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Technical note

On the numerical approach for simulating reactor thermal hydraulics under seismic conditions

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ABSTRACT

The motions of bubbles and free interfaces in oscillating two-phase flow fields are simulated numerically to assess the methodology for simulating reactor thermal hydraulics under seismic conditions. Two numerical methods are compared: one is to model the oscillating flow filed directly using the moving grid of the ALE method, and the other is to simulate the effect of oscillation using an external force acting on the fluid in a stationary grid. The two-phase flow field is simulated by the level set method. The theoretical back ground and the limitation of the two methods are discussed, and the calculated results using the external force are shown to coincide with those using the moving grid. It is found that the interfacial area between liquid and gas phases, which is one of the most important parameters for the nuclear reactor safety analysis, is affected largely by the oscillation.

1. Introduction

Thermal–hydraulic phenomena with liquid and gas two-phase flows are seen widely in various engineering fields, and predictions of complicated interfacial phenomena between two phases are of practical importance. In nuclear engineering field, characteristics of two-phase flows have been intensively studied both experimentally and numerically under wide variety of thermal–hydraulic conditions concerning with nuclear reactor safety. Empirical correlations were made and implemented into the reactor safety analysis codes, and the codes have been used for safety evaluation, licensing, and assessment of accident management. Evaluation of thermal–hydraulics under seismic conditions becomes of interest since the nuclear accident at Fukushima Daiichi power plant in 2011. The basic equations and the empirical correlations of safety analysis codes are, however, developed for static conditions, and two-phase flow phenomena under seismic conditions are not well known. Fluid flows in reactor components are externally oscillated and the integrity and coolability would be affected. In some reactor components, induced fluid motion results in large pressure impact on structures. Thermal conditions such as heat transfer between fluid and structure are also affected. Variation of two-phase flow conditions may also have an effect upon neutronics in the core, since the coolant density as the neutron moderator is affected.

Free surface behaviors of liquid sodium in oscillating reactors have been studied for fast breeder reactors (FBRs) (Chang et al., 1988, 1989; Sakurai et al., 1989; Amano et al., 1993; Kimura et al., 1995). Numerical simulations were performed in some studies to obtain the surface motion, where the oscillatory motion of reactor tank was taken into account as the external force term in fluid equations (Chang et al., 1988, 1989; Amano et al., 1993). Stability analyses of boiling water reactors (BWRs) under seismic conditions have been performed (Hirano and Tamakoshi, 1996). The safety analysis code TRAC-BF1 was modified to take into account the effect of seismic oscillation on thermal hydraulics. The oscillating acceleration was added to the momentum equation as an external force term, as was the case for FBRs, and the coupled effect of the thermal hydraulics and the point kinetics was discussed. Three-dimensional effects have been studied later by coupling TRAC-BF1 with a three-dimensional kinetics code (Satou et al., 2011), 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 external force term in the fluid equations, instead of taking into account directly the oscillation of reactor components.

The growth of the surface wave in a partially filled oscillating container is known as sloshing, and is important for structural integrity of the container. Sloshing has been studied experimentally and numerically in relation to, for instance, sea transport of oil and liquefied natural gas (Liu and Lin, 2008; Chen and Price, 2009), seismic response of liquefied petroleum gas tank in petrochemical industry (Curadelli et al., 2010), and so on. The effect of

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oscillating container on fluid motion was, in some cases, taken into account by including an external force induced by the container motion in the momentum equation of fluid (Liu and Lin, 2008; Chen and Price, 2009), as was the case for FBRs and BWRs. The calculation grid for fluid simulation was, in other cases, moved directory according to the container motion (Curadelli et al., 2010). The method using the external force is easy and simple from the view point of numerical simulation, and could easily be applied for reactor safety analyses. The method using the moving grid, however, seems apparently to be corresponding to the real phenomena, and the validation of the method using the external force has not been discussed well.

In this study, oscillating two-phase flow fields including bubbles or free interfaces are simulated numerically as sample problems, and the numerical approach for simulating reactor thermal hydraulics under seismic conditions is studied. Two numerical methods are compared: one is to model the oscillating flow filed directly using the moving grid of the Arbitrary Lagrangian–Eulerian (ALE) method (Hirt et al., 1974), and the other is to simulate the effect of oscillation using an external force acting on the fluid on the stationary grid. The two-phase flow field is simulated by the level set method (Sussman and Smereka, 1997) in both cases. The theoretical back ground and the limitation of the two methods are discussed. Effects of oscillation on interfacial area, which is one of the most important parameters for the nuclear reactor safety analysis, are also discussed.

2. Numerical simulation of oscillating two-phase flow fields

2.1. Equations for two-phase flows

Equations for the two-phase flow field under non oscillating conditions are the equation of continuity and the incompressible Navier–Stokes equations:

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

and

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

where ρ, u, p and μ, respectively, are the density, velocity, pressure and viscosity, D is the viscous stress tensor, F_s is the surface tension force, and g is the gravitational acceleration.

The level set method is applied to obtain the interface between liquid and gas phases. In the level set method, the level set function φ, which is the distance function defined as $\varphi = 0$ at the interface, $\varphi < 0$ in the liquid region, and $\varphi > 0$ in the gas region, is calculated by solving the transport equation using the flow velocities. The time evolution of the level set function is given by

$$\frac{\partial \phi}{\partial t} + (u \cdot \nabla)\phi = 0 \tag{3}$$

The surface tension force in Eq. (2) is given by

$$F_s = \sigma\kappa\delta\nabla\phi \tag{4}$$

where σ, κ and δ are the surface tension, curvature of the interface, and Dirac delta function, respectively. The curvature is expressed in terms of φ:

$$\kappa = \nabla \cdot \left(\frac{\nabla\phi}{|\nabla\phi|}\right) \tag{5}$$

The density and viscosity are given, respectively, by

$$\rho = \rho_l + (\rho_g - \rho_l)H \tag{6}$$

and

$$\mu = \mu_l + (\mu_g - \mu_l)H \tag{7}$$

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

$$H = \begin{cases} 0 & (\phi < -\varepsilon) \\ \frac{1}{2}\left[1 + \frac{\phi}{\varepsilon} + \frac{1}{\pi}\sin\left(\frac{\pi\phi}{\varepsilon}\right)\right] & (\varepsilon \le \phi \le \varepsilon) \\ 1 & (\varepsilon < \phi) \end{cases} \tag{8}$$

where ε is a small positive constant for which $\nabla\phi = 1$ for $|\phi| \leqslant \varepsilon$.

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

$$\frac{\partial \phi}{\partial \tau} = (1 - |\nabla\phi|)\frac{\phi}{\sqrt{\phi^2 + \alpha^2}} \tag{9}$$

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 (Chang et al., 1996):

$$\frac{\partial \phi}{\partial \tau} = (M_o - M)(1 - \kappa)|\nabla\phi| \tag{10}$$

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

In this study, the ALE method is applied for the moving grid method, and the grid velocity U is included in the convective term in the momentum equation:

$$\rho\left\{\frac{\partial u}{\partial t} + [(u - U) \cdot \nabla]u\right\} = -\nabla p + \nabla \cdot (2\mu D) - F_s + \rho g \tag{11}$$

and in the transport equation for the level set function:

$$\frac{\partial \phi}{\partial t} + [(u - U) \cdot \nabla]\phi = 0 \tag{12}$$

Eqs. (11) and (12), which are the governing equations for the moving grid method, become Eqs. (2) and (3), respectively, when the grid velocity is zero.

The flow velocity u is then assumed to be divided into two parts: the moving grid velocity U and the induced velocity u':

$$u = u' + U \tag{13}$$

The momentum equation for the external force method is thus obtained by

$$\rho\left\{\frac{\partial u'}{\partial t} + (u' \cdot \nabla)u'\right\} = -\nabla p + \nabla \cdot (2\mu D') - F_s + \rho g - \rho\frac{\partial U}{\partial t} \tag{14}$$

where D' is the viscous stress tensor for the induced velocity. The last term in the right hand side of Eq. (14) is the external force term on the stationary grid. It is noted that

$$(u' \cdot \nabla)U = 0 \tag{15}$$

is assumed for deriving Eq. (14). Eq. (15) indicates that the grid velocity is not varied spatially, since the induced velocity is not zero generally. The grid velocity should thus be the same for all calculation grids. In other words, it is assumed for the external force method that the flow channel is rigid and not deformed. The transport equation for the level set function is given by

$$\frac{\partial \phi}{\partial t} + (u' \cdot \nabla)\phi = 0 \tag{16}$$

Eqs. (14) and (16), which are the governing equations for the external force method, become Eqs. (2) and (3), respectively, when the grid velocity is zero. It is thus obvious that the moving grid method is equivalent to the external force method. It should, however, be noted that the calculated velocity field by the moving grid method