Numerical simulation of nucleate boiling in shallow liquid

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This paper presents a numerical investigation on nucleate boiling in a condition of low liquid level, where the liquid height is comparable with the bubble departure diameter. A coupled volume-of-fluid and level-set method (VOSET) was used to deal with the moving liquid-vapor interface, and a microlayer model was adopted for the thin liquid film around the three-phase contact line. The heat flux obtained by numerical simulation was compared with those calculated by experimental correlations, and the outcomes matched. The numerical results provide a reasonable explanation for the augment of heat transfer coefficient of nucleate boiling as the liquid level decreases to a certain value.

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1. Introduction

Nucleate boiling is one of complex problems associated with fluid flow, heat transfer and phase change. It starts from bubble seeds generated on a superheated wall, but the mechanism regarding how and where the bubble nucleates is not very clear until now. However, the behavior of the bubble seeds after formation is better understood. As a bubble seed forms on a solid surface, it absorbs energy from the overheated liquid around it and grows more volume.

On the mechanism of nucleate boiling, it has been commonly believed that the departure of a bubble can carry a portion of superheated liquid away form the wall [1]. Apart from that, it has been demonstrated that a liquid film lies behind a growing bubble, and high local heat flux flows through it. These findings can give reasonable explanations for the high heat transfer coefficient of nucleate boiling. In the recent two decades, a number of researchers have explored CFD simulations on nucleate boiling using various interface tracking methods, obtaining more details of this phase change problem. A mesh-free method was used by Yoon et al. [2] to simulate a whole process of a bubble including its growth, departure and rising. Son et al. [3] performed a numerical simulation on a single bubble’s growth and departure using a modified level-set method with phase change taken into consideration. Additionally, a microlayer model was developed for the effect of the liquid film around the contact line. The methods proposed by Son et al. [3] were further developed and applied for other problems by Son et al. [4], Son and Dhir [5], Nam et al. [6], Mukherjee and Dhir [7], Mukherjee and Kandlikar [8], Aktinol and Dhir [9], Shin et al. [10] performed a three-dimensional simulation on the growth and departure of a single bubble using level contour method. A coupled volume-of-fluid and level-set method (VOSET) [11], was modified for the phase change by the present authors and was applied in a two-dimensional numerical simulation on nucleate boiling [12].

The overall heat transfer coefficient of nucleate boiling is affected by a large number of factors. It has been reported by Kopchikov and Voronin [13] that the heat transfer coefficient could be significantly increased as the liquid level decreases to a certain height. Later this phenomenon was re-confirmed by Xin and Tong [14]. However, little research has been devoted to its mechanism. In the present study, we performed a two-dimensional numerical simulation on nucleate boiling in shallow liquid level to find some features different from those in deep liquid level. The nucleation of bubble seeds, however, will be not discussed here. Instead, they were provided as given conditions for the simulations. Here we need to point out that the 2D model adopted in this study is a huge simplification, and a two-dimensional bubble is far away from the real case in 3D. However, there also exists many numerical studies where 2D models successfully demonstrated the features of film boiling [15,16,17] as well as nucleate boiling [2,5,12]. Therefore, we consider 2D model is able to provide at least a qualitative understanding on the effect of liquid level in nucleate boiling.

2. Numerical methods

Nucleate boiling can be considered as a multi-scale system problem [18] due to the existence of the micro liquid film around the three-phase contact line, which is sketched in Fig. 1. Generally, the thickness of the liquid film varies from molecular size to several micrometers, which is much smaller than the cell size in CFD...
simulation. However, large amount of heat is transferred through the microlayer despite its small scale. Thus, a simulation using a relatively large mesh size should consider the effect of microlayer by solving it separately.

In the present study, the heat transferred through the microlayer was solved by a simplified microlayer model proposed by Lee and Son [19], where the interface near the contact line is assumed to be linear. The heat transfer rate by the microlayer in this model is estimated by:

$$Q_{\text{microlayer}} = \frac{k_{l}(T_{\text{w}} - T_{\text{sat}})}{\tan \varphi} \ln \left( \frac{h_{\text{ev}}}{2k_{l}} + 1 \right). \quad (1)$$

where $h$ is the size of a computational cell in macro region and $h_{\text{ev}}$ is calculated by:

$$h_{\text{ev}} = \sqrt{\frac{2}{\pi R_{\text{sat}} T_{\text{sat}}} \frac{\rho_{v} Y_{l}^{2}}{\lambda_{l}}} \quad (2)$$

It was demonstrated by Lee and Son [19] that the microlayer heat transfer obtained by this model is very close with that obtained by the original microlayer model proposed by Son et al. [3] without simplification, as long as $h \gg k_{l}/h_{\text{ev}}$. Evidently, this condition holds in the present simulation. The three-phase contact line is actually a contact point on the heating wall in our 2D model. Therefore, the heat flux in microlayer was solved using Eq. (1) for each contact point, and the evaporation rate that corresponds to the microlayer heat transfer was distributed to the reconstructed interface segments within a certain distance to the contact point.

Nucleate boiling is a kind of two-phase flow with moving interfaces. For tracking the interface, we used a coupled volume-of-fluid and level-set method, VOFSET [11], where the interface is tracked by updating volume fractions and level-set function is calculated from the updated volume fractions geometrically. Owing to the use of both VOF and level-set functions, VOFSET can not only keep the mass conservation very well, but also calculate the interface curvature accurately. Considering phase change on the interface, the advection equation of VOF function can be expressed as:

$$\frac{\partial C}{\partial t} + \nabla \cdot (u_{C} C) = \frac{m}{\rho_{v}}, \quad (3)$$

where $m$ denotes the mass transfer rate produced by the evaporation on the interface. The continuity equation and momentum equation can be written as:

$$\nabla \cdot u = \left( \frac{1}{\rho_{v}} - \frac{1}{\rho_{l}} \right) m, \quad (4)$$

$$\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla u = -\nabla p + \nabla \cdot (\eta \nabla u + \eta \nabla u^{T}) + \sigma \kappa \nabla H, \quad (5)$$

where the surface tension is written as a source term in the momentum equation using CSF model. The right hand term in the continuity equation represents the volume expansion due to evaporation. The interface curvature and properties appearing in the momentum equation are calculated by the level-set function, $\phi$, which are written as follows.

$$\kappa = \nabla \cdot \frac{\nabla \phi}{|\nabla \phi|} \quad (6)$$

$$\rho = H \rho_{l} + (1 - H) \rho_{v} \quad (7)$$

The temperature on the interface is assumed to maintain the saturate temperature corresponding to the environment pressure.

The mass transfer rate that appears in Eqs. (3) and (4) is consisting of micro and macro portions:

$$m = m_{\text{microlayer}} + m_{\text{macro}}. \quad (9)$$

The micro portion is produced by the microlayer around a contact point, which has been discussed above. The macro portion is produced by evaporation on the interface, which is determined by the Stefan condition:

$$m_{\text{macro}} = \frac{1}{\Delta V} \int \rho dA = \frac{1}{\Delta V} \int \left( \lambda_{v} \frac{\partial T}{\partial n} |_{v} - \lambda_{l} \frac{\partial T}{\partial n} |_{l} \right) dA. \quad (10)$$

where $\Delta V$ and $\Gamma$ denote respectively a finite volume and the interface inside it. The temperature gradients on the interface are estimated by normal probe approach proposed by Udaykumar et al. [20].

3. Computational setup

Fig. 2 sketches the 2D model of the present numerical study. The computational domain was chosen as the influence region of one nucleation site, thus the width of the domain is determined by the sites density. Taking advantage of symmetric condition, the simulations were carried out in half of the influence domain, which is marked in gray in Fig. 2. Fig. 3 displays the two cases in deep and shallow liquid levels as well as the boundary conditions. A constant overheat, $T_{w}$, was specified as 7 K on the bottom wall. A constant pressure was given at outlet, i.e., the top boundary. The simulations covered the time from 0 to 1 s. The properties used in our simulation are specified as those of liquid and vapor water at 1 atm, which are list in Table 1. The contact angle was specified as 38’ and the initial temperature was set as the saturate temperature except for a 1mm-thick overheated layer. The grid size used in this numerical study was specified as 0.1 mm, and it is smaller
4. Results and discussion

4.1. Boiling in deep liquid level

Fig. 4 is the evolution of the interface of the deep liquid case from 0 to 0.11 s, showing the whole process including growth and departure of the first bubble. It can be seen that the bubble expanded on the wall at the early period while maintaining a circular shape. As the bubble grew to a certain size, its base began to shrink and finally resulted in the departure of the bubble. Fig. 5 shows the liquid-vapor interface, fields of temperature and velocity at time 0.13 s, in which we can see the first bubble was rising and the second one was in growth. Additionally, some vortexes can be observed around the rising bubble, which carried a portion of hot liquid away from the wall. Under the effect of the rising bubble, some overheated liquid flows along the surface of the bubble behind, which provided more energy supporting its growth.

The average heat flux, which was obtained by adding up micro and macro portions, was plotted in Fig. 6. It shows that the average heat flux fluctuates periodically with 9 sudden troughs on the curve. These troughs are due to the fact that the contact points on the wall vanished as bubbles departed, which means no micro-layer existed on the wall until the next bubble seed was formed. Therefore, it can be indicated from Fig. 6 that there were totally 9 bubbles departed from the wall in the period covered by the simulation. Comparing the heat flux before and after 0.5 s, we can find that the heat flux at the early period is relatively lower, and that it almost reached the quasi-steady state after the departure of the fourth bubble. The lower heat flux before 0.5 s is owing to the initial temperature field. In order to evaluate the overall heat transfer...
performance, we averaged the heat flux in the quasi-steady period ranging from 0.5 s to 1 s. Table 2 compares this time-averaged heat flux with those predicted by some experimental correlations [24–26]. It should be noted that, we considered the equivalent density of nucleate sites by assuming the bubble occupies the area of a square whose side is equal to the width of the computational domain in x direction. Table 2 shows that the heat flux obtained by our simulation is slightly lower, but in the same order of magnitude compared with those predicted by experimental correlations.

4.2. Boiling in shallow liquid level

Now attention is turned to boiling in shallow liquid (see Fig. 3(b)) where the initial liquid level was set as 5 mm. Fig. 7 displays the liquid-vapor interfaces at some instances. We can see that, under the effect of the liquid level, the evolution of the interface became much more complicated than that in deep-liquid case. The water level kept oscillating as the bubbles broke up in succession on the liquid level. It is interesting to find in some cases a growing bubble could merge into the upper vapor region before departure (see 0.27 s in Fig. 7) when the water level above this bubble was relatively low.

Fig. 8 compares the average wall heat fluxes in shallow and deep liquid, where we can see an obvious enhancement in heat transfer by the liquid level. The heat flux curve of the case in shallow liquid shows a two-stage feature. The first stage generally refers to the period before the departure of the second bubble, when the heat flux is almost equal to that in deep-liquid condition. It indicates that the influence of the liquid level is small. As the second bubble departed from the wall, however, the heat flux increased significantly and then kept oscillating around a relatively higher value.

In order to find the reason for the higher heat flux in the second stage, the fields of temperature and velocity at instances of 0.5 s and 1.0 s are displayed in Fig. 9. As can be seen that, several vortexes were formed in the fluid, which removed more hot liquid from the wall and therefore decreased the thickness of the thermal layer. Note that these vortexes are different with those formed under a rising bubble, and they appear neither in the results in the deep-liquid case nor in the first stage of the shallow-liquid case.

Fig. 8 suggests that the average wall heat flux experienced an evident increase in the period between 0.2 s and 0.25 s. The interface positions, fields of velocity and temperature at the two instances are displayed in Fig. 10, where we can observe the formation of vortexes by oscillation of the liquid level. At time 0.2 s, the liquid levels at the left & right sides of the domain were relatively higher, while the liquid level at the central was lower. In the following 0.05 s, the liquid at the regions at the left & right sides generally moved downwards while the liquid at the central part moved upwards. Such motions of the liquid produced new vortexes around the wall, as can be seen in Fig. 10 (0.25 s). These
vortices then removed additional superheated liquid in the thermal layer around the wall, and therefore enhanced the convective heat transfer at its local. After 0.25 s, continuing oscillation of the liquid level kept producing such vortices around the wall, which maintained the wall heat flux at the higher value.

In summary, the result of the shallow-liquid case presented here suggests that the hot liquid is carried off not only by departures of bubbles, but also by oscillations of the liquid level. Accordingly, higher heat flux can be expected in nucleate boiling with lower liquid level under the same wall overheat.

The numerical results by our simulations can provide an explanation for the heat transfer enhancement by the low liquid level in nucleate pool boiling. As the boiling forms a new bubble, it creates more liquid-vapor interface as well as more surface energy. On the other hand, as the bubble breaks up at the liquid level, the interface area tends to decrease under the effect of surface tension. During this process, a part of the surface energy lying on the interface will be transformed into fluid kinetic energy around the liquid level. Therefore, a merger of a bubble into the upper vapor can produce additional disturbing in the liquid and enhance the heat transfer at its local. If the water level is too high and thus too far from the heating wall, however, the disturbing as well as its effect in heat transfer enhancement by the bubbles’ breakups will be weaken.

Finally, we would like to point out that, the present study is based on a 2D model. A 3D simulation needs to be carried out to get a better insight into the effect of low liquid level and to reveal more general quantitative relation. In this regard, the 3D-version VOSET method [27] can be adopted for tracking the interface. This work is now underway in the authors group and the results will be reported elsewhere in the future.

5. Conclusions

A two-dimensional numerical simulation was carried out to study the mechanism of the heat transfer enhancement of nucleate pool boiling in shallow liquid level. Based on our numerical results, several conclusions are made as follows.

(1) The wall heat flux in the deep liquid case fluctuates periodically with the successive departures of bubbles. The average heat flux obtained by our numerical simulation is consistent with those obtained by experimental correlations.

(2) The wall heat flux in the shallow liquid case has shown a two-stage characteristic. The heat flux in the first stage is almost the same with that in deep liquid case. After the second bubble departed from the wall, the wall heat flux increased significantly and then kept fluctuating around a higher value.

(3) The reason for the higher heat flux in the second stage lies in the fact that the liquid level keeps oscillating as the bubbles breaking up in succession, and that the oscillation results in new vortices that removes more hot liquid away from the wall.

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