Journal of Magnetism and Magnetic Materials xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Numerical simulation of bubble deformation in magnetic fluids by finite volume method

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ARTICLE INFO

Keywords:
Magnetic fluid
Finite Volume Method
Constrained Interpolation Profile
Level-set method
Self-correcting procedure and Bubble deformation

ABSTRACT

Bubble deformation in magnetic fluids under magnetic field is investigated numerically by an interface capturing method. The numerical method consists of a coupled level-set and VOF (Volume of Fluid) method, combined with conservation CIP (Constrained Interpolation Profile) method with the self-correcting procedure. In the present study considering actual physical properties of magnetic fluid, bubble deformation under given uniform magnetic field is analyzed for internal magnetic field passing through a magnetic gaseous and liquid phase interface. The numerical results explain the mechanism of bubble deformation under presence of given magnetic field.

1. Introduction

The visualization of bubble behavior in the magnetic fluid is one of the most important issues in basic fluid science and engineering applications of magnetic fluid. In energy transfer device [1,2], for instance, which uses boiling-magnetic fluid with two-phase flow, the vapor bubble behavior affects the energy conversion efficiency significantly. Among many applications of magnetic fluid with gaseous phase, measuring bubble or droplet of magnetic fluid are essential. In reality, however, there always exists the difficulty of the observation of those bubble behaviors due to the fact that the fluid is opaque. There are few attempts to date that Ueno et al. and Korlie et al. [3–5] have calculated a bubble behavior in a magnetic fluid by using VOF (Volume of Fluid) method. However, the dynamic characteristic and the distribution of magnetic flux density around bubble have not yet fully verified and discussed. There are always some difficulties of calculating two-phase flow field with internally generated magnetic field. The difficulties are, in fact, often found in calculating the internal magnetic field distribution in capturing the interface by decoupling magnetic field calculation against the dynamic motion. Particularly, the magnetic field solver associated with dynamics fluid motion has not been fully discussed and developed for the continuity and conservation of magnetic flux density. This is mainly due to the difficulty to satisfy the continuity and the conservation of magnetic flux density by only solving the Laplace equation of a scalar potential. Considering the difficulties, Araseki et al. [6] have successfully investigated the continuity and conservation of magnetic field for solid-liquid phase interface by using self-correcting procedure. In this paper, taking into consideration of the self-correcting procedure, a new numerical technique is fully presented to overcome the interface problem for general gaseous-liquid interface, which couples with gas bubble in a column of magnetic fluid. Results obtained for rising incompressible bubble behavior with an actual magnetic fluid are presented and a phenomenological behavior of the bubble deformation is discussed.

2. Methods

2.1. Govern equations

In order to investigate the bubble deformation under magnetic field, a numerical simulation using a finite volume formulation, which employs a regular Cartesian grid, was carried out. The governing equations in 2D incompressible gaseous-liquid two-phase flow problem can be described by the following formula:

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

$$\frac{\partial \boldsymbol{u}}{\partial t} + \nabla\cdot(\boldsymbol{u}\boldsymbol{u}) = -\frac{1}{\rho}\nabla p + \nu\Delta\boldsymbol{u} + \boldsymbol{F}_{sf} + \boldsymbol{F}_{mg} \tag{2}$$

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

where $\boldsymbol{u}$ is the velocity, ρ is the density, p is the pressure, ν is dynamic viscosity, $\boldsymbol{F}_{sf}$ is surface force, $\boldsymbol{F}_{mg}$ is magnetic force and φ is VOF function. Eq. (1) shows incompressible continuity equation for both gas and liquid phase. Eq. (2) shows the momentum equation with surface force and magnetic body force. Eq. (3) shows advection equation of

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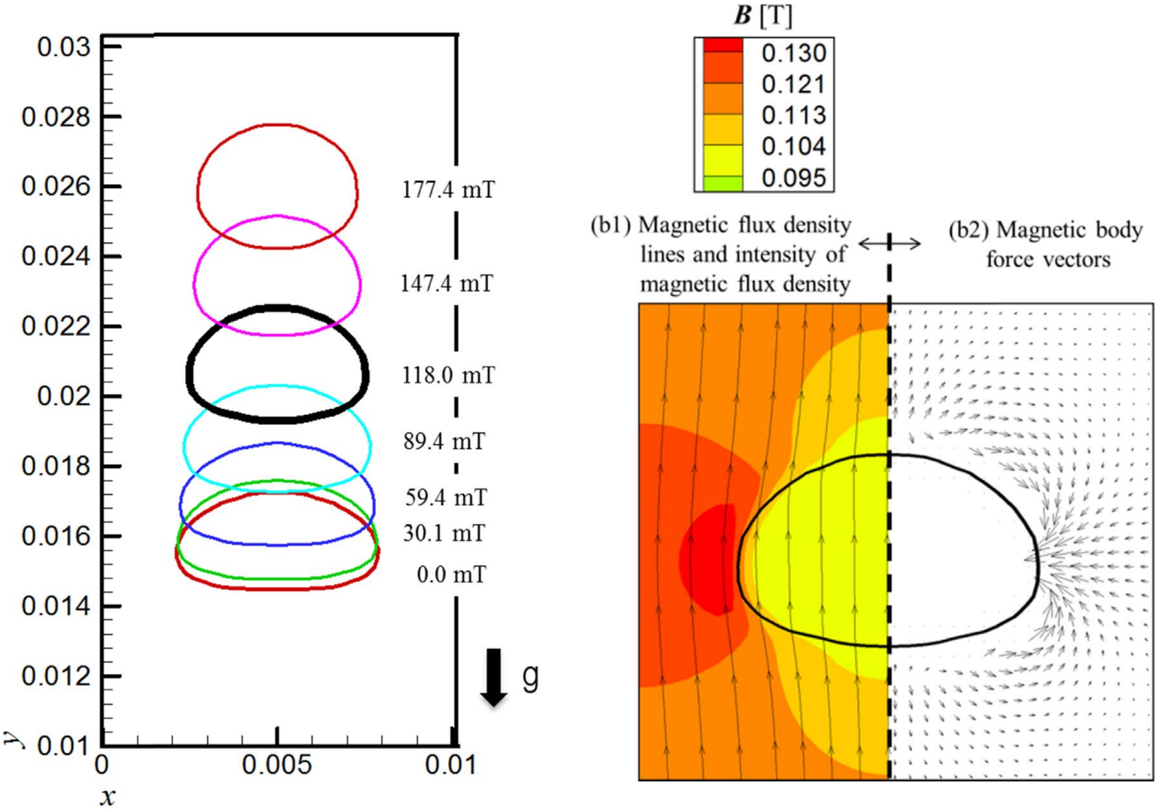
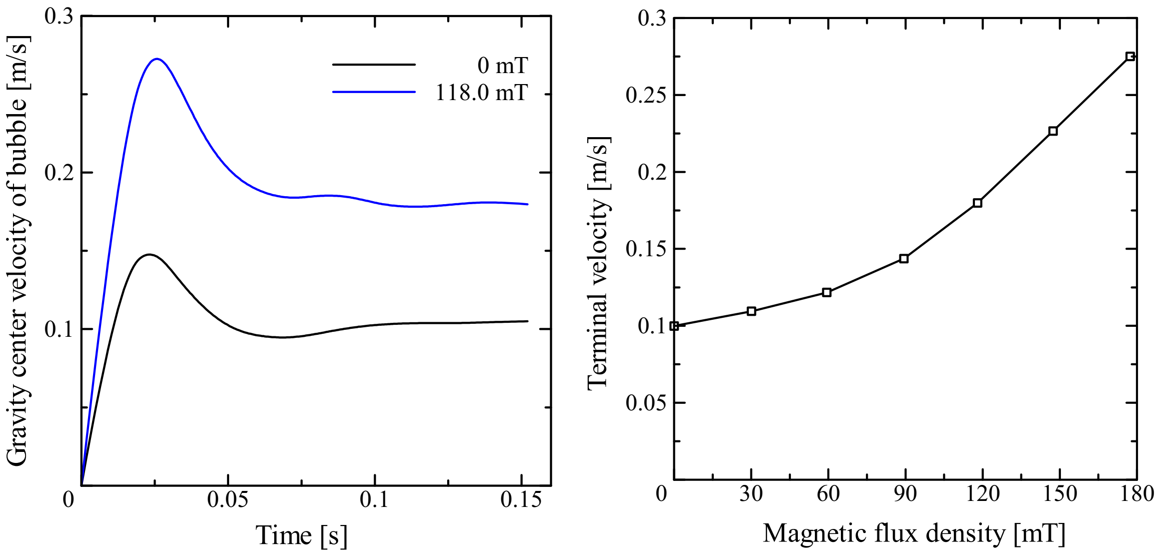
http://dx.doi.org/10.1016/j.jmmm.2016.10.012
Received 30 June 2016; Received in revised form 29 September 2016; Accepted 2 October 2016

Please cite this article as: Yamasaki, H., Journal of Magnetism and Magnetic Materials (2016), http://dx.doi.org/10.1016/j.jmmm.2016.10.012



(a) (b)

Fig. 1. Calculation results of bubble behavior under uniform magnetic field; Re=8.5 and We=1.445; (a) Bubble deformations under various magnetic flux density intensity (heavy line shows bubble line at 118.0 mT), (b) Magnetic flux density lines and intensity magnetic flux density (as shown color contour) [left (b1)] and magnetic body force vectors [right(b2)] with magnetic flux density of 118.0 mT.



(a) (b)

Fig. 2. Calculation results of rising velocity of bubble: (a) time evaluation of gravity center velocity of bubble under magnetic flux density of 0 and 118.0 mT, (b) terminal velocity at different magnetic flux density of 0, 30.1, 59.4, 89.4, 118.0, 147.4 and 177.4 mT.

VOF function. In the calculation of magnetic gaseous-liquid two-phase flow field, the magnetic field distribution is key factor to decide the magnetic body force $\boldsymbol{F}_{mg}$. The solution procedure for the other calculations, Eqs. (2) and (3) are followed in the Sections 2.2–2.6.

2.2. Advection term

CIP-CSL3 (Constrained Interpolation Profile-Conservative Semi-Lagrangian 3) is used [7] as conservation advection equation solver in FVM framework in the present investigation for solving flow field equations presented in Eqs. (1) and (2). CIP method is a kind of higher-