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On the Numerical Approach for Simulating Thermal Hydraulics under Seismic Condition

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***Abstract*—**The two-phase flow field and the motion of the free surface in an oscillating channel are simulated numerically to assess the methodology for simulating nuclear reacotr thermal hydraulics under seismic conditions. Two numerical methods are compared: one is to model the oscillating channel directly using the moving grid of the Arbitrary Lagrangian-Eulerian method, and the other is to simulate the effect of channel motion using the oscillating acceleration acting on the fluid in the stationary channel. The two-phase flow field in the oscillating channel is simulated using the level set method in both cases. The calculated results using the oscillating acceleration are found to coinside with those using the moving grid, and the theoretical back ground and the limitation of oscillating acceleration are discussed. It is shown that the change in the interfacial area between liquid and gas phases under seismic conditions is important for nuclear reactor thermal hydraulics.

***Keywords*—**Two-phase flow, simulation, seismic condition, moving grid, oscillating acceleration, interfacial area

I. Introduction

THERMAL-HYDRAULIC phenomena with two-phase flows are seen widely in nuclear engineering fields, and predictions of complicated interfacial phenomena are of practical importance. Characteristics of two-phase flows have been intensively studied both experimentally and numerically under wide variety of flow conditions concerning with nuclear reactor safety. Two-phase flow phenomena under seismic conditions are, however, not well known. Free surface behaviors of liquid sodium have been studied for fast breeder reactors (FBRs). Numerical simulations were performed in some studies to obtain the surface motion, where the motion of reactor vessel was taken into account as the oscillating acceleration in fluid equations [1,2]. Stability analyses of boiling water reactors (BWRs) under seismic conditions have been performed by modifying the safety analysis code TRAC-BF1 to take into account the effect of seismic oscillation on thermal hydraulics [3]. The oscillating acceleration was added to the momentum equation of two-phase flows and the coupled effect of the thermal hydraulics and the reactor point kinetics was discussed. Three-dimensional effects have been studied later by coupling TRAC-BF1 with a three-dimensional kinetics code [4], and spatial distributions of void fraction and core power were shown to be affected. In these studies, seismic effects on thermal hydraulics were modeled through the additional acceleration term in the fluid equations, instead of taking into account the oscillation of reactor components.

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Although the reactor safety analyses code could easily be modified to include the additional acceleration term, validation of this methodology has not yet been discussed. In this study, the two-phase flow fields including bubbles or free surface in an oscillating channel are simulated numerically as typical sample problems of the nuclear reactor thermal hydraulics under seismic condition, and the numerical approaches using moving grid and oscillating acceleration are studied. The first sample problem is a bubbly flow, where the effect of oscillation on bubble motion is studied, and the second sample problem is a free-surface, where the effect of oscillation on surface deformation is studied. Large surface deformation is simulated in the second problem, though the oscillating surface problem at the resonant frequency is known as sloshing [5,6]. Incompressible Navier-Stokes equations are solved using the level set method [7]. In the level set method, the level set function, which is the distance function from the two-phase interface, is calculated by solving the transport equation using the flow velocities. The motion of the channel is modeled by the Arbitrary Lagrangian-Eulerian (ALE) method [8], where the computational grid points are moved with the velocity of the channel. Both the liquid-phase and the gas-phase flow fields with the interfacial motion induced by the oscillating channel are thus obtained in this study. The simulation results are compared with the case using the oscillating acceleration, where the acceleration term is added to the Navier-Stokes equations, and the numerical approach using the oscillating acceleration is discussed. The effect of oscillation on the interfacial area, which is of importance for evaluating mass and energy exchanges between gas and liquid phases, is discussed.

II. Numerical Simulation

A. Governing Equations

Governing equations for the two-phase flow field are the equation of continuity and the incompressible Navier-Stokes equations:

$$\nabla \cdot u = 0 \tag{1}$$

and

$$\rho \frac{\mathrm{D}u}{\mathrm{D}t} = -\nabla p + \nabla \cdot (2\mu D) - F_s + \rho g \tag{2}$$

where ρ, u, p and μ, respectively, are the density, the velocity, the pressure and the viscosity, D is the viscous stress tensor, F_s

is a body force due to the surface tension, and g is the gravitational acceleration. The surface tension force is given by

$$F_s = \sigma\kappa\delta\nabla\phi \tag{3}$$

where σ, κ, δ and ϕ are the surface tension, the curvature of the interface, the Dirac delta function and the level set function, respectively. The level set function is a distance function defined as $\phi=0$ at the free surface, $\phi<0$ in the liquid region, and $\phi>0$ in the gas region. The curvature is expressed in terms of ϕ:

$$\kappa = \nabla\cdot\left(\frac{\nabla\phi}{|\nabla\phi|}\right) \tag{4}$$

The density and viscosity are given, respectively, by

$$\rho = \rho_l + (\rho_g - \rho_l)H \tag{5}$$

and

$$\mu = \mu_l + (\mu_g - \mu_l)H \tag{6}$$

where the subscripts g and l denote gas and liquid phases, respectively, and H is the smeared Heaviside function defined by

$$H = \begin{cases} 0 & (\phi < -\varepsilon) \\ \frac{1}{2}[1 + \frac{\phi}{\varepsilon} + \frac{1}{\pi}\sin(\frac{\pi\phi}{\varepsilon})] & (-\varepsilon \le \phi \le \varepsilon) \\ 1 & (\varepsilon < \phi) \end{cases} , \tag{7}$$

where ε is a small positive constant for which $\nabla\phi = 1$ for $|\phi| \le \varepsilon$. The time evolution of ϕ is given by

$$\frac{\mathrm{D}\phi}{\mathrm{D}t} = 0 \tag{8}$$

In this study, the ALE method is applied, and the computational grid is moving with the same velocity as the velocity of the oscillating channel. The substantial derivative terms in (2) and (8) are thus defined by

$$\frac{\mathrm{D}}{\mathrm{D}t} = \frac{\partial}{\partial t} + (u - U)\cdot\nabla \tag{9}$$

where U is the velocity of the computational grid.

In order to maintain the level set function as a distance function, an additional equation is solved:

$$\frac{\partial\phi}{\partial\tau} = (1 - |\nabla\phi|)\frac{\phi}{\sqrt{\phi^2 + \alpha^2}} \tag{10}$$

where τ and α are an artificial time and a small constant, respectively. The level set function becomes a distance function in the steady-state solution of the above equation. The following equation is also solved to preserve the total mass of liquid and gas phases in time [9]:

$$\frac{\partial\phi}{\partial\tau} = (M_o - M)(1 - \kappa)|\nabla\phi| \tag{11}$$

where M denotes the mass corresponding to the level set function and M_0 denotes the mass for the initial condition.

The finite difference method is used to solve the governing equations. The staggered mesh is used for spatial discretization of velocities. The convection terms are discretized using the second order upwind scheme and other terms by the central difference scheme. Time integration is performed by the second order Adams-Bashforth method. The SMAC method is used to obtain pressure and velocities.

B. Simulation conditions

The simulation conditions are described here. The two-phase flow field with bubbles or free surface in a channel is simulated in the following. The flow channel is assumed to be a small part of the reactor core of the BWR. The flow channel between the fuel rods is simulated as a two-dimensional numerical test section. The channel width corresponds to the minimum distance between two fuel rods in the BWR core. The fluid properties are almost the same as those under the BWR operating condition: the pressure is 7.1 MPa and the temperature is the saturation temperature.

The flow channel is set in an oscillatory motion in one horizontal direction. The oscillation of the channel location in the horizontal direction is given by

$$x = A\cos(2\pi t / T) \tag{12}$$

where A = 0.182 m and T = 0.104 s are, respectively, the amplitude and the period of the oscillation. These are the maximum values observed on May 26, 2003, at Rikuzen Takada city in Japan. The velocity of the computational grid is used in the present moving grid method and is given as the differential of the channel location,

$$U = -A(2\pi / T)\sin(2\pi t / T) \tag{13}$$

In this study, the case with the oscillating acceleration is compared with the moving grid method. The oscillating acceleration is given as the differential of the channel velocity,

$$f = -A(2\pi / T)^2\cos(2\pi t / T) \tag{14}$$

The above acceleration is applied as the additional acceleration term in the momentum equation given by (2), and the channel is not moved and U=0 in (9) for the case with the oscillating acceleration.

III. Results and Discussion

A. Behavior of two bubbles

The behavior of two bubbles in the oscillating channel is simulated here as the first sample problem. The simulation model is shown in Fig. 1. The channel width is 4.0 mm and the channel height is also 4.0 mm. Slip wall condition is applied at the left and right boundaries, while the periodic boundary condition is applied at the top and bottom boundaries. Two bubbles are placed on the vertical center line as shown in Fig. 1. The diameter of the bubble is 1.2 mm, and the locations of the bubble center are 1.0 mm and 3.0 mm from the bottom. The densities of liquid and vapor are 737.6 kg/m^3 and 37.34 kg/m^3, and the viscosities are 9.384 x 10^{-5} kg/m^{2}s and 1.911 x 10^{-5} kg/m2s, respectively. The surface tension is set to 0.01735 N/m. The gravitational acceleration is not considered in this case to see the effect of oscillation clearly.

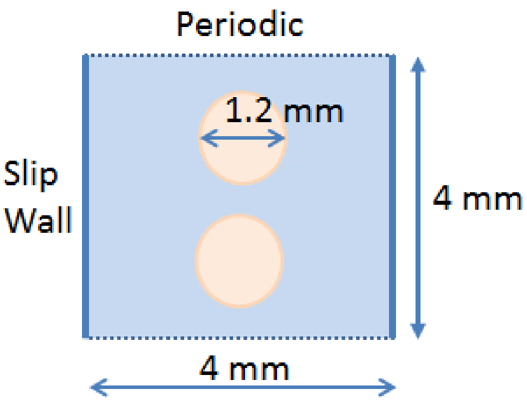

Fig. 1 Simulation model for two bubbles.

Two-dimensional simulation region shown in Fig. 1 is divided into 80 x 80 equal-size calculation cells, and thus the mesh cell size is 0.05 mm x 0.05 mm. The time step size is 5.0 μs. The maximum relative errors for the pressure calculation (2), the reinitialization (10), and the mass correction (11) are, respectively, set to 1.0 x 10^{-5}, 1.0 x 10^{-4}, and 1.0 x 10^{-2} during iterations.The calculated two-phase flow fields during one oscillation period are shown in Fig. 2, where the bubbles are indicated as the red region, while the liquid phase is indicated as the blue region. The flow velocities are shown as the black velocity vectors. The results using the moving grid are shown on the left and those using the oscillating acceleration are on the right. It is found that two flow fields are almost the same. The bubbles are moving to the left side of the simulation region at 0.02 s, and then go back to the centre at 0.04s. This indicates the liquid phase is moving to the right first at 0.02 s, and then goes back in contrast to the bubbles.

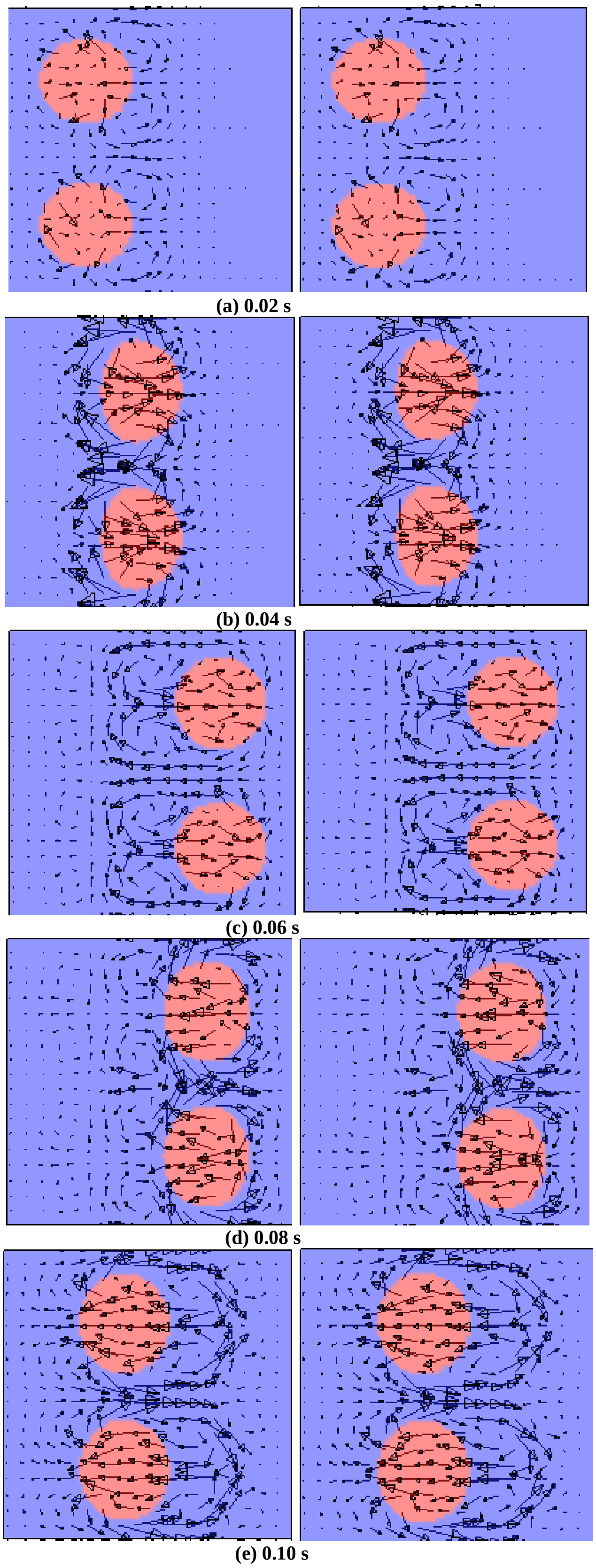

Fig. 2 Flow field with bubbles:left : moving grid, right : oscillating acceleration

Large vortex flows are seen in these flow fields starting from the front side of the bubbles and ending at the leer side. The bubbles move to the right at 0.06 s, and then go back to the centre at 0.08 s, and slightly pass the centre to the left at 0.10 s.

B. Behavior of free surface

The behavior of free surface in the oscillating channel is simulated here as the second sample problem. The simulation model is shown in Fig. 3. The channel width is 4.0 mm and the channel height is 20.0 mm. 80 x 400 equal-size calculation cells are used, and the mesh cell size and the time step size are the same as those for the first sample problem. Slip wall condition is applied at all the boundaries. In the real BWR flow channel, the liquid-phase water comes from the bottom and the vapor goes through the top, since the phase change occurs due to the nuclear heating. This complicated flow is not considered here, and the effect of oscillation on the free surface is simply studied. The initial level of the free surface is 8.0 mm as shown in Fig. 3. The fluid properties such as densities, viscosities and surface tension are corresponding to the BWR operating condition and the same as the first sample problem. The gravitational acceleration is considered in this case to see the effect of oscillation on the free surface.

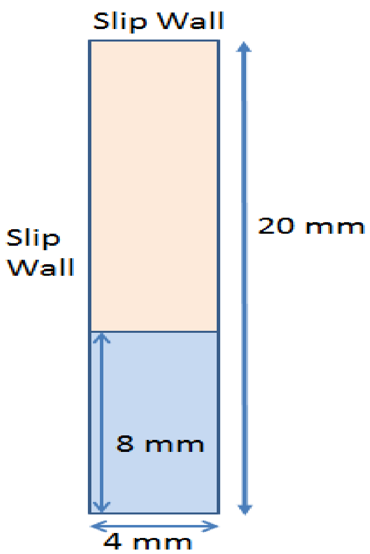

Fig. 3 Simulation model for free surface

The time evolution of the surface shape and the flow fields during two oscillation periods are shown in Fig. 4, where the results using the moving grid are shown in the top part, and the results using the oscillating acceleration are shown in the bottom part. It is found that two flow fields are almost the same as was the case in the first sample problem. Large deformation of the surface shape and complicated flow fields are well simulated.

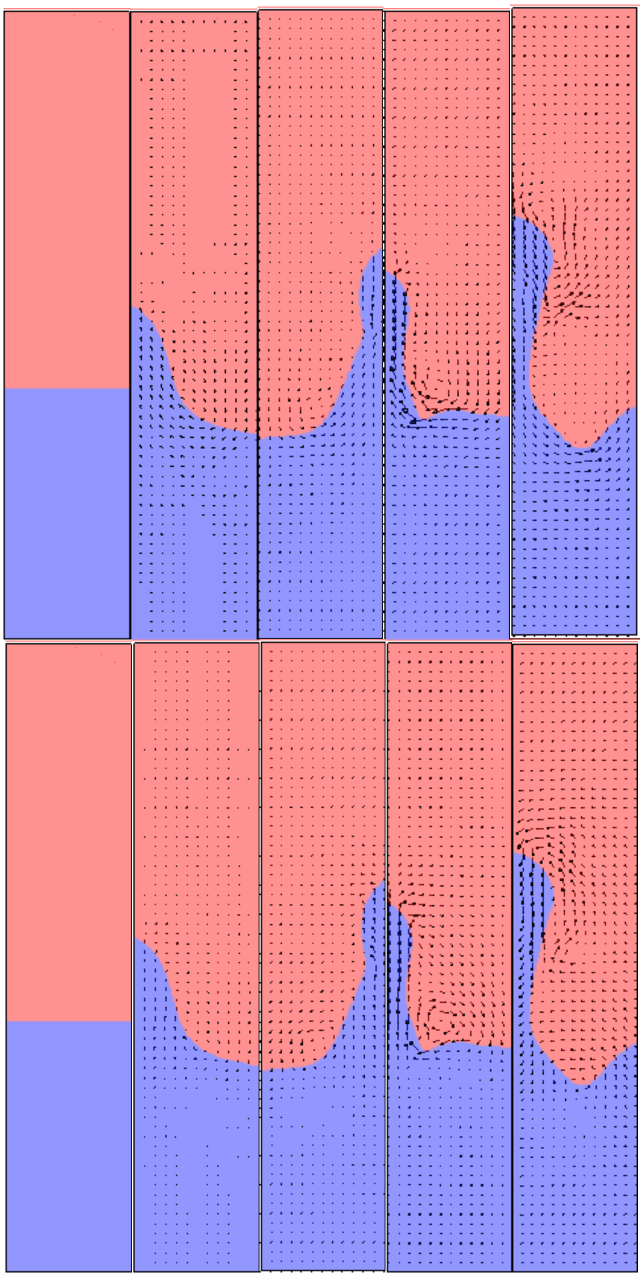

Fig. 4 Flow field with free surface :top : moving grid, bottom : oscillating acceleration

C. Relation between moving grid and oscillating acceleration

The behaviors of bubbles and free surface are shown to be the same under the oscillating condition for the case using the moving grid and the case using the oscillating acceleration. The relationship between the two methods is discussed in the following. The momentum equation for the moving grid is given by (2) and (9) as

$$\frac{\partial u}{\partial t}+[(u-U)\cdot\nabla]u=-\frac{1}{\rho}\nabla p+\frac{1}{\rho}\nabla\cdot(2\mu D)-\frac{1}{\rho}F_s+g \quad (15)$$

where U is the channel or the grid velocity given by (13). The flow velocity is then assumed to be divided into two parts: the grid velocity U and the induced velocity u',

$$u = u' + U \tag{16}$$

The momentum equation then becomes

$$\frac{\partial u'}{\partial t} + u' \cdot \nabla u' = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla \cdot (2\mu D') - \frac{1}{\rho}F_s + g - \frac{\partial U}{\partial t} \tag{17}$$

where D' is the viscous stress tensor for the induced velocity u'.It is assumed in (17) that the grid velocity is not varied spatially.

The last term in the right hand side of (17) is the oscillating acceleration given by (14), and (17) is the momentum equation for the case using the oscillating acceleration. It is thus obvious that the momentum equation, (15), for the moving grid is equivalent to the momentum equation, (17), for the oscillating acceleration. The calculated two-phase flow field using the moving grid thus becomes the same as the result using the oscillating acceleration as shown in Figs. 2 and 4. It is also found that the numerical simulations are correctly performed for both the methods.

It should be noted that the calculated velocity field using the moving grid includes the grid velocity, while that using the oscillating acceleration does not include the grid velocity. The velocity field using the moving grid is, in other words, observed on the fixed coordinate, while that using the oscillating acceleration is observed on the moving coordinate with the grid velocity [10]. The grid velocity is thus added to the calculated flow velocity for the case using the oscillating acceleration shown in Figs. 2 and 4 for comparison.

D.Interfacial area concentration

It is seen in the previous section that bubbles and free surfaces are much affected by the oscillatory motion of the channel. The effect of oscillation on the free surface shape is significant as shown in Fig. 4. Variations of interfacial area are thus discussed here, since the interfacial area is important to evaluate the heat and mass exchange between the gas and liquid phases. Time evolutions of the interfacial area are shown in Fig. 5, where the volume-averaged interfacial area so called interfacial area concentration is indicated. The interfacial area concentration is defined here by the interfacial length divided by the channel area. For the two-dimensional case shown in Fig. 3, the initial value of the interfacial area concentration is thus 4/(4x80)=0.0025, as shown in Fig. 5. The interfacial area shown in Fig. 5 is obtained by using the efficient evaluation method for the volume fraction and the interfacial area [11].

The interfacial area increases about 80 % from the initial value at about 0.025 s. The interfacial area then decreases to the initial value, and then increases again. The surface level increases along the right wall initially until 0.025 s, and becomes the flat shape at about 0.04 s. The surface level increases along the left wall until 0.07 s. The surface shape at 0.05 s is shown in Fig. 4. The surface becomes flat again at about 0.08 s, and increases again along the right wall. The surface shape at 0.1 s is shown in Fig. 4. The surface shape is much deformed, and the interfacial area concentration becomes large according to the deformation. The surface becomes flat again at about 0.14 s, and increases again along the left wall. The surface shape is complicated at 0.15 s and 0.2 s as shown in Fig. 4, and the interfacial area concentration is very large. The oscillation period is 0.104 s, and almost two peaks are found in the interfacial area in one oscillation period. It is found that the interfacial area concentration is much affected by the oscillation, and the interfacial heat and mass transfer between the liquid and gas phases would become very large. The effect of oscillation on the interfacial transfer terms has not been discussed in reactor safety analyses under seismic condition [3,4]. The interfacial transfer terms generally include empirical correlations. The empirical or experimental correlations are obtained under the static conditions, and the effect of oscillation is not considered. This point should be reminded for the reactor safety analyses under the seismic condition, since overall two-phase flow phenomena including interfacial transfer might be much affected by the oscillation.

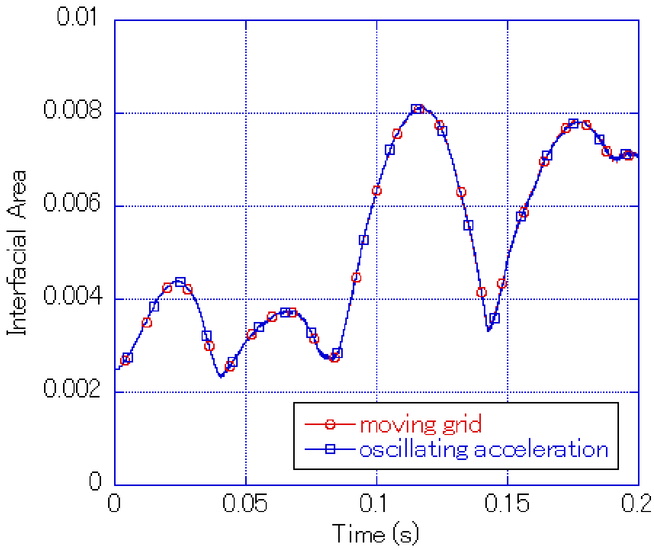

Fig. 5 Effect of oscillation on interfacial area

IV. Conclusion

The two-phase flow field and the motion of the free surface in an oscillating channel have been simulated numerically to assess the numerical approach for simulating nuclear reactor thermal hydraulics under seismic conditions. The moving grid method, where the oscillating channel was modeled directly using the moving grid of the ALE method with the oscillating velocity, was compared with the oscillating acceleration method, where the effect of channel motion was simulated using an oscillating acceleration acting on the fluid in a stationary channel. The two-phase flow field in the channel was simulated using the level set method in both cases.It was shown that the calculated results using the oscillating acceleration coinsided with those using the moving grid, and the momentum equation for the case with the oscillating acceleration was equivalent to that for the moving grid. The calculated velocity field for the ocillating acceleration was, however, the induced velocity field, which did not include the oscillating velocity of the channel. The effects of oscillation on the interfacial area concentration were shown. The interfacial area concentration is one of the most important parameters for the nuclear reactor safety, since the heat and mass exchange occur through the interface between gas and liquid phases. It was shown that the interfacial area concentration was very much affected by the oscillation of the channel. The variation of the interfacial area obtained using the oscillating acceleration coincided again with that using the moving grid. In this study, the simple two-phase flow fields with two bubbles or free surface were simulated numerically as the sample problems for the thermal hydraulics under seismic conditions, and the governing equations had no empirical correlations. For simulating engineering two-phase flow problems such as reactor thermal hydraulics, two-fluid model codes such as the reactor safety analysis code TRAC would be used generally. Such safety analysis codes include large number of empirical correlations, which are obtained under the static conditions with constant gravitational acceleration. Fluid equations or calculation conditions including the empirical correlations should thus be treated carefully not only for the oscillating acceleration but also for the moving grid.

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