Multi-bubble Simulation of Film Boiling in a Vertical Oscillating System

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1. Introduction

Film boiling is of great importance in nuclear safety. Film boiling heat transfer directly influences the integrity of the nuclear fuel cladding in case of accidents involving loss of coolants. The film boiling may occur on a heating wall in an oscillating system under earthquake conditions. Although most existing studies for film boiling were done, they were limited to stationary fluid system [1-9]. For this reason, we have investigated the effect of the fluid system oscillation on the film boiling heat transfer.

Our previous study was based on single-mode simulations [10]. That study gave some useful insights into heat transfer characteristics on the vertically oscillating system. However, the oscillation frequency was limited to low frequencies.

This study is to extend the oscillation frequency range. Multi-bubble simulations are carried out to investigate the film boiling heat transfer in a vertical oscillation system.

2. Numerical method

The mass equation is given by

$$\frac{\partial \alpha_v}{\partial t} + \nabla \cdot (\alpha_v \mathbf{u}) = \frac{\dot{m}}{\rho_v} \quad (1)$$

$$\frac{\partial \alpha_l}{\partial t} + \nabla \cdot (\alpha_l \mathbf{u}) = -\frac{\dot{m}}{\rho_l} \quad (2)$$

where α, $\mathbf{u}$, and ρ are the volume fraction, velocity, and density, respectively. The subscript v denotes the vapor phase and $\dot{m}$ is the vapor generation rate from the liquid phase to the vapor phase. The momentum equation is

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot [\mu(\nabla \mathbf{u} + \nabla \mathbf{u}^T)] + \mathbf{F}_{st} + \rho(\mathbf{g} - \ddot{\mathbf{R}}) \quad (3)$$

where p is the pressure, μ is the viscosity, $\mathbf{F}_{st}$ is the volumetric surface tension force vector, $\mathbf{g}$ is the gravitational acceleration vector, and $\ddot{\mathbf{R}}$ is the system acceleration vector. The acceleration of vertical system oscillation is assumed as follows:

$$\ddot{\mathbf{R}} = \ddot{R}\mathbf{j} = A(2\pi f)^2 \sin(2\pi f t)\mathbf{j} \quad (4)$$

where A is the oscillation amplitude, f is the oscillation frequency.

The energy equation is

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho h \mathbf{u}) = \nabla \cdot (\lambda \nabla T) - \dot{m}L \quad (5)$$

where h is the enthalpy, λ is the thermal conductivity, and L is the latent heat.

The vapor generation is computed using Sun's model [9].

$$\dot{m} = 2\lambda_v (\nabla \alpha_v \cdot \nabla T) / L \quad (6)$$

This model can be exclusively used for saturated boiling.

The coupled level-set and volume-of-fluid (CLSVOF) method is used to track the interface between vapor and liquid.

3. Simulation Conditions

Fig. 1 shows the multi-bubble simulation domain. Vapor and water properties at a near-critical pressure ($p/p_{cr} = 0.99$) are used. At this pressure conditions, film boiling may occur at the small temperature differences. Thus, the heating wall temperature was set to 10 K higher than the saturation temperature.

The height of the domain was set as the most unstable wavelength of the Rayleigh-Taylor instability and the horizontal length was 5 times the height. The periodic boundary conditions were imposed on the left and right side. The initial vapor film height is given by a random waves.

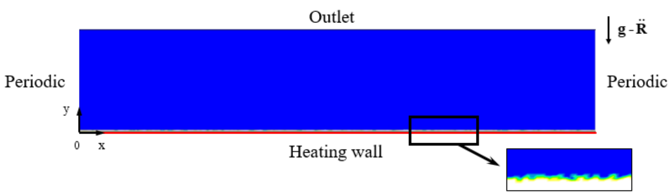

Fig. 1. Multi-bubble simulation domain (width= $5\lambda_d$, height= λ_d)

4. Results

Fig. 2 shows the space-averaged Nusselt number distribution with time for stationary case. Compared to the our single-bubble film boiling simulation, multiple vapor bubbles can be generated at the same time on the heating wall. Thus, the space-averaged heat transfer shows a less periodic pattern.

Tsui et al [11] calculated the Berenson semi-empirical correlation taking the properties of the mean film temperature with a modified Jacob number. For $\Delta T = 10$ K, The time- and space-averaged Nusselt number they calculated is 5.27. The time- and space-averaged

Nusselt number of our present result is 5.214 which is close to the value of 5.27. The simulation result shows good agreement with the correlation.

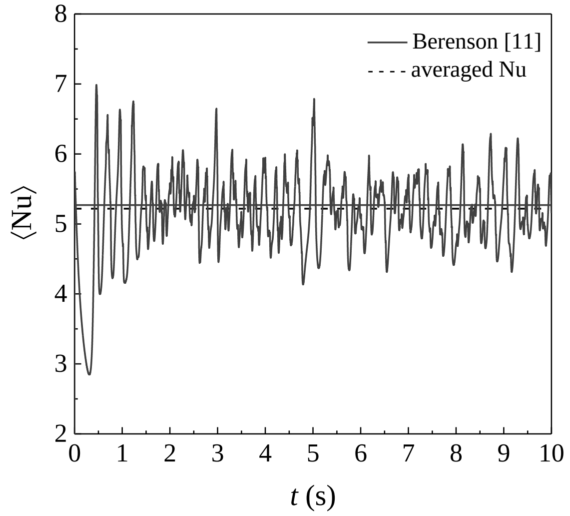

Fig. 2. Nusselt number with time for the stationary case ($\Delta T = 10$ K)

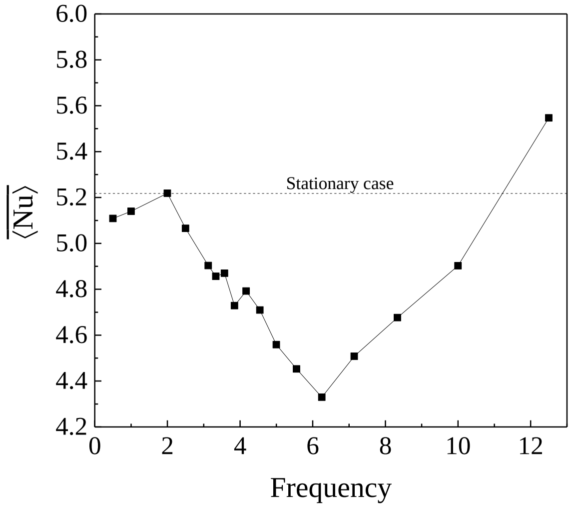

Fig. 3. Effect of f on heat transfer for $A = 4$ mm and $\Delta T = 10$ K

Fig. 3 shows the effect of oscillation frequency on the wall heat transfer for A=4 mm and $\Delta T = 10$ K . At a low frequencies such as 1 Hz and 2 Hz, the averaged heat transfer is close to the stationary case. The heat transfer decreases with increasing frequency until the applied frequency becomes 6.25 Hz. This trend is similar to our previous study based on single-bubble simulations [10]. And then, the averaged heat transfer increases with increasing frequency. In the region with frequencies from 6.25 Hz to 12.5 Hz, the more oscillation frequency increase, the faster a bubble detaches. Although rising bubble is not uniform volume, the faster bubble detachment prevent the vapor layer thicking. For this reason, the averaged heat transfer begins to increase when the applied frequency is greater than 6.25 Hz. For higher frequencies than 12.5 Hz, the interface is in contact with the heating surface. Thus, it is no longer film boiling due to the relatively high frequencies.

5. Conclusions

Numerical simulations were done for multi-bubble film boiling on oscillating surface. It was observed that the fluid system oscillation may decrease the wall heat transfer within a specific range of oscillation frequencies. We are looking for detail physics why the averaged heat transfer decreases and increase.

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