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PRELIMINARY CONSIDERATION TO AVOID ERUPTIVE FLOW BOILING IN MICROCHANNELS

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ABSTRACT

With boiling flows in very smooth heated channels, in general, the bulk liquid is superheated before the bubble formation takes place at the wall surface. Thus the eruptive boiling occurs once the superheat requirement for nucleation is satisfied, and this can be a source of flow instability. In the present work, a preliminary consideration has been given to predict the limiting heat flux for stable boiling in microchannels. The minimum heat-flux value to avoid this eruptive boiling is inversely proportional to the square of the channel diameter, and becomes enormously large as the channel diameter decreases. The stable heat-flux limit also depends on the cavity size in the channel wall. A map showing stable nucleation criteria was given and discussions were made on the simplifying assumptions made for the analysis.

INTRODUCTION

Recently, micro-evaporators are becoming of interest as potential heat sinks for cooling of high heat-flux electronic components. Micro-evaporators have advantages of high heat-removal performance and uniform operating temperature because those utilize the phase-changing phenomenon. On the other hand, there are also drawbacks in using this device: large pressure drop across the channel and unstable operation due to boiling. Thus, in order to reduce the pressure drop, the micro-evaporators are designed to have multiple parallel microchannels with common manifolds(headers) at both ends for distribution of coolants. Nevertheless, the two-phase flow instability with boiling still exists and induces severe fluctuations of flow and system pressure, which may cause dryout of the channel. Besides, flow mal-distribution between the parallel microchannels is often observed, and this also enhances the flow instability. Thereby, thermal deterioration or breakdown of the electronic components may occur. In order to resolve those problems, fundamental studies have been performed on the flow boiling in microchannels, mostly on heat transfer and pressure drop across the channels. (Jiang et al., 1999; Jiang et al., 2001a; Zhang et al., 2002a; Zhang et al., 2002b; Jiang et al., 2001b; Koo et al., 2001; Hetsroni et al., 2001; Hetsroni et al., 2002; Peles et al., 2001; Qu and Mudawar, 2002)

Jiang at al. (1999, 2001a) fabricated a transparent heat-sink system consisting of an array of triangular microchannels ranging between 40 ~ 80 microns in hydraulic diameters, a heater and a temperature sensor array to visualize the flow pattern and to measure the temperature distribution. At the low heat-flux range, active nucleation sites were very rare, especially after the fabrication residues had been cleaned up during the first run, though there are local bubble formations. As the intermediate power level, an unstable slug flow appeared as large bubbles formed at the upstream manifold were forced into the microchannels. At the higher heat-flux condition, a stable annular flow was developed. Thus the bubbly flow, commonly observed in microchannels was not developed in their experiment.

Jiang et al. (2001b), Koo et al. (2001), and Zhang et al. (2002a, 2002b) performed experimental and modeling works on boiling microchannel flow using either single or multi-channels under the uniform heat-flux conditions. Zhang et al. (2002b) reported dependence of the flow pattern on the channel size. For the channel with 113 microns in hydraulic diameter, as the heat flux was increased, nucleation bubbles were formed, grew and detached to flow downstream and eventually changed to a stable annular flow through the bubble coalescence. In this case, the wall temperature could be maintained uniformly. On the other hand, with the 44-micron channel, no bubble nucleation was observed and the highly superheated liquid turned almost immediately into a mist flow through abrupt boiling. In this region, the annular flow with a thin liquid film exists for a very short distance, but quickly turns into the mist flow. According to Zhang et al. (2002b), the wall temperature keeps increasing with increasing of the heat input because the heat transfer coefficient in the mist flow regime is much lower than in the annular flow. This unusual superheat is due to lack of the active nucleation site since the wall surface roughness mostly becomes small with the smaller channel size. By creating small artificial cavities through the micro fabrication process, the degree of superheat can be lowered drastically, and the bubble nucleation/detachment (and hence, the stable annular flow) is observed even with the small-diameter microchannels. Jiang et al. (2001b) and Zhang et al. (2002a) also reported that such an eruptive boiling causes the two-phase flow instability. Koo et al. (2001) proposed a one-dimensional flow model to predict heat transfer and pressure drop in microchannels, based on their observation; immediate transition from the single-phase liquid flow to the homogeneous misty flow, without the bubbly and plug-flow regimes, after the eruptive boiling. Anyhow, these results prove that bubble nucleation can be induced and a stable two-phase flow is available by creating (and controlling) the cavity size.

Hetsroni et al. (2001, 2002) and Peles et al. (2001) reported various phenomena of boiling two-phase flow inside microchannels for cooling of electronic devices. The hydrodynamic instability observed was in agreement with that reported by Jiang et al. (2001b), Koo et al. (2001), and Zhang et al.(2002a, 2002b). They also reported that the flow pattern changed from single-phase liquid flow to annular flow almost abruptly through a narrow transition range. Among them, Peles et al. (2001) introduced a one-dimensional model for boiling flow in microchannels, similar to the model of Koo et al. (2001), but with the assumption of the single-phase vapor flow after the phase change. However, the accuracy of the predicted pressure drop and heat transfer rate is still to be checked because of this oversimplification.

Qu and Mudawar (2002) also reported that it was very difficult to sustain the bubbly flow regime in a micro-channel. Instead, transition to the slug flow regime occurred shortly after the boiling incipience. For a multichannel system, flow patterns were complicated by the parallel channel instability.

There has been a novel work reported by Peng et al. (1998) on the boiling two-phase flow in microchannels. They introduced a concept of minimum evaporating space for bubble nucleation and explained that, below this size, two-phase flow may be developed without obvious nucleation but through the ‘fictitious boiling.’ They also argued that the boiling phenomenon was changing as channel diameter was reduced to about 100 microns that is in the size range of the active wall cavities (10 ~ 180 microns) at the heated surface of the macro-size channels. However, this concept is not widely accepted. Recently, Kandlikar (2002) has argued that, through his extensive review of the existing works on the flow boiling inside the microchannels, the nucleate boiling is available in microchannels as well, and the high speed visualization has to be done to verify the fact.

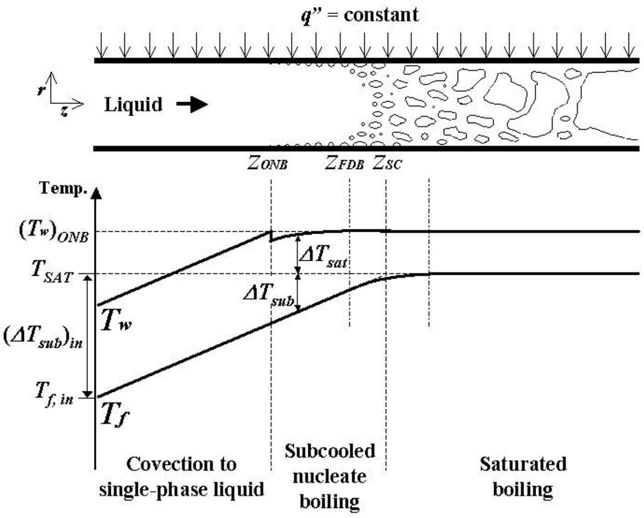
In the present work, to explain the phenomenon of abrupt (or eruptive) boiling frequently observed inside the microchannel, the wall nucleation criterion has been re-examined. Then, dependence of the boiling phenomenon on the channel size and the surface roughness has been discussed as a preliminary consideration to avoid the eruptive flow boiling.

ERUPTIVE FLOW BOILING

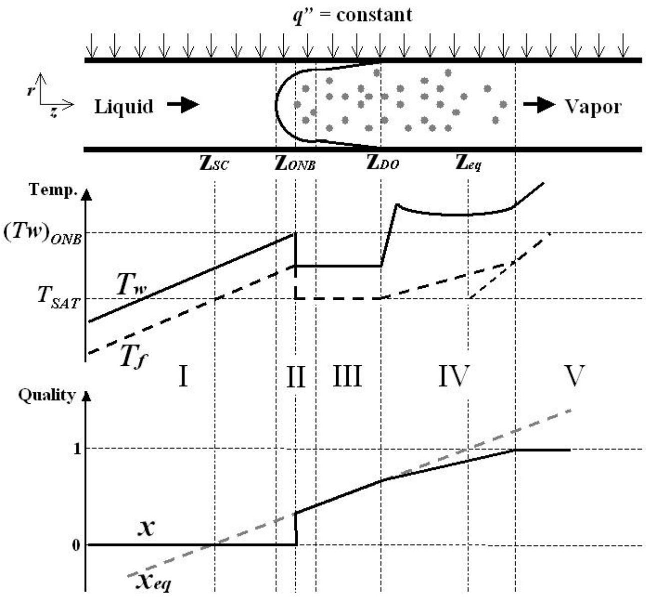
Eruptive boiling is characterized by changing of the flow pattern from the highly superheated liquid flow to the annular-mist flow by rapid bubble growth and quick filling of the channel cross section. Thus, the local pressure rises sharply and the flow stop or even reversal may occur, finally lead to the two-phase flow instability or premature dryout. This occurs in channels with smooth wall surfaces, such as glass or silicon surfaces, where there is not enough number of active nucleation cavities.

Figures 1(a) and 1(b) illustrate variations of the fluid and surface temperatures and the quality along the flow direction for the nucleate flow boiling with stable bubble formation and the eruptive flow boiling, respectively, in uniformly heated channels. With the stable nucleate boiling, as illustrated in Fig. 1(a), bubbles are nucleated at the subcooled condition and grow to coalesce each other and forms large slug bubbles. Then the flow pattern changes gradually into annular flow as the quality is increased along the flow direction. For the eruptive flow boiling (Fig. 1(b)), in reality, the flow is highly transient due to the flow instability with strong cyclic oscillations, and Fig. 1(b) depicts the instant just prior to nucleation in a cycle. Therefore, the annular flow at the downstream is the rear part of the previously erupted bubble. In region I, both the wall and the fluid temperatures rise linearly (in parallel to each other) along the flow direction because the channel is heated uniformly. With the smooth channels, the liquid temperature (T_f) rises above the equilibrium saturation temperature (T_{SAT}) until the superheat requirement of the wall temperature for nucleation ($(T_w)_{ONB}$) is satisfied. Once the wall temperature reaches $(T_w)_{ONB}$, as shown in region II, bubble nucleation occurs, followed by rapid growth of the vapor phase due to excess heating of the bulk liquid. At the downstream, region III, the short annular-flow regime is formed, and then quickly turned into the mist flow denoted by region IV. Koo et al. (2001) and Peles et al. (2001) have adopted this concept in modeling the microchannel boiling flow as introduced in the previous section.

PREDICTION OF BOILING INCIPIENCE (ONB)



(a) Wall- and liquid-temperature distributions in stable nucleate boiling



(b) Wall- and liquid-temperature and quality distributions in eruptive flow boiling

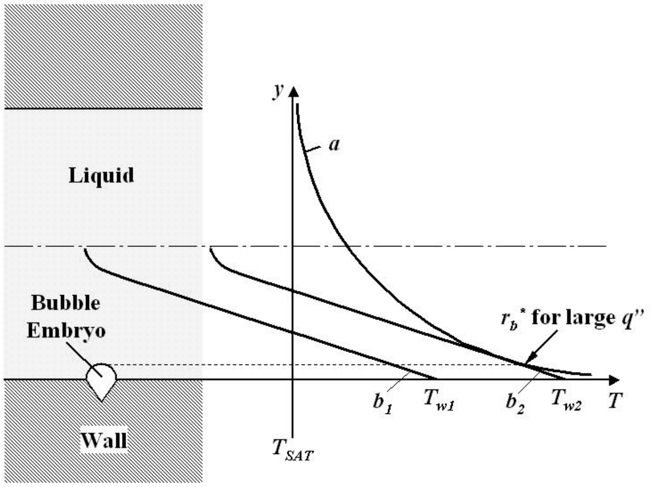
Fig. 1 Schematic illustration of flow boiling models

For macro-scale channels, various models for bubble nucleation have been developed as summarized in the text of Collier and Thome (1996). However, it should be checked if the conventional models for macro-scale channels are also valid for microchannels. There have been several works reported by Peng et al. (1998), Mitrovic (2001) and Ghiaasiaan and Chedester (2002) regarding the boiling incipience in microchannels. According to the correlation by Peng et al. (2002), the degree of superheat is inversely proportional to the channel hydraulic diameter, which implies that the minimum heat flux for bubble formation would be much larger with the smaller channel size. Mitrovic (2001) predicted the bubble survival condition in saturated liquid flowing inside a microchannel by taking account of the laminar temperature profile along the cross section. Here, the heat-flux requirement is inversely proportional to the square of the hydraulic diameter. The disagreement of this result with that of Peng et al. (1998) was caused by using different models in their works. Ghiaasiaan and Chedester (2002) analyzed the available data to predict the boiling incipience of water in microtubes (0.1 ~ 1 mm range) and suggested to use the model of Davis and Anderson with a modification coefficient, taking account of the thermocapillary and hydrodynamic forces on the bubble nuclei. However, the experimental data they relied on were for larger diameters (1 ~ 1.45 mm) than the size of their interest and, moreover, a fully turbulent flow assumption may not be applicable to most of the microchannels since the Reynolds numbers are usually very small. Nevertheless, all those previous results show that, in principle, there is no difference between micro- and macro-channels concerned with the nucleation process, and the superheat requirement should be higher with the smaller channel diameter. Therefore, in the present work, the conventional model by Davis and Anderson was adopted to predict occurrence of the eruptive boiling assuming the flow is fully developed and laminar in microchannels; and the details are discussed in the following part.

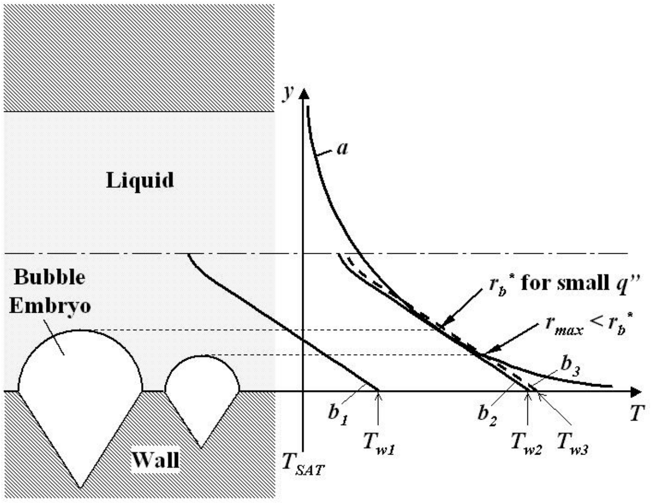
In Fig. 2, the abscissa and ordinate are the temperature and distance from the channel wall, respectively. Curve *a* shown in the figure denotes the superheat requirement of the thermal layer adjacent to the wall, based on the vapor nucleation theory as

$$T_g - T_{SAT} = \frac{2\sigma T_{SAT} v_g}{i_{fg} r_b} \tag{1}$$

with the radius of the vapor embryo (bubble nucleus) r_b replaced by y, the distance from the wall. Curves b_1 and b_2 in the figure represent the liquid temperature distributions along the channel cross section at different axial locations with the same heat flux, and parallel to each other because the heat transfer coefficient is constant for a fully developed laminar flow. Figures 2(a) and 2(b) represent the cases of the stable nucleate boiling (Fig. 1(a)) and the eruptive boiling (Fig. 1(b)), respectively. Unless there is any restriction on the wall cavity size distribution and when the heat flux becomes high enough for the temperature distribution curve (curve b_2) to touch the vapor nucleation curve (curve *a*), the bubble nucleation starts at the cavities of the critical radius ($r_b = r_b^*$) assuming that there is no temperature distortion near the bubble in the thermal layer. For the case of Fig. 2(a), the bubble nucleation occurs though the core portion stays below the saturation temperature. On the other hand, for the case of Fig. 2(b), the temperature at the core portion should be much higher than the saturation condition to induce bubble nucleation, which



(a) Nucleation under the stable flow boiling condition



(b) Nucleation under the eruptive flow boiling condition

Fig. 2 Illustration of wall nucleation

causes the unstable eruptive boiling. If the maximum size of the active cavities (r_{max}) in the channel wall restricted to be smaller than the critical value ($r_b{}^*$), higher wall temperature (T_{w3}) is required to induce bubble nucleation, which is only available at the further downstream location for a fixed heat-flux value. This case is represented by crossing of curves *a* and b_3 in Fig. 2(b).

At the present stage, a couple of important aspects should be emphasized; the wall superheat requirement (curve *a* represented by Eq. (1)) remains the same regardless of the channel size, but the heat flux for bubble nucleation depends on the liquid temperature profile (curve *b*) and the maximum active cavity size. In other words, the boiling incipience strongly depends upon the channel size and wall surface roughness. Let's consider a circular microchannel with diameter *D*. Then the temperature distribution along the radial direction of the circular cross section is obtained to be

$$T_f = T_w - \frac{q^{''}D}{k_f}\left(\frac{3}{8} - \frac{\bar{r}^2}{2} + \frac{\bar{r}^4}{8}\right) \tag{2}$$

with $\bar{r} = 2r/D$. If $\bar{r}$ is replaced by $1-\bar{y}$, where $\bar{y} = 2y/D$, to express Eq. (2) in terms of the normalized distance from the wall surface, the temperature distribution becomes as follows:

$$T_f = T_w - \frac{q^{''}D}{8k_f}\left(\bar{y}^4 - 4\bar{y}^3 + 2\bar{y}^2 + 4\bar{y}\right) \tag{3}$$

Here, the value of $\bar{y}$ stays between 0 and 1. Mostly, the cavity size is much smaller than the channel diameter (i.e., $r_b << D/2$), and the applicable range of $\bar{y}$ should be much smaller than the unity (i.e., $\bar{y} << 1$). Thus, by neglecting the higher order terms, Eq. (3) can be simplified as:

$$T_f = T_w - \frac{q^{''}}{k_f}y \tag{4}$$

Equation (4) means that the liquid temperature distribution is linear near the wall. If there is no specific restriction on the cavity size distribution, the critical cavity size $r_b{}^*$ corresponds to the point of tangential contact between curves *a* (Eq. (1)) and b_2 (Eq. (4)) as

$$T_f = T_g \tag{5}$$

$$\frac{dT_f}{dy} = \frac{dT_g}{dr_b} = \frac{dT_g}{dy} \tag{6}$$

and obtained as

$$r_b{}^* = \left(\frac{2\sigma T_{SAT} v_g k_f}{q^{''} i_{fg}}\right)^{1/2} \tag{7}$$

$$q^{''}_{ONB} = \frac{i_{fg} k_f}{8\sigma T_{SAT} v_g}[(T_w - T_{SAT})_{ONB}]^2 \tag{8}$$

Also, the heat flux can be written in terms of the temperature difference between the wall and the fluid as

$$q^{''} = h_f[T_w(z) - T_f(z)] \tag{9}$$

and the lower limit of the eruptive boiling occurs at $T_f(z) = T_{SAT}$. Therefore, Eq. (9) becomes

$$(q''_{ONB})_{erup} = h_f(T_w - T_{SAT})_{ONB} \tag{10}$$

and, by eliminating $(T_w - T_{SAT})_{ONB}$ by using Eq. (8), the following equation can be obtained:

$$(q''_{ONB})_{erup} = \frac{8h_f^2 \sigma T_{SAT} v_g}{k_f i_{fg}} = \frac{8\sigma T_{SAT} v_g}{k_f i_{fg}} \left(\frac{Nu \cdot k_f}{D_h} \right)^2 \qquad (11)$$

For uniform heating of laminar flows, the Nusselt number (Nu) is always constant to be 4.36, and, except for the channel hydraulic diameter, all other parameters are considered constant because those are the fluid properties. It should be noted that, to generalize the result, the hydraulic diameter (D_h) was used instead of diameter (D) since the Nusselt number is always constant for a fully developed laminar flow regardless of the channel cross-section shape. The important conclusion deducible from Eq. (11) is that the minimum heat flux to avoid the eruptive boiling is inversely proportional to the square of the channel diameter. That is, the heat flux should be much higher to have a stable nucleate boiling with the microchannels. This result coincides, at least qualitatively, with the observation made by Zhang et al. (2002b), where the eruptive boiling occurred with the small-diameter channel (44 microns) while the stable boiling with the larger one (113 microns) with the same surface condition. The solid line in Fig. 3 represents the minimum heat-flux condition for the stable wall nucleation with no limitation to the cavity size, showing the trend of decrease with increasing of the channel diameter. It should be mentioned that Eq. (8) is derived under the assumption of no distortion of liquid temperature around the bubble nuclei, i.e., $y = r_b^*$ at the contact point of curves a and b_2 in Figs. 2(a) and (b). However, in practice, the liquid temperature becomes distorted around the bubble nuclei, and the actual heat flux for the onset of nucleate boiling appears to be lower than Eq. (8). Thus, the line showing in Fig. 3 should be considered as the sufficient condition to avoid the eruptive boiling. In other words, the criterion line in Fig. 3 should be shifted in parallel to the lower heat-flux range to be quantitatively correct.

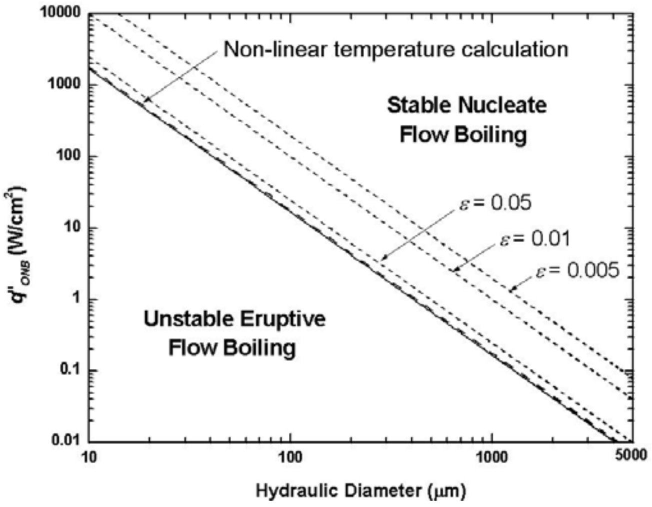


Fig. 3 Stable flow boiling limit (Water at 1 bar)

As already noted, Eq. (11) is for the case with no limitation in the active wall-cavity size. However, if the maximum cavity size is limited to be smaller than the critical value, r_b^*, corresponding to line b_3 in Fig. 2(b), the wall superheat requirement for boiling incipience for a given value of heat flux appears to be as follows:

$$(T_w - T_{SAT})_{ONB} = \frac{2\sigma T_{SAT} v_g}{r_{\max} i_{fg}} + \frac{q''_{ONB} r_{\max}}{k_f} \qquad (12)$$

To obtain the criterion to avoid eruptive boiling, the term $(T_w - T_{SAT})_{ONB}$ in Eq. (12) is eliminated using Eq. (10) to get

$$(q''_{ONB})_{erup} = \frac{2\sigma T_{SAT} v_g}{r_{\max} i_{fg}} \left(\frac{1}{h_f} - \frac{r_{\max}}{k_f} \right)^{-1} \qquad (13)$$

By introducing the relative surface roughness of the channel wall as $\varepsilon = r_{max}/D_h$, the above equation can be rewritten as follows:

$$(q''_{ONB})_{erup} = \frac{2\sigma T_{SAT} v_g}{i_{fg}} \frac{Nu \cdot k_f}{\varepsilon(1-\varepsilon Nu)} \frac{1}{D_h^2} \qquad (14)$$

As can be realized from this equation, for a given fluid, the minimum heat flux to avoid the eruptive boiling is a sole function of the tube geometry (i.e., D_h and ε). For a fixed value of the relative surface roughness(ε), the heat-flux criterion for eruptive boiling is, again, inversely proportional to the square of the channel hydraulic diameter. In addition, since the value of ε is smaller than the unity, the heat-flux criterion obtained by Eq. (14) is always larger than that by Eq. (11), and increases with decreasing of the ε value. In Fig. 3, various criteria with different values of ε were exhibited with the dotted lines. With the smaller value of the ε, the region of the eruptive boiling increases drastically. This implies that, to avoid eruptive boiling, the surface roughness should be maintained above a certain value once the channel size is fixed. The surface roughness effect has been reported earlier by Zhang et al. (2002b). They used the channels (28 ~ 73 microns in hydraulic diameters) with enhanced walls (with cavities of 4 ~ 8 microns in diameters). They observed the stable boiling flow in 61-micron and 72.5-micron channels, which has never been observed in smooth-wall channels below 100 microns in their previous experiments. However, in a smaller channel (47 micron in hydraulic diameter), the flow tends to be unstable even though the surface roughness remains the same, which corresponds to the trend represented by the dotted lines in Fig. 3. Another thing to note with Eq. (14) is on another extreme case of ε, approaching $1/Nu$. Since the Nusselt number is 4.36 for the case of uniform heating, the maximum available value of ε seems to be 0.229. This case means the maximum cavity size should be about the half of the channel radius, which is not likely to exist in reality. If the relative surface roughness is of the order of 0.1, the analytical approach for straight channels shouldn't be used since this is, in practice, a corrugated channel rather than the straight one. Close look at the microscopic pictures of the real microchannels, made through the micro-fabrication process, the surfaces are strikingly smooth, mostly below 0.01. Thus the extreme case of large ε doesn't have to be considered.

Finally, to check the effect of the higher order terms of the liquid temperature profile, Eq. (3) was used to obtain the criterion of the eruptive boiling and the result was plotted as the staggered line in Fig. 3. There is no significant difference between the result with the linear simplification (Eq. (4)) and that with the laminar temperature profile, and the linear assumption is considered acceptable at the near wall region in predicting the boiling incipience.

CONCLUSIONS

In the present paper, the condition of occurrence of eruptive boiling has been examined based on the conventional bubble nucleation model. Stable bubble formation was also predicted with microchannels. To estimate the criterion for bubble nucleation in microchannels, the classical model of Davis and Anderson with the linear liquid temperature distribution in the thermal wall layer has been adopted and confirmed to be valid in view of the previous experimental observations. The low heat-flux limit to avoid eruptive flow boiling appears to be inversely proportional to the square of the hydraulic diameter of the microchannel. Especially, with the limited surface roughness of the channels, the minimum heat flux to obtain the stable flow boiling should be much higher. A tentative map showing the region of stable nucleation was provided with the hydraulic diameter and the surface roughness taken as the parameters, which will be useful in preliminary consideration to avoid the eruptive boiling in microchannels.

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