LATTICE BOLTZMANN SIMULATION OF BOILING HEAT TRANSFER IN A SHEAR FLOW

by

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In this work a two-phase lattice Boltzmann method was used to numerically study the behavior of liquid-vapor phase change induced by a heated plate under the action of shearing. The effects of the action of shearing on the bubble growth and departure were investigated in terms of the flow features, the average heat flux and the bubble releasing period. It is shown that the shear flow significantly enhances the heat transfer of the system in two respects: increasing the average heat flux and decreasing the bubble releasing period. The effects of the intensity of the shear flow and the gravity force on the bubble releasing period were examined as well. The most striking finding is that there exists a sudden jump in the period at a critical shear intensity of the flow. The reason behind this abnormal behavior is that the residual part of bubble is nearly condensed after the bulk of bubble departs from the heated plate.

Key words: *boiling, bubble departure, shear flow, lattice Boltzmann method*

Introduction

The phenomenon of boiling heat transfer is very common in many industrial applications, which results from the liquid-vapor phase transition in a two-phase flow. The phase transition has a significant influence on the two-phase flow in terms of heat transfer rate as well as flow features. Understanding the mechanism of phase transition between liquid and vapor may provide a promising way of heat enhancement for industrial applications.

The lattice Boltzmann method (LBM), originated from the Boltzmann equations, has received considerable attention in the modelling of multi-phase flow due to its several remarkable advantages. So far, much effort has been devoted to the numerical study of pool boiling, for which the LBM was usually adopted. Hazi and Markus [1] studied the bubble departure diameter and release frequency in stagnant and slowly flowing fluid using the LBM. They found that the static contact angle has no influence on the bubble departure diameter, while the bubble release frequency increases exponentially with it. Ryu and Ko [2] performed lattice Boltzmann simulations to study the behavior of heat transfer induced by multiple nucleate sites. A relationship between the heat flux and the number of nucleate sites was proposed by them [2]. Based on the pseudo-potential model [3], Gong and Cheng [4] developed an improved two-phase lattice Boltzmann model, which was used to simulate the phase change in pool boiling for two dimensions [5, 6] and three dimensions [7]. Using the LBM proposed by Lee [8], Begmohammadi *et al.* [9] presented a numerical study on

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the bubble growth and departure from superheated surface for liquid vapor density ratio up to 1000. Their results [9] reveal that the bubble departure diameter decreases as the density ratio increases while the bubble release period shows the opposite trend. Sadeghi *et al.* [10] proposed a 3-D LBM for the simulations of pool boiling with high liquid-vapor density ratio, which was based on the Lee's method [8]. Recently, the LBM was used to numerically investigate the enhancement of heat transfer in pool boiling involving a type of hydrophilic-hydrophobic mixed surfaces. According to these studies [11-13], the use of the mixed surface may promote the bubble nucleation and departure, and hence enhance the heat transfer of system under certain conditions. In addition the LBM, much attention has been paid to new numerical schemes for solving partial differential equations [14, 15].

In comparison with the pool boiling, study on the heat transfer involving phase-change in flowing fluid (*i. e.* the flow boiling) is rare, which, however, is the general case for the engineering applications. It is known that the bulk of liquid is quiescent for the pool boiling. When the liquid is driven by a force, *e. g.* Poiseuille flow or shear flow, the inertia of the liquid cannot be neglected, which makes the situation more complex than the pool boiling. Limited study shows that the external flow has a noticeable influence on the vapor bubble departure and the behavior of heat transfer. For instance, as shown by Hazi and Markus [1], the bubble departure diameter decreases exponentially with the flow driving pressure gradient. Similarly, Sun *et al.* [16] conducted a numerical study on the nucleate boiling in slowly flowing fluid. They [16] found that the bubble diameter and the release frequency have exponential and linear relationship with inlet velocity, respectively. However, the general case of vapor-liquid-flows with phase change is far from completely understood in comparison with its simplified counterpart (*i. e.* the pool boiling). Much attention should be paid to this issue. Therefore, the objective of this work is to present a numerical study on the behavior of heat transfer involving the phase change induced by a heated plate in a shear flow. The focus is on the effects of the action of shearing on the bubble growth and departure. The improved LBM proposed by Gong and Cheng [4] was used here.

Methodand problem

The two-phase LBM [4] is briefly introduced here. The single-relaxation-time lattice Boltzmann equations are used to solve the fluid density, ρ, and velocity, $\boldsymbol{u}$, which are expressed:

$$f_i(\boldsymbol{x}+\boldsymbol{e}_i\Delta t, t+\Delta t) - f_i(\boldsymbol{x},t) = -\frac{1}{\tau_f}\left[f_i(\boldsymbol{x},t) - f_i^{(\mathrm{eq})}(\boldsymbol{x},t)\right] + \Delta f_i \tag{1}$$

where $f_i(\boldsymbol{x}, t)$ is the density distribution function corresponding to the microscopic velocity $\boldsymbol{e}_i$, Δt – the time step of the simulation, τ_f – the relaxation time, $f_i^{(\mathrm{eq})}(\boldsymbol{x}, t)$ – the equilibrium distribution function which is given:

$$f_i^{(\mathrm{eq})} = w_i\rho\left[1 + \frac{\boldsymbol{e}_i\cdot\boldsymbol{u}}{c_s^2} + \frac{(\boldsymbol{e}_i\cdot\boldsymbol{u})^2}{2c_s^4} - \frac{\boldsymbol{u}^2}{2c_s^2}\right] \tag{2}$$

where c_s is the speed of sound, and w_i are weights related to the lattice model, Δf_i – the discrete form of the body force, which accounts for the inter-particle interaction force, the gravitational force and the interaction force between solid surface and fluid [4]. The fluid density and velocity are obtained:

$$\rho = \sum_i f_i \rho\boldsymbol{u} = \sum_i \boldsymbol{e}_i f_i \tag{3}$$

Due to the forcing term [4], the real fluid velocity of fluid $\boldsymbol{U}$ is modified:

$$\rho \boldsymbol{U} = \sum_i \boldsymbol{e}_i f_i + \frac{\Delta t}{2}\boldsymbol{F} \tag{4}$$

Similarly, the latice Boltzmann equations are also proposed [4] to solve the temperature field of fluid, T:

$$g_i(\boldsymbol{x}+\boldsymbol{e}_i\Delta t, t+\Delta t) - g_i(x,t) = -\frac{1}{\tau_g}\left[g_i(\boldsymbol{x},t) - g_i^{(\text{eq})}(\boldsymbol{x},t)\right] + \Delta t w_i \phi \tag{5}$$

where τ_g is the relaxation time for the fluid temperature and $g_i^{(\text{eq})}(\boldsymbol{x}, t)$ is the corresponding equilibrium distribution function:

$$g_i^{(\text{eq})} = w_i T\left[1 + \frac{\boldsymbol{e}_i \cdot \boldsymbol{u}}{c_s^2} + \frac{(\boldsymbol{e}_i \cdot \boldsymbol{U})^2}{2c_s^4} - \frac{\boldsymbol{U}^2}{2c_s^2}\right] \tag{6}$$

The source term ϕ is responsible for the phase change:

$$\phi = T\left[1 - \frac{1}{\rho c_v}\left(\frac{\partial p}{\partial T}\right)_\rho\right]\nabla \cdot \boldsymbol{U} \tag{7}$$

where p is the pressure and c_v – the heat capacity. Then the temperature is obtained:

$$T = \sum_i g_i \tag{8}$$

In order to account for the pressure involving phase transition, the Peng-Robinson (P-R) equation of state [17] is adopted.

Note that for both f_i and g_i, the 9-velocity model in two dimensions (*i. e.* D2Q9) is used here, which has the following discrete velocity vectors:

$$\boldsymbol{e}_i = \begin{cases} (0,0) \text{ for } i=0 \\ (\pm 1, 0)c,\ (0,\pm 1)c \text{ for } i = 1 \text{ to } 4 \\ (\pm 1, \pm 1)c \text{ for } i = 5 \text{ to } 8 \end{cases} \tag{9}$$

where $c = \Delta x/\Delta t$ is the lattice speed and Δx is the lattice space. For simplicity, both the lattice space and the time step are set to be 1 in the simulations, *i. e.* $\Delta x = \Delta t = 1$.

The purpose of this work is to present a numerical study on the behavior of boiling heat transfer in a shear flow. Figure 1 shows the schematic diagram of the problem. The liquid of density ρ_s and temperature T_s is filled in a 2-D domain with dimensions $L \times H$. A heated plate of length L_h and temperature T_h is placed in the middle of the bottom wall. The upper wall is driven to move with a constant speed U, which eventually results in shear flow in the domain. The periodic boundary conditions are applied in the horizontal direction. In the simulations, the parameters are fixed as follows unless otherwise specified: $L = 800$, $H = 400$, $L_h = 10$, and $T_h = 0.98T_c$. The temperature of the saturated liquid is chosen as $T_s = 0.9T_c$ (T_c is the critical temperature of the liquid), which corresponds to the coexistence densities $\rho_L \approx 2.324\rho_c$ and $\rho_G \approx 0.228\rho_c$ (*i. e.* $\rho_L/\rho_G \approx 10$). Note that ρ_L and ρ_G are the densities of the liquid and the vapor, respectively, ρ_c is the critical density of the liquid. It should be stated here that the parameters are all in lattice units, which is very common in the lattice Boltzmann simulations.

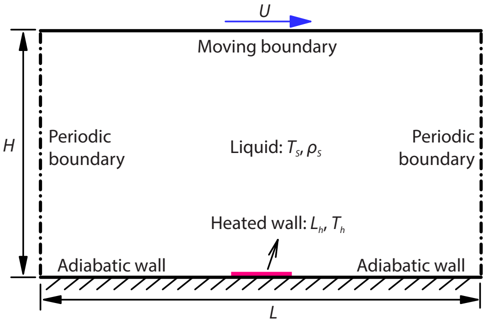

Figure 1. Schematic diagram of the present problem

Validation

In the case of pool boiling, the bubble release frequency plays a key role in the process of heat transfer, which has been an everlasting topic from both numerical and theoretical points of view. According to the balance between adhesive force and buoyant force experienced by a vapor bubble, Fritz [18] obtained a formulation for the departure diameter which is related to the magnitude of gravity force (*i. e.* $|g|$):

$$D_b \sim \sqrt{\frac{\sigma}{|g|(\rho_L - \rho_G)}} \tag{10}$$

where σ is the surface tension. Equation (10) indicates a power-law relationship between D_b and $|g|$, *i. e.* $D_b \sim |g|^{-0.5}$. Similarly, Zuber [19] developed a formulation for the release frequency of vapor bubble:

$$t_c = \frac{1}{f} \sim D_b \left[\frac{\sigma |g| (\rho_L - \rho_G)}{\rho_L^{\ 2}} \right]^{-0.25} \tag{11}$$

From eqs. (10) and (11), it is easy to reach the following power-law relationship: $t_c \sim |g|^{-0.75}$.

To validate our computational code, the process of bubble growth and departure resulting from a superheated wall was simulated. The computational domain is the same as mentioned above. The temperature of the heated plate is $T_h = 0.97T_c$. Other parameters are the same as those described in the section. Four sets of $|g|$ are taken into account, *i. e.* 2×10^{-5}, 4×10^{-5}, 6×10^{-5} and 8×10^{-5}. Figures 2(a) and 2(b) shows the bubble departure diameter and the releasing period, respectively. Note that the least-square scheme was used to obtain the fitting curves in fig. 2. It can be clearly seen that the power-law dependence of both D_b and t_c on the gravity force is realized.

Results and discussion

As shown in fig. 1, the behavior of vapor-liquid phase transition in a shear flow is considered in this work. In doing so the intensity of the external flow is adjusted by varying the value of $U(0 \le U \le 0.12)$. Note that $U = 0$ represents the case of pool boiling, which was extensively studied in the past. Figure 3 presents the process of vapor bubble growth and departure resulting from the heated plate for the pool boiling (*i. g.* $U = 0$) by showing the density contour

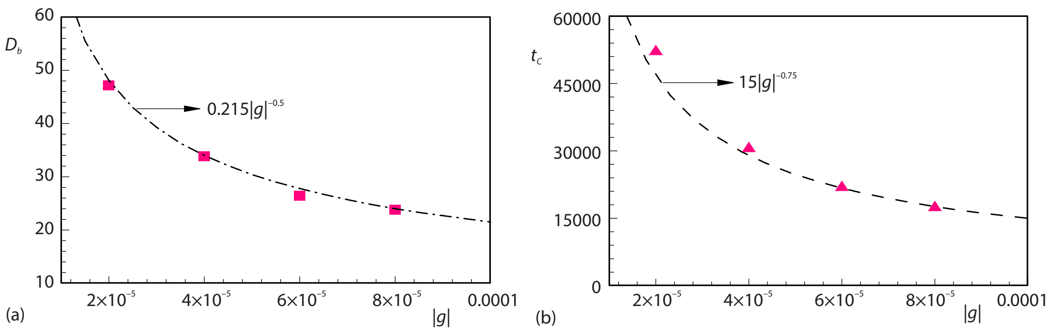

Figure 2. Results for pool boiling with a superheated wall; (a) the departure diameter and (b) the releasing period of vapor bubble as a function of the gravitational force; note that the symbols (both squares and triangles) represent the simulation results and the lines (both dashed and dash-dotted lines) are the fitting curves

as well as the streamlines. As expected, due to the heated plate two re-circulation zones which are rotating in opposite directions are generated on both sides of the vapor bubble, fig. 3(a). This enhances the heat transfer through the transition from natural-convection forced convection. Then, a bubble neck is clearly seen when the buoyant effect becomes strong, fig. 3(b). Eventually, this bubble neck breaks, leading to the occurrence of bubble departure, fig. 3(c). This process is repeated, which enhances the rate of heat transfer in the way that the flow is greatly disturbed by the motion of vapor bubbles.

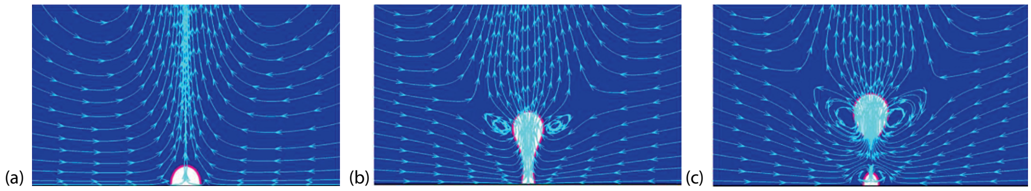

Figure 3. Bubble growth and departure for the pool boiling (*i. e.* *U* = 0) during one period

However, the situation is different when there is external flow, *i. e.* flow boiling. Figure 4 shows the process of bubble growth and departure in a shear flow for $U = 0.05$ during one period. Due to the action of shearing, the bubble is seen to incline towards the downstream in the shear flow, fig. 4(a) and 4(b), which becomes more significant under stronger action of the shearing. In addition, only one re-circulation zone emerges on the right side of the bubble, fig. 4(c), which is much larger than those in pool boiling, fig. 3. This is partially responsible for the enhancement of heat transfer in flow boiling. Another significant difference is that the external flow speeds up the bubble departure greatly, which will be presented later in this section. Once the bubble departs from the wall, it quickly drifts towards the downstream, figs. 4(d) and 4(f).

Things could be quite strange when the action of shearing becomes stronger. Figure 5 shows the process of bubble growth and departure for $U = 0.1$. The general feautre seems similar to that of fig. 4. However, there are still two significat differencesbetween them.As shown in fig. 5, the size of the re-circulation zone is much smaller for $U = 0.1$. In other words, the rate of heat transfer may be lower if the external flow is stronger. This will be discussed later. More importantly, for $U = 0.05$, it is clear that there is a residual part of bubble on the heated plate when the bulk of bubble departs from the wall, fig. 4(e). This residul bubble will grow and eventually depart in the next cycle, fig. 4(a). By constrast, as shown in figs. 5(e) and 5(f), the residual

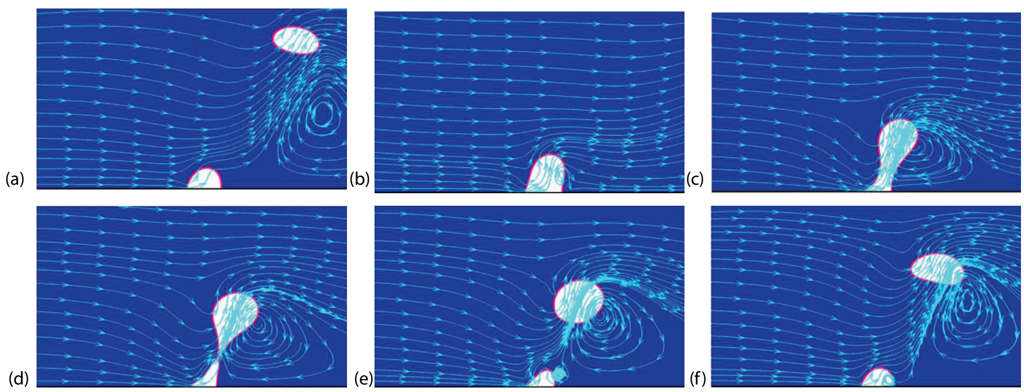

Figure 4. Bubble growth and departure of flow boiling for *U* = 0.05 during one period

part of bubble will be quickly condensed after the bulk leave the wall. As a consequence, one can hardly observe the vapor bubble on the wall before the next cycle begins for $U = 0.1$. This behavior has a significant effect on the heat flux of the heated plate, which is shown in fig. 6.

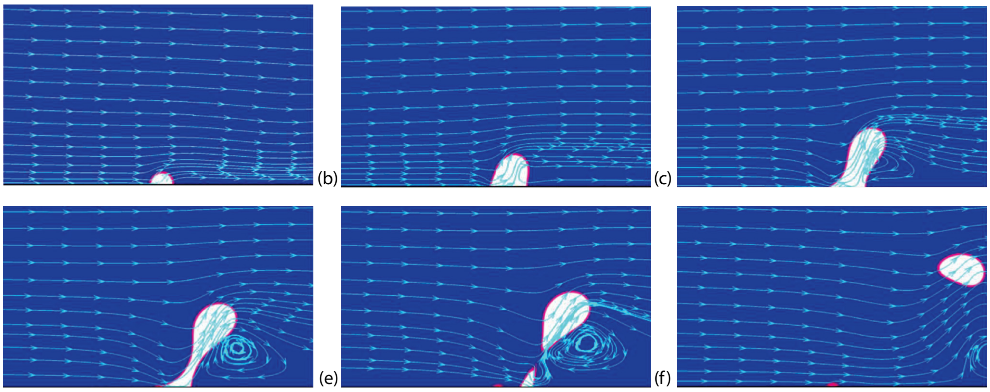

Figure 5. Bubble growth and departure of flow boiling for *U* = 0.1 during one period

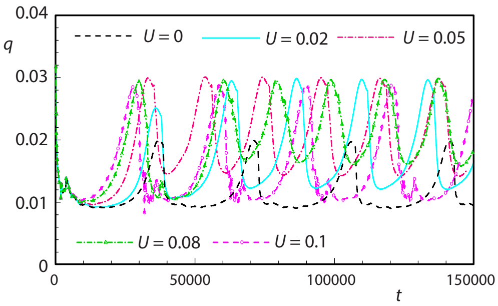

Figure 6. Time history of heat flux of the heated plate for different intensities of the shear flow

As shown in fig. 6, the heat flux, given by eq. (12), indicates that the heat transfer due to the heated plate in a shear flow is also periodic. Note that λ is the thermal conductivity which is fixed at $\lambda = 1$ for the sake of simplicity.

$$q = -\int_{\text{plate}} \lambda \frac{\partial T}{\partial n} \mathrm{d}x \tag{12}$$

The value of q is seen to be much higher for the flow boiling ($U > 0$) than for the pool boiling ($U = 0$), suggesting that the external flow noticeably improves the rate of heat transfer when other conditions remain unchanged. This is primarily owing to the fact that the external flow (*i. e.* the shear flow) greatly enhances the forced convection. Therefore, it may be expected that the stronger the shear flow the higher the rate of heat transfer for the present system, *e. g.* $U = 0.02$, 0.05, and 0.08. However, this is not the case for $U = 0.1$, as shown in fig. 6. In comparison with $U = 0.08$, the minimum value of q is seen to be much lower for $U = 0.1$, resulting in a smaller (averaged) heat flux. This is consistent with the aforementioned fact that the residual part of bubble is condensed by the strong shear flow as shown in fig. 5.

To further shed light on this issue, the bubble releasing periods for different intensities of the shear flow ($0 \leq U \leq 0.12$) are presented in fig. 7. Three sets of gravity force are taken into account, *i. e.* $|g| = 2 \times 10^{-5}$, 2.5×10^{-5}, and 3×10^{-5}. It is seen that the period decreases sharply from $U = 0$ (*i. e.* the pool boiling) to $U > 0$ (*i. e.* the flow boiling). Then, a nearly linear relationship between t_c and U is observed for all values of $|g|$. The slope is also indicated in the figure for each case, which decreases with increasing $|g|$. In addition, the most significant feature of fig. 7 is that the period shows a sudden jump at a certain U. Taking $|g| = 3 \times 10^{-5}$ for instance, the period is about 19000 at $U = 0.085$, which, however,is larger than 30000 at $U = 0.1$. The sudden change in the period suggests that the bubble grows and departs from the wall at a much slower speed when U is larger than a critical value (*e. g.* $U = 0.085$ for $|g| = 3 \times 10^{-5}$).The reason behind this strange behavior is still the same as aforementioned (*i. e.*

fig. 5). When the residual part of bubble is almost condensed by the liquid it will take a long time for the bubble to grow and eventually depart from the heated plate.

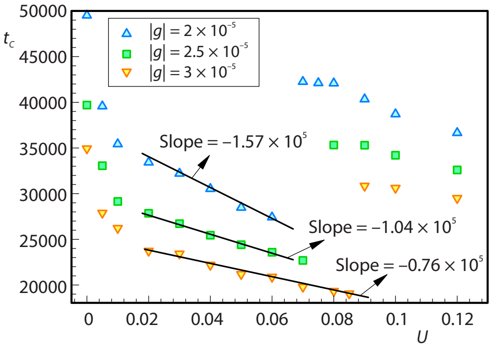

Figure 7. Dependence of the bubble releasing period, t_c, on the intensity of the shear flow, *U*

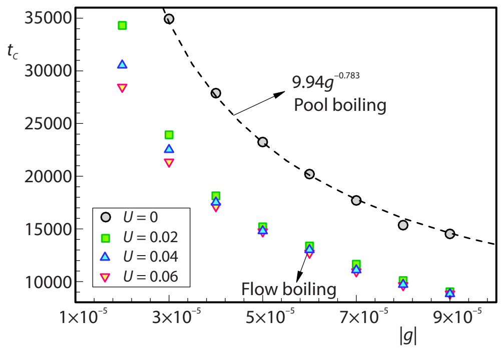

Figure 8. Dependence of the bubble releasing period, t_c, on the magnitude of the gravity force, $|g|$

Figure 8 shows the dependence of the bubble releasing period on the gravity force for different intensities of the shear flow (*i. e.* $U = 0$, 0.02, 0.04, and 0.06). For $U = 0$, *i. e.* the case of pool boiling, a power-law relationship between t_c and $|g|$ ($t_c \sim |g|^{-0.78}$) is seen, which is close to the theoretical prediction (*i. e.* $t_c \sim |g|^{-0.75}$). By contrast, the power-law relationship does not hold for the case of flow boiling, *i. e.* $U > 0$. Moreover, for a fixed $|g|$ the period is obviously smaller as the shear flow becomes stronger (*i. e.* larger U). In other words, the external flow accelerates the occurrence of bubble departure. However, as the gravity force increases the effect of U on the period becomes insignificant. For instance, there is little discrepancy between the periods resulting from $U = 0.02$-0.06 for $|g| = 9 \times 10^{-5}$. This can be explained as follows. In a shear flow the bubble departure is jointly determined by the combined effects of the gravity force and the shearing. When the gravity force is small the action of shearing dominates the process of bubble departure. The situation flips over as the gravity force becomes large.

Conclusions

A two-phase LBM was used to numerically study the influence of the shear flow on the vapor-liquid phase change resulting from a heated plate in a cold liquid. Firstly, the method was validated by the benchmark test of pool boiling with a single nucleate site. Then, the focus of the study moves to the behavior of bubble growth and departure in a shear flow. Our concluding remarks are as follows.

- The results show that the shear flow greatly enhances the heat transfer for the present system in two respects: increasing the heat flux of the heated plate and decreasing the bubble releasing period.
- As the intensity of the shear flow increases, the average heat flux firstly increases then decreases. This is due to the fact that the residual part of vapor bubble is nearly condensed by the liquid when the shear flow becomes strong enough.
- In comparison with the pool boiling, the power-law relationship between the releasing period and the gravity force does not hold for the flow boiling. As the gravity force increases, the effect of the shearing on the period becomes insignificant. The most striking observation is that there exists a sudden jump in the period at a critical intensity of the shear flow. The reason behind this is the same as stated in eq. (2).

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