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On the transition from partial to fully developed subcooled flow boiling

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Abstract

The subject of the present study is to relate the boiling heat transfer process with experimentally observed bubble behaviour during subcooled flow boiling of water in a vertical heated annulus. It presents an attempt to explain the transition from partial to fully developed flow boiling with regard to bubble growth rates and to the time that individual bubbles spend attached to the heater surface.

Within the partial nucleate boiling region bubbles barely change in size and shape while sliding a long distance on the heater surface. Such behaviour indicates an important contribution of the microlayer evaporation mechanism in the overall heat transfer rate. With increasing heat flux, or reducing flow rate at constant heat flux, bubble growth rates increase significantly. Bubbles grow while sliding, detach from the heater, and subsequently collapse in the bulk fluid within a distance of 1–2 diameters parallel to the heater surface. This confirms that bubble agitation becomes a leading heat transfer mode with increasing heat flux. There is however, a sharp transition between the two observed bubble behaviours that can be taken as the transition from partial to fully developed boiling. Hence, this information is used to develop a new model for the transition from partial to fully developed subcooled flow boiling.

1. Introduction and review of the literature

1.1. Bubble behaviour in subcooled flow boiling

Flow boiling of a heated liquid is characterized by the appearance of vapour bubbles initiating from the heater surface. Heterogeneous bubble nucleation occurs within small pits and cavities called nucleation sites. In order to activate a nucleation site, the temperature of the surface has to exceed the saturation temperature of the liquid at the local pressure. If, at the same location, the temperature of the bulk liquid remains below saturation, the process is known as subcooled flow boiling. During subcooled flow boiling, a significant increase in the heat flux can occur with a correspondingly small change in the wall temperature.

Kandlikar [1] has recently reviewed the distinct regions and locations of subcooled flow boiling. These are shown in Fig. 1. The graph shows the variation of the wall and bulk liquid temperatures along the heater surface. The location B is called the onset of nucleate boiling (ONB). After ONB an increasing amount of vapour increases the heat transfer rate. However, the amount of void (i.e. vapour) remains low and fairly constant. As shown, at a certain location B″, the slope of the void growth curve changes significantly resulting in a dramatic increase in the amount of vapour. This location is known as the onset of significant void (OSV). Beyond this, Kandlikar [1] has named the region between OSV and the onset of saturated flow boiling as the significant void flow region.

Shown in Fig. 2 is the variation of the local heat flux with wall superheat along the same surface (boiling curve). The boiling curve upstream of point B denotes single-phase forced convection boiling. A change in the slope of the boiling curve at B indicates initiation of the

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Nomenclature

Bo	Boiling number
c_p	specific heat (J/kg K)
D_{max}	maximum bubble diameter (m)
G	mass flux (kg/m^2 s)
h	convection heat transfer coefficient (W/m^2 K)
i_{fg}	latent heat of evaporation (J/kg)
Ja^*	modified Jakob number $Ja^* = c_p \Delta T_{sub}/i_{fg}$
k	thermal conductivity (W/m K)
Lp_{ejc}	parallel displacement from inception to normal detachment (sliding distance) [m]
M	molecular weight (kg/kmol)
Nu	Nusselt number
p	pressure (N/m^2)
Pr	Prandtl number
q	heat flux (W/m^2)
Re	Reynolds number
T_b	bulk liquid temperature (K)
T_{cr}	critical temperature (K)
T_{sat}	saturation temperature (K)
ΔT_{sat}	superheat $\Delta T_{sat} = T_w - T_{sat}$ (K)
ΔT_{sub}	subcooling $\Delta T_{sat} = T_{sat} - T_b$ (K)
T_w	wall temperature (K)

Greek symbol

ρ	density (kg/m^3)

Subscripts

FC	forced convection
FDB	fully developed boiling
l	liquid phase
ONB	onset of nucleate boiling
OSV	onset of significant void
PDB	partially developed boiling
tp	two-phase
TRANS	transition from partial to fully developed boiling
v	vapour phase

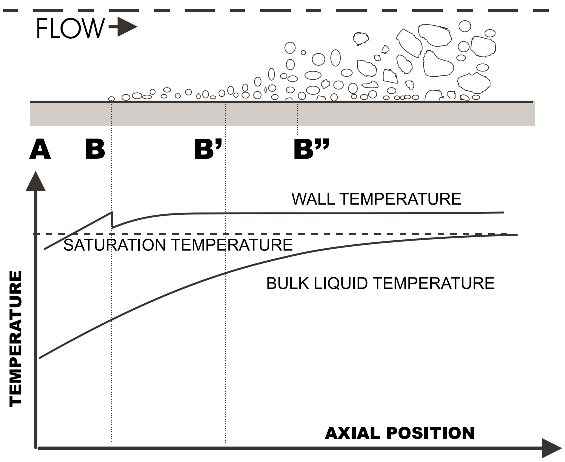

Fig. 1. Subcooled flow boiling.

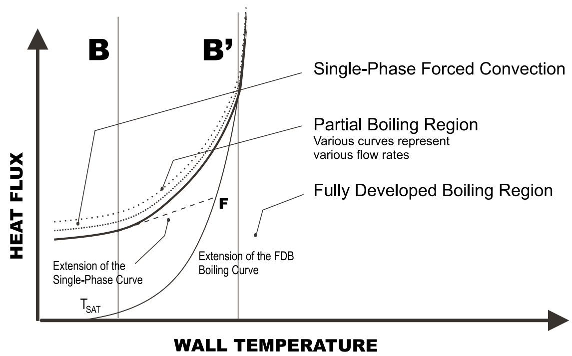

Fig. 2. Flow boiling curve.

boiling process. Downstream of ONB, the boiling curve deviates from the straight single-phase forced convection line due to additional heat removed through evaporation. The dual effect of convection and evaporation is notable until, at a certain location B′, the evaporating effect becomes dominant. This is evident from the merger of boiling curves, calculated from experimental data for various flow rates (shown as doted lines) at B′. The first boiling region is called the partially developed boiling (PDB) region or, the highly subcooled region while the second is known as fully developed boiling (FDB) or, the low subcooled region. The FDB region extends beyond OSV. Continuing on the change of the two-phase flow pattern induces another change in the heat transfer mode. This is due to a large increase in void which accelerates the liquid phase making the convective term significant again. The last region corresponds to the significant void flow. The flow regime here can be bubbly, slug, or annular depending on the phasic structure within the flow [2]. The current discussion will be focused on the earlier regions mentioned here.

Several recent photographic studies [3–5] addressed bubble behaviour during subcooled flow boiling. Typical bubbles are seen to grow while sliding along the heater until they reach a maximum radius. From this point on, they start shrinking before they detach. After detachment, they are propelled into the subcooled bulk liquid and subsequently collapse. Photographic studies have shown that bubbles are typically flattened after inception. While sliding along the surface of the heater, they change in shape and become elongated, remaining attached to the wall. The typical bubble at ejection is shaped like an inverted pear [3].

The above mentioned bubble behaviour is typical for the major part of the region between ONB and OSV. Bubbles grow and collapse without significant influence from neighbouring bubbles, hence the term "isolated bubble region" can be applied. Nevertheless, in the immediate neighbourhood of the ONB the bubble behaviour is somewhat different. Bibeau and Salcudean [3] and Fraser et al. [5] observed bubbles sliding long distances along the heater without changing significantly in size or shape. Bubble detachments were rare and most likely due to turbulent fluctuations. Occasional bubble coalescence was also seen to cause detachments. As the heat flux was increased at constant flow, the transition to the isolated bubble region behaviour occurs abruptly. It can be expected that, following this transition, the heat transfer mode will change as well.

1.2. Two-phase heat transfer correlations

A question arises as to whether a single heat transfer correlation can be applied over the entire region covering ONB to OSV. Single-phase forced convection correlations fail to predict heat transfer during subcooled flow boiling. Heat transfer equations for the nucleate boiling region should account for convective as well as evaporative heat transfer mechanisms. Both of these were taken into account in Chen [6] correlation by having two separate terms. The first term is the convective term or the "all liquid" heat transfer term which is calculated using a single-phase forced convection correlation multiplied by an enhancement factor. The enhancement factor is always greater than unity and takes into account the enhancement of convective heat transfer (acceleration) due to increasing vapour quality. The second term is the evaporative term and is a modification of the Forster and Zuber [7] correlation for pool boiling heat transfer multiplied by a suppression factor. The suppression factor is always less than unity, accounting for a reduction in the thermal boundary layer with increasing flow. Chen [6] correlation was initially proposed only for saturated flow boiling and is widely used for low-pressure heat transfer calculations. However, as pointed out by Spindler [8], Chen's correlation does not extend well into subcooled flow boiling.

Gungor and Winterton [9] modified Chen's correlation by redefining the enhancement factor. They made it a function of the Martinelli parameter, as in Chen's correlation, but included a dependence on the Boiling number (*Bo*) as well. They also suggested using Cooper [10] correlation for pool boiling heat transfer instead of Forster and Zuber [7]. For subcooled boiling they recommend an enhancement factor set to unity while retaining the suppression factor. They argued that suppression is also due to bubbles condensing within the cooler bulk liquid or collapsing while attached to the heater surface. This would diminish the effect of the vapour phase in the convective term. Another correlation with improved accuracy is that of Liu and Winterton [11]. They used a power-type addition model for testing subcooled flow experimental data. The convective term was calculated by using Dittus–Boelter correlation and the evaporative term by using Cooper's pool boiling correlation. Models based on Kutateladze's power-type addition model, which accounts for further suppression of boiling, appear to agree better with experimental data for the case of subcooled boiling.

Other strictly empirical, curve fit type of correlations, give an explicit relation between heat flux and temperature difference (usually the wall superheat), in the form of $q = f(\Delta T)$. Recent comprehensive reviews of these correlations are given in Kandlikar [1], and Guglielmini et al. [12]. A brief summary follows here. One of the first models was that of McAdams et al. [13] who simply proposed a single curve relating the heat flux to wall superheat. They suggested that heat transfer during FDB was independent of water velocity, pressure and degreee of subcooling. Several studies conducted later modified their correlation [1,14–18]. Some correlations include a correction factor for different pressures [15,16,18]. They are shown in Table 1.

Another type of heat transfer correlation can be found through dimensional analysis methods. It has been shown that the heat transfer coefficient, contained in the Nusselt number, can be expressed as a function of boiling number (*Bo*), Jacob number (*Ja*), Prandtl number (*Pr*), and density ratio (ρ_l/ρ_v). The boiling number takes into account the effect of heat flux and liquid velocity. The modified Jacob number (with the wall superheat replaced by the liquid subcooling) describes the ratio of latent to sensible heat. The pressure effect is accounted for by the density ratio. Shown in Table 2 are some of these correlations, chosen to be tested in the current study. These correlations are valid for both the partial and fully developed boiling as long as the subcooling is present. They have been reviewed in detail by Spindler [8].

Correlations for the partial nucleate boiling are usually equations that span the single-phase forced convection curve and the FDB curve. Few authors have attempted to discuss the nature and reasons for the occurrence of the partial boiling. Some correlations listed in Table 3. include [1,14,19,20]. Models for transition from partial to fully developed boiling are usually products of applying various partial and fully developed boiling correlations. Again, very scarce information can be found in the open literature about the nature and

Table 1
Heat transfer correlations for fully developed subcooled flow boiling

McAdams et al. [13]	$q = 4.77\Delta T_{sat}^{3.86}$
Jens and Lottes [16]	$\Delta T_{sat} = 25q^{0.25}\exp(p/62)$
Thom et al. [15]	$\Delta T_{sat} = 22.65q^{0.5}\exp(p/87)$
Shah [14]	$q = h_{FC}230Bo^{0.5}\Delta T_{sat}$ where h_{FC} from Dittus–Boelter correlation
Aladiev [17]	$\Delta T_{sat} = [39.2 - 0.1(T_{sat} - 273.16)]q^{0.3}$
Labuntzov [18]	$\Delta T_{sat} = \frac{1 - 0.0045p}{3.4p^{0.18}}q^{0.3}$
Kandlikar [1]	$q = [1058h_{FC}\Delta T_{sat}(Gi_{fg})^{0.7}]^{3.33}$ where h_{FC} from Petukhov and Popov [33] correlation

Table 2
Heat transfer correlations for subcooled flow boiling. Classification given by Spindler [8]. The modified Jacob number is $Ja^* = (c_p\Delta T_{sub})/i_{fg}$

Papell [34]	$Nu_{tp}/Nu_l = 90Bo^{0.7}Ja^{*-0.84}(\rho_v/\rho_l)^{0.056}$
Badiuzzaman [35]	$Nu_{tp}/Nu_l = 178Bo^{0.75}Ja^{*-0.9}(\rho_v/\rho_l)^{-0.06}(\Delta T_{sub}/T_{sat})^{0.45}$
Moles and Shaw [24]	$Nu_{tp}/Nu_l = 78.5Bo^{0.67}Ja^{*-0.5}(\rho_v/\rho_l)^{-0.03}Pr^{0.45}$

causes for transition. Some models are listed in Table 4. Few other correlations can be found in the literature [12].

1.3. Location of the transition point

A method of locating the transition point was first proposed by McAdams et al. [13]. They defined it as the intersection of forced convection and FDB curves. After compiling data from various sources, Shah [14] found that plotting $\Delta T_{sub}/\Delta T_{sat}$ vs. Bo showed two distinct boiling regimes. One, dependent on subcooling and flow rates while the other, independent of these. Transition occured at $\Delta T_{sub}/\Delta T_{sat} = 2$ and was used to indicate the change from partial to fully developed boiling. Kandlikar [1] used the same procedure, locating the intersection of the extension of the single-phase curve and fully developed curve. They suggest the beginning of FDB can be obtained by multiplying the heat flux at that particular point by 1.4, as suggested earlier by Engelberg-Forster and Grief [21].

2. Results from the current study

The current study is concerned with investigating only subcooled flow boiling. The purpose of this study is to investigate the connection between partial and fully developed boiling with the two experimentally observed bubble behaviours. The investigation is based on a series of experiments performed earlier [3,5]. The data were obtained at low pressures and low flow rates. The study has two parts. The first is concerned with testing existing heat transfer correlations and developing a new one valid over the range of the data (including both, the partial boiling and the fully developed boiling region). The second part concerns the transition point from partial to fully developed boiling and its relation to the corresponding changes in observed bubble behaviour.

2.1. Experimental data

Experiments were carried out on the vertical annular test section with the inner heated surface, using water as a working fluid. Two sets of experimental data were obtained for this study. Both sets of data were for water at pressures ranging from 1 to 3 bar and liquid velocities ranging from 0.08 to 0.8 m/s. The first set contains about 1500 data points. Heat fluxes and surface temperatures were measured from low temperature single-phase forced convection heat transfer to heat transfer beyond OSV. These data were obtained by Bibeau and Salcudean [3]. The second set of data are high-speed photographic information obtained for a total of 61 points in the FDB region which, along with the heat flux and surface temperature measurements, includes bubble behaviour data (size and sliding distances of typical bubbles). Details about the experimental apparatus and procedure can be found in [22] for the first data set and in [5] for the high-speed photographic data.

Table 3
Heat transfer correlations for partially developed subcooled flow boiling

Bergles and Rohsenow [19]	$\frac{q}{q_{FC}} = \left[1 + \left[\frac{q_{FDB}}{q_{FC}}\left(1 - \frac{q_{FDBi}}{q_{FDB}}\right)\right]^2\right]^{0.5}$ q_{FDB}, not specified; correlation suitable for particular boiling conditions, q_{FDBi}, represents q_{FDB} at ONB
Pokhvalov et al. [20]	$\Delta T_{sat} = \Delta To\left[1 + \left(\frac{\Delta To}{\Delta q}h_{FC}\right)^{1.5}\right]^{-2/3}$ $\Delta To = 0.11\frac{T_{cr}^{0.82}M^{0.18}}{p^{0.36}}\Delta q^{0.36}e^{-5.6T_{sat}/T_{cr}}$ $\Delta q = q - h_{FC}\Delta T_{sub}$
Shah [14]	$\Delta T_{sat} = \left(\frac{q}{0.54\Psi_0 h_{FC}}\right)^{8.33}\Delta T_{sub}^{-7.83}$ $\Psi_0 = \left\lvert \begin{array}{l} Bo > 0.3\times10^{-4} \Rightarrow 230Bo^{0.5} \\ Bo < 0.3\times10^{-4} \Rightarrow 1 + 46Bo^{0.5} \end{array}\right.$ where h_{FC} from Dittus–Boelter correlation
Kandlikar [1]	$q = a + b\Delta T_{sat}^m$ $a = q_{ONB} - b(\Delta T_{sat,ONB})^m$ $b = \frac{\left[1058h_{FC}\Delta T_{sat,TRANS}(Gi_{fg})^{-0.7}\right]^{3.33} - q_{ONB}}{\Delta T_{sat,TRANS}^m - \Delta T_{sat,ONB}^m}$ $m = n + c_q$ $c = \frac{2.33}{\left[1058h_{FC}\Delta T_{sat,TRANS}(Gi_{fg})^{-0.7}\right]^{3.33} - q_{ONB}}$ $n = 1 - c_{q_{ONB}}$ where the $\Delta T_{sat,ONB}$ and q_{ONB} are from Hsu [36], and Sato and Matsumura [37], h_{FC} from Petukhov and Popov [33] correlation

Table 4
Transition from partially to fully developed subcooled flow boiling

Bowring [38]	$q_{TRANS} = 1.4q_{INTERSECT}$, where $q_{INTERSECT}$ is the intersection between the single-phase forced convection curve and the fully developed boiling curve
Shah [14]	$\frac{\Delta T_{sub}}{\Delta T_{sat}} = 2;\quad q_{TRANS} = h_{FC}230\left(\frac{q_{TRANS}}{Gi_{fg}}\right)^{0.5}\frac{\Delta T_{sub}}{2}$
Kandlikar [1]	$q_{TRANS} = \frac{1.4\left[\left(\frac{q_{TRANS}}{1.4}\right)^{0.3} + 1058h_{FC}(Gi_{fg})^{-0.7}\Delta T_{sub}\right]}{1058(Gi_{fg})^{-0.7}}$ iterative procedure needed; ΔT_{sub} calculated for $q = q_{TRANS}/1.4$

2.2. Comparison to existing heat transfer correlations

The Chen-type correlations typically overpredict the heat transfer rates. An example is shown in Fig. 3. The best results were obtained by the correlation of Liu and Winterton and the modified Gungor and Winterton correlation. This is congruent with the findings of Hasan et al. [23] who conducted experiments using R-113. They emphasized the poor applicability of the Chen type correlations for subcooled nucleate flow boiling.

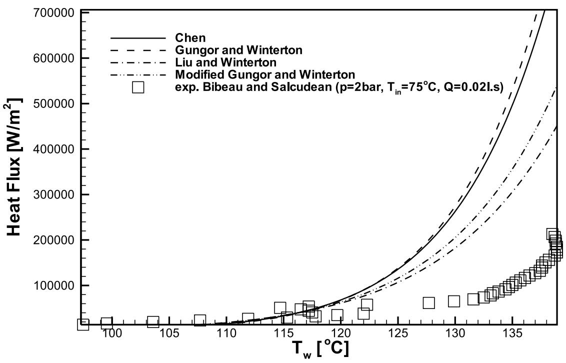

Fig. 3. Comparison of Chen-type correlations with experimental data.

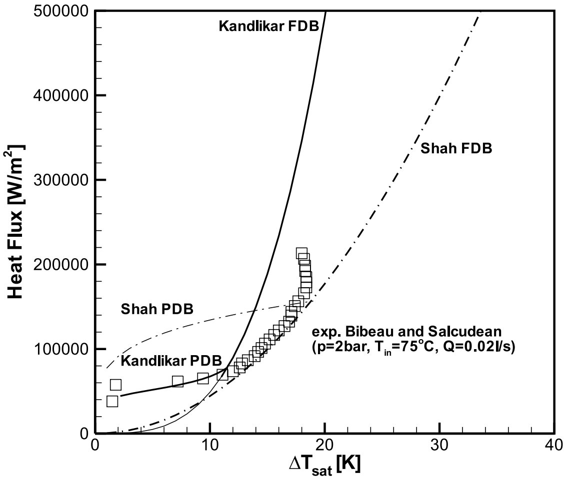

Fig. 5. Correlations of Shah [14] and Kandlikar [1] in partial and fully developed boiling.

Kandlikar's recent review shows good agreement between his correlation for the fully developed region with the experimental data of Bergles ans Rohsenow [19]. He also found that the correlations of Shah [14] and Thom et al. [15] underpredict the heat transfer rate. The present analysis shows, and this is illustrated in Fig. 4, that most of models of this type, with the exception of Shah [14], overpredict the heat transfer coefficient for a given wall superheat. Shah's model was the only one that shows excellent agreement with our data, however, only at low flow rates. Shown in Fig. 5 is the result of applying Shah and Kandlikar's model for both, partial and fully developed boiling, on Bibeau and Salcudean's experimental data sample. Good agreement with the model of Shah can be noticed in the FDB zone as well as good agreement with the model of Kandlikar in the partial boiling region (PDB). As pointed out in [14], poor results of the Shah correlation in the PDB zone have been related to ΔT_{sat} being strong function of h_{FC} and hence subject to accurate prediction of the convective heat transfer coefficient.

Good results over the whole range of experiments were also obtained with the correlation of Moles and Shaw [24]. However, the coefficients in the correlation were subject to modification. A modification of the Moles and Shaw correlation is, hence, proposed in this study and is given by:

$$\frac{h_{tp}}{h_{FC}} = \exp(14.542)Bo^{0.729}Ja^{*^{-0.354}}\left(\frac{\rho_v}{\rho_l}\right)^{1.811}Pr^{7.032} \tag{1}$$

The larger exponent for the density ratio than the original suggests a stronger influence of pressure on the overall heat transfer rate. However, perhaps this can be expected since the bubble size range over our pressure range (1–3 bar) changed significantly. At higher pressures such a large variation does not occur. The single-phase heat transfer coefficient, h_{FC}, is calculated by the

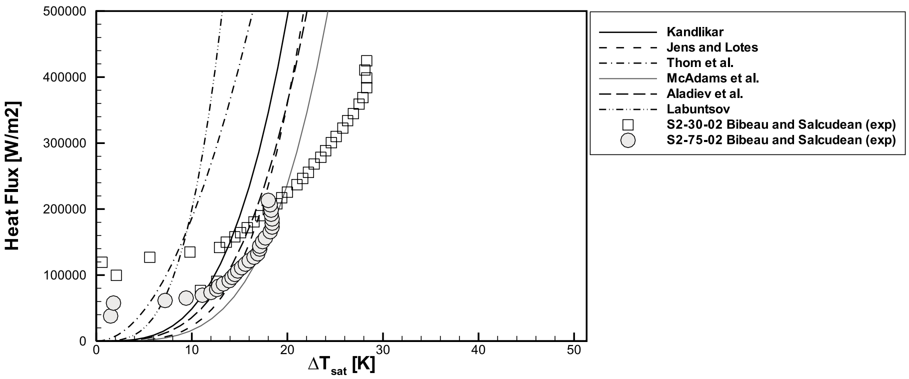

Fig. 4. Correlations for fully developed flow boiling: experiment S2-30-02 ($p = 2$ bar, $T_{in} = 30$ °C, $Q = 0.02$ l/s)—high subcooling, experiment S2-75-02 ($p = 2$ bar, $T_{in} = 75$ °C, $Q = 0.02$ l/s)—low subcooling.

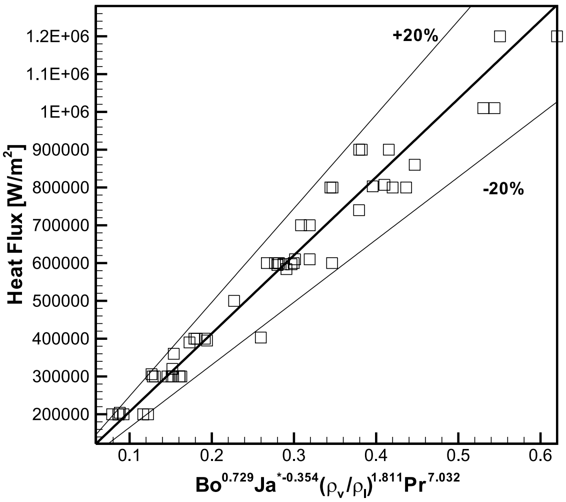

Fig. 6. Proposed heat transfer correlation.

Dittus–Boelter correlation. As shown in Fig. 6, the new correlation agrees very well with our data.

2.3. Transition from partial to fully developed subcooled flow boiling

Most authors agree that, in addition to liquid single-phase forced convection, there are two other main mechanisms governing heat transfer during boiling. The first mechanism has been suggested by Gunther and Kreith [25]. It is based on additional turbulent mixing (microconvection) due to the presence of the vapour phase. The second mechanism was discussed by Bankoff [26] and stresses the importance of the latent heat transport to the bubble. The concept involves heat transferred to the bubble through microlayer evaporation, while simultaneously transferring heat to the cooler fluid via condensation along the top of the bubble. The latent heat transport mechanism has been analyzed in detail by Bankoff and Mikesell [27], Snyder and Robin [28], among others.

Upon analyzing the microlayer evaporation of Gunther's high heat flux experimental data, Plesset and Prosperetti [29] concluded that latent heat transport represents only a small fraction of the total heat transfer. They suggested that latent heat transport may be significant in saturated and slightly subcooled boiling but becomes less important at higher subcooling, presumably due to shorter exposure time. They did not consider the sliding effect. On the other hand, Bankoff and Mikesell [27] have demonstrated that uncertain predictions in bubble internal pressure, through a kinetic theory approach, can cause large errors in the amount of latent heat transport. Such heat transport was assumed to account for as much as 40% of the total heat, thus questioning the relative importance of these two major heat transfer mechanisms. The latent heat contribution may even prevail in the case of sliding bubbles due to significant augmentation of microlayer evaporation, as pointed out by Tsung-Chang and Bankoff [30].

Fraser et al. [5] have discussed in details two types of bubble behaviour that depend on the heat flux. There are clearly two different heat transfer modes associated with the two types of bubble behaviour. The first type, which starts right after the ONB, describes bubbles that slide long distances on the heater before eventually being ejected into the liquid. The amount of void at the early stages of the boiling process is insignificant. The explosive bubble growth, soon after nucleation, is later replaced by balanced evaporation and condensation rates leaving bubbles with fairly constant size and shape for a significant amount of time. The changes in size and occasional detachments occur mainly due to local instabilities, turbulent fluctuations or bubble coalescence. It was shown earlier [5] that bubble sliding velocities do not differ significantly from that of the bulk liquid. Hence, it can be concluded that the heat transfer in the low heat flux region is mainly associated with forced convection in the bulk liquid (macroconvection) and evaporation (latent heat). Within this region, the overall heat transfer coefficient depends on the mass flow rate. This corresponds to the partial nucleate boiling.

High-speed photographs shown in Fig. 7 illustrate typical low heat flux bubble behaviour observed in the current study. They also show detachment and subsequent reattachment of a bubble, a phenomenon relatively frequent in the low heat flux area. The authors are not addressing this phenomenon in the present study, although it is important to note that such detachments and reattachments do not significantly affect the overall heat transfer rate.

With increasing heat flux and fixed flow rate the amount of bubbles (number of active nucleation sites) rise, thus increasing the influence of the evaporative component in the overall heat transfer. The sliding distances become much shorter. Typical bubbles slide for a maximum of a couple of diameters before being ejected in the liquid core. The bubble lifetimes are much shorter (in the order of a couple of milliseconds). The initial fast bubble growth is reduced due to increasing condensation rates at the top of the bubble and balances off at the moment the bubble reaches it's maximum diameter. The condensation rate becomes larger than the growth rate while the bubble is still attached to the wall. Hence, departing bubbles are typically smaller than their maximum size. They are also elongated in the direction normal to the wall. Detachments are regular and significantly affect the overall heat transfer. The bubble behaviour in this region is shown in Fig. 8.

Three main contributions can be distinguished for the purpose of the heat transfer analysis. The first two

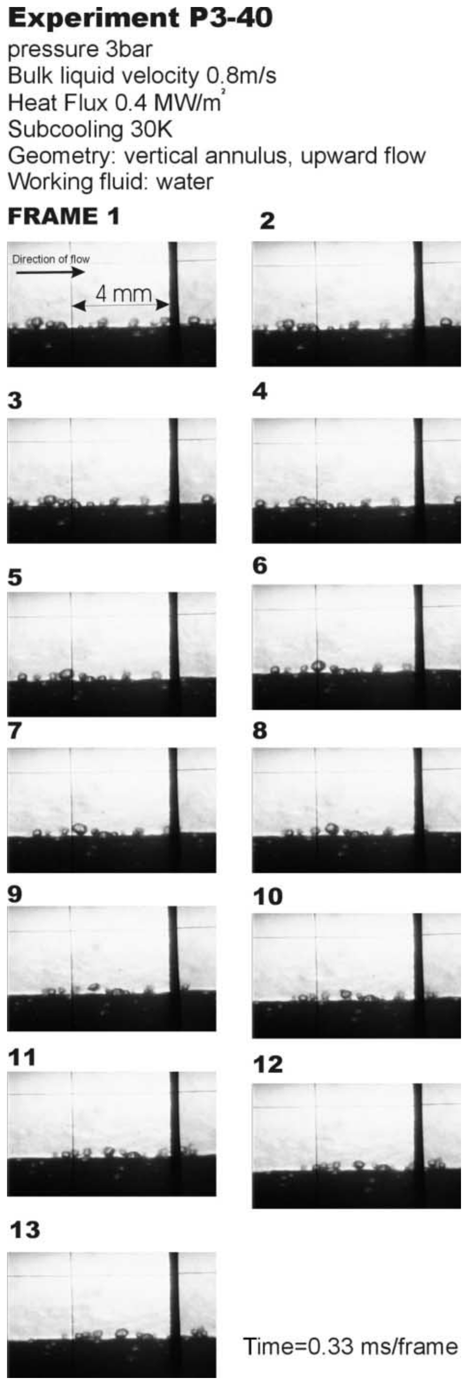

Fig. 7. Photographs of the low heat flux region.

are common for both, the partial nucleate boiling region and the FDB region:

(1) *The forced convection in the bulk liquid—"macroconvection"*: The bulk liquid is flowing mainly undisturbed by the bubbles (low void). Local disturbances certainly cause additional turbulence and microconvection although that does not seem to be affecting the heat transfer significantly. This is evident from the fact that for the low heat flux region, the heat transfer coefficient agree relatively well with single-phase forced convective correlations.

(2) *The evaporation*: Most of the evaporation in the case of subcooled boiling occurs in the thin, liquid layer underneath the bubble, called microlayer. In the partial nucleate boiling region most of the heat "consumed" by the bubble is being released at the top in form of latent heat, due to condensation. If the evaporation rate is balanced by the condensation rate, like in partial boiling, the heat flux removed by evaporation remains fairly constant. As a result the q vs. ΔT_{sat} curve remains flat. A small increase in the heat transfer rate with increasing wall temperature is due to the activation of new nucleation sites.

(3) *The "microconvection"* would be a characteristic of the FDB. It is associated with the fast bubble growth. Some hot liquid surrounding the cavity at the initial stage is pushed away from the wall by the growing bubble. Also, the bubble that detaches from the wall travels fast into the fluid core leaving space for some cooler liquid to rush in and locally cools down the surface. The experimental evidence for this type of behaviour exists and is characterized by the waiting time, the time that is needed for the surface temperature to reach again the bubble initiation level. More active nucleation sites and lower bubble lifetimes as the wall temperature rises lead to more significant "bubble agitation" and result in the dramatic increase of heat transfer rates and the slope of the q vs. T_{sat} curve.

It has been experimentally observed that, as one departs from the "low heat flux region" characterized by small amount of bubbles sliding over significant lengths on the heater and rare detachments, the increase in the heat flux for a constant flow rate leads to a dramatic drop in sliding distances. As one enters the isolated bubble region, the heat transfer mode changes accordingly. One can suggest that this transition corresponds to the transition from partial to fully developed boiling. The change of typical sliding distances scaled with the maximum diameters vs. Bo, from the experimental data at $p = 2$ and 3 bar, is shown in Fig. 9.

Further analysis requires the introduction of certain simplifications:

– It can be shown that the subcooling (within the experimental range 10–30 K) has relatively low influence on the overall bubble behaviour as compared to the effect of the heat flux and flow rate. Transition from the low heat flux region to the isolated bubble region has been noticed at all subcoolings.

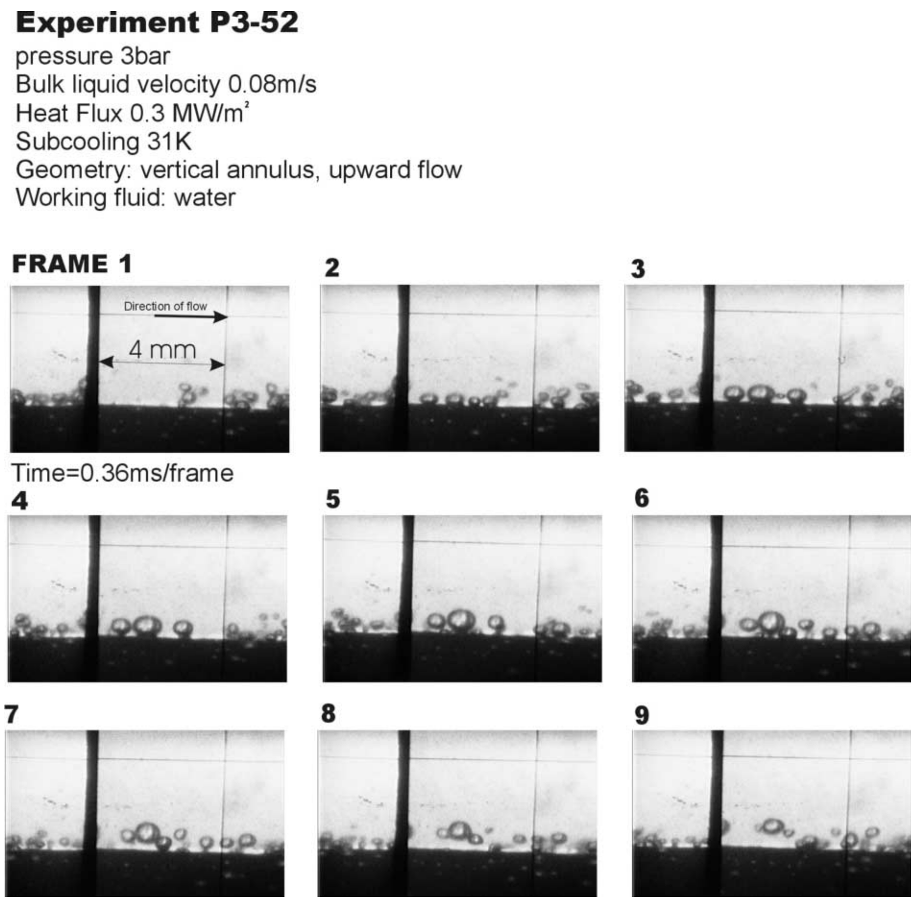

Fig. 8. Photographs of the isolated bubble region.

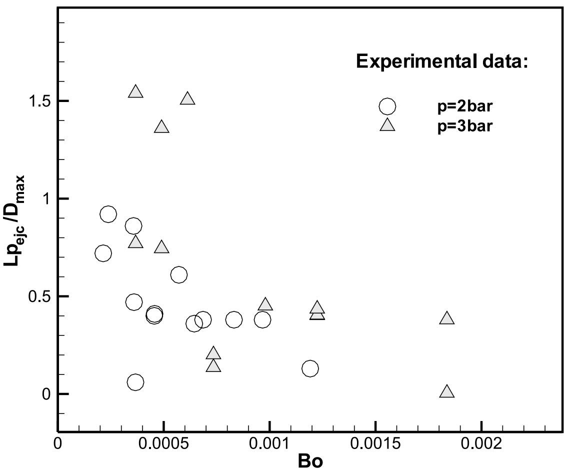

Fig. 9. Normalized parallel displacement—experimental data.

– The effect of the pressure appears to be minor in this case and it is excluded from the analysis.

– Local disturbances of the velocity field and thermal boundary layer due to turbulence or to the presence of the growing bubble as well as the roughness of the surface are not taken into account.

Having adopted these simplifications, one is left with the concept that the thickness of the thermal boundary layer relative to the size of the bubble (i.e. evaporation over condensation rate) regulates the overall bubble behaviour and hence the heat transfer. In other words, there is a high heat flux and high flow rate situation which renders the same behaviour of the bubble (smaller bubble, thin thermal layer) as a corresponding low heat flux and low flow rate experiment (larger bubble, thicker thermal layer). In this simplified model it is assumed that all experimental data can be represented by a single curve, as shown in Fig. 10. The slope of the curve shows that the flow rates (convective boiling term) do not affect the overall heat transfer in the FDB, which was also suggested by Shah [14]. In that case the change of *Bo* corresponds to the change of the heat flux.

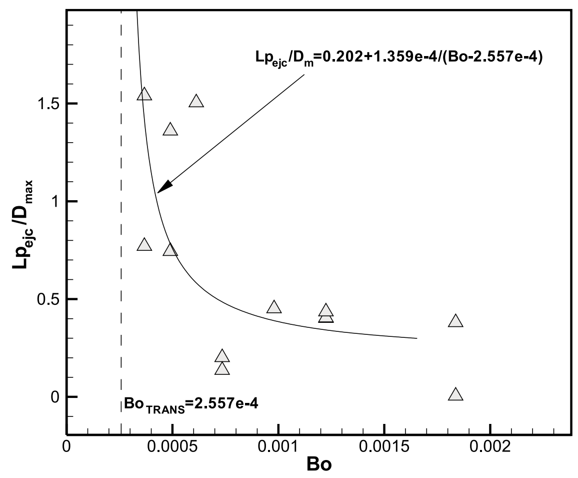

Fig. 10. Normalized parallel displacement correlation shown with experimental data at $p = 3$ bar.

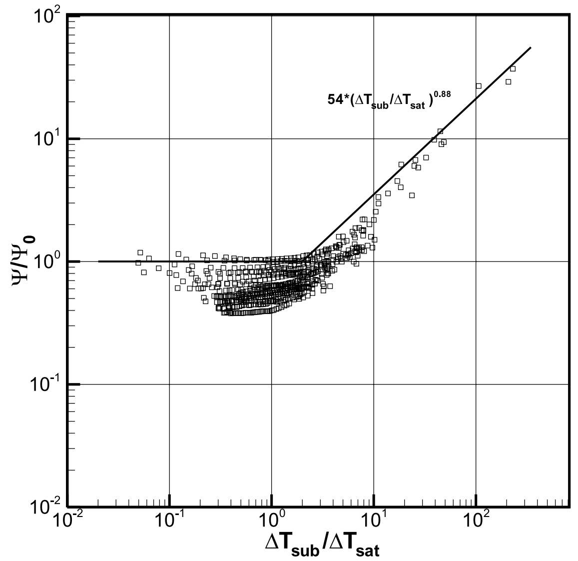

Fig. 11. Transition point prediction from Shah [14] model compared with experimental data of Bibeau and Salcudean $p = 2$ bar [3].

Having examined the drop of the sliding distances, one can assume that the limit of the curve $Lp_{\rm ejc}/D_{\max}$ vs. Bo when $Lp_{\rm ejc}/D_{\max} \to \infty$ renders $Bo_{\rm TRANS}$, or, in other words, the heat flux that corresponds to the transition point. Fig. 10 shows the experimental data correlated with Eq. (2). From the limit of Eq. (2) the transition boiling number equals to $Bo_{\rm TRANS} = 2.557 \times 10^{-4}$.

$$\frac{Lp_{\rm ejc}}{D_{\max}} = 0.202 + \frac{1.359 \times 10^{-4}}{Bo - 2.557 \times 10^{-4}} \tag{2}$$

The Shah correlation can be used for comparison. Shown in Fig. 11 is the application of Shah correlation to the experimental data at $p = 2$ bar. Similar graphs can be obtained for all pressures within the experimental range. It is evident that the transition from partial to fully developed boiling occur at $\Delta T_{\rm sub}/\Delta T_{\rm sat} = 2$, which is in excellent agreement with Shah's observations. In addition to this, if one calculates the Boiling number, Bo, which corresponds to the transition point, from the transition curve equation (3) as suggested by Shah, one will obtain the value of $Bo_{\rm TRANS} = 2.52 \times 10^{-4}$ which corresponds to the limit of the curve $Lp_{\rm ejc}/D_{\max}$ vs. Bo in Fig. 10. The transition curve [14] is given by:

$$\frac{\Delta T_{\rm sub}}{\Delta T_{\rm sat}} = 6.3 \times 10^{-4} Bo^{1.25} \tag{3}$$

Eq. (3) is valid for $\Delta T_{\rm sub}/\Delta T_{\rm sat} \leqslant 2$, which corresponds to lower Bo. For higher Bo numbers the value $\Delta T_{\rm sub}/\Delta T_{\rm sat}$ remains constant and equals to 2. Introducing $Bo_{\rm TRANS} = 2.557 \times 10^{-4}$ and $\Delta T_{\rm sub}/\Delta T_{\rm sat} = 2$ into Eq. (1) one can obtain the heat flux corresponding to the transition from partial to fully developed boiling for the given range of pressures, subcooling and flow rates. The proposed model for the transition point from partial to fully developed boiling is:

$$q_{\rm TRANS} = A \cdot \Delta T_{\rm sub}^{0.646} \tag{4}$$

where:

$$A = \frac{3}{2} h_{\rm FC} \exp(14.542)(2.557 \times 10^{-4})^{0.729} \left(\frac{c_p}{i_{\rm fg}}\right)^{-0.354} \times \left(\frac{\rho_{\rm v}}{\rho_{\rm l}}\right)^{1.811} Pr^{7.032} \tag{5}$$

$$h_{\rm FC} = 0.023 \frac{k_{\rm l}}{D} Re^{0.8} Pr^{0.4} \tag{6}$$

The comparison of the present model with the models of Shah and Kandlikar for the transition point is shown in Fig. 12. The graphs show the transition point at various flow rates and subcooling of 10, 20 and 30 K, at pressure of $p = 1$ bar. Identical results have been obtained at pressures of 2 and 3 bar. The parameter on the horizontal axes represents the normalized transition heat flux. It corresponds to the location of the transition point relative to the ONB and OSV. The model used for the prediction of ONB is that of Hahne et al. [31]. The location of the OSV has been calculated using the modification of the model of Saha and Zuber, given by Bibeau and Salcudean [32] for the same experimental setup. Remarkable agreement with the model of Kandlikar [1] has been obtained for all pressures and subcoolings. The agreement is better at higher subcoolings. Similar observation can be made after comparing data with the model of Shah [14]. Bubble dynamics analysis

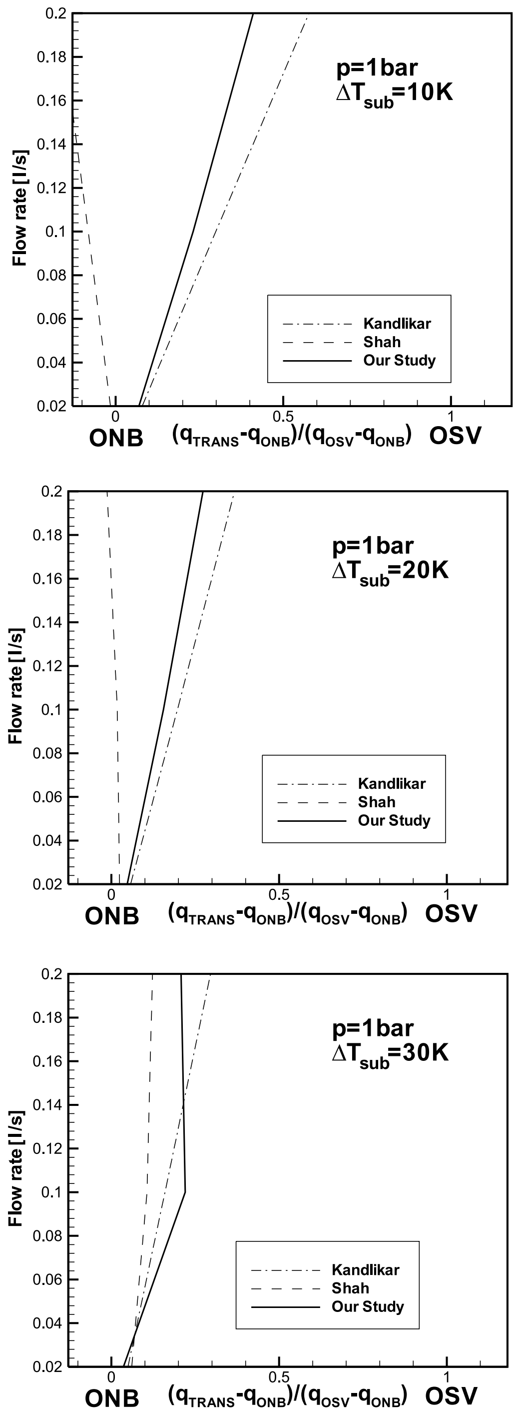

Fig. 12. Prediction of the transition point, Comparison of the proposed model with models of Kandlikar [1] and Shah [14] for $p = 1$ bar.

which will reveal the reasons for the sharp change in the bubble behaviour is beyond the scope of the present analysis.

3. Conclusions

A simple model for the transition point from partial to fully developed flow boiling has been proposed. The first step in modelling included the modification of the heat transfer correlation of Moles and Shaw [24]. The new heat transfer correlation fits the experimental data of Bibeau and Salcudean [3] and Fraser et al. [5] with high accuracy.

The transition point model is based on the observed change of the bubble behaviour with the boiling number *Bo* and sharp drop of bubble sliding distances prior to ejection. The low heat flux region corresponds to the partial boiling and the dominant heat transfer mode is that of latent heat. The change in the bubble behaviour promotes bubble agitation and microconvection as the heat transfer mode and indicates the transition to FDB.

The simplicity of the model lays in the inclusion of the parameter $Lp_{\mathrm{ejc}}/D_{\max}$ (normalized sliding distance of the bubble prior to ejection) which is assumed to be independent of the subcooling and pressure, and hence function of *Bo* solely. The limit of this function when $Lp_{\mathrm{ejc}}/D_{\max} \to \infty$ returns the *Bo* number which corresponds to the transition point. The obtained transition boiling number Bo_{TRANS} and the ratio $\Delta T_{\mathrm{sub}}/\Delta T_{\mathrm{sat}}$ show excellent agreement with the model of Shah. With the fixed transition *Bo* number and $\Delta T_{\mathrm{sub}}/\Delta T_{\mathrm{sat}}$, one can obtain the location of the transition from partial to fully developed boiling from the heat transfer correlation.

The authors are aware of the limitations of such simplified model. At this stage the model is restricted to the experimental range of subcooling (10–30 K) and low liquid velocities (0.08–0.8 m/s) due to available experimental data. Although it appears to be within accepted limits of accuracy for the given range of experiments, it is generally not acceptable that the transition is limited to one particular point (i.e. $Bo_{\mathrm{TRANS}} = 2.557 \times 10^{-4}$ and $\Delta T_{\mathrm{sub}}/\Delta T_{\mathrm{sat}} = 2$). The transition curves in Shah's model permit more flexibility, which explains the discrepancy between the two models in Fig. 12. However, the authors believe that the observed link between the sliding distances (bubble behaviour) and changes in heat transfer is a step forward toward better understanding of the transition from partial to fully developed boiling. Further investigation of the change in bubble behaviour and inclusion of the effect of subcooling in the analysis is needed.

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