Numerical simulation of bubble shape and heat transfer during nucleate pool boiling of FC-72

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ABSTRACT

In this study, we performed numerical simulations of nucleate boiling to evaluate the formation of microlayer, which is a thin liquid film forming on the heated solid surface. To evaluate the formation condition of microlayer of FC-72, numerical simulations were performed for three wall superheat conditions of 5 K, 10 K, and 15 K. As the result, the microlayer is formed under the wall superheat of 15 K. In addition, the influence of microlayer formation on the heat transfer was significant, indicating that the wall surface temperature decreased the most when the superheat was 15 K.

1. Introduction

Nucleate boiling has a higher heat transfer ability than other heat transfer process because it transports heat by latent heat with a phase change. Therefore, nucleate boiling is expected to apply the cooling system, for such as high-performance computer processors, power semiconductor devices, and other high heat generating devices. In nucleate boiling, evaporative heat transfer is primarily dominated by bubble formation near the wall. Under the bubble, where the vapor appears to be in direct contact with the wall from a macroscopic view, a layer called a microlayer may form below the bubbles(1).

The microlayer is a liquid film several micrometers thick that is deposited and formed when the liquid remains on the solid surface because the expansion velocity of the bubble is greater than the movement velocity of the solid-gas-liquid contact line. The thinness of the microlayer lowers thermal resistance and promotes bubble growth by supplying more vapor to the bubbles. Regarding study on microlayer, it has been observed that the thickness of the micro-liquid film during nucleate boiling of water or ethanol at atmospheric pressure increases with increasing distance from the bubble generation site(2). The contribution of microlayer evaporation to total evaporation has also been measured and found to be about 39% for ethanol and 14-44% for water(3).

Comparing with water and ethanol, the microlayer rarely observes in the nucleate boiling of the dielectric fluid, such as FC-72. On the other hand, Schweikert et al (4) measured the length and thickness of the microlayer and their dependence on the superheat and de-wetting rate were confirmed. In their experiment, the liquid film was formed during extracting heating plate from the liquid pool. Therefore, the applicability of experimental results by Schweikert et al. to the nucleate boiling should be investigated. The objective of this study is to investigate the formation of microlaryer in the nucleate boiling of FC-72 by numerical simulation and to evaluated the influence of wall superheat and bubble growth rate.

2. Numerical method

2.1 Governing equation

In this study, a phase change model developed by Herbert (5) et al. and a gas-liquid two-phase flow analysis method developed by Kunkelmann (6) and Batzdorf (7) were incorporated into numerical simulations. The simulation code is based on OpenFOAM, which is an open source library for developing partial differential equation solvers. The governing equations for this calculation are the equation of continuity for incompressible flow, the Navier-Stokes equation, the fluid energy equation, the heat conduction equation for solids, and the advection equation for the VOF function.

The continuity equation is given by Equation (1).

$$\nabla \cdot \boldsymbol{u} = \Sigma_V, \tag{1}$$

where, $\boldsymbol{u}$ is the velocity, Σ_V is the source term, reflecting the volume change during the phase change due to the density difference between the two phases. The Navier-Stokes equation is given by Equation (2).

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u}\right) = -\nabla p + \nabla(\mu\nabla\boldsymbol{u}) + \sigma\kappa\nabla F, \tag{2}$$

where, ρ is the density, t is the time, p is the pressure, μ is the dynamic viscosity, σ is the surface tension, κ is the curvature, F is fluid fraction in VOF method. Two phase flow was simulated by considering the surface tension. The energy equation for the fluid is given by Equation (3).

$$\frac{\partial(\rho c T)}{\partial \mathrm{t}} + \nabla\cdot(\rho c\boldsymbol{u}T) = \nabla\cdot(k\nabla T) + \Sigma_e, \tag{3}$$

where, c is the specific heat, T is the temperature, k is the thermal conductivity, Σ_e is the source term considering latent heat. Since the convection term is zero in the solid phase, the heat conduction equation for solids is given by Equation (4).

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$$\frac{\partial(\rho cT)}{\partial \mathrm{t}} = \nabla \cdot (k \nabla T). \quad (4)$$

The advection equation for the VOF function is given by Equation (5).

$$\frac{\partial F}{\partial \mathrm{t}} + \nabla \cdot (\boldsymbol{u}F) + \nabla \cdot \left(|\boldsymbol{u}|\boldsymbol{n}_{int}F(1-F)\right) = \Sigma_V F, \quad (5)$$

where, F is volume fraction of fluid, $\boldsymbol{n}_{int}$ is the unit normal vector of the interface, Σ_V is the source term similar to Equation (1).

2.2 Numerical model

Figure 1 shows the computational domain, boundary conditions, and coordinate axes used in the simulation. The computational domain is an axisymmetric region centered on the y-axis. As shown in Fig. 1, the computational grid is 2 mm long and 1 mm wide for the liquid and 1 mm long and 1 mm wide for the solid. The grid sizes are progressively finer: 4 μm, 2 μm, 1 μm, and 0.5 μm, respectively. The initial bubble diameter was set to 40 μm and the contact angle of the bubbles to 20° for computational stability. In order to evaluate the dependence of microlayer formation on superheat in nucleate boiling of FC-72, numerical analyses were performed for three cases of superheat: 5 K, 10 K, and 15 K.

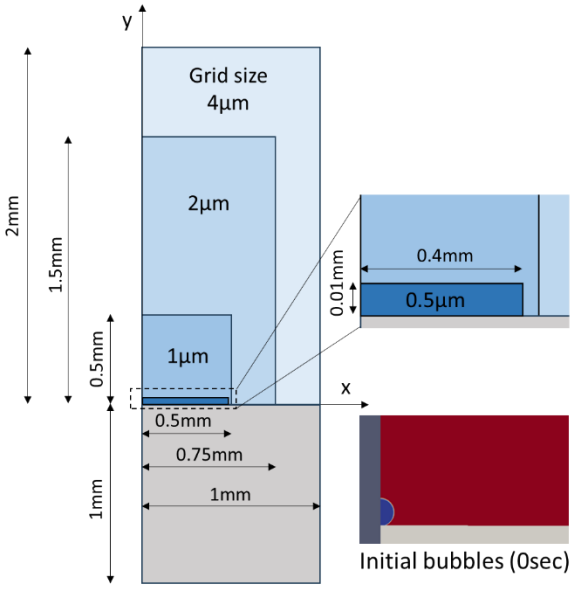


Figure 1. The computational domain.

3. Results and Discussion

3.1 Bubble generation process

The growth process of bubbles at superheat temperatures of 5 K, 10 K, and 15 K is shown in Figs. 2. At superheat of 5 K, no microlayer is formed. At superheat of15 K, the expansion velocity of the bubbles is greater than the migration velocity of the solid-air-liquid contact line, and a microlayer with a thickness of 1 to 1.5 μm and a length of about 0.14 mm is formed, which maintains in 1 ms. In the case of superheat of 10 K, the interface shape looks similar to the microlayer at 0.5 ms but such deformation of interface disappears at 1 ms. The higher the degree of superheat, the faster the expansion speed of bubbles, confirming the dependence of microlayer formation on the degree of superheat. The bubble departure time was 14.86 ms at 5 K, 6.18 ms at 10 K, and 6.28 ms at 15 K. The bubble departure diameter was 0.45 mm at 5 K, about 0.6 mm at 10 K, and about 0.8 mm at 15 K.

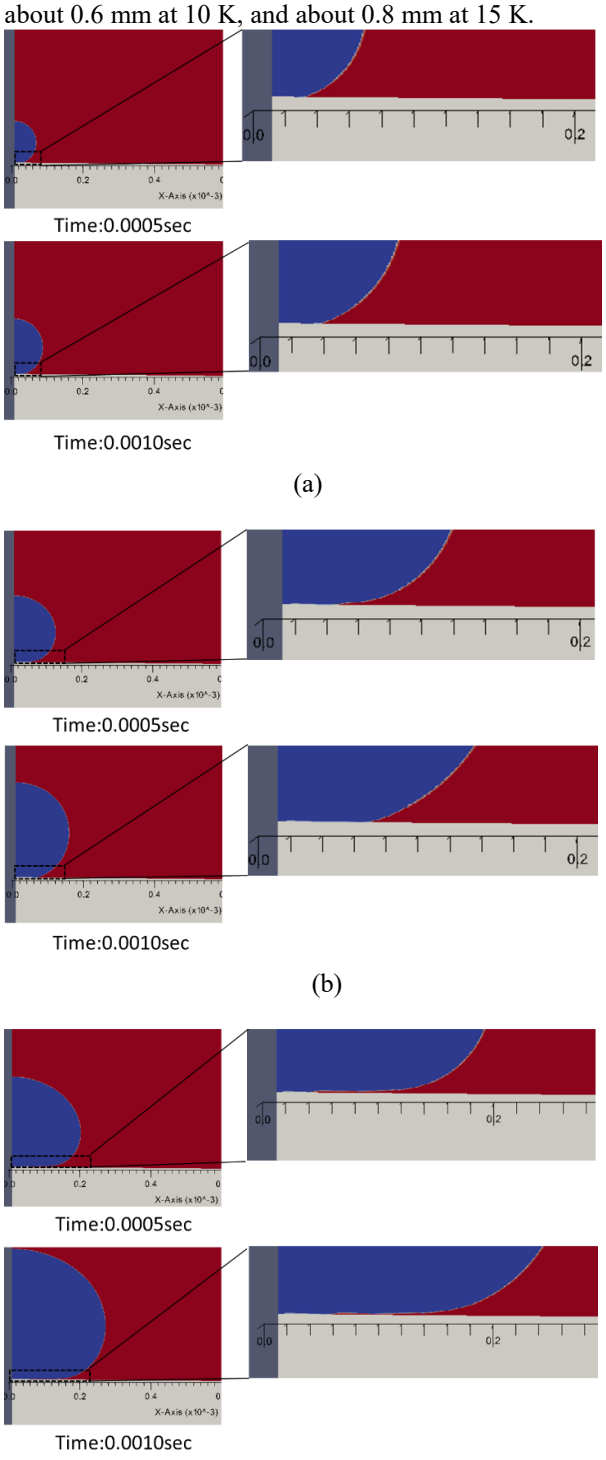


Figure 2. Bubble growth and liquid film formation at various degree of superheat, (a)5K, (b)10K, (c)15K

3.2 Temperature in Solid Region

Figure 3 shows the temperature distribution in the solid

wall at 1 ms. In the case of superheat values of 5K and 10K, where no microlayer is formed, a temperature decrease can be observed near the solid-liquid contact point. In the case of 15 K superheat, a temperature decrease can be observed in the area where a microlayer is formed. Figure 4 shows the normalized temperature distribution on the solid surface. Normalized temperature is defined as follows,

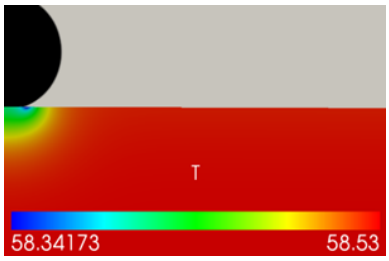
$$\theta = \frac{T - T_{sat}}{\Delta T_{sat}} \tag{6}$$

A large temperature drop can be seen in the case of superheat of 15K. In the case of 15 K superheat, the temperature drop area is about 0.2 mm from the bubble starting point, and in particular, the largest temperature drop can be seen around 0.1 mm. The length of the microlayer formed is about 0.14 mm, indicating the contribution of the liquid film to heat transfer. The respective temperature drops were about 3.5% at 15 K, 0.8% at 10 K, and 0.3% at 5 K.

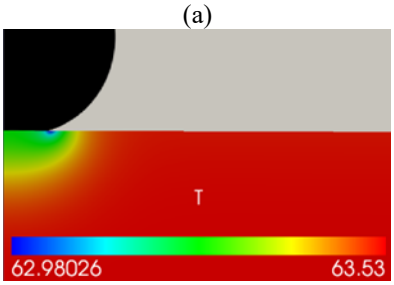
4. Concluding Remarks

In this study, in order to clarify the relationship between superheat and microlayer formation in nucleate boiling of FC-72, we performed direct numerical simulations considering heat conduction in the solid and obtained the following findings.

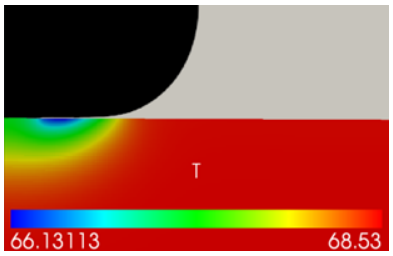
1. Microlayers formed at wall superheat of 15 K, while no microlayers formed at wall superheat of 5 K and 10 K, and the contact line followed the bubble expansion.
2. In the case of wall superheat of 15 K, a large temperature drop occurred in the region where the microlayer was generated. The drop was about three times larger in dimensionless temperature than in the case with no microlayers.



(a)



(b)



(c)

Figure 3. Temperature distribution inside the wall at 1 ms, (a) ΔT_{sat}=5K, (b) ΔT_{sat}=10K, (c) ΔT_{sat}=15K

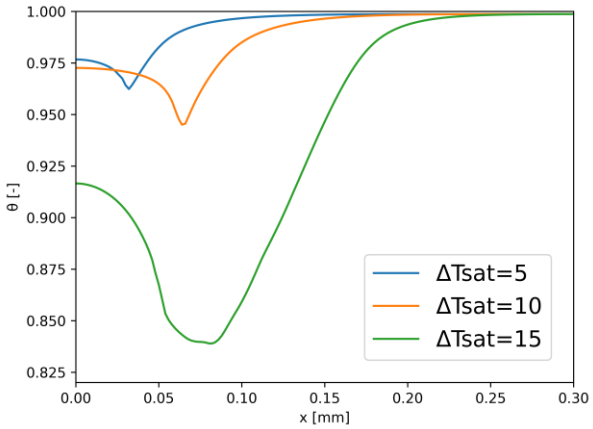


Figure 4. Normalized wall surface temperature distribution

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References

(1) M.G. Cooper, A. Lloyd, The microlayer in nucleate pool boiling, Int. J. Heat Mass Transf. 12 (8) (1969), 895–913

(2) Y. Utaka, Y. Kashiwabara, M. Ozaki, Microlayer structure in nucleate boiling of water and ethanol at atmospheric pressure, Int J. Heat and Mass Transfer. 57 (1) (2013), 222-230.

(3) Y. Utaka, K. Hu, Z. Chen, T. Morokuma, Measu rement of contribution of microlayer evaporation applying the microlayer volume change during nu cleate pool boiling for water and ethanol, Int. J. Heat Mass Transf. 125 (2018), 243–247.

(4) K. Schweikert, A. Sielaff, P. Stephan, On the tra nsition between contact line evaporation and micr olayer evaporation during the dewetting of a supe rheated wall, Int. J. Thermal Sciences, 145 (2019).

(5) S. Herbert et al., Local heat transfer and phase change phenomena during single drop impingement on a hot surface, International Journal of Heat and Mass Transfer, 61 (2013), 605-614.

(6) C. Kunkelmann, Heat transfer and evaporation during single drop impingement onto a superheated wall, Ph.D. thesis, Technische Universität Darmstadt, Darmstadt, 2015.
(7) S. Batzdorf, Numerical Modeling and Investigation of Boiling Phenomena, Ph.D. thesis, Technische Universität Darmstadt, Darmstadt, 2011.