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A numerical simulation of single bubble growth in subcooled boiling water

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ABSTRACT

Water-cooling blanket is closely related to system safety in future fusion reactor for it can cooling down the reactor. The process of cooling in water-cooling blanket may involve bubble generation under subcooled boiling condition. Although many researchers have investigated bubble generation numerically, the details of bubble generation in subcooled boiling remain unclear. In this paper a two-dimensional bubble growth simulation under subcooled nucleate boiling condition has been conducted using VOF (Volume of Fluid) method in ANSYS FLUENT. A phase change model was adopted by adding extra mass source term and energy source term to the Navier-Stokes equations in the cells adjacent to vapor-liquid interface. The variations of bubble contour before bubble departure, temperature fields, velocity fields and contribution of heat flux from superheated layer and subcooled fluid can be obtained by simulation. The results were compared with existing datum of visual experiment in previous literature to verify the validity of the simulation.

1. Introduction

While the subcooled coolant flows through a superheated channel in water-cooling blanket during the cooling process in fusion reactor, the one-phase flow will transfer into two-phase flow at the ONB (Onset of Nucleate Boiling) point where the wall temperature exceeds the saturation temperature sufficiently. The generation of bubbles is a basic problem in ONB research, although bubbles can improve heat transfer capability significantly, they can also lead to critical-thermal hydraulic events such as CHF (Critical Heat Flux) and OFI (Onset of Fluid Instability), thus affecting the safety of reactor.

To figure out the mechanism of bubble growth in subcooled nucleate boiling, many efforts have been done in the last few decades. Numerical simulation is one of the most important means to investigate two phase flow problem and the VOF method is a popular interface capturing methods adopted by many researchers. Welch and Wilson (2000) calculated mass transfer rate directly from the heat flux at the liquid–vapor interface coupled with VOF, but it may show a deformed bubble shape due to the numerical error in phase change model despite good mass conservation. Hardt and Wondra (2008) proposed a phase-change model based on VOF. The mass transfer rate estimated from the evaporation heat transfer coefficient is artificially shifted to liquid side or vapor side for condensation and evaporation to avoid the deformation of the interface. Tomar et al. (2005) developed a phase change model based on coupled Level Set and VOF method. There are little research about this method in literature although it's reported mass conservative and interface topologies accurate.

Most of previous works simulated bubble growth under saturated boiling condition, simulation of bubble growth in subcooled boiling is more difficult while there are few papers about it. In this paper the VOF method in ANSYS FLUENT was used to simulate bubble growth process in subcooled boiling under two-dimensional condition. The mass flow was calculated by a phase change model proposed by Lee (Lee and Veziroglu, 1980) according to local temperature, and was artificially moved to the cells adjacent to vapor-liquid interface. Extra mass source M_{ml} was added at the bubble base in accordance with experimental data to simulate the evaporation of micro layer.

Fig. 1 presents a bubble in subcooled fluid, Q_{sd} is the energy released by bubble cap in subcooled domain, Q_{sl} stands for the energy absorbed by bubble cap in superheated liquid layer, Q_c is the total energy absorbed by bubble cap, Q_{ml} accounts for the evaporation energy of micro layer, Q_t stands for the total energy. And q is determined as heat flows, q_{sd}, q_{sl}, q_c, q_{ml} and q_t are calculated by temporal differentiation of Q_{sd}, Q_{sl}, Q_c, Q_{ml}, and Q_t respectively. The relationships of them are shown as follows:

$$Q_c = Q_{sl} - Q_{sd} \tag{1}$$

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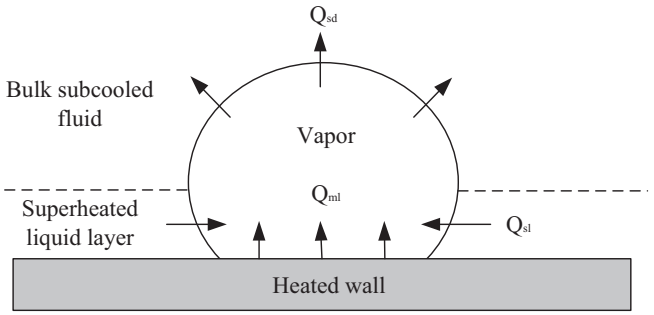


Fig. 1. Single bubble growth in the subcooled water.

$$Q_t = Q_{ml} + Q_c = Q_{ml} + Q_{sl} - Q_{sd} \tag{2}$$

2. Numerical simulation

2.1. Governing equations

The equations need to be solved in simulations are the conservation equations for mass, energy, momentum and volume fraction.

$$\nabla \cdot (\rho u) = \dot{\rho} \tag{3}$$

$$\frac{\partial \rho cT}{\partial T} + \nabla \cdot (u \cdot \rho cT) = \nabla \cdot (\lambda \cdot \nabla T) + h \tag{4}$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla (u \cdot \rho u) = -\nabla p + \nabla \cdot (\mu \cdot \nabla u) + S_s + S_g \tag{5}$$

$$\frac{\partial \alpha_l}{\partial t} + \nabla \cdot (u \cdot \alpha_l) = \frac{\dot{\rho}}{\rho} \alpha_l \tag{6}$$

The source term $\dot{\rho}$ on the right sides of Eqs. (3) and (6) is mass transfer in phase change process, and the source term h of Eq. (4) is energy change during the phase transition. The two volumetric forces S_s and S_g in Eq. (5) account for surface tension force and gravity respectively. The CSF (Continuum Surface Force) model proposed by Brackbill et al. (1992) has been implemented in VOF calculations. In CSF model, the surface tension can be written in terms of the pressure jump across the surface. The force at the surface can be expressed as a volume force using the divergence theorem. It has the following form:

$$S_s = \sigma \frac{\alpha_l \rho_l \kappa_v \nabla \alpha_v + \alpha_v \rho_v \kappa_l \nabla \alpha_l}{0.5(\rho_l + \rho_v)} \tag{7}$$

$$n_l = \nabla \alpha_l, n_v = \nabla \alpha_l \tag{8}$$

$$\vec{n} = \frac{n}{|n|} \tag{9}$$

$$\kappa_l = \nabla \cdot \vec{n}_l, \kappa_v = \nabla \cdot \vec{n}_v \tag{10}$$

Whereσrepresents surface tension coefficient, $\rho$is density, α stands for volume fraction in control volume n is the surface normal. The curvature,κ, is defined in terms of the divergence of unit normal $\vec{n}$. Subscripts l and v stand for liquid phase and vapor phase respectively. In the cells who contain two phases, physical properties such as density, dynamic viscosity and thermal conductivity can be calculated by average volume fraction.

2.2. Phase change model

The phase change model proposed by Lee (Lee and Veziroglu, 1980) was implemented in calculation and it can be written as Eqs. (11), (12) and (13), where T and T_{sat} are local temperature and local saturation temperature respectively. If T exceed T_{sat}, the evaporation occurs. Liquid phase would transfer into the vapor phase and the mass source can be written as:

$$M = c_l \alpha_l \rho_l \frac{T - T_{sat}}{T_{sat}} \tag{11}$$

If T is equal to T_{sat}, neither evaporation nor condensation would occur. Otherwise the condensation occurs. Vapor phase would change into liquid phase. And the mass is:

$$M = c_v \alpha_v \rho_v \frac{T - T_{sat}}{T_{sat}} \tag{12}$$

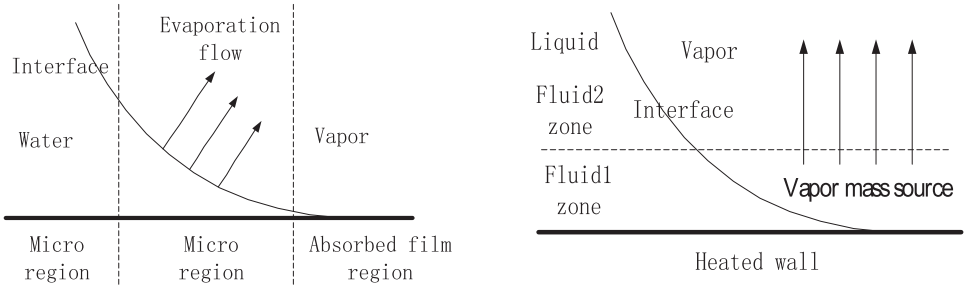
where c_l and c_v are the relaxation coefficients which can be modified artificially to control the phase change rate during the calculation. According to Wei and Pan (2011), the coefficients are set as 100 s^{-1} to keep the interface temperature around T_{sat}. After many attempts, $c_l = c_v = 800\ s^{-1}$ is adopted here. The energy absorbed/released during phase change, h, could be calculated by Eq. (13) where the h_{lv} is latent heat.

$$h = h_{lv} M \tag{13}$$

Assumed that the *iso*-line of 0.5 vol fraction is vapor-liquid interface, when evaporation or condensation occur, the mass sources are added at cells who are closed to interface but not exactly contain the interface. The mass sources of liquid and vapor have same value but adverse sign. Thus the interface can be kept from deformation during calculation and mass is conservative.

2.3. Micro layer

Micro layer is the thin liquid layer between the bubble and heating wall when bubble is growing up. Tiny thickness and drastic evaporation are two features of micro layer. Many researches has been done to investigate micro layer. Jung and Kim (2014) found that the thickness of micro layer is only about few micrometers by laser interferometry experiment. Yabuki and Nakabeppu (2014) deduced that about 50% of the total evaporation is contributed by micro layer during bubble growth by analyzing experiment results. Fig. 2 shows



Figs. 2 and 3. Actual micro region evaporation (left) and a simplify method in simulation (right).