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MECHANISTIC MODEL FOR VOID DISTRIBUTION IN FLASHING FLOW

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ABSTRACT

A problem of discharging of an initially subcooled liquid from a high pressure condition into a low pressure environment is quite important in several industrial systems such as nuclear reactors and chemical reactors. A new model for the flashing process is proposed here based on the wall nucleation theory, bubble growth model and drift-flux bubble transport model. In order to calculate the bubble number density, the bubble number transport equation with a distributed source from the wall nucleation sites is used. The model predictions in terms of the void fraction are compared to Moby Dick and BNL experimental data. It shows that satisfactory agreements could be obtained from the present model without any floating parameter to be adjusted with data. This result indicates that, at least for the experimental conditions considered here, the mechanistic prediction of the flashing phenomenon is possible based on the present wall nucleation based model.

INTRODUCTION

A thorough understanding of the physics governing phase change during discharging of an initially subcooled liquid from and high enthalpy/high pressure conditions into a low pressure environment is quite important in safety analysis of boilers, steam generators, chemical and process plants. Particularly, the phenomenon has received considerable attention in the nuclear reactor safety analysis. The discharge rate of coolant from a broken primary coolant pipe controls the rate of heat transfer in the core and determines the requirements for emergency cooling and safety equipment as well as the containment structure design to remedy reactor loss of coolant accidents. The dynamics of discharge and critical flow phenomena for single-phase fluids are well understood and quite acceptable analytical models are available. However, for two-phase flow a number of problems arise, particularly for short pipes and nozzles. This is because the mechanical and thermal non-equilibrium effects as a consequence of liquid flashing may play an important role in the process.

In predicting two-phase flow transients, the interfacial transfer terms are among the most essential factors in modeling. These interfacial transfer terms in a two-fluid model specify the rate of phase change, momentum exchange and heat transfer at the interface between phases. In the two-fluid model formulation [1-4], the transport processes of each phase are expressed by their own balance equations. Therefore, it is

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expected that the model can predict more detailed changes and phase interactions than a mixture model such as the drift flux model [5,6]. The weakest link in the two-fluid model is the constitutive equations for the interfacial interaction terms. The difficulties arise due to the complicated motion and geometry of the interfaces in a general two-phase flow. The interfacial transfer terms are strongly related to the interfacial area and to the local mechanisms, such as the degree of turbulence near the interfaces [1]. Basically, the interfacial transport of mass, momentum and energy is proportional to the interfacial area concentration and to a driving force. This area concentration defined as the interfacial area per unit volume of the mixture, characterizes the kinematic effects; therefore, it must be related to the structure of the two-phase flow field. On the other hand, the driving forces for the interphase transport characterize the local transport mechanism, and they must be modeled separately. Basic macroscopic parameters related to the structure of two-phase flows, particularly of a dispersed (bubbly or droplet) flow, are the void fraction, particle number density, interfacial area concentration and the particle shape factor. From geometric considerations it is demonstrated that the particle number density is a key parameter in determining the interfacial area concentration but it has not been sufficiently investigated in the literature [7].

Realizing the significance of the bubble number density as an important parameter for predicting the interfacial area in a two-phase flow a model for flashing process is proposed here based on the wall nucleation theory and bubble growth model. In order to calculate the bubble number density, the bubble number transport equation is used.

FLASHING PHENOMENA

Flashing can be considered as a continuous process which occurs in several stages. Generally speaking, flashing occurs when liquid is brought to the region where the local pressure is below the saturation pressure corresponding to the liquid temperature. In a flowing systems, such as a flow in a pipe or in a nozzle, a depressurization is caused by the friction or acceleration pressure drop which brings the liquid from initially subcooled to saturated conditions. With further decreases in the pressure, liquid becomes superheated and the nucleation process starts. The degree of superheat required for starting the nucleation may depend on the flow and surface conditions for a particular flow system, and the depressurization rate. For a pipe flow, at least in the beginning the bubble nucleation process is certainly dominated by the wall heterogeneous nucleation. The process is initially relatively slow, but it rapidly increases with increasing liquid superheat. According to Reocreux's experiments [8], this wall dominated vaporization zone was 20 to 120 cm in length. With relatively low liquid velocities in Reocreux's experiments, the residence time for generated vapor bubbles in this zone was of the order of a few ten milliseconds. The length of the nucleation zone is a strong function of the flow velocity and the depressurization rate. For the BNL nozzle experiment [9] with similar pressure and temperature conditions as in Reocreux's experiment, the length of the nucleation zone was of the order of a centimeter only. This resulted from higher flow velocities, depressurization rates and liquid superheating. A reliable predictive method is not yet established for the width of the bubble nucleation zone in a flowing flashing, system, nor are accurate criteria developed for the point of the flashing inception.

After the inception point, a local fluid pressure in a pipe decreases rapidly resulting in almost exponential increases of the liquid superheat. All vapor bubbles generated in the nucleation zone flowing through this region of the channel will experience sharp drops in the pressure resulting in the explosive bubble growth. Jones and Zuber [10] have found that for the variable pressure field where the pressure decays with the time according to a power law t^n, the bubble radius varies as $t^{n+1/2}$ while the void fraction changes as $t^{3(n+1/2)}$. These very fast growing bubbles are accelerated more rapidly than the liquid phase. Initially more bubbles are concentrated near the wall. Therefore the void profile is double peaked, however after a short distance the concentration profile becomes flatter, with the distribution parameter C_o approaching unity. Besides the flashing inception point, it is considered that this "turning-point" with $C_o = 1.0$ is equally important for the thermohydraulics of the flashing, because it indicates the full migration of the bubbles to the core of the flow and sufficiently developed bubble profile. Vapor bubbles generated up to this turning point represent the majority of the bubble population which controls the vapor generation rate downstream in the channel. Bubbles generated downstream will have shorter growth time and much narrower changes in the pressure field, thus resulting in a lower partial void fraction. Saha et al. [11] in their model for vapor generation in flashing flow through nozzles chose the inception point as the channel location after which the downstream nucleation can be neglected.

Further downstream, bubbles continue to expand and accelerate with a tendency to agglomerate into slug bubbles and into a continuous vapor core toward the annular flow regime. The development of those regimes in flashing flow depends on many parameters, including the pressure, flow rate, depressurization rate, surface conditions, presence of dissolved gases or impurities and local surface irregularities which may serve as nucleation and/or cavitation sites.

In recent years, the problem of flashing flow has often been studied in relation with the critical flow problem. Various models applicable to flashing with critical flow have been proposed in the past. Review and descriptions of these models have been presented by Ardron and Furness [12], Jones and Saha [13,14], Weisman and Tentner [15], Abdollahian et al. [16] and Wigni and D'Auria [17].

Alamgir and Lienhard [18] developed a semi-empirical correlation to predict the pressure undershoot at the flashing inception point for a rapid static decompression of hot water. Jones [19] used their correlation, and introducing a turbulence effect at the flashing onset point. Then he correlated Reocreux's [8] and Seynhaeve, et al. [20] data for straight pipes. Reocreux [8] used as a criterion for the flashing inception based on the superheat at the location where the pressure deviates from a linear axial profile. Our calculations [21] show that for Reocreux's experiments this inception point falls in the region where the local void fraction varies between 0.04 and 0.06. For these conditions, the generated vapor phase is still distributed in the vicinity of the wall and the distribution parameter C_o is much lower than 1. This indicates that the void distribution profile is qualitatively similar to the one for subcooled boiling [6].

Edwards [22] proposed model assuming that the vapor phase is always at saturation and that Plesset and Zwick's [23] model could be applied for bubble growth in the initial phase of the flashing. Two arbitrary parameters; the time-delay in bubble nucleation and the number of bubbles

per unit mass of liquid were correlated using the Fauske [24] and Zaloudek [25] data. The time-delay was on the order of 1 msec, and the bubble numbers chosen by Edwards lay between 10^8 - 10^{11} bubbles/lb, i.e., about 2×10^5 - 2×10^8 bubble/cm^3.

Malnes [26] assumed that the presence of dissolved gases has an important role in the flashing. He also made the assumption of a constant number of bubbles per unit volume which is a function of a property group as

$$N_b = \left(\text{Const. } g \frac{\rho_f}{\sigma}\right) \tag{1}$$

Instead of making this assumption about the constant number of bubbles, Rohatgi and Reshotko [27] used a kinetic theory and proposed an expression for the rate of production of vapor nuclei as

$$\dot{N} = N_h \frac{2\sigma}{\pi m} \exp\left| - \frac{W_{cr}}{k\, T_f} \phi \right| \tag{2}$$

where m, W_{cr} and k are the mass of the molecule, critical work required to create an unstable bubble nucleus and Boltzmann constant, respectively. In order to match Simoneau's experimental data [28], they recommended a value of $\phi = 5 \times 10^{-6}$ for the factor of heterogenity and N_h = 1-2 nuclei/cm^3 for the number of heterogeneous nucleation sites. Studovic [29] also used a kinetic theory approach to describe initial conditions for active nuclei vapor phase generation and modified Jones and Zuber model [10] for convex shape of pressure distribution. He used his own experimental data from the converging-diverging nozzle, Reocreux's and data from the CANON experiment to correlate the vapor generation rate.

Following the theory of homogeneous nucleation, and using a liquid compression model, Lienhard and co-workers [30] proposed an expression for the bubble number density for a high pressure static decompression of water given by

$$N_b = \frac{\tilde{Z}}{\left(Ja_T + b\, Ja_p\right)^3} \tag{3}$$

where Ja_T and Ja_p represents Jakob number based on initial superheat and a flashing Jakob number. From various available experimental data they found that the mean value of 1.6×10^4 bubbles/cm^3 describes the Z data within 25 percent scatter. They assume that the number density N_b remains constant during the flashing developments.

Wolfert [31] made an attempt to calculate the vapor generation, allowing relative movement between the vapor bubbles and the liquid. The effect of relative velocity has been incorporated in the interfacial heat transfer coefficient using the expression of Aleksandrov [32] as,

$$h = \frac{\sqrt{3\, k_f}}{\sqrt{\pi\, \alpha_f t}} \left[1 + \sqrt{\frac{2\, V_{gj}\, t}{3\, R_b}} \right] \tag{4}$$

with the values of V_{gj} = 0.15 m/s and the number of bubbles N = 5×10^3 bubbles/cm^3. He obtained the best agreement with Edwards and O'Brien's [33] standard experiment.

To predict vapor distribution in the BNL nozzle experiments, Saha [34], has provided a justification for Wolfert's model and he proposed a modified expression for the interfacial heat transfer coefficient with the relative bubble velocity as,

$$h = \frac{\sqrt{3\ k_f}}{\sqrt{\pi\ \alpha_f t}} \left[1 + \frac{C_1}{3} \frac{V_{gj}\ t}{R_b} \right]^{1/2} \tag{5}$$

A good agreement with the BNL flashing experiment data of Wu, et al. [9] was obtained by best-fit calculations of the number of bubbles. For reported experiments, the number density of bubbles varies between 3×10^3 and 8×10^4 bubbles/cm^3.

In later papers, Jones and Shin [35,36] proposed a wall cavity model to predict a flashing inception in the nozzles. The model predicts a one-sided activation criterion where the minimum active cavity size is obtained as a function of the bubble waiting time. Using Kocamustafaogullari and Ishii's [7] correlation for nucleation site density, they attempted to find a bubble number density and the void fraction at the nozzle throat (onset of flashing). They tried to match the above quoted best-fit values of the number of bubbles for BNL nozzles.

BUBBLE NUMBER TRANSPORT EQUATION

Kocamustafaogullari and Ishii [7] analyzed the problem of nucleation site density in the pool and convective boiling, and developed a bubble number density balance equation. Following their procedure, the local bubble number density equation for flashing flow in a channel (Fig. 1) can be expressed as,

$$\frac{\partial N_b}{\partial t} + \nabla\left(N_b \cdot \vec{v}_b\right) = \phi_{so} - \phi_{si} \tag{6}$$

where ϕ_{so}, ϕ_{si} and $\vec{v}_b$ are the bubble source term due to the bulk nucleation, bubble sink term due to bubble collapses or coalescences and local bubble velocity, respectively.

For most engineering applications Eq. (6) can be simplified by means of proper averaging. The advantage of such an approach is two-fold. First, the variables appearing in the final equation will have explicit definitions in terms of averaged values. Consequently, it will be easy to compare predicted results with experimental data, which in two-phase flow are most often presented in terms of average values. Secondly, by means of space averages it will be possible to reduce the number of space variables and to treat the problem as a one-dimensional one.

In order to simplify Eq. (6) into a one-dimensional form and to express it by means of averaged values of the variables, this locally formulated equation is integrated over the channel cross-sectional area $A_c(z)$. By applying the Leibnitz theorem and the Gauss-Ostrogradskii divergence theorem over surfaces, Eq. (6) can be expressed in the following form,

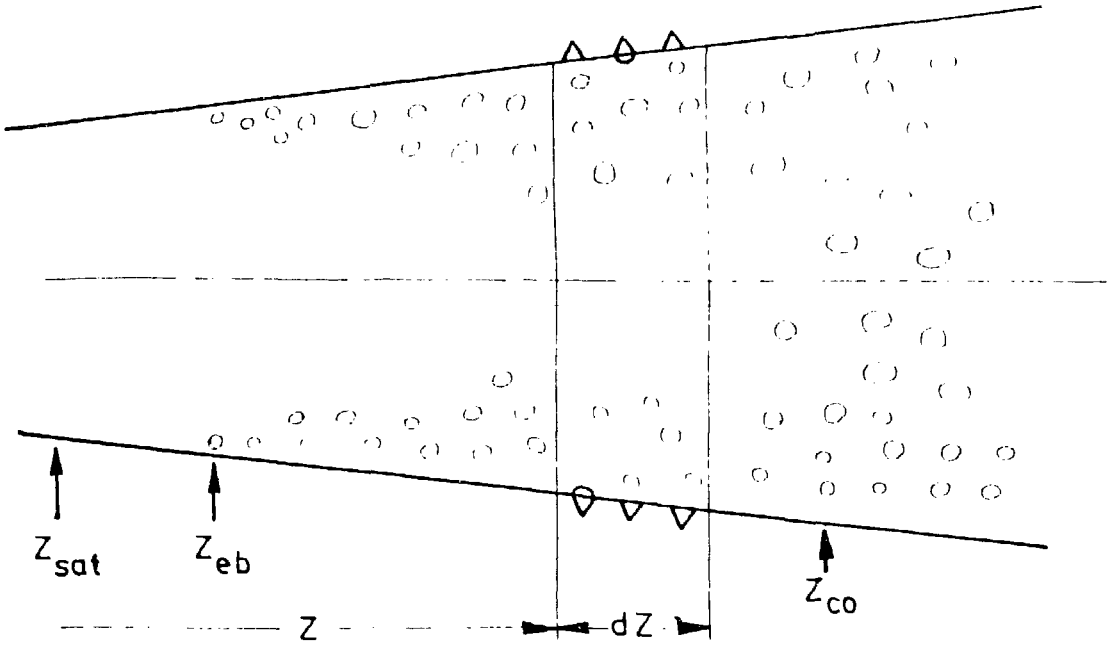

FIGURE 1. A schematic representation of the channel bubbly flow for flashing model

$$\frac{\partial}{\partial t}\left(A_c \langle\langle N_b \rangle\rangle\right) + \frac{\partial}{\partial z}\left(A_c \langle\langle N_b \rangle\rangle \bar{v}_b\right) = - \int_{\xi(z)} \frac{\hat{n}\, N_b\left(\vec{v}_b - \vec{v}_\xi\right)}{\left(\hat{n} \cdot \hat{n}_\xi\right)} d\xi$$

$$+ A_c\left(\langle\langle \phi_{so} \rangle\rangle - \langle\langle \phi_{si} \rangle\rangle\right) \tag{7}$$

The first term on the right-hand side represents the flux of bubbles generated from the active nucleation sites at the channel wall. In terms of the bubble nucleation site density N_a and the frequency f of bubbles generated from a nucleation site, the bubble flux term can be given by

$$-\hat{n} \cdot N_b\left(\vec{v}_b - \vec{v}_\xi\right) = N_a f \tag{8}$$

Substituting Eq. (8) into Eq. (7) one obtains

$$\frac{\partial}{\partial t}\left(A_c \langle\langle N_b \rangle\rangle\right) + \frac{\partial}{\partial z}\left(A_c \langle\langle N_b \rangle\rangle \bar{v}_b\right)$$

$$= - \int_{\xi(z)} \frac{N_a f}{\left(\hat{n} \cdot \hat{n}_\zeta\right)} d\xi + A_c\left(\langle\langle \phi_{so} \rangle\rangle - \langle\langle \phi_{si} \rangle\rangle\right) \tag{9}$$

Equation (9) is the one-dimensional, area-averaged bubble number density transport equation, which is applicable for a channel with variable cross-sectional plane. For the case of flow in the pipe with a constant cross-sectional area, it can be simplified to the form,

$$\frac{\partial \langle\langle N_b \rangle\rangle}{\partial t} + \frac{\partial}{\partial z}\left(\langle\langle N_b \rangle\rangle \bar{v}_b\right) = \langle \phi_w \rangle + \langle\langle \phi_{so} \rangle\rangle - \langle\langle \phi_{si} \rangle\rangle \tag{10}$$

The perimeter-averaged bubble generation rate from active nucleation sites at the channel wall is given by

$$\langle \phi_w \rangle = \frac{1}{A_c} \int_{\xi} (N_a f) d\xi = \frac{\langle N_a \rangle f \xi}{A_c} \tag{11}$$

with the assumption that the frequency f is uniform around the channel perimeter.

Bubble nucleation in the bulk liquid can occur either as homogeneous or heterogeneous nucleation. The classical homogeneous nucleation theory assumes that a bubble is formed in the bulk liquid by the vaporization of molecules of the liquid into a cavity. This cavity may be considered as any space within the liquid phase unoccupied by liquid molecules, thus it can be either empty or occupied by vapor. According to the Volmer-Doring-Zeldovich theory [38], the homogeneous nucleation rate can be expressed by

$$J_{ho} = \rho_f Av\ B \exp\left[-W_{cr}/kT\right] \tag{12}$$

where Av and B and are the Avogadro's number and frequency with which a molecule within the liquid interacts with its neighbors.

Foreign particles and dissolved gas normally provide ample nuclei to act as centers of vapor formation. Vapor generation from preexisting nuclei in the liquid is usually called heterogeneous nucleation. The presence of particles and dissolved gas reduces the liquid superheat required to maintain a bubble in unstable equilibrium. Heterogeneous nucleation rate can be expressed in the similar form as,

$$J_{he} = \rho_f Av\ B \exp\left[-W_{cr}\phi/kT\right] \tag{13}$$

where ϕ is the factor of heterogenity. This factor modifies the critical work needed to create a cavity for a heterogeneous nucleation case. In the papers by Ward et al. [39] and Forest and Ward [40] it has been shown that the presence of dissolved gas can initiate nucleation even at temperatures below the saturation corresponding to the local liquid pressure. Unfortunately, for water all those theories yield extremely high liquid superheats, especially at lower pressure. As stated by Skripov [41], it is possible that for some reason the classical theory itself is not applicable to water at $p < 0.5\ p_{cr}$.

The third term on the right-hand side of Eq. (10), the sink term $\langle\langle \phi_{si} \rangle\rangle$, takes care of reduction in bubble number density due to coalescence of bubbles into larger bubbles or bubble collapse. The coalescence is assumed to be insignificant up to the void fraction α_{co} corresponding to the point with a reasonably homogeneous distribution of a vapor phase in the bulk liquid, i.e., the point where the distribution parameter C_o reaches the unity value. For the flow conditions in the Reocreux's [8] and BNL [9] experiments the distribution parameter C_o has a value of 1.0 for the void fraction α in the vicinity of 0.1 according to the drift flux correlation [6]. Certainly this assumption can be extended up to

the void fraction of 0.3 beyond which the flow regime transition to the slug or churn-turbulent flow occurs.

VOID DISTRIBUTION IN FLASHING

Considering a steady-state flashing flow in a channel with a variable cross-sectional area, a one-dimensional transport equation for predicting the average bubble number density can be expressed as

$$\frac{\partial}{\partial z}\left(A_c N_b V_b\right) = \left(\phi_w + \phi_{ho} + \phi_{he} - \phi_{si}\right)A_c \tag{14}$$

where ϕ_w, ϕ_{ho}, ϕ_{he} and ϕ_{si} are the sources due to wall, homogeneous and bulk heterogeneous and bulk heterogeneous nucleations and the sink due to coalescence or collapse, respectively. Furthermore, various averaging symbols are omitted for simplicity. The sink term may be neglected for the initial stage of a flashing flow, thus after an integration from z_{sat} to z, one obtains

$$A_c N_b(z) v_b(z) = \int_{z_{sat}}^{z} A_c\left(\phi_w + \phi_{ho} + \phi_{he}\right)dz \tag{15}$$

Here z_{sat} is the point at which the liquid reaches the saturation state, see Fig. 1. Equation (15) can be solved for the bubble number densities at the flashing inception point $N_{b,zeb}$ and the turning point $N_{b,zco}$, respectively, i.e.,

$$N_{b,zeb} = \frac{1}{A_c v_{b,zeb}} \int_{z_{sat}}^{z_{eb}} A_c\left(\phi_w + \phi_{ho} + \phi_{he}\right)dz \tag{16}$$

$$N_{b,zco} = \frac{1}{A_c v_{b,zco}} \int_{z_{sat}}^{z_{co}} A_c\left(\phi_w + \phi_{ho} + \phi_{he}\right)dz \tag{17}$$

It is noted that at the turning point the distribution parameter C_o reaches 1, thus a considerable number of bubbles migrated to the central part of a flow channel. The wall nucleation rate ϕ_w may be expressed by using the correlation developed by Kocamustafaogullari and Ishii [7,37] for nucleation site density. They found that the wall nucleation site density can be correlated in dimensionless form as

$$N_{ns}^{*} = R_c^{*-4.4} f\left(\rho^{*}\right) \tag{18}$$

The nondimensional site density is defined by

$$N_{ns}^{*} = N_{ns} D_d^2 \tag{19}$$

and the nondimensional critical cavity radius by

$$R_c^* = \frac{R_c}{(D_d/2)} \quad \text{with} \quad R_c = \frac{2\sigma T_{sat}}{(T_w - T_{sat})\rho_g h_{fg}} \tag{20}$$

where D_d is the bubble departure diameter. The property function is correlated in terms of the density ratio as

$$f(\rho^*) = 2.157\ 10^{-7} \left(\frac{\Delta\rho}{\rho_g}\right)^{-3.12} \left(1 + 0.0049\ \frac{\Delta\rho}{\rho_g}\right)^{4.13} \tag{21}$$

Originally the correlation was developed for pool and convective boiling, and the data were correlated by using different effective superheat for those two types of boiling. Our calculations show that this correlation can be generalized even for the flashing flow by introducing appropriate superheat in the boundary layer where the bubble is generated. For convective boiling, the effective liquid superheat to which the nucleation sites and growing bubbles at the wall are exposed fluctuates between $(T_w - T_{sat})$ and 0 due to the nucleation, evaporation and liquid convection. Therefore, in the sense of averaged values, the mean superheat is in the order given by $\Delta T_{sup,sc} \simeq \Delta T/2$. However, in the correlation development for the nucleation site density, the apparent superheat ΔT has been used. On the other hand, in flashing flow, the bulk liquid is superheated. Thus the effective superheat for nucleation is ΔT, because there is always sufficient supply of superheated liquid at the wall. The bubbles are initiated from smaller wall cavities and the bubbles grow much faster than in convective boiling. Thus it is postulated here that the active nucleation site density correlation obtained for the pool and forced convective boiling could be used to predict the active nucleation site density in flashing with an effective average superheat $\Delta T_{sup,f} = \Delta T_{sup}$ rather than $\Delta T_{sup,sc}$. Practically this will result in smaller critical radiuses of cavities. Thus the effective nucleation site density for flashing flow is given by modifying Eq. (18) as

$$N_{ns}^* = \frac{1}{(D_d/2)} \left\{ \frac{2\sigma T_{sat}}{2(T_f - T_{sat})\rho_g h_{fg}} \right\}^{-4.4} f(\rho^*) \tag{22}$$

Jones and Shin [35] reported the values for the minimal critical cavity sizes they got from their analytical wall cavity model. Our calculations, using the superheat $\Delta T_{sup,f}$, and the effective critical cavity size expression by Kocamustafaogullari and Ishii [7], are within a few percentages to theirs. A bubble departure diameter D_d, necessary to obtain an active nucleation site density N_{ns} is determined by the Kocamustafaogullari [12] model given by

$$D_d = 2.64\ 10^{-5}\ \theta \left(\frac{\sigma}{g\Delta\rho}\right)^{0.5} \left(\frac{\Delta\rho}{\rho_g}\right)^{0.9} \tag{23}$$

To estimate the frequency of bubble departures the expression given by Zuber [13] is adopted here, thus

$$D_d\ f = 1.18 \left[\frac{\sigma g(\rho_f - \rho_g)}{\rho_f^2}\right]^{1/4} \tag{24}$$

Using the expressions given by Eqs. (11) and (19)-(24) one can find the bubble nucleation rate at the wall. Furthermore, by integrations given

by Eqs. (15) and (17) it is possible to determine the bubble number densities at the location of flashing inception and the turning point, i.e. where the distribution parameter C_o has the value of ~1.0.

Applying the bubble growth law in the variable pressure field [10] it is possible to estimate a bubble radius by

$$R(t) = \left(\frac{\rho_{g,o}}{\rho_g}\right)^{1/3} \left\{ R_o + \frac{2K_s}{\pi} J_{aT} \sqrt{\alpha_f t} + \frac{2K_s}{\sqrt{\pi}} J_{ap} \frac{\sqrt{\alpha_f}}{\Omega} \left[\Omega t - D(\sqrt{\Omega t}) \right] \right\} \tag{25}$$

where Ω and $D(\Omega t)$ represents time constants for pressure variation and the Dawson integral. With the idealization that all bubbles are spherical, the void fraction can be given by

$$\alpha(t) = N_b(z) \frac{4}{3} \pi R_b^3(t) \tag{26}$$

if the bubbles have the uniform size $R_b(t)$. However, in most applications bubble sizes are not uniform due to the differences in residence times. This effect is considered below.

At an early stage of the steady state flashing process in a channel, the wall nucleation due to fluid superheat caused by the pressure drop controls the process. Thus in Eq. (14), the wall nucleation source, ϕ_w, dominates the right-hand side term. The sink term, ϕ_{si}, due to the bubble collapse or coalescence is basically zero in bulk superheated liquid and for very small bubbles which are in early stages of the bubble growth. The bulk homogeneous nucleation source ϕ_{ho} is negligible because the liquid superheat is relatively low. Thus the preferred site nucleation such as the wall nucleation should be much more significant than ϕ_{ho}. The bulk heterogeneous nucleation source ϕ_{he} can be significant only if a considerable amount of dissolved gas is present in the liquid. For the present study it is assumed that the effect of dissolved gas is negligible on the nucleation process.

From the above considerations, the bubble number transport equation becomes

$$\frac{\partial}{\partial z} \left(A_c N_b v_b \right) \simeq A_c \phi_w \tag{27}$$

By integration from the boiling initiation point, z_{sat}, to z_1, one obtains

$$N_b(z_1) = \frac{1}{A_c(z_1) v_b(z_1)} \int_{z_{sat}}^{z_1} \phi_w A_c \, dz \tag{28}$$

Here the number density $N_b(z_1)$ includes the contributions from all the bubbles nucleated upstream of point z_1.

The local contribution can be considered by introducing a new parameter $n_b(z_1, z)$ which is defined by

$$n_b(z_1, z) = \frac{\phi_w(z) A_c(z)}{A_c(z_1) v_b(z_1)} \tag{29}$$

This parameter represents the contribution from the nucleation sites at location z, i.e., a number of bubbles per unit length of a channel originating at z and arriving at z_1.

Finally, by using the Lagrangian description, the void fraction at the channel location z can be expressed as

$$\alpha(z_1) = \int_{z_{sat}}^{z_1} \frac{4}{3} \pi R^3(t(z))\, n_b(z_1, z)\, dz \qquad (30)$$

COMPARISON WITH EXPERIMENTAL DATA

The present model has been applied to steady-state flashing experiments conducted in a vertical channel. In the present study, an attempt was made to compare the model predictions with the Reocreux's experimental data. Also, one BNL experimental run [9] was compared with the present model. A detailed description of the Reocreux's experiment is given in Ref. 8. The test channel was made in two parts. The lower part consisted of a stainless steel tube with an internal diameter of 20 mm and with a length of 2160 mm. The upper part made up the test channel proper. It consisted of a cylindrical part with an internal diameter of 20 mm followed by a divergent section with a peak angle of 7° and length 327 mm and a last cylindrical part with a diameter of 60 mm. Initially subcooled water at low pressures (0.21 to 0.34 MPa) entered the test section at the bottom and flowed upwards. As the pressure decreased, flashing began and two-phase mixture flowed through the cylindrical and the diverging part of the channel. Pressure and area-averaged void fractions were measured along the length of the test section. The accuracy of the pressure measurement was within 1% of the reading and that for the void fraction was within 0.05. The accuracy for the fluid temperature measurement was within 0.1°C.

The test section for BNL experiment was made of stainless steel with a total length of 787 mm, including a symmetrical converging-diverging portion of 559 mm in length. The inside diameters at both ends were 51 mm and the throat inside diameter was 25 mm. An Experiment was run with upward flows initially subcooled water at low pressures varied between 0.2 and 0.8 MPa.

Some results of the present model predictions of bubble number density distribution along the Reocreux's channel for run 403 are shown in Fig. 2. It can be noticed that the main contribution of void coming from the bubbles generated in the section between z_{sat} and net vapor generation location. Contribution of bubbles generated downstream is much smaller, due to the differences in residence time.

The above model formulation is used to calculate the void fraction in the region where the wall nucleation effect is important. However, at a certain point the effect of the new wall nucleations on the void fraction become rapidly insignificant in the downstream section because of the increased number density and a relatively large average bubble size. In this bubble expansion region, some simplification can be made by setting the bubble source term ϕ_w to be zero. In the present analysis it has been assumed that at the downstream of the location in the channel where the distribution parameter C_o reaches unity the contribution of the newly

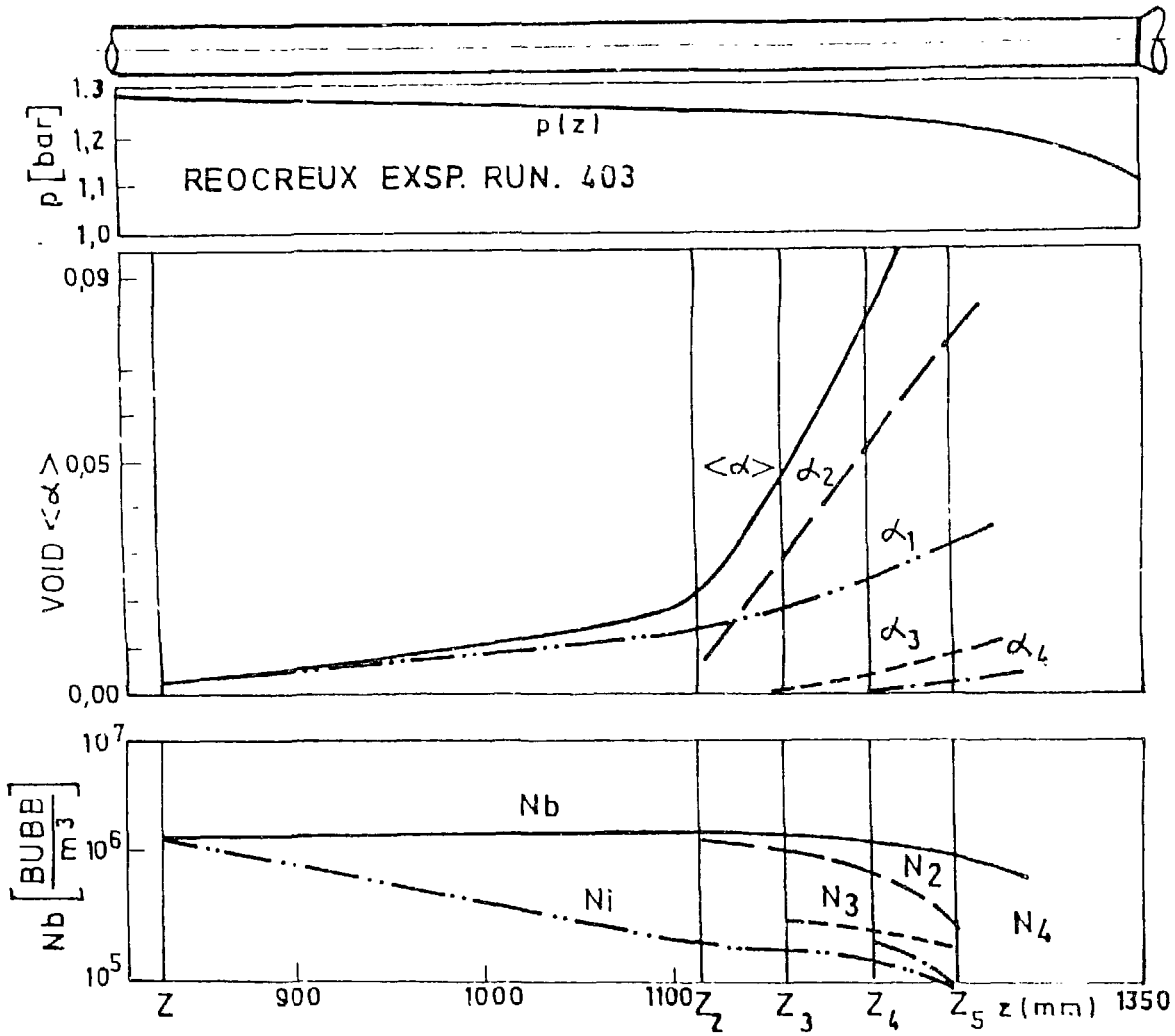

FIGURE 2. Bubble number density distribution along the Reocreux's test channel

generated bubbles from wall nucleation may be neglected. For the void fraction calculation the results of the comparisons between the present model predictions and the Reocreux's experimental trial 400 are given in Fig. 3. The model predictions are in fairly good agreement with the Reocreux's data up to the critical flow plane (throat) in his test channel. At the downstream of the throat (z_{col} = 1351 mm) the model predicts void lower than experimental values. One of the reasons is probably the presence of the secondary flows in the vicinity of the throat. Reocreux reported [8] that radial distribution of the void in the diverging zone indicates that a two-phase mixture does not expand completely. The same phenomenon was observed in the experiments with visualization using the glass test channel. In the same figure are also shown the results from the model with the assumption that two-phase jet leaves the throat without any expansion, and that the space between the jet and channel wall is filled with vapor phase. It can be seen from this figure that calculated void profile is very close to the experimentally observed up to the characteristic length of (2~3) D_{tube} from the throat.

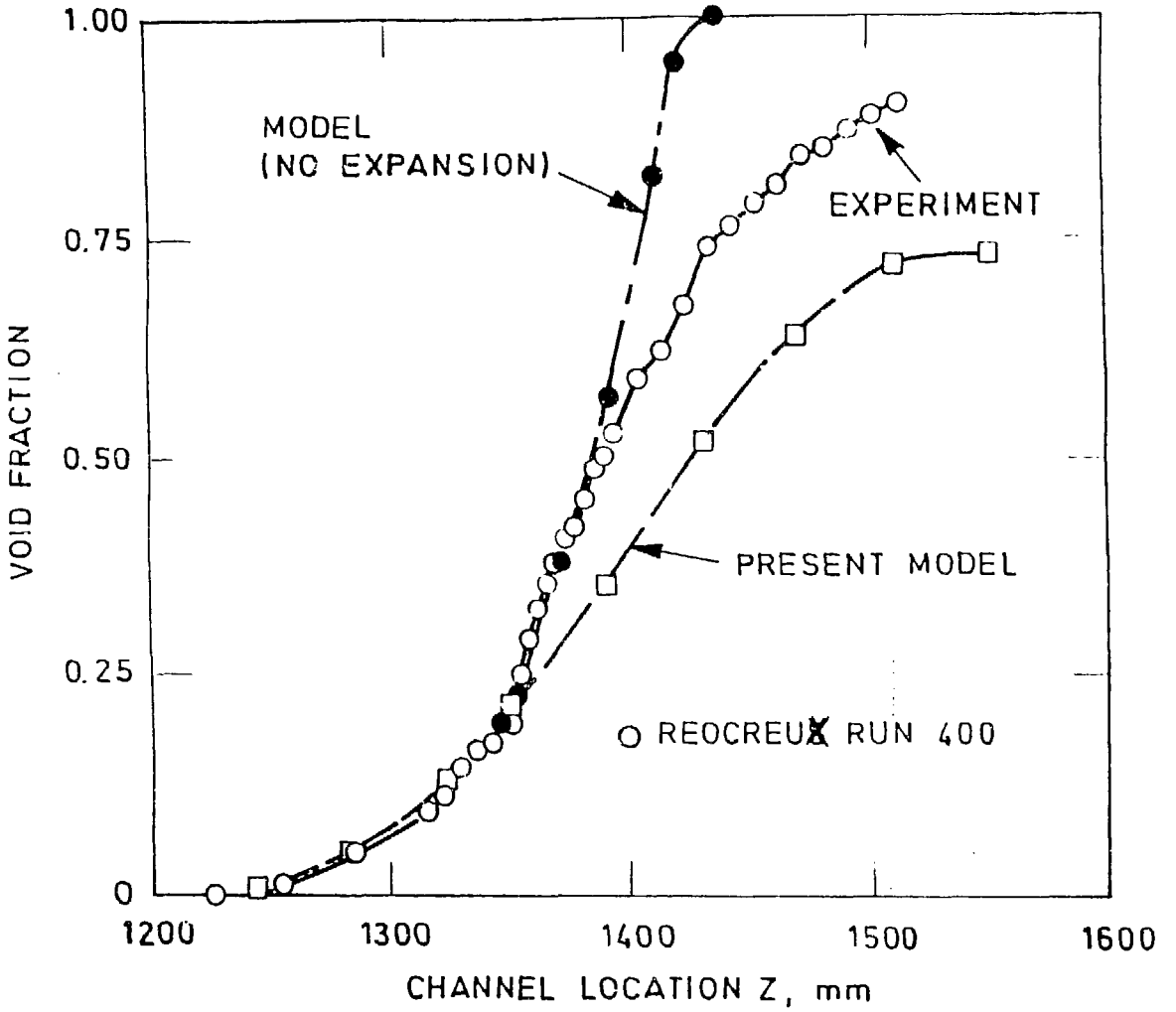

FIGURE 3. Comparison between the present model predictions and the Reocreux's experimental trial 400

The comparisons between the model predictions and the experimental data for BNL nozzle are given in Fig. 4. Because of much higher velocities than in Reocreux's case, the presence of roll waves immediately after the throat (304.8 mm) have even more influence on the void distribution in the divergin, part of the channel.

CONCLUSIONS

A new model for flashing flow based on wall nucleations is proposed here and the model predictions are compared with some experimental data. In order to calculate the bubble number density, the bubble number transport equation with a distributed source from the wall nucleation sites was used. Thus it was possible to avoid the usual assumption of a constant bubble number density. Comparisons of the model with the data shows that the model based on the nucleation site density correlation appears to be acceptable to describe the vapor generation in the flashing flow. For the limited data examined, the comparisons show rather satisfactory agreement without using a floating parameter to adjust the model. This result indicates that, at least for the experimental conditions considered here, the mechanistic predictions of the flashing phenomenon is possible on the present wall nucleation based model.

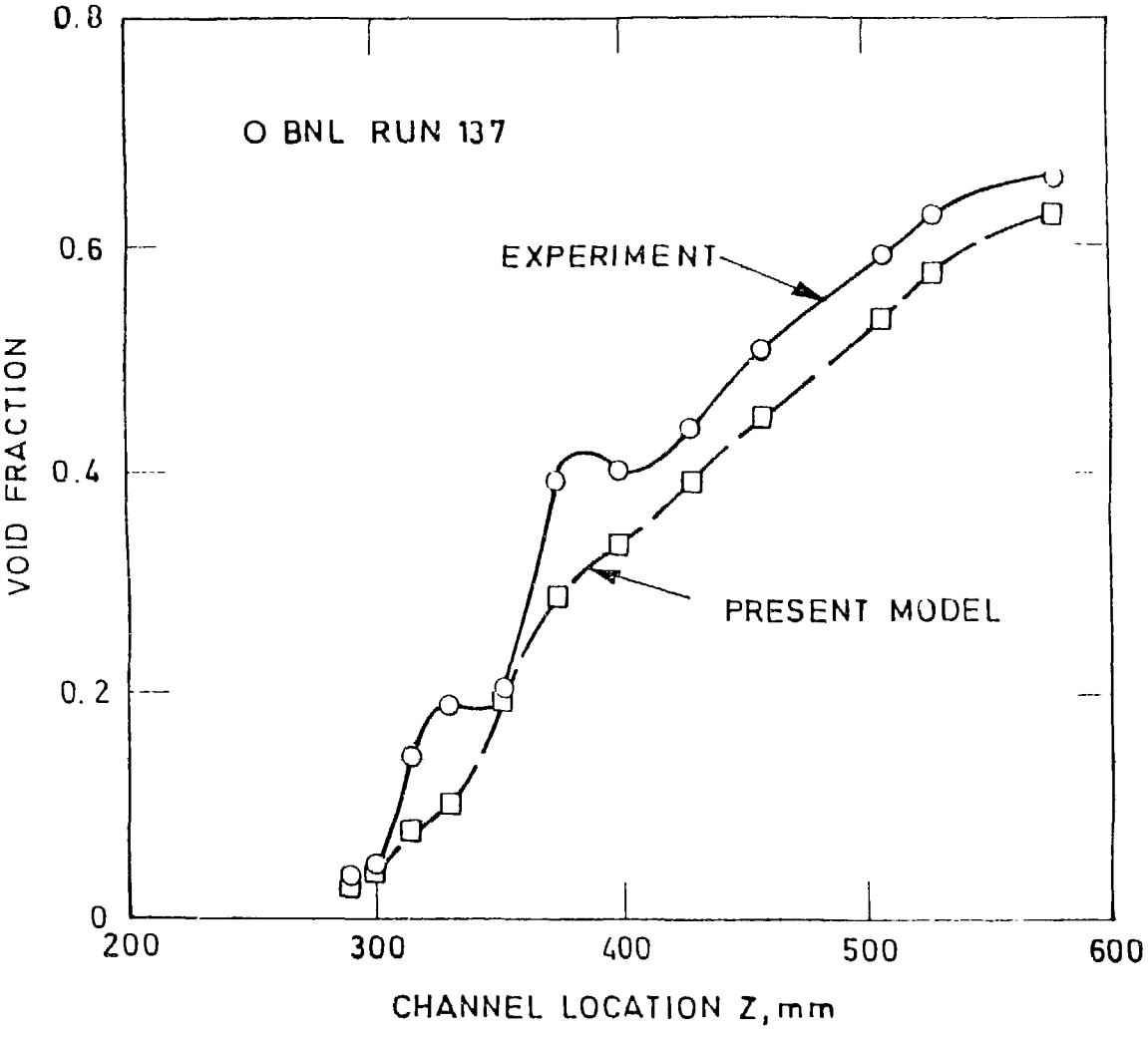

FIGURE 4. Comparison between the present model and BNL experiment-run 137

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NOMENCLATURE

A_c	Cross sectional area
A_v	Avogadro's number
B	Frequency of interaction of a molecule with its neighbors (≈k T/Planck's constant)
C_o	Distribution parameter
D_d	Bubble departure diameter
f	Bubble generation frequency

h	Interfacial heat transfer coefficient
J	Frequency of nucleation events per unit volume
j	Volumetric flux
Ja_p	Flashing Jakob number based on depressurization superheat
Ja_T	Jakob number based on initial superheat
k	Boltzmann constant
k_f	Thermal conductivity of liquid
$\dot{N}$	Rate of production of vapor nuclei
N_a	Active nucleation site density at wall
N_b	Bubble number density
N^*	Dimensionless active nucleation site density
$\hat{n}$	Unit vector normal to the channel wall directed away from the fluid
$\hat{n}_\xi$	Unit vector normal to ξ located in the cross sectional plane and directed away from the fluid
R_b	Bubble radius
R_c	Critical cavity size
R_o	Initial bubble radius
R_c^*	Dimensionless critical cavity radius defined as Rc/(Dd/2)
T	Temperature
t	Time
T_f	Bulk fluid temperature
T_{sat}	Saturation temperature
T_w	Wall temperature
v	Volume
$\vec{v}_b$	Local bubble velocity
$\bar{v}_b$	Mean bubble velocity
V_{gj}	Drift flux velocity
v_p	Bubble relative velocity
W_{cr}	Critical work required to create an unstable bubble nucleus
z	Axial coordinate
z_{eb}	Axial coordinate at point of flashing incipient
z_{co}	Axial coordinate at point where C_o reaches 1.0
α	Void fraction
α_f	Thermal diffusivity of liquid
ξ	Wetted (or heated) perimeter
ρ	Density
σ	Surface tension between liquid and vapor
ϕ	Heterogenity correction factor for critical work for bubble nucleation

ϕ_{he} Heterogeneous bulk liquid nucleation rate

ϕ_{ho} Homogeneous bulk liquid nucleation rate

ϕ_{si} Bulk sink rate due to recondensation

ϕ_{so} Bubble source rate due to bulk liquid nucleation

ϕ_{w} Bubble nucleation rate from active cavities

Subscripts

b Bubble

f Liquid phase

g Vapor phase

he Heterogeneous

ho Homogeneous

eb Ebullition

w Wall

Superscripts

* Dimensionless quantities

Averages

<< >> Area average

< > Line average

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