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Two-dimensional numerical simulation of single bubble rising behavior in liquid metal using moving particle semi-implicit method

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ABSTRACT

Gas-lift pump in liquid metal cooling fast reactor (LMFR) is an innovative conceptual design to enhance the natural circulation ability of reactor core. The two phase flow characteristics of gas–liquid metal make significant improvement of the natural circulation capacity and reactor safety. It is important to study bubble flow in liquid metal. In present study, the rising behaviors of a single nitrogen bubble in 5 kinds of common stagnant liquid metals (lead bismuth alloy (LBE), liquid kalium (K), sodium (Na), potassium sodium alloy (Na–K) and lithium lead alloy (Li–Pb)) and in flowing lead bismuth alloy have been numerically simulated using two-dimensional moving particle semi-implicit (MPS) method. The whole bubble rising process in liquid was captured. The bubble shape, rising velocity and aspect ratio during rising process of single nitrogen bubble were studied. The computational results show that, in the stagnant liquid metals, the bubble rising shape can be described by the Grace's diagram, the terminal velocity is not beyond 0.3 m/s, the terminal aspect ratio is between 0.5 and 0.6. In the flowing lead bismuth alloy, as the liquid velocity increases, both the bubble aspect ratio and terminal velocity increase as well. This work is the fundamental research of two phase flow and will be important to the study of the natural circulation capability of Accelerator Driven System (ADS) by using gas-lift pump.

1. Introduction

In the conceptual design of liquid metal cooling fast reactor and the Accelerator Driven System (ADS), the traditional mechanical pump in primary coolant circuit was replaced by gas-lift pump (Cinotti and Gherardi, 2002). Fig. 1 shows lead bismuth cooling ADS device (PDS-XADS) scheme (Tohru et al., 2005), the subcritical reactor was cooled by lead bismuth natural cycle without primary circuit pump. The two phase flow of LBE-inert gas in ascension channel could significantly improve natural circulation capacity. Russia also adopts gas-lift pump in their conceptual design of 900 MWt lead bismuth cooling fast reactor (RBEC-M) (Mikityuk et al., 2002). The two-phase flow characteristics of LBE-inert gas have obviously influence on the natural cycle of system ability and reactor safety. However, there are few studies on the bubble flow in liquid metal, and it is difficult to obtain the visualization of bubble rising process in liquid metal. Consequently, it is of great significance to numerically simulate the two-phase flow characteristics.

The finite difference method (FDM), finite volume method (FVM) and finite element method (FEM), are common traditional mesh-based methods. In these methods, because of the severe distortion of computing cells near two-phase interface, the accurate configuration of movable interface is too much complicated or even difficult. The computational efficiency is also very low and computation sometimes fails. So other novel methods appeared to overcome these disadvantages, such as the moving grid method, the front tracking method (Unverdi and Tryggvason, 1992), the level set method (Smereka and Sethian, 2003), the volume-of-fluid method (VOF) (Scardovelli and Zaleski, 1999), and the boundary-integral algorithm (Dhotre and Smith, 2007). Among them, moving particle semi-implicit (MPS) method, proposed by Koshizuka and Oka (1996) is one promising particle method, which is on the basis of smoothed particle hydrodynamics (SPH). Comparing with the above methods, MPS method has the following distinguished features. Interface tracing technique is its inherent feature for different fluid or phase which can be represented by different type of particles, so interface can be easily captured and its resolution accuracy scales with particle size. No additional governing equation for tracing interface is needed. Principally, it can be used to treat arbitrary deformation and easier to implement.

Compared with 3D, 2D simulation of MPS method is possible to perform the bubble rising behavior, and the calculation results of

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Nomenclature

C_D	drag coefficient
D	bubble diameter (m)
d	space dimension
d_{eq}	bubble equivalent diameter (m)
E	bubble aspect ration
E_0	Eotvos number
g	gravity acceleration (m/s^2)
k	steam liquid interface curvature (m^{-1})
M	Morton number
$\mathbf{n}$	unite vector of phase interface
n	particle density
p	pressure (Pa)
$\mathbf{r}$	particle location vector
r_e	particle effective radius (m)
Re	Reynolds number
t	time (s)
T	temperature (K)
$\mathbf{u}$	particle velocity vector
u_{gu}	terminal rising velocity of bubble (m/s)
w	kernel function
Greek symbols	
φ	scalar variable
λ	diffusion model parameter
μ	kinematic viscosity (kg/ms)
ρ	density (kg/m^3)
σ	surface tension coefficient
Superscript/subscript	
f	liquid
g	gas
i,j	particle no

2D are similar to that of 3D simulation. So in present study, the bubble flow characteristics of a single inert gas bubble in five kinds of stagnant liquid metals and flowing lead bismuth alloy were studied by two dimensional MPS method. In the process of bubble rising, the deformation of bubble shape, the rising velocity and the aspect ratio were analyzed, and the numerical simulation results were compared with Grace's diagram and empirical correlations.

2. Numerical method and calculation procedure

MPS method described by Lagrangian method, does not have the discrete convective term which may cause numerical dissipation. The differential operator in the fluid control equation is replaced by the particle interaction model using the kernel function. The incompressible characteristic of fluid is realized by keeping a constant particle density number in flow field. The momentum equations and pressure term are solved using semi-implicit method and implicit method, respectively. The other terms are solved using explicit method.

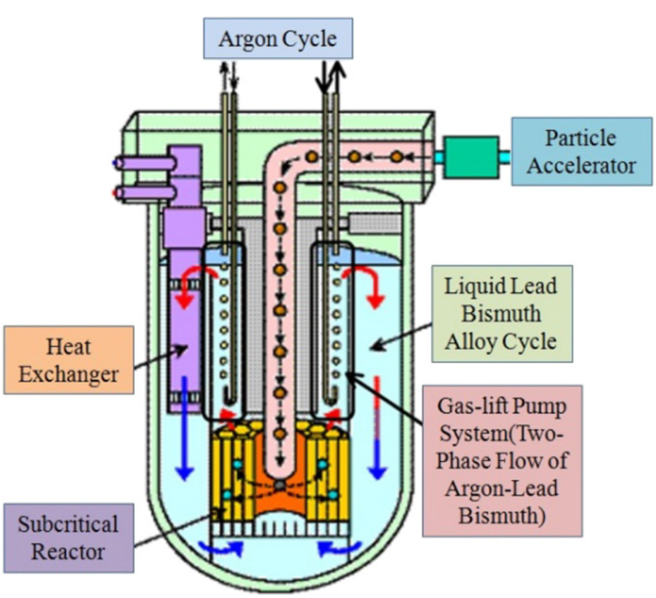

Fig. 1. ADS schematic.

2.1. Control equation

The continuity, Navier–Stokes and energy equations for incompressible viscous flows are:

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

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} - \mathbf{u}^c)\cdot\nabla\mathbf{u}\right) = -\nabla p + \mu\nabla^2\mathbf{u} + \sigma\kappa\cdot\mathbf{n} + \rho\mathbf{g} \tag{2}$$

Where, $\mathbf{u}$ is the fluid velocity and $\mathbf{u}^c$ represents the motion of a computing point which is adaptively configures during the calculation. κ is curvature of the interface, which is calculated in the surface tension function of MPS method. An arbitrary calculation is allowed between fully Lagrangian ($\mathbf{u}^c = \mathbf{u}$) and Eulerian ($\mathbf{u}^c = 0$) calculations so that a sharp fluid front is calculated accurately by moving the computing points in Lagrangian coordinates while the fixed boundaries are described with Eulerian coordinates (Yoon et al., 1999).

2.2. Numerical method

In MPS method, each differential operator appeared in the governing equations is replaced by the particle interaction models where a particle interacts with others in its vicinity covered with a weight function $w(r,r_e)$, where r is the distance between two particles and r_e is the radius of interaction area. There are several kernel function expressions proposed by different researchers. Among them, Koshizuka's equation has been widely adopted since it has simple expression and reasonable physical meaning. So Koshizuka's kernel function has been proposed in the study (Koshizuka and Oka, 1996).

$$w(r,r_e) = \begin{cases} \frac{r_e}{r} - 1 & (0 \le r \le r_e) \\ 0 & (r_e \le r) \end{cases} \tag{3}$$

Since the area that is covered with this weight function is bounded, a particle interacts with a finite number of neighboring particles as shown in Fig. 2 (Tian et al., 2009).

The particle distribution in the flow field is evaluated by particle number density in MPS method. The particle number density of i in the position r_i is defined by: