB) in the tube length. The equation using $Z^{+}_{\rm mp}$ (the squares in Fig. 2) is only slightly better than the equation

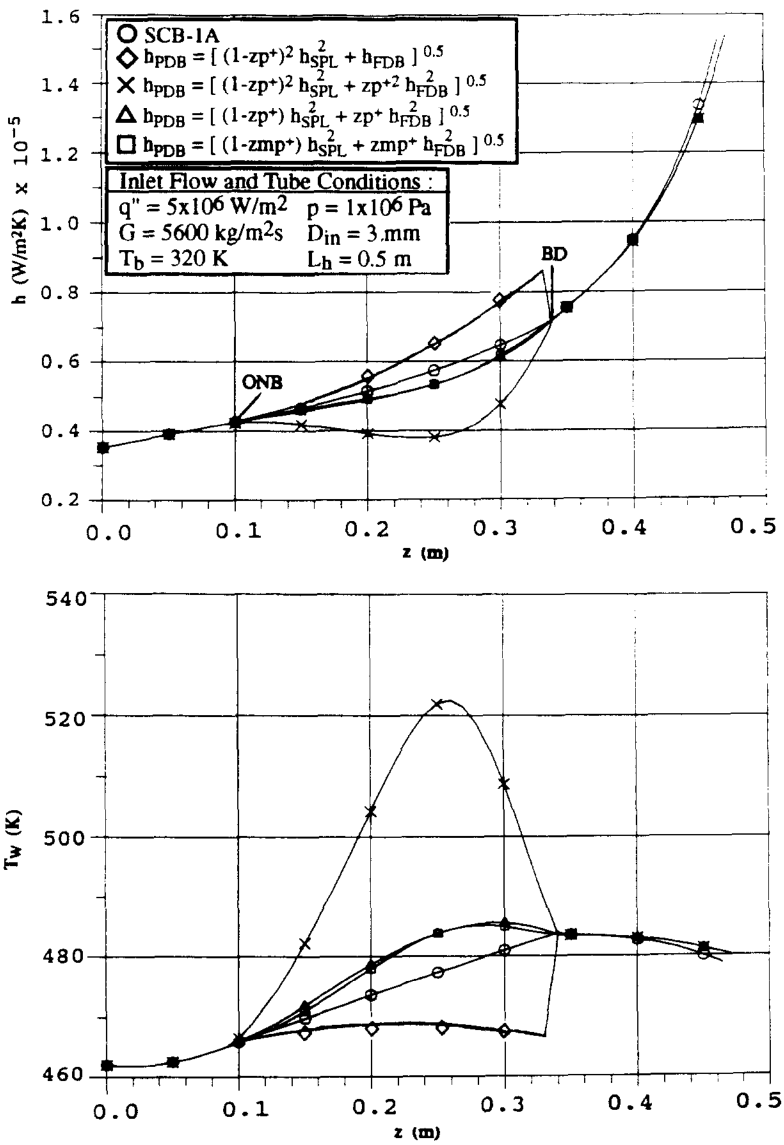


FIG. 2. Comparison of the predictions of various models and model refinements of the heat transfer coefficient in the PDB regime for the case with an axially uniform heat flux.

using Z_p^+ (the triangles in Fig. 2) for the case shown. Z_{mp}^+ was selected for the SCB-2A Code because it provides a slightly better transition of the wall temperature at BD than Z_p^+.

NEAR-WALL VOID MODEL IN THE PDB REGIME

A model for the growth of the near-wall bubble layer in PDB is required, even though this bubble layer normally has a small effect on the pressure drop and flow conditions except for very small diameter tubes (typically less than 3 mm diameter) and/or low pressures on the order of an atmosphere or less. Because of the small effect of the bubble layer on the pressure drop, a simple linear increase in the layer thickness starting at ONB (or starting at the tube inlet if the flow entered the tube in the PDB regime) was chosen for the SCB-1A Code [4]. The new model for the SCB-2A Code now allows for a near-wall void at the tube inlet if the flow starts in the PDB regime (i.e. where the wall superheat at the inlet is already above that given by the Davis and Anderson equation):

$$\alpha_w = Z_p^+ \alpha_{w(BD)}. \tag{4}$$

The value of the near-wall void fraction at Bubble Departure, $\alpha_{w(BD)}$, is given by the Rouhani correlation [15] (see Appendix, equation (A7)).

A typical result for the case where the flow enters the tube in the PDB regime is shown in Fig. 3. The new SCB-2A Code gives a better representation of the near-wall void fraction in the tube, but as mentioned above, it has almost no effect on the pressure drop in the PDB regime in most cases.

IMPROVED FDB REGIME MODEL

The basic model adopted for both the SCB-1A Code and the SCB-2A Code for estimating the nonequilibrium volumetric quality, x', and volumetric void fraction, α', in the core flow in the FDB regime is based on the drift flux model of Kroeger and Zuber [16] (see Appendix for equations). In order to force the nonequilibrium quality and void fraction to decrease back toward zero with axially decreasing heat fluxes for the new SCB-2A Code, the Z^+ term in the Kroeger and Zuber model has to be modified. The modified Z_{mf}^+ is evaluated *locally* in terms of the local subcooling and the *local prediction* of the subcooling at the BD (Bubble Departure) point:

$$Z_{mf}^+ = \frac{G_c}{G_{c(BD)}} \frac{C_{pf}}{C_{pf(BD)}} Z_f^+ \quad \text{for } Pe > 70\,000 \tag{5}$$

$$Z_{mf}^+ = \frac{k}{k_{BD}} Z_f^+ \quad \text{for } Pe < 70\,000 \tag{6}$$

where

$$Z_f^+ = \left[1 - \frac{\Delta T_{SUB}}{\Delta T_{SUB(BD)S\text{-}Z}}\right]. \tag{7}$$

All parameters in these equations are now evaluated at the local step in the calculation. Previously, in the SCB-1A Code, the parameters at the BD point were evaluated only once at the location where bubble departure was encountered. This approach is no longer valid when we allow decreasing heat fluxes which can result in the flow leaving the FDB regime and transitioning back to PDB.

Now when Z_{mf}^+ is zero at either BD or SBD, both the nonequilibrium quality and void fraction are forced to be zero, as required. Note that the mass fluxes, G_c and $G_{c(BD)}$, are the values of mass flux of the core flow, which is larger than the mass flow rate divided by the tube cross-sectional area whenever the flow is in a region where there is some blockage caused by the near-wall void.

The use of Z_{mf}^+ also improves the agreement with the uniform-heat-flux pressure drop data of Dormer and Bergles [2] at low pressure. An example is shown in Fig. 4, where the triangles indicating the calculations of the SCB-2A Code using Z_{mf}^+ show better agreement with the data than the circles using Z^+ as in the SCB-1A Code. (See Appendix, equation (A18) for the definition of Z^+.)

The new SCB-2A Code uses the same model as the SCB-1A Code for the decay of the near-wall bubble layer after the BD point. The bubble layer is assumed to decay to zero in about one-quarter of the distance from the BD point to the predicted OBB (Onset of Bulk Boiling) point [4]. This is a purely empirical model, since it is not at present possible to predict when the near-wall void disappears and is replaced by what we call the volumetric void. The near-wall void fraction decay in the FDB region is best modeled by the use of Z_f^+ as follows:

$$\alpha_w = \alpha_{w(BD)} \left[\frac{0.25 - Z_f^+}{0.25}\right] \quad \text{for } 0 \leqslant Z_f^+ \leqslant 0.25. \tag{8}$$

This decay can be seen clearly in Fig. 3 for a uniform heat flux case. For the case of an axially decreasing heat flux, the new code allows the near-wall bubble layer to build up in the FDB regime to the value at BD in exactly the reverse manner as the SBD (suppression of bubble departure) point is approached.

SCB-2A CODE VALIDATION

The new SCB-2A Code has been compared directly to a part of the data base for axially uniform heat fluxes used to validate the SCB-1A Code [4]. In most cases, the SCB-2A Code gave almost as good predictions of the pressure drops as the SCB-1A Code (see Springsteen [14] for details). However, since the SCB-1A Code has been more thoroughly validated, we recommend that it still be used for *uniform* axial heat fluxes.

We have not yet found accurate SCB pressure drop data for axially nonuniform heat fluxes to use in validating this part of the SCB-2A Code. Consequently, the code results for axially nonuniform heat fluxes must be used with some caution until such validation is accomplished.

CRITICAL HEAT FLUX CORRELATION

After an examination and comparison of many subcooled boiling CHF correlations, the Gambill correlation [17] was tentatively chosen for use in the SCB-1A Code [18]. This correlation has been retained in the new SCB-2A Code for the time being, since it tends to be somewhat more conservative (i.e. to predict lower CHF) than many of the other SCB correlations examined.

The following modification of the Gambill correlation has been incorporated in both the SCB-1A and SCB-2A Codes. For tubes smaller than 0.008 m inner diameter:

$$CHF = CHF_{(\mathrm{Gambill})}\sqrt{\left(\frac{0.008}{D_i}\right)}. \tag{9}$$

This modification is based on the correction suggested for the USSR Academy of Sciences CHF data [19]

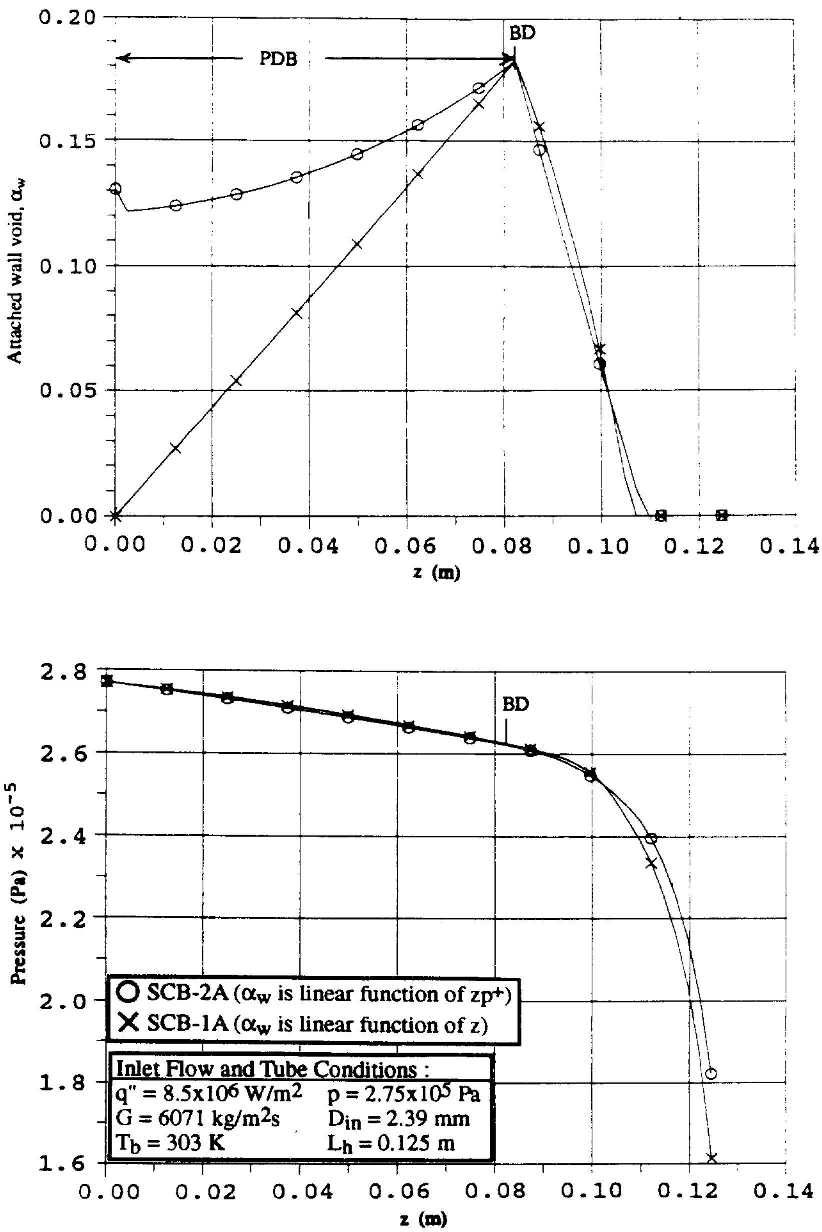


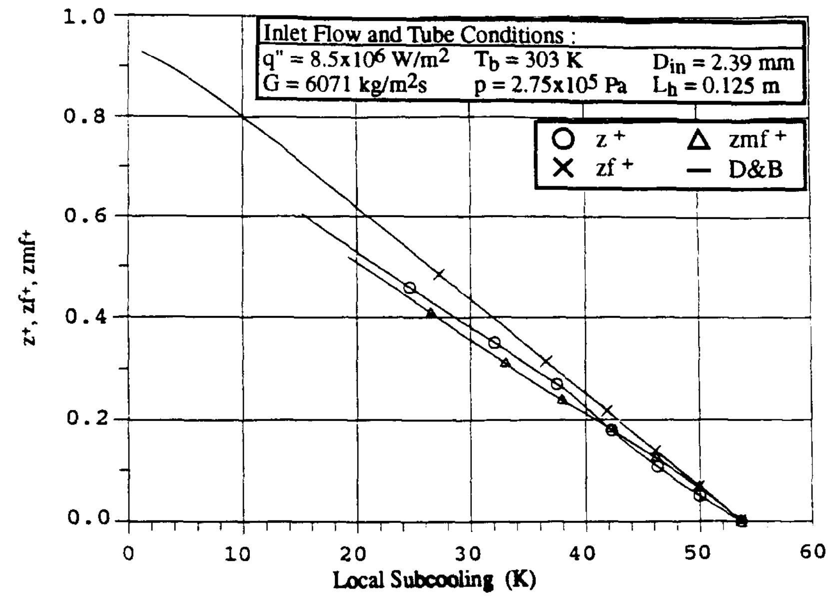
FIG. 3. Comparison of the attached (and near-wall) void fraction predicted by the model in the earlier SCB-1A Code with the present model in the SCB-2A Code and its effect on the pressure loss for the case of an axially uniform heat flux with the flow entering in the PDB regime.

and is supported by CHF data of Bergles [20] in small diameter tubes.

PREDICTED RESULTS FOR LINEAR AXIAL HEAT FLUX PROFILES

The SCB-2A Code has been designed to accept a wide variety of axial heat flux profiles as long as there are no step discontinuities present. There is also an upper limit on the magnitude of the acceleration pressure gradient of 3.0×10^6 Pa m^{-1} which is a limit carried over from the SCB-1A Code (see [4, 18]). Sets of runs were made for triangular, truncated sinusoidal and displaced cosine-shaped axial heat flux profiles (see Springsteen [14] for details). Only the representative results for the linear profiles will be described here.

The results predicted by the SCB-2A Code for a family of linear axial heat flux profiles (Fig. 5(a)), all giving the same bulk temperature rise (Fig. 5(b)), are shown in Fig. 5(c)–(g). The tube is assumed to be horizontal. For Profiles L2, L3 and L4, the flow enters the tube in the PDB regime, while for Profile L5 the flow enters in the SPL regime and for Profile L1 the



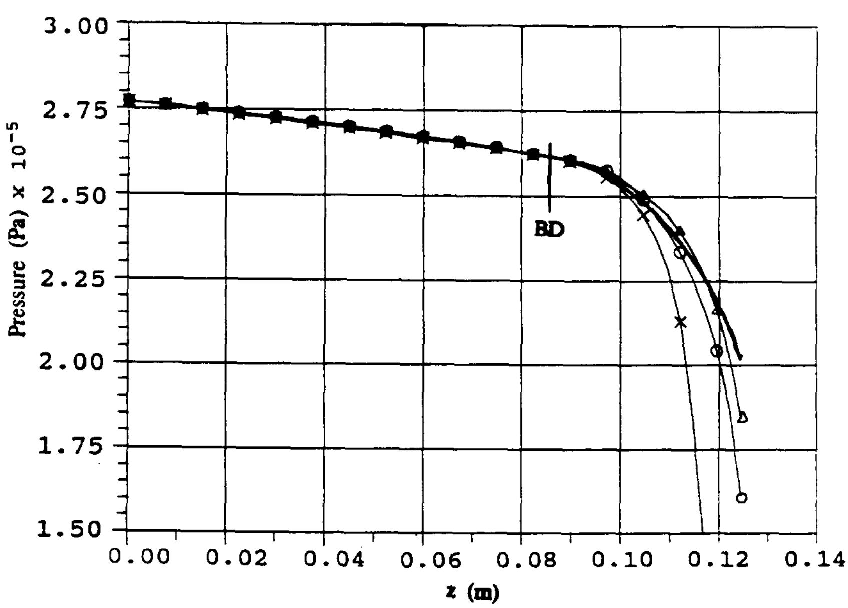


FIG. 4. Comparison of the predicted pressure profiles using various models for the nondimensional axial distance, z^+, in the FDB regime for the conditions of experimental case D&B 11A. (The experimental data are represented by the heavier curve without symbols.)

flow enters in the FDB regime. Since the SCB pressure drops are dominated by the acceleration pressure gradient, the overall pressure drop (Fig. 5(e)) is largest for Profiles L3, L4 and L5 which generate the largest volumetric void fraction, α' (Fig. 5(c)).

The rapidly increasing heat fluxes of Profiles 4 and 5 also cause the subcooling to decrease rapidly, which in turn causes the predicted CHF to decrease. The net result is that the CHF Safety Factor (defined as the predicted local CHF divided by the actual local heat flux) decreases below unity before the end of the tube for these two profiles (Fig. 5(f)). If the tube did not burn out, the OBB point would be reached shortly thereafter due to the rapid rate of decrease of local pressure and hence the local saturation temperature.

The heat transfer coefficient (Fig. 5(g)) has its most rapid growth for Profiles L4 and L5 in the FDB regime toward the tube exit. This is expected, since the wall

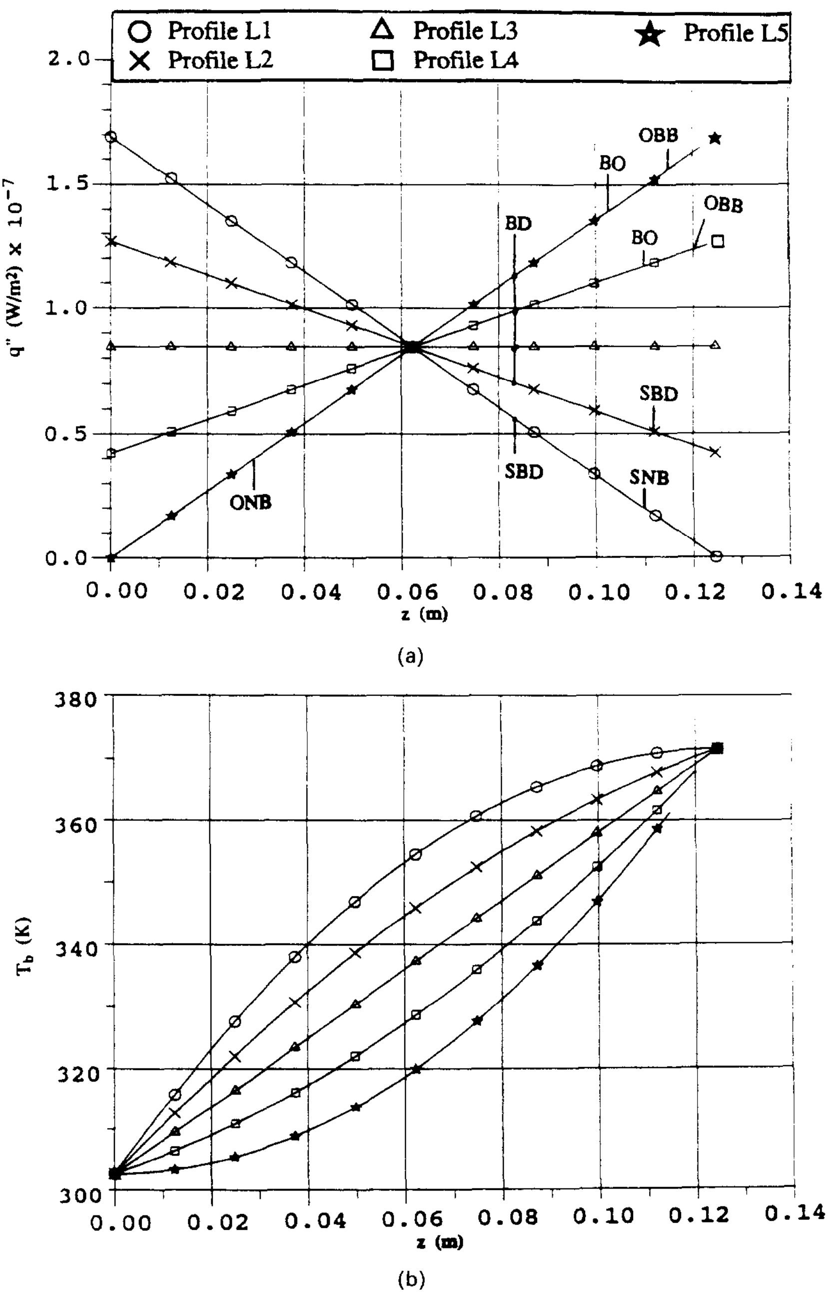


FIG. 5. (a) Family of axially linear heat flux profiles and (b) the corresponding variation of the water bulk temperature. (c) Comparison of the nonequilibrium void fraction and (d) the attached (and near-wall) void fraction for the linear axial heat flux profiles of (a). (e) Comparison of the pressure variation and (f) the CHF safety factor for the linear axial heat flux profiles of (a). (g) Comparison of the heat transfer coefficients and (h) the inner wall temperature for the linear axial heat flux profiles of (a).

temperature is only decreasing slowly (Fig. 5(h)) while the bulk temperature (Fig. 5(b)) and the heat flux (Fig. 5(a)) are both increasing rapidly, causing the heat transfer coefficient to increase rapidly:

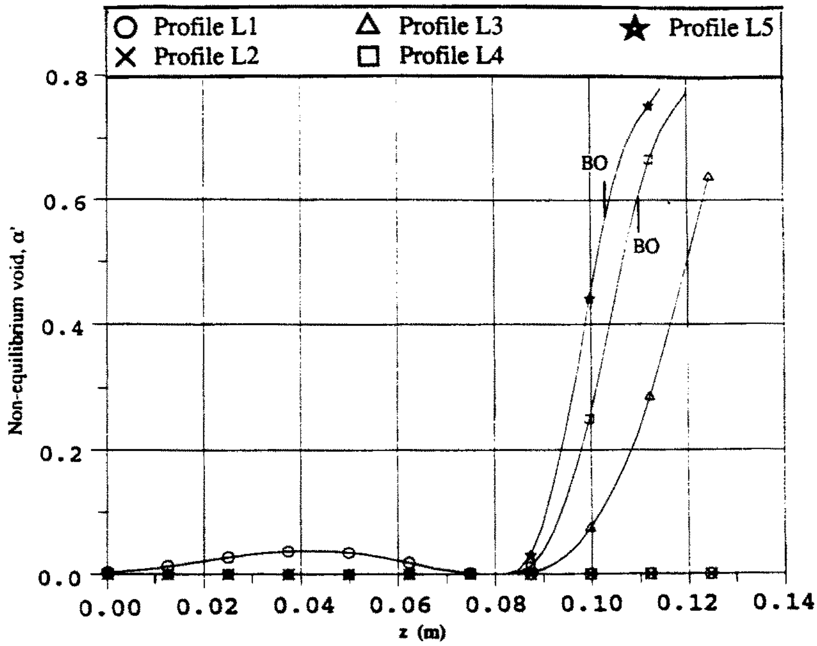
$$h = \frac{q''}{T_w - T_b}. \tag{10}$$

It is a bit more difficult to see why the wall temperature is decreasing slowly for most of the FDB regime. The inner wall temperature in the FDB regime is determined using the Jens and Lottes correlation (in S.I. units):

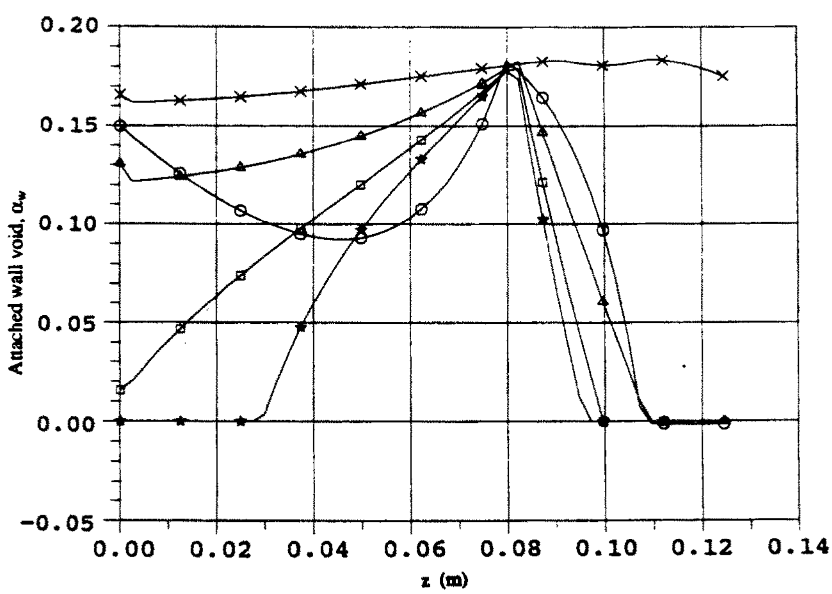
$$\Delta T_{SAT(J\&L)} = 25\left(\frac{q''}{10^6}\right)^{0.25} \exp -\left(\frac{p}{62\times 10^5}\right). \tag{11}$$

The wall temperature is then given by:

$$T_w = T_{SAT} + \Delta T_{SAT(J\&L)}. \tag{12}$$



(c)



(d)

FIG. 5.—*Continued.*

The local saturation temperature is decreasing due to the decreasing pressure, while the Jens and Lottes ΔT_{SAT} is increasing slowly due to the decreasing pressure. The net effect is that the local wall temperature in FDB decreases slowly. Only when the nonequilibrium void fraction, α', causes the pressure (and hence the local saturation temperature) to start dropping rapidly does the wall temperature also begin to drop rapidly.

The predictions of Fig. 5 show that even for simple linear axial heat flux profiles, a rich variety of phenomena occur. The results depend sensitively on the slope of the heat flux profile even though the mass flow rate, inlet pressure and temperature, the total heat added and the final increase in the bulk temperature are the same for all cases.

CONCLUSIONS

A computer code, SCB-2A, has been developed to predict the behavior of convective subcooled boiling

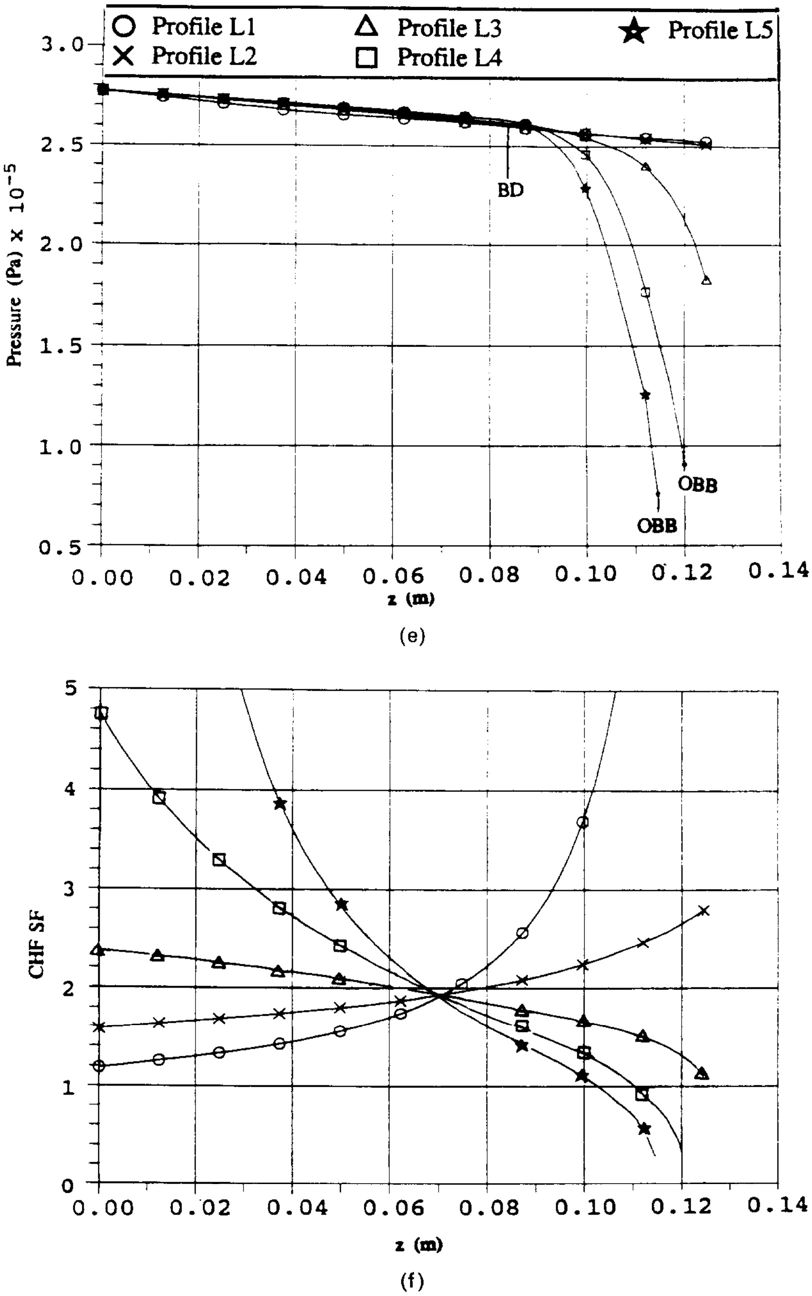


FIG. 5.—*Continued.*

flows of water in round tubes subjected to nonuniform axial heat flux profiles. It is based on the well-validated SCB-1A Code (Hoffman and Wong [4]) for uniform axial heat fluxes. Two new transition points, SNB (Suppression of Nucleate Boiling) and SBD (Suppression of Bubble Departure) have to be modeled in order to account correctly for the two-phase SCB flow behavior with decreasing heat flux profiles. In addition, several other changes have had to be made to the SCB-1A Code to be able to handle nonuniform axial heat flux profiles.

The new SCB-2A Code still agrees almost as well as the original SCB-1A with the experimental data for *uniform* heat fluxes. We have not yet found suitable SCB pressure drop and heat transfer data for *non-uniform* axial profiles to use to validate the code for these cases.

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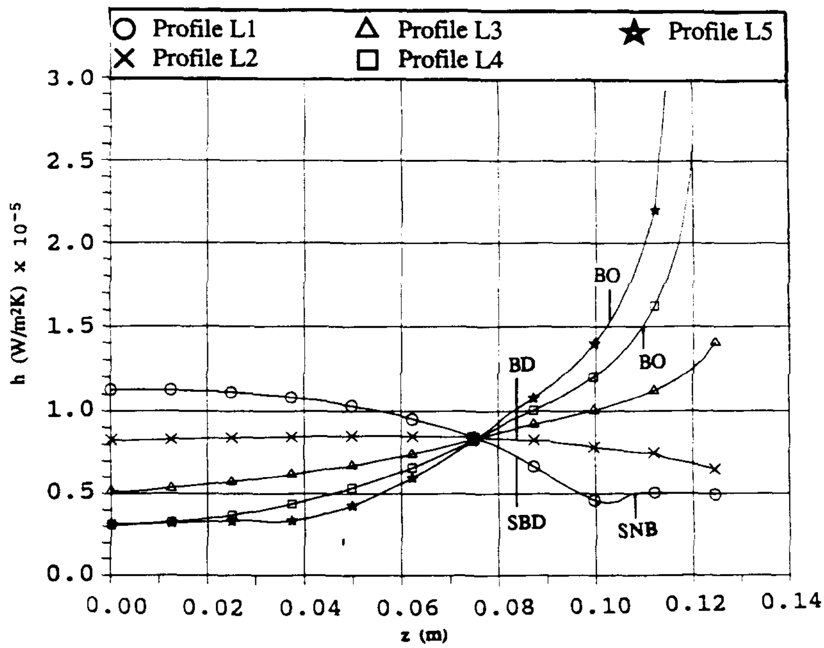
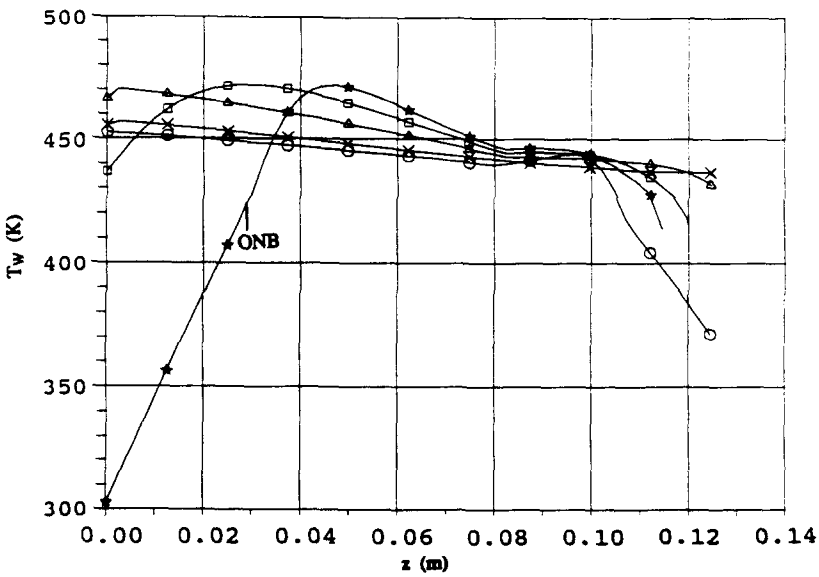


(g)



(h)

FIG. 5.—*Continued.*

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APPENDIX: EQUATIONS IN THE SCB-2A MODEL

Single phase liquid regime

Owens and Schrock [1], Dormer and Bergles [2] and others have suggested using the wall viscosity divided by the bulk viscosity to some power to correct for the effect of heating. The SCB-1A and SCB-2A Codes incorporate this correction factor with the exponent, n, chosen as 0.3:

$$\frac{f}{f_{iso}} = \left[\frac{\mu_w}{\mu_b}\right]^n \tag{A1}$$

where the smooth-tube Fanning isothermal friction factor, f_{iso}, is given by:

$$f_{iso} = 0.046\,Re_b^{-0.2} \qquad 2300 \leqslant Re_b \leqslant 10^6. \tag{A2}$$

A modified f_{iso} is used for Reynolds numbers above 10^6 (see ref. [18] for details). Agreement of the pressure drop predictions with the SPL data is excellent in almost every case, with overall agreement within about $\pm 20\%$.

The SPL heat transfer coefficient used in the code is that specifically recommended for water in ref. [21].

$$h = 0.445 f_{iso} c_{pf} G \left[\frac{Re}{10^4}\right]^{0.0685} [Pr]^{-0.53} \left[\frac{\mu_b}{\mu_w}\right]^m \tag{A3}$$

where m ranges from 0.02 to 0.08 for Reynolds numbers greater than 12 500 (see ref. [18] for details).

Onset of nucleate boiling

The Davis and Anderson equation [6] is used for prediction of the ONB point:

$$\Delta T_{SAT(ONB)} = \frac{B}{r_{C(MA)}} + \frac{q'' r_{C(MA)}}{k_f} \tag{A4}$$

where

$$B = \left[\frac{2\sigma T_{SAT} v_g}{i_{fg}}\right]. \tag{A5}$$

The critical cavity radius, r_{CRIT}, is normally used in the code in place of the maximum-active cavity radius, $r_{C(MA)}$, when the latter is not known:

$$r_{CRIT} = \sqrt{\left(\frac{Bk_f}{q''}\right)}. \tag{A6}$$

However, the Davis and Anderson equation also permits use of the actual maximum active cavity radius when this is known for a particular fluid/surface combination.

Partially developed boiling regime

In order to calculate the friction and acceleration pressure drops in the PDB regime, it is necessary to account for the various effects of the growing near-wall bubble layer. First, Rouhani's empirical correlation [15] for the average radius of bubbles at the bubble departure (BD or OSNVG) point is used to predict the effective near-wall void fraction at bubble departure:

$$\alpha_{w(BD)} = \frac{4}{D_i}\left[1.59 \times 10^{-4}\left(\frac{p}{10^5}\right)^{-0.237}\right] \tag{A7}$$

where D_i is in meters and p is in Pascals. Then $\alpha_w(z)$ in the PDB regime is calculated using equation (4) in the text. The SPL friction coefficient is used to calculate the friction pressure drop in the PDB regime with no enhancement for the effective roughness of the bubble layer, since it is uncertain how to include the effect of sliding bubbles in the near wall region on the friction coefficient. (See the discussion of other possible ways to model this in ref. [4].)

Even using the smooth-wall friction factor, there is still a strong enhancement of the SPL friction pressure gradient in the PDB regime due to the near-wall bubble layer through its blockage effect. The local core-flow mass flux, G_c, is used instead of the inlet mass flux, G, to calculate the local pressure gradient:

$$G_c(z) = \frac{G(z)}{1-\alpha_w(z)}. \tag{A8}$$

In order to improve the agreement with the small-diameter-tube runs, we introduced an empirical reduction factor, K_{red}, in equation (4) in the SCB-1A Code to reduce the effective near-wall void fraction, α_w, for tube inner diameters less than about 3 mm (see refs. [4, 18] for details). This feature has been retained in the new SCB-2A Code.

Onset of significant net vapor generation or bubble departure point

The prediction of the OSNVG or BD point is based on the empirical correlation of Saha and Zuber [7]:

$$\Delta T_{SUB(BD)} = \frac{q''D}{455k_f} \quad \text{for} \quad Pe < 70\,000 \tag{A9}$$

$$\Delta T_{SUB(BD)} = \frac{153.8q''}{Gc_{pf}} \quad \text{for} \quad Pe > 70\,000. \tag{A10}$$

A minor modification of this Saha–Zuber correlation to account for the effect of different heat fluxes was proposed in ref. [18] and used in the SCB-1A Code. This modification was retained in the SCB-2A Code.

Fully developed boiling regime

The basic analytical equations used in the SCB-1A and SCB-2A Codes for the pressure gradients due to friction, flow acceleration and gravity in the FDB regime are based on the separated flow model [19] modified for use in the subcooled boiling regime:

$$\left[\frac{dp}{dz}\right]_{fric} = -\left[\frac{2f_{fo}G^2v_f}{D}\right](\phi_{fo})^2 \tag{A11}$$

$$\left[\frac{dp}{dz}\right]_{accel} = -G^2\frac{d}{dz}\left[\frac{(x')^2v_g}{\alpha'} + \frac{(1-x')^2v_f}{(1-\alpha')}\right] \tag{A12}$$

$$\left[\frac{dp}{dz}\right]_{grav} = -g\sin\theta\left[\frac{\alpha'}{v_g} + \frac{(1-\alpha')}{v_f}\right]. \tag{A13}$$

The main modification for use of the separated flow model in the SCB regime is to replace the equilibrium quality and void fraction normally used in the bulk boiling regime by the nonequilibrium quality, x', and the nonequilibrium volumetric void fraction, α', in the FDB regime. The total pressure drop is obtained by integrating each of these pressure gradient terms along the tube and summing them. The Martinelli–Nelson two-phase friction multiplier [22], $(\phi_{fo})^2$, is used to be consistent with the separated flow model.

In order to model the nonequilibrium volumetric void fraction, α', the drift flux model developed by Kroeger and Zuber [16] is used:

$$\alpha'(z) = \frac{x'(z)}{\left[\frac{C_o(\rho_f-\rho_g)}{\rho_f}\right]x'(z) + \left[C_o + \frac{\bar{u}_{gj}}{u_{fo}}\right]\frac{\rho_g}{\rho_f}} \tag{A14}$$

where

$$\bar{u}_{gj} = 1.41\left[\frac{\sigma g(\rho_f-\rho_g)}{\rho_f^2}\right]^{0.25}. \tag{A15}$$

This is the weighted mean drift velocity for vertical upflow in tubes. For horizontal tube orientations, this velocity was set to zero.

The nonequilibrium quality was evaluated from the model of Kroeger and Zuber [16] using one of their empirical equations for the variation of the bulk fluid temperature in the FDB regime:

$$x'(z) = \left[\frac{c_{pf}\Delta T_{SUB(BD)}(Z^+ - T^*)}{i_{fg} + c_{pf}\Delta T_{SUB(BD)}(1-T^*)}\right] \tag{A16}$$

where

$$T^* = \left[\frac{T_f(z) - T_f(z_{BD})}{T_{SAT} - T_f(z_{BD})}\right] = \tanh[Z^+] \tag{A17}$$

and where the original Z^+ of Kroeger and Zuber [16] used in the SCB-1A Code was:

$$Z^+ = \frac{z - z_{BD}}{z_{OBB} - z_{BD}}. \tag{A18}$$

The new SCB-2A Code uses Z^+_{mf} given by either equation (5) or (6) of the text in place of Z^+. We found that a constant value for the radial void distribution parameter, C_o, of 1.25 gave the best all around agreement with the runs in our data base.

Range of validity of the SCB-2A Code for axially uniform heat fluxes

The original SCB-1A Code was validated over the following range of parameters for water flows in round tubes and was found to agree with our data base consisting of about 110 runs to within $\pm 20\%$:

$q'' = 0$–9.7 MW m^{-2};	$G = 2500$–$10\,000$ kg m^{-2} s^{-1}
$p_{in} = 0.2$–2.8 MPa;	$\Delta T_{SUB(in)} = 10$–200°C
$D_i = 1.6$–9.5 mm;	$L/D_i = 49$–192

$[dp/dz]_{accel} < 3.0$ MPa m^{-1}.

The new SCB-2A Code is almost as accurate as the SCB-1A Code as far as *uniform* axial heat fluxes are concerned.