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Numerical Investigation of DNB for a Subcooled Flow Boiling in an Oscillating Pipe

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1. Introduction

The demand for reliable power sources has led to the development of small-sized and transportable nuclear power plants, including the Floating-type nuclear power plant (FNPP). FNPP has gained attention as a potential electricity supply measure for areas with limited power grid access, such as island regions. However, because these marine reactors are operated in the ocean, they are subject to the effects of waves. The dynamic multi-dimensional forces generated by the waves influence the reactor core and lead to unsteady and multidimensional flow within the core [1]. Accurately predicting the Critical Heat Flux (CHF) characteristic is therefore essential for the safety design of marine nuclear reactors.

Studies on CHF characteristics under motion conditions have been conducted by researchers from various countries. Isshiki et al. [2] analyzed two simplified atmospheric models of water-cooled marine reactor core loops and observed that heaving motion and inclination decreased the CHF. Zhang et al. [3] conducted experimental studies on CHF in vertical pipes under oscillation

Numerical simulation has been widely used to investigate CHF characteristics under motion conditions. Ishida et al. [4] developed a system code using RETRAN-02 to study the thermal-hydraulic behavior of marine reactors under oscillation. Hwang et al. [5] utilized the MARS code to investigate CHF in marine reactors. Gui et al. [6] developed an analysis code based on a three-fluid model to study CHF characteristics in rectangular channels.

While there have been numerous studies on CHF under motion conditions, there is limited research available on Departure from Nucleate Boiling (DNB) under similar conditions. Most of the current studies focus on dry-out type CHF, and therefore, research on DNB under motion conditions is rare. Hwang et al. [7] investigated the characteristics of CHF under rolling conditions of amplitudes between 15º to 40º and 6s period and observed that DNB was enhanced under rolling motion with high mass flux. On the other hand, Liu et al. [8] conducted numerical simulations in a rectangular channel with an amplitude of 30º and 3s period, and they observed that DNB decreased under rolling motion.

Previous studies on CHF under motion conditions primarily focused on dry-out CHF and not on DNB. Additionally, existing research on the influence of motion conditions on DNB is unclear and often contradictory. In this study, we simulated DNB in a vertical pipe under oscillation using ANSYS FLUENT and analyzed the thermal-hydraulic characteristics of DNB-enhanced cases under rolling conditions.

2. Methods and Results

2.1 Wall Boiling Model

In order to predict DNB in oscillating conditions, a model for wall heat flux was developed. Subcooled boiling was identified as a critical factor in DNB, and an improved boiling model based on the RPI model of Kurul and Podowski [9] was utilized in this study. The total wall heat flux (q_w'') was calculated as the sum of the heat flux transferring to the liquid phase and the heat flux transferring to the gas phase (q_G''). The heat flux to the liquid phase was further divided into three components: convective heat flux (q_C''), evaporation heat flux (q_E''), and quenching heat flux (q_Q''). The total heat flux was expressed using the following equation.

$$q_w'' = f(\alpha_l)(q_C'' + q_Q'' + q_E'') + (1 - f(\alpha_l))q_G'' \quad (1)$$

The $f(\alpha_l)$ refers the area fraction of the liquid phase, and thus $1 - f(\alpha_l)$ is the area fraction of the gas phase. The area fraction is based on the model of Ioilev et al. [10]. The four heat fluxes are described as follows.

$$q_C'' = h_l(T_w - T_l)(1 - A_b) \quad (2)$$

$$q_E'' = V_d N_w \rho_g h_g f \quad (3)$$

$$q_Q'' = 2\sqrt{k_l \rho_l Cpf / \pi}(T_w - T)A_b \quad (4)$$

$$q_G'' = h_G(T_w - T_h) \quad (5)$$

The h_l and h_g represent the turbulent heat transfer coefficients of liquid and gas phases. T_w, T_l, and T_g stand for the temperature of heated wall, the liquid phase, and the gas phase, respectively. A_b denotes the proportion of heated wall covered by nucleating bubble. f represents the bubble departure frequency from Cole correlation [11].

2.2 Interfacial Mass Transfer

In the subcooled boiling, there is not only evaporation at the heated wall but also condensation in the bulk of the fluid. In consideration of this, Γ_w and Γ_i were set to represent the vapor generation rate near the wall and the subcooled condensation rate in the bulk, respectively. Γ_w and Γ_i are expressed as follows.

$$\Gamma_w = \frac{q_E'' A_{wall}}{L + c_{p,l}(T_{sat} - T_l)} \tag{6}$$

$$\Gamma_i = \frac{h_{sl} A_i (T_{sat} - T_l)}{L + c_{p,l}(T_{sat} - T_l)} \tag{7}$$

A_{wall} and A_i denote the face area of the corresponding cell divided by the volume of the cell and area of the interface, respectively. h_{sl} refers the interfacial heat transfer coefficient.

2.3 Momentum Equation

Momentum equations must include the effect of the arbitrary motion of the pipe to simulate oscillating pipes precisely. The two-fluid momentum equations in the non-inertial frame of reference [12] are used for the gas and liquid momentum equations as follows.

$$\begin{aligned}
&\frac{\partial}{\partial t}(\alpha_g \rho_g \mathbf{u}_g) + \nabla \cdot (\alpha_g \rho_g \mathbf{u}_g \mathbf{u}_g) = \\
&-\alpha_g \nabla p + \nabla \cdot [\alpha_g (\boldsymbol{\tau}_g + \boldsymbol{\tau}_g^{\mathrm{Re}})] + \alpha_g \rho_g \mathbf{g} + \mathbf{u}_i \Gamma_g \\
&+\mathbf{M}_i - \alpha_g \rho_g [\ddot{\mathbf{R}} + \dot{\Omega} \times \mathbf{r} + 2\Omega \times \mathbf{u}_k + \Omega \times (\Omega \times \mathbf{r})]
\end{aligned} \tag{8}$$

$$\begin{aligned}
&\frac{\partial}{\partial t}(\alpha_l \rho_l \mathbf{u}_l) + \nabla \cdot (\alpha_l \rho_l \mathbf{u}_l \mathbf{u}_l) = \\
&-\alpha_l \nabla p + \nabla \cdot [\alpha_l (\boldsymbol{\tau}_l + \boldsymbol{\tau}_l^{\mathrm{Re}})] + \alpha_l \rho_l \mathbf{g} - \mathbf{u}_i \Gamma_g \\
&-\mathbf{M}_i - \alpha_l \rho_l [\ddot{\mathbf{R}} + \dot{\Omega} \times \mathbf{r} + 2\Omega \times \mathbf{u}_k + \Omega \times (\Omega \times \mathbf{r})]
\end{aligned} \tag{9}$$

$\boldsymbol{\Omega}$ and $\mathbf{R}$ are the rotational vector and the position vector of the pipe viewed from the absolute coordinates, respectively. $\mathbf{M}_i$ denotes the interfacial momentum transfer acting on the gas phase, which contains the drag force, lift force, wall lubrication, and turbulent dispersion. $\boldsymbol{\tau}_g^{\mathrm{Re}}$ and $\boldsymbol{\tau}_l^{\mathrm{Re}}$ represent the turbulent Reynolds stress tensors for the gas and liquid phases, respectively. The $k-\varepsilon$ turbulence model is used to calculate the Reynolds stress.

3. Numerical Condition and Validation

3.1 Numerical Condition

The simulation domain consists of a pipe with inner diameter 9.5 mm and a total length of 1220 mm. The heated section is 1000 mm long, and 110 mm long adiabatic sections are attached to the both ends of the heated section. Working fluid is R-134a, and the flow direction is upward, normal to the boundary. The axis of rotation is located 280 mm above the whole pipe, which is 1500 mm away from the pipe inlet. The amplitudes of rolling motion used in this study are 15°, 30°, and 40°, with a period of oscillation of 6 seconds. The angle of the rolling pipe in time-flow is decided as follows.

$$\theta = \theta_{\max}[1 - \cos(2\pi t / T)] \tag{10}$$

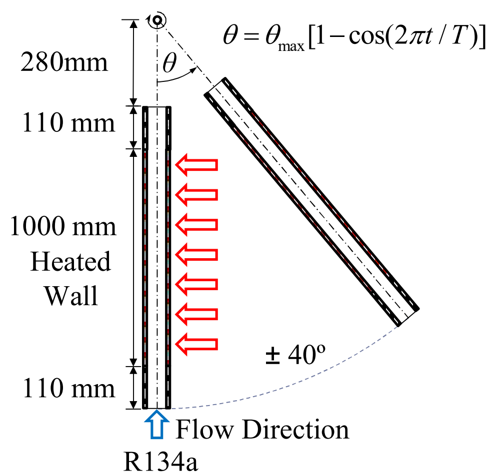

Fig. 1. Schematic diagram of simulation domain of the rolling pipe.

3.2 Numerical Model Validation

A set of data from experimental CHF research were selected to validate the present model [7]. The mass flux and pressure of the selected case are 500 kg/m^{2}s and 24 bar, respectively. The inlet subcooled enthalpy is 32.2 KJ/kg. Wall heat flux was increased by 0.5 KW/m^2 to identify the heat flux value of the DNB. Each heat flux step took 3 seconds for convergence. When the maximum wall volume fraction exceeds the critical volume fraction of 0.8, the maximum wall temperature increases rapidly, and it is considered a DNB occurrence.

Three meshes with different numbers of grids were tested in the vertical stationary condition and compared with the experimental result. The meshes have the same grid size for the first layer thickness, but radial and axial grid sizes are different. Three meshes are varied with the amount of grid, and each mesh has 301,000, 636,000, and 926,000 grids, respectively. The numerical results show some difference from the experimental data; however, the results of 636,000 grids mesh and 926,000 grids mesh are similar. In this study, the results of meshes with more grids than 636,000 are expected to be similar, thus it was determined as converged after

636,000 grids. The mesh with 636,000 grids was used for further numerical simulation.

4. Results and Discussion

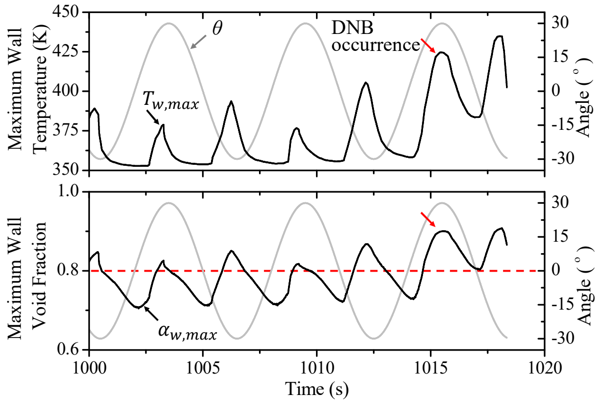

Fig. 2. Maximum wall temperature and maximum wall volume fraction of the oscillating pipe at DNB (Amplitude = 30º).

Numerical simulation was conducted for upward flow of R-134a with different oscillation amplitude: 15º, 30º and 40º. The mass flux, pressure, and inlet subcooled enthalpy of the oscillating pipe are 500 kg/m^{2}s, 24 bar, 32.2 KJ/kg respectively. Wall heat flux was ascended by 0.5 MW/m^2 every 6 seconds, which is 1 period of oscillation.

Fig. 2 shows the maximum wall temperature and the maximum wall void fraction when DNB appeared. As shown in Fig. 2, at the point of maximum inclination (±30º), the maximum wall temperature temporarily peaks out when the maximum wall void fraction exceeds the critical void fraction value of 0.8, and the maximum wall temperature drops as the void fraction gets lower than 0.8. As the maximum wall temperature intermittently rises sharply for a short time and periodically, the DNB is determined when the maximum wall void fraction rises but stays higher than the critical value after passing the maximum inclination.

To validate the simulation results, the DNB ratio is compared with experimental data. The DNB ratio is a ratio of the DNB heat flux of oscillating pipe versus the DNB heat flux of stationary vertical pipe, representing how much DNB is enhanced or reduced due to the oscillation. Data are compared at Table I, and the comparison of the experimental DNB ratio and the predicted DNB ratio appears well-fit. This excellent result confirms the validity of the present model set for predicting DNB in the oscillating pipe by numerical simulation.

Amplitude	0º (Stationary)	15º	30º	40º
CFD DNB Prediction	80.5 kw/m²	83.5 kw/m²	86 kw/m²	88 kw/m²
CFD DNB Ratio	1	1.037	1.068	1.093
Experiment DNB Ratio	1	1.040	1.060	1.081

Table I. Comparison of the CFD DNB ratios with experimental data.

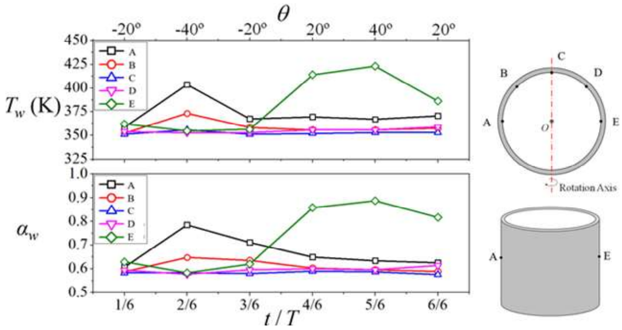

Fig. 3. Wall temperature and wall volume fraction at series of radial points near the end of heated surface at the period of DNB occurred (Amplitude = 40º).

The simulation of the DNB precursor revealed a correlation between the oscillating pipe's void fraction behavior and temporary temperature increase as well as DNB occurrence. To illustrate this correlation, Fig. 3 shows the instantaneous wall temperature and void fraction at various radial data points near the heated section's exit during the DNB occurrence period. The data were collected every second at 1/6T intervals. As demonstrated in Fig. 3, the void fraction at points A and E increases at the maximum inclination (±40º) due to buoyancy. Heat flux increases at 3/6T, and DNB occurs at 5/6T. Even when the pipe isn't at the maximum inclination, the void fraction remains above the critical value, and the wall temperature remains high after DNB occurs.

While the pipe is inclined, buoyancy creates a stack of bubbles on the downward-facing surface, leading to local instantaneous void fraction increases and DNB. However, due to the oscillation, the maximum inclination angle does not persist, and the buoyancy effect soon disappears, causing the stack of bubbles to vanish as the angle changes. As a result, the overheated surface returns to subcooled nucleate boiling and cools down to near the saturation temperature. The same process is repeated on the opposite surface when the pipe is inclined to the opposite side. This process explains the periodic rise and fall of the maximum wall temperature and void fraction under oscillation.

3. Conclusions

Based on the results of the numerical simulations with the improved RPI wall boiling model, it was determined that the rolling motion has a significant impact on the DNB in a vertical pipe under oscillating conditions. To investigate this effect, a series of subcooled boiling simulations were conducted with varying oscillation amplitudes, and the resulting DNB ratios were compared to experimental data to validate the accuracy of the numerical model. The simulated DNB ratios were found to be in precise agreement with the experimental data, with an average absolute relative error of only

0.5%, indicating that the numerical model is appropriate for use in current studies.

The simulation of the oscillating pipe showed that there were periodic changes in void fraction and temperature at the maximum inclination angle, which resulted in DNB enhancement compared to the stationary condition. Using the changes in void fraction, velocity, turbulent kinetic energy, and heat flux distribution over time, the vital factors affecting DNB enhancement were estimated. The phenomenon of DNB enhancement under oscillation can be explained by the effect of buoyancy, which plays a major role in DNB degradation by pushing bubbles against the downward facing heated surface while the pipe is inclined, leading to an increase in the local instantaneous maximum void fraction at the maximum inclination angle where the effect of buoyancy is greatest.

On the other hand, the rolling motion continuously changes the angle of the pipe, eventually eliminating the effect of buoyancy and cooling down the overheated surface. Additionally, increasing the local instantaneous void fraction also increases axial velocity and turbulent kinetic energy, which stimulates the removal of bubbles from the heated surface, further enhancing DNB. As a result, despite the negative effect of buoyancy, DNB can be enhanced under oscillating conditions.

The results of this study, which provide insight into the mechanism of DNB enhancement under oscillation, can be useful in establishing a CHF prediction model for the safety analysis of marine reactors. To expand the applicable conditions of the numerical model used in this study, quantitative predictions of DNB should be conducted in the future. Furthermore, since the behavior of voids under oscillation is significant in the prediction of DNB, DNB predictions for rod bundles under oscillation should be performed to enable the application of the DNB prediction model to the safety analysis of actual marine reactors.

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