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A Comparison of Predictive Models for the Onset of Significant Void at Low Pressures in Forced-Convection Subcooled Boiling

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The predictive models for the onset of significant void (OSV) in forced-convection subcooled boiling are reviewed and compared with extensive data. Three analytical models and seven empirical correlations are considered in this paper. These models and correlations are put onto a common basis and are compared, again on a common basis, with a variety of data, The evaluation of their range of validity and applicability under various operating conditions are discussed. The results show that the correlations of Saha-Zuber (1974) seems to be the best model to predict OSV in vertical subcooled boiling flow.

Key Words : Onset of Flow Instability, Onset of Significant Void, Forced-Convection Subcooled Boiling, Analytical Models, Empirical, Comparison

Nomenclature

C_{pf}	: Specific heat
D	: Tube diameter
D_b	: Bubble departure diameter
D_h	: Tube hydraulic diameter
D_i	: Inner diameter
D_o	: Outer diameter
f	: Friction factor
G	: Mass velocity
g	: Acceleration due to gravity
h	: Heat transfer coefficient
h_{fg}	: Latent heat of vaporization
h_{fs}	: Liquid saturation enthalpy
h_l	: Subcooled boiling liquid-phase heat transfer coefficient
k_f	: Thermal conductivity
N	: The number of data
Nu	: Nusselt number
p	: Pressure
Pe	: Peclet number
Pr	: Prandtl number
q''	: Heat flux
Re	: Reynolds number
$T_{f,OSV}$	: Fluid temperature at OSV
T_f	: Fluid temperature
$T_{f,in}$	: Inlet fluid temperature
T_{sat}	: Saturation temperature
ΔT_{OSV}	: Degree of subcooling at OSV, $T_{sat} - T_{f,OSV}$
V_f	: Fluid velocity
Y_b^+	: Dimensionless distance from the wall to the bubble tip

Greek symbols

θ	: Contact angle
μ_f	: Fluid viscosity
σ_a	: Standard deviation
ρ_f	: Fluid density
σ	: Surface tension
τ_w	: Wall shear stress

1. Introduction

A Ledinegg instability may occur in a heated channel when two-phase pressure loss exceeds the driving pressure difference between the channel inlet and outlet. This results in a sudden reduction of the flowrate, thus giving rise to significant vapor generation inside the channel. This, in turn, may cause channel wall overheat, leading to a dangerous burnout condition. This instability is

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commonly characterized by a minimum in the pressure drop versus flow rate curve, which is referred to as the onset of flow instability (OFI). Experimental evidence shows that the onset of significant void (OSV) generally signals OFI in a system with pressure driven boundary condition. (Johnston, 1988; Dougherty et al., 1990) This is because the sudden decrease in mean flow density results in an increased pressure gradient owing to the combined effects of friction and acceleration. With pressure boundary conditions, rather than specified inlet flowrates, this can lead rapidly to flow instability, and consequent dryout and overheating.

According to Collier (1981), OSV is a transition from partial boiling to fully-developed subcooled boiling, where the heating surface is covered with bubbles. Prior to OSV vapor bubbles cannot survive in the relatively cold core liquid. Prior to, and after, detachment of individual bubbles from the heating surface, a bubble boundary layer builds up at the wall. Thus, OSV may be regarded as the destabilization of this bubble boundary layer, principally by shear forces exerted by the core liquid.

The OSV phenomenon has attracted much attention since an early work of Bowring (1962). In recent years, interest in the OSV phenomenon has grown in conjunction with the safety analysis of nuclear reactors. In a particular reference loss-of-flow accident in a pressurized-water reactor, the flow through the channels decreases rapidly owing to the decrease in the pressure difference across the channels resulting from the pipe break. The power also decreases, following the reactor trip. There is thus a race between the decreases in flowrate and power which determines the conditions within the channels, and ultimately the temperature of the fuel elements. Normally, the flow is all-liquid, but as the flow decreases, it is possible to have the onset of nucleate boiling (ONB). This corresponds to the appearance of the first bubble on the walls. Since the bulk of the liquid at the point of appearance is subcooled, the bubbles usually do not immediately detach from the wall. As the flow decreases further, the point of ONB moves backwards along the wall surface, resulting in a formation of a bubble boundary layer in the vicinity of the wall. The appearance of the bubble boundary layer causes the pressure gradient to increase, owing to the increased apparent roughness of the wall. At some point, owing to the detachment of the individual bubbles or the instability of the bubble boundary layer, there is significant vapor generation and mixing of bubbles with the core liquid. The onset of significant void precedes and is very close to OFI. Many works have been carried out in order to improve the understanding of the OSV phenomenon in connection with the nuclear safety analysis.

A number of investigators have attempted to derive the criteria for OSV in vertical, forced-convection subcooled boiling flow. However, a purely theoretical approach is very difficult, and most investigators have therefore set up simplified equations with extensive idealization and employ some empirical correlations for flow and heat transfer parameters. In general, they show that these analytical models agree well with their own experimental data or selected data in their range of validity. A number of small scale experiments have been performed in order to investigate OSV under various conditions and flow variables. These extensive experiments have produced a number of useful empirical correlations which are of practical importance.

Despite these efforts, the initiation mechanism of significant vapor generation is not well-understood as yet. Some discrepancies between models and the experimental data are found in the literature and significant scatter of data is also revealed from one investigator to another. It is the objective of this paper to put these models onto a common basis and to compare them, again on a common basis, with a variety of data. The evaluation of their range of validity and applicability under various operating conditions will be also included in this paper.

2. A Brife Review of the OSV Models

A number of predictive models for the onset of significant void (OSV) have been developed over the past thirty years. A few models have been derived from theoretical analyses, although some empirical adjustments or parameters were needed to fit the data. Examples of this category include the work of Levy (1967), Staub (1968), and Rogers et al. (1987). Several empirical models have also emerged. In these models the OSV data have been correlated into simple equations, which include geometrical dimensions, fluid properties, and flow parameters such as the mass flux and the heat flux. The work of Bowring (1962), Saha and Zuber (1974), and Unal (1975) are notable among these models. These models will be introduced very briefly here.

2.1 Analytical models

Three analytical models can be found in the literature up to the present time. These models are mechanistic models for predicting the OSV point in vertical, upwards, subcooled flow boiling. Attention was focused in the models on the thermal and hydrodynamic conditions under which a bubble starts to depart from the heated surface. A force balance exerted on a single bubble was set up to establish a criterion for the onset of bubble departure. The balance has three components in vertical upflow, which are buoyancy and wall shear forces acting to detach the bubble, and the surface tension force tending to hold it on the wall. Note that the drag force was substituted for the wall shear force in the model of Rogers et al. (1987), following Al-Hayes and Winterton (1981).

From the force balance, a dimensionless distance to the top of the bubble is calculated. It is argued in all three models that the liquid temperature at the top of the bubble should be at least equal to the saturation temperature when the bubble leaves. Incorporating the classical temperature profile for fully-developed, single-phase, turbulent flow obtained first by Martinelli (1947), the degree of liquid subcooling at OSV has been calculated.

These models show that the degree of liquid subcooling at OSV, ΔT_{osv}, is in general expressed as follows:

$$\Delta T_{osv} = \Delta T_{osv}(q'',\ h,\ \rho_f,\ \mathrm{Pr},\ C_{pf},\ \tau_w,\ Y_b^+) \quad (1)$$

where Y_b^+ is the dimensionless distance from the wall to the top of the bubble. Levy (1967) and Rogers et al. (1987) used the Dittus-Boelter equation in calculating the heat transfer coefficient, h. However, the definition of Y_b^+ is different from one author to another. Levy (1967) derived from the force balance:

$$Y_b^+ = 0.015\sqrt{\sigma D_h \rho_f}\,\frac{1}{\mu_f} \quad (2)$$

while Staub (1968) suggested the following equation:

$$Y_b^+ = \frac{D_b}{2}\,\frac{\rho_f V_f \sqrt{f/8}}{\mu_f} \quad (3)$$

Meanwhile, the following equation was derived by Rogers et al. (1987):

$$Y_b^+ = \frac{D_b}{2}\,\frac{\rho_f}{\mu_f}\sqrt{\frac{\tau_w}{\rho_f}}\,(1+\cos\theta) \quad (4)$$

These three models are very similar in nature. All use the same method for establishing a criterion for the onset of bubble departure and adopt the same condition for the temperature at the bubble top. However, it is interesting to note that different bubble shapes were assumed in the analyses from one author to another. Levy (1967) considered a full spherical bubble, but Staub (1968) postulated that the bubble shape at OSV would be a hemisphere. In the work of Rogers et al. (1987), the bubble was treated as a truncated sphere, with a contact angle at the surface equal to the equilibrium contact angle.

2.2 Empirical correlations

Due to the complicated nature of the subcooled nucleate boiling phenomenon, it is often convenient to predict OSV by means of empirical correlations. Several correlations by various investigators have been produced over the past thirty years. Seven correlations can be found in the literature up to the present time: Bowring (1962), Thom et al. (1965), Ahmad (1970), Dix (1971), Saha and Zuber (1974), Sekoguchi et al. (1974), and Unal (1975). According to these correlations, the degree of liquid subcooling at OSV may be expressed in terms of the following quantities:

$$\Delta T_{OSV} = \Delta T_{OSV}(p,\ D_h,\ q',\ G,\ T_{f,in},\ \mathit{fluid}$$

properties) (5)

The earliest work, that of Bowring (1962), includes the pressure term explicitly in the correlation, whereas the other correlations contain the effect of pressure only through the fluid properties. The inlet temperature is included only in the Ahmad correlation (1970). The correlations of Bowring (1962) and Thom et al. (1965) were presented in dimensional form. On the other hand, the correlations of Saha and Zuber (1974), Unal (1975), Ahmad (1970), Sekoguchi et al. (1974) and Dix (1971) were given in dimensionless form. Saha and Zuber (1974) suggested two dimensionless parameters, the Stanton number and the Nusselt number, based upon the argument that at low mass fluxes OSV is controlled by local thermal conditions, whereas at high mass fluxes it is hydrodynamically controlled. The remaining correlations show the ratio of the heat flux transferred to the liquid phase to the total heat flux at OSV. Unal (1975) proposed that this ratio has two different values for water, depending upon the liquid velocity. In the correlation by Dix (1971), this ratio is a function of the Reynolds number. In contrast, the Ahmad correlation (1970) uses the local heat transfer coefficient at OSV, as in the Dittus-Boelter type equation. The flow orientation is vertical upwards for most of these correlations whereas those of Saha and Zuber (1974) and Unal (1975) have no restriction on the flow orientation.

The correlations are introduced briefly below.

- Bowring (1962)

$$\Delta T_{OSV}=\eta\frac{q''\rho_f}{G} \tag{6}$$

and

$$\eta\times 10^6=14.0+0.1p \tag{7}$$

where p is the system pressure in bar and G, q'', and ρ_f are expressed in SI units.

- Thom et al. (1965)

$$\Delta T_{OSV}=0.02h_{fs}\frac{q''}{Gh_{fg}} \tag{8}$$

- Ahmad (1970)

$$\Delta T_{OSV}=\frac{q''}{h_l} \tag{9}$$

where

$$\frac{h_l D_h}{k_f}=2.44\sqrt{\mathrm{Re}}\left(\frac{C_{pf}\mu_f}{k_f}\right)^{\frac{1}{3}}\left(\frac{h_{in}}{h_{fs}}\right)^{\frac{1}{3}}\left(\frac{h_{fg}}{h_{fs}}\right)^{\frac{1}{3}} \tag{10}$$

- Dix (1971)

$$\Delta T_{OSV}=0.00135q''\frac{\mathrm{Re}^{0.5}}{h} \tag{11}$$

- Saha and Zuber (1974)

$$\mathrm{Nu}=\frac{q''D_h}{k_f\Delta T_{OSV}}=455 \text{ for } \mathrm{Pe}\leq 70{,}000 \tag{12}$$

$$St=\frac{q''}{G\,C_{pf}\Delta T_{OSV}}=0.0065 \text{ for } \mathrm{Pe}>70{,}000 \tag{13}$$

- Sekouguchi et al. (1974)

$$\Delta T_{OSV}=13.5\frac{h_{fg}}{C_{pf}}\left(\frac{q''}{h_{fg}G}\right)^{0.65} \tag{14}$$

- Unal (1975)

$$\Delta T_{OSV}\frac{h}{q''}=a=const \tag{15}$$

where

$a=0.24$ for $V_f\geq 0.45m/s$

$a=0.11$ for $V_f<0.45m/s$

3. Experimental Data

A number of experiments have been performed to study OSV or OFI over the past decades. In early works, experiments for relatively high pressures were carried out in connection with evaluation of the performance of high-pressure boiler system. (Egen et al., 1957; Bartolemei and Chanturiya, 1967; Rouhani, 1968) Recently, interest in low-pressure data ($p \leqq 5$ bar) has grown in conjunction with the safety analysis of nuclear systems. The low-pressure data are summarized in Table 1. All data are for water.

Among these, the data of Whittle and Forgan (1967) and Dougherty et al. (1990) were obtained in a systematic way for various combinations of geometrical and operating conditions in a vertical, upwards forced-convection subcooled boiling flow. The data set of Whittle and Forgan (1967) encompasses the OFI data in vertical flow with rectangular ducts of four different sizes. The aspect ratio of the channels ranges between 7.9 and 18.2, so that the flow could be considered to

Table 1 summary of the low-pressure data sets.

Author(s)	Geometry (m)	Pressure (bar)	Heat flux (W/m^2)	Mass velocity (kg/m^{2}s)	Measurement parameter
Dougherty et al. (1990)	Circular (D) 0.0091−0.0284	2.40−4.50	1.249−3.164	1296.1−9376.1	Pressure drop
Whittle & Forgan (1967)	Rectangular (Dh) 0.0026−0.0057 Circular (D) 0.0064	1.17−1.72	0.420−3.480	815.9−11183.4	Pressure drop
Sekoguchi et al. (1974)	Circular (D) 0.0136−0.0158	1.27−4.07	0.0465−0.0458	293.3−1947.3	Local voidage (electrical probes)
Edelman & Elias (1981)	Circular (D) 0.0113	1.03	0.015−0.096	27.5−185.0	Vol. void fraction (x-ray radiation) (γ-ray radiation)
Staub et al. (1967)	Rectangular (Dh) 0.0139	1.10−3.00	0.308−0.792	320.8−2770.5	Vol. void fraction (x-ray radiation) (γ-ray radiation)
Evangelisti & Lupoli (1969)	Annular (D_h) 0.006	1.13	0.437−0.885	608.0−1416.0	Vol. void fraction (γ-ray radiation)
Rogers et al. (1987)	Annular (D_h) 0.0089	1.55	0.32−1.18	66.8−438.5	Vol. void fraction (γ-ray radiation)
Ferrell (1964)	Circular (D) 0.0118	4.10	0.363	539.8−1064.5	

be reasonably two-dimensional. The OFI data were determined, under various operating conditions, as a minimum point in the pressure drop -flowrate curve for constant heat flux. At a given geometrical condition, the OFI heat flux is presented, using the inlet temperature and the exit pressure as variables. Thus, these data can be regarded as the OSV data as described in the beginning part of "Introduction". Dougherty et al. (1990) gives OFI data for vertical downwards flow in round tubes of six different diameters. The OFI data were determined by a similar method as by Whittle and Forgan (1967)

The other sets in Table 1 represent the OSV data in vertical upwards flow. All data were obtained by means of void fraction measurement either with electrical probes or by an optical technique. These sets include the data for circular tubes (Sekoguchi et al., 1974; Edelman and Elias, 1981; Ferrell, 1964), rectangular channels (Staub et al., 1967) and annuli (Evangelisti and Lupoli, 1969; Rogers et al., 1987).

4. Comparison and Discussion

Comparisons of analytical models of Levy (1967), Staub (1968) and Rogers et al. (1987) with the low-pressure data are shown in Figs. 1 ~3, respectively. The legends are indicated in Fig. 1 and are identical for Figs. 1~9.

It is shown that the model of Staub (1968) (Fig. 2) appears to be in good agreement with the data of Dougherty et al. (1990), Whittle and Forgan (1967), Staub et al. (1967), and Ferrell (1964). These data reflect moderate and relatively high heat flux conditions. The model of Levy (1967) (Fig. 1) overpredicts ⊿Tosv for most of the data. However, the data scatter does not appear to be significant, except for the data of Sekoguchi et al. (1974), as shown in Fig. 1. The

Levy model seems to be reasonable if some modifications could be made, because it has no preference for any particular data set. It should be mentioned that the data of Sekoguchi et al. (1974) do not seem to be reliable because they deviate considerably from the values predicted by all other models and correlations, as seen in Figs. 1∼9. In Fig. 3, a wide spread of the experimental data is indicated and a substantial difference between the data and the prediction by Rogers et al. (1987) can be found. The model of Rogers et al. (1987) originally aims at prediction of OSV at low velocities in upflow subcooled nucleate boiling. The range of the liquid velocity of their concern was less than 1.0(m/s). In this region, the buoyancy effect on the mechanism of bubble departure is thought to be important. (Lee and Bankoff, 1992) This may be the main reason of the large discrepancies between the model of Rogers et al. (1987) and the experimental data, most of which have velocities larger than 1.0 (m/s)

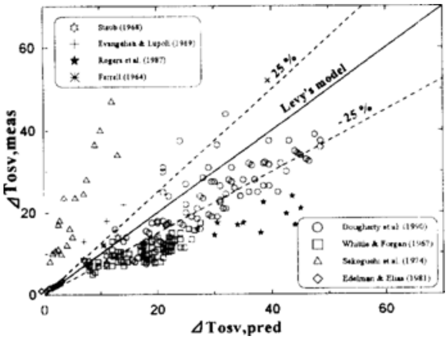

Fig. 1 Comparison of the model of Levy (1967) with the low pressure data.

The comparisons between empirical correlations and the identical data sets are shown in Figs. 4∼9. In these comparisons, the correlation of Thom et al. (1965) was excluded because of its significant underestimates of ΔT_{OSV}.

The correlations of Saha and Zuber (1974) and Unal (1975) generally seem to be in good agree-

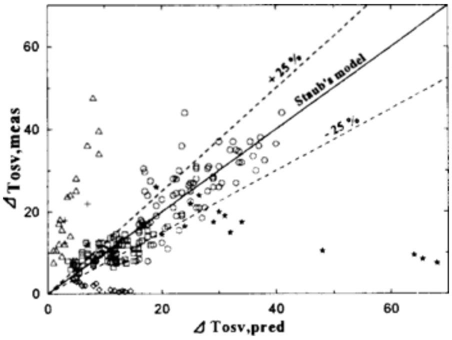

Fig. 2 Comparison of the model of Staub (1968) with the low pressure data.

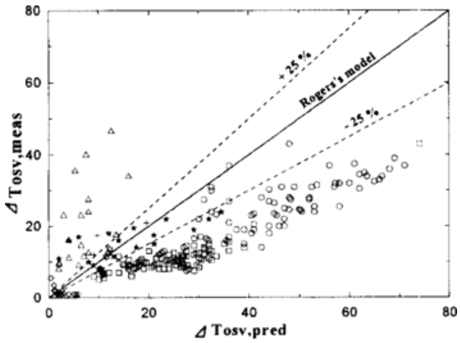

Fig. 3 Comparison of the model of Rogers et al. (1967) with the low pressure data ($\theta=30°$).

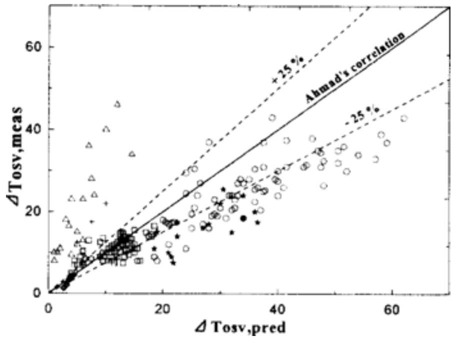

Fig. 4 Comparison of the correlation of Bowring (1967) with the low pressure data.

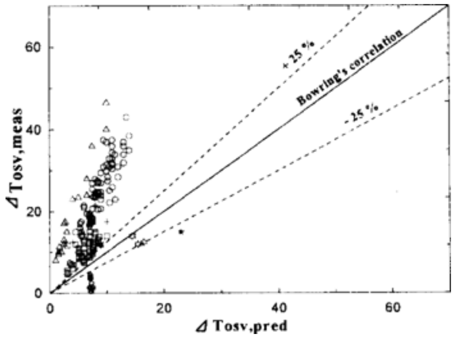

Fig. 5 Comparison of the correlation of Ahmad (1970) with the low pressure data.

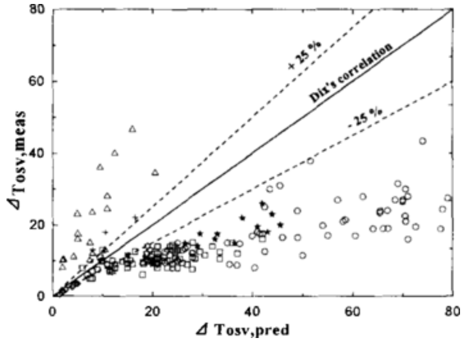

Fig. 6 Comparison of the correlation of Dix (1967) with the low pressure data.

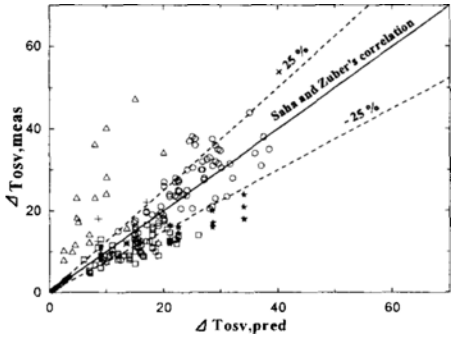

Fig. 7 Comparison of the correlation of Saha and Zuber (1974) with the low pressure data.

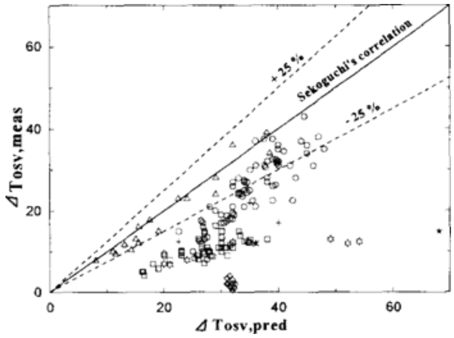

Fig. 8 Comparison of the correlation of Sekoguchi et al. (1974) with the low pressure data.

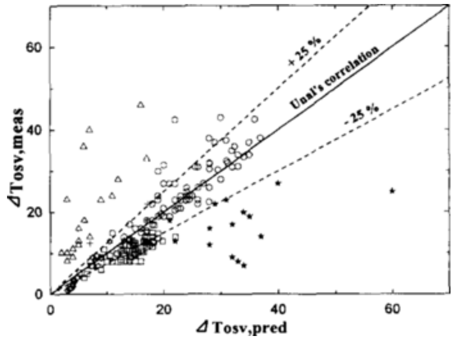

Fig. 9 Comparison of the correlation of Unal (1974) with the low pressure data.

ment with the data. The Saha-Zuber correlation is very simple and convenient, and has been widely used in computer codes for nuclear safety analysis. The Saha-Zuber correlation is based on Peclet number data up to 400,000. However, it was pointed out recently by Lee and Bankoff (1992) that the use of the correlation beyond this limit may be questionable. The Bowring correlation (1962) (Fig. 4) tends to underpredict ΔT_{OSV} for most of data whereas the Dix correlation (1971) (Fig. 6) has an opposite trend. The Bowring correlation (1962) was originally developed based on the high-pressure data ranging between 11 and 138bar. It includes an empirical constant to consider the effect of pressure as seen in Equation (6). Thus, it may be said that the Bowring correlation (1962) can not be applied to low-pressure regions below the lower limit indicated by the author. On the other hand, the Dix correlation (1971) was suggested based on the R-114 data. From the comparison with the water data here, one may note that it is not preferable to apply the correlation to fluid medium other than R-114, although the correlation is given in a dimensionless form.

The Ahmad correlation (1970) seems to agree well with the data of low ΔT_{OSV}. The Ahmad correlation (1970) is the only one to include the effect of the liquid inlet enthalpy explicitly. The correlation of Sekoguchi et al. (1974) (Fig. 8) fits well with their data only.

To evaluate each model on a common basis, the standard deviation, defined by the following equation, was calculated.

$$\sigma_a=\sqrt{\frac{1}{N}\sum_{i=1}^{N}[(\Delta T_{osv,meas})_i-(\Delta T_{osv,pred})_i]^2} \qquad (16)$$

The results show that the Saha-Zuber correlation (1974) has the lowest value of σ_a, 6.55 among the empirical correlations. For analytical models, the Levy model (1967) indicates that σ_a

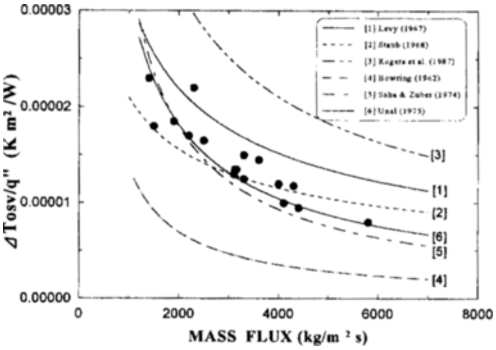

Fig. 10 Comparison of the data of Dougherty et al. (1990) (D=0.0255 and 0.0284m, p=2.4bar) with various models.

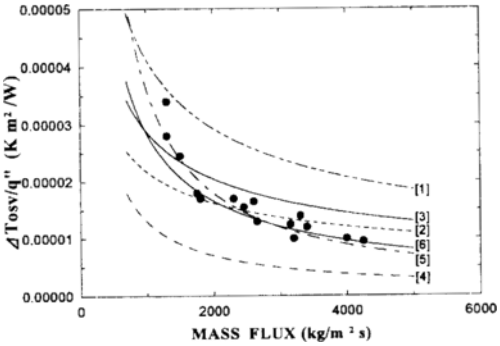

Fig. 11 Comparison of the data of Dougherty et al. (1990) (D=0.0255 and 0.0284m, p=4.4bar) with various models.

=9.83, whereas the Staub model has 10.39.

Parametric effects on OSV will be discussed from the results of comparisons between selected models and the data of Dougherty et al. (1990) and Whittle and Forgan (1967). The models selected here for comparisons are those of Levy (1967), Staub (1968), Rogers et al. (1987), Bowring (1962), Saha and Zuber (1974), and Unal (1975). Figures 10 and 11 show comparisons of these models with the data of Dougherty et al. (1990). The tube diameters of the data are 0.0255 and 0.0284m but the diameter was taken to be 0.027m, an arithmetic mean of two diameters, in evaluating the models. The operating pressures are 2.4 and 4.4bar, respectively. All models and the data predict that $\Delta T_{OSV}/q''$ simply decreases as the mass flux is increased.

Among these models, the correlations of Saha and Zuber (1974) and Unal (1975) are the closest ones to the data. Similar trends are indicated in Figs. 12 and 13, which show the data of Dougherty et al. (1990) for D=0.0091m. The effect of pressure can be inferred from Figs. 10 ~13 by comparison of data sets at p=2.4bar and

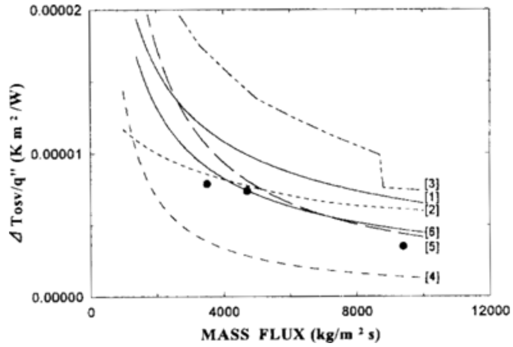

Fig. 12 Comparison of the data of Dougherty et al. (1990) (D=0.0091m, p=2.4bar) with various models.

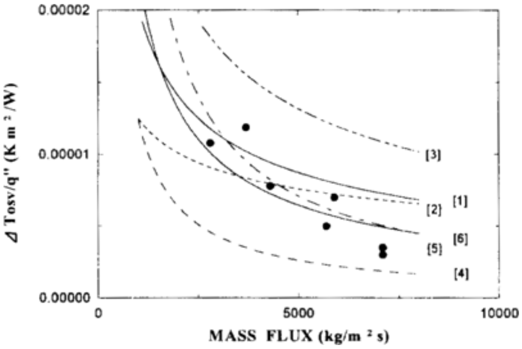

Fig. 13 Comparison of the data of Dougherty et al. (1990) (D=0.0091m, p=4.4bar) with various models.

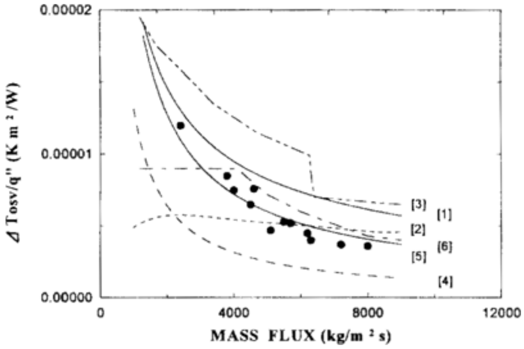

Fig. 14 Comparison of the data of Whittle and Forgan (1967) (D_h=0.0026m, p=1.17bar) with various models.

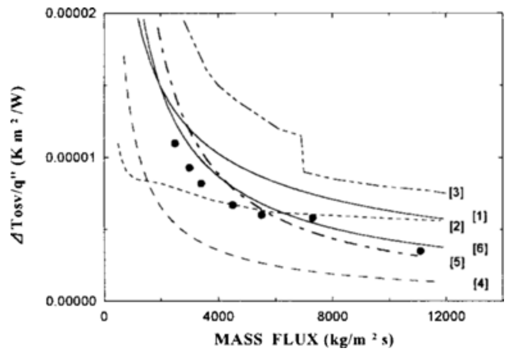

Fig. 15 Comparison of the data of Whittle and Forgan (1967) (D_h=0.0064m, p=1.17bar) with various models.

4.4bar. It has a tendency to increase $\Delta T_{OSV}/q''$ at fixed mass flux. This result coincides with the Bowring correlation which is the one to consider the effect of the pressure explicitly. Figures 14 and 15 show comparisons of the selected models with the data of Whittle and Forgan (1967). The prediction by the correlations of Unal (1975) and Saha and Zuber (1974) fits well with the data.

5. Summary and Conclusions

The predictive models for the onset of significant void (OSV) in forced-convection subcooled boiling have been reviewed and compared with extensive data. Analytical models of Levy (1974), Staub (1968) and Rogers et al. (1987) and empirical correlations of Bowring (1962), Thom et al. (1965), Ahmad (1970), Dix (1971), Saha and Zuber (1974), Sekoguchi et al. (1974) and Unal (1975) are included in this paper. A brief introduction of each model was made. These models and correlations were compared to the extensive data at low pressures. The results show that the Saha-Zuber correlation (1974) is the best one to fit with whole sets of data among the correlations and the model of Levy (1967) among the analytical models. Selected models were compared with the data of Dougherty et al. (1990) and Whittle and Forgan (1967) to investigate parametric effects on OSV. Both the models and the data predicted that $\Delta T_{OSV}/q''$ simply decreases as the mass flux is increased. Among these models, the correlations of Saha and Zuber (1974) and Unal (1975) were the closest ones to the data. The pressure has a tendency to increase $\Delta T_{OSV}/q''$ at fixed mass flux. This result coincides with the Bowring correlation which is the one to consider the effect of the pressure explicitly.

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