

Three-dimensional numerical computation of gas-liquid two-phase flow under pseudo microgravity environment using a superconducting electromagnet

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Abstract

By using the strong magnetic field generated by a superconducting electromagnet, theoretically it is possible to produce the pseudo microgravity environment on the ground. The final goal of this research is to obtain knowledge of fluid control under a strong magnetic field using a superconducting electromagnet. In this study, in order to examine a method for accurate CFD computation, we carried out computation for a gas-liquid two-phase flow under a strong magnetic field. A milk crown phenomenon inside the bore of superconducting electromagnet is studied. The liquid is assumed to be an aqueous gadolinium nitrate solution (15%). The CLSVOF method is used for the computation of the two-phase flow and the HSMAC method is used for the pressure correction. We evaluate how much the interior of the superconducting electromagnet is in a pseudo microgravity environment by using the equation expressing the gravity level. In addition, in order to speed up the calculation, GPU parallel computation is performed, realizing about 22 times faster than CPU single computation. As a result, we succeeded in investigating a method for computation a gas-liquid two-phase flow in a strong magnetic field.

Keywords : Superconducting electromagnet, Two-phase flow, Computation, GPU

1. Introduction

In the microgravity environment, even substances with different specific gravities are uniformly dispersed, and convection caused by the density difference does not occur. Moreover, since impurities do not mix in such an environment, development of new materials including nano-skeletons has been conducted. Under the high magnetic field produced by a superconducting magnet, the magnetic body force acting in ordinary fluids such as air or water is almost the same order as the gravitational body force. Therefore, we are convinced that the pseudo microgravity environment on the ground can theoretically be reproducible, and the above-mentioned development can be done on the ground. In order to acquire the control techniques for such two-phase flows by the use of high magnetic field, we compute the behavior of gas-liquid two-phase flow inside the superconducting electromagnet.

2. Computational model

The computational model used in this study is shown in **Fig.1**. A cuboid container was installed inside the bore of the superconducting electromagnet. The interior is assumed to be gas-liquid two-phase flow (A gadolinium nitrate aqueous solution and air). The concentration of gadolinium nitrate in the aqueous solution is 15% in weight. For the superconducting electromagnet, a helium-free superconducting magnet manufactured by Sumitomo Heavy Industries, Ltd. is modeled.

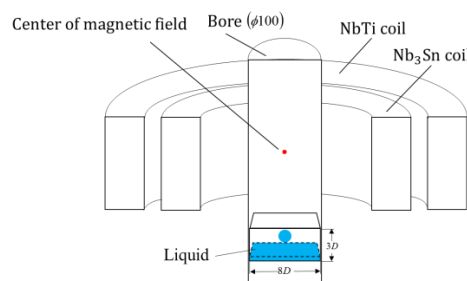


Fig. 1: Computational model in this study.



3. Computation method

3.1 Handling of phase^{1) 2)}

In this study, CLSVOF method is used as an interface capturing method along with the two-phase flow computation. The CLSVOF method is a method of solving the advection equation of the interface using the smoothed Heaviside function (H_α) calculated from the Level Set function (ϕ) with the property of distance function. In a multiphase flow such as a gas-liquid two-phase flow, physical properties differ in each phase. Therefore, the physical property values are set using the smoothed Heaviside function.

3.2 Governing equations^{3) 4)}

The dimensionless governing equations used in this study are shown below.

$$\vec{\nabla} \cdot \vec{U} = 0 \quad (1)$$

$$\frac{\partial \vec{U}}{\partial \tau} + (\vec{U} \cdot \vec{\nabla}) \vec{U} = -\frac{1}{\rho_c} \vec{\nabla} P + \frac{1}{\rho_c} \vec{\nabla} \cdot (2\mu_c \mathbf{E}) + \frac{\Gamma}{\rho_c} \vec{F}_{SF} + M \vec{F}_M - G \vec{e}_z \quad (2)$$

$$\frac{\partial C}{\partial \tau} + \vec{\nabla} \cdot (C \vec{U}) - C \vec{\nabla} \cdot \vec{U} = 0 \quad (3)$$

$$\vec{B} = -\frac{1}{4\pi} \iiint_V \frac{\vec{R} \times d\vec{s}}{R^3} dV \quad (4)$$

Here, R in equation (4) is the distance between the point on the coil and the computation point, \vec{R} is the vector from the point on the coil to the computation point, and V is the volume of the coil. The fluid handled in this study assumed incompressible Newtonian fluid. For the discretization of the space, an equally spaced staggered grid system is used. As a discretization method, the Euler explicit method is used as the time derivative term, the third order accuracy upstream difference method is used as the advection term, and the other terms such as the diffusion term and the interfacial force term are approximated with the second order central difference method. The boundary conditions in this study are slip-free condition, no inflow / outflow condition. \mathbf{E} (Strain rate tensor), \vec{F}_{SF} (interfacial force term) and \vec{F}_M (magnetization force term) appearing in equation (2) are shown below.

$$\mathbf{E} = \frac{1}{2} (\vec{\nabla} \otimes \vec{U} + {}^t(\vec{\nabla} \otimes \vec{U})) \quad (5)$$

$$\vec{F}_{SF} = \kappa \vec{\nabla} H_\alpha = -\vec{\nabla} \cdot \left(\frac{\vec{\nabla} \phi}{|\vec{\nabla} \phi|} \right) \vec{\nabla} H_\alpha \quad (6)$$

$$\vec{F}_M = \chi_c (\vec{B} \cdot \vec{\nabla}) \vec{B} \quad (7)$$

The gravitational level inside the superconducting electromagnet X_G was obtained by using the following evaluation formula at the central axis of the bore.

$$X_G = M_G B_z \frac{\partial B_z}{\partial Z} - 1 \quad (8)$$

The dimensionless variables and numbers were set as follows.

$$\begin{aligned} \bar{X} &= \frac{\bar{x}}{D}, \bar{U} = \frac{\bar{u}}{\mu_G / (\rho_G D)}, \bar{B} = \frac{\bar{b}}{i \mu_m / D}, \tau = \frac{t}{\rho_G D^2 / \mu_G}, P = \frac{p}{\mu_G^2 / (\rho_G D^2)}, \rho_c = \frac{\rho}{\rho_G}, \mu_c = \frac{\mu}{\mu_G}, \\ \chi_c &= \frac{\chi}{\chi_G}, \bar{\rho} = \frac{\rho_L}{\rho_G}, \bar{\mu} = \frac{\mu_L}{\mu_G}, \bar{\chi} = \frac{\chi_L}{\chi_G}, G = \frac{g \rho_G^2 D^3}{\mu_G^2}, \Gamma = \frac{\gamma \rho_G D}{\mu_G^2}, M = \frac{\chi_G \rho_G^2 \mu_m i^2}{\mu_G^2}, M_G = \frac{\chi_L i^2 \mu_m}{g D^3} \end{aligned}$$

Here, μ_m is the magnetic permeability in vacuum and i the electric current of the coil of the superconducting magnet and sets 164A. The subscripts G and L of each physical property value represent gas and liquid respectively.

The computational conditions were set as follows as shown in **Table 1**.

Table 1 Computational condition.

Parameter	Value	Parameter	Value
Number of grids (X, Y, Z)	384, 384, 144	Representative length (D)	0.005 (m)
Computation time(τ)	8.0	Gravitational acceleration (g)	9.8 (m/s ²)
Time step ($\Delta\tau$)	5.0×10^{-4}	Surface tension (γ)	0.053 (N/m)
Reynolds number (Re)	815.97	Impact velocity (u_0)	2.35 (m/s)
Weber number (We)	0.64	Gas density (ρ_G)	1.25 (kg/m ³)
Froude number (Fr)	10.62	Gas viscosity (μ_G)	1.8×10^{-5} (Pa · s)
Dimensionless number about magnetic field (M)	7.34×10^{-5}	Gas susceptibility (χ_G)	3.0×10^{-7} (m ³ /kg)
Dimensionless number about gravity level(M_G)	3.12×10^{-3}	Liquid density (ρ_L)	1032 (kg/m ³)
Density ratio (ρ)	825	Liquid viscosity (μ_L)	1.7×10^{-3} (Pa · s)
Viscosity ratio (μ)	93.6	Liquid susceptibility (χ_L)	1.13×10^{-7} (m ³ /kg)
Magnetic susceptibility ratio ($\bar{\chi}$)	0.38	Current value (i)	164 (A)
		Permeability in vacuum (μ_m)	$4\pi \times 10^{-7}$ (H/m)

The concentration of the gadolinium nitrate aqueous solution is 15%. It is expressed by the following equation showing concentration dependency by Matsushima et al.⁵⁾ n represents the concentration (kg-solute/kg-solution) of the aqueous solution.

$$\chi_L = (8.377 \times 10^{-7})n - 8.460 \times 10^{-9} \quad (9)$$

3.3 Parallel computation on GPU⁴⁾

In this study, by a parallel computation on GPU, high speed computation has been realized. However, it is impossible to correct the pressure field repetitively by using the HSMAC method in usual parallel computation. Because the pressure correction has a dependant relationship with adjacent points, so it is impossible to simply compute each grid by parallelization. Therefore, when correcting the pressure field by parallel computation, the Red and Black method is used. In this model, the computation of time has been improved about 22 times faster by the parallel calculation on GPU.

4. Result

Computational result of gravity level inside the bore of superconducting electromagnet at the central axis when the central magnetic field is 9.8 Tesla is shown in **Fig. 2**. The horizontal axis represents magnetic force and the vertical axis represent bore height. The container is installed so that zero gravity point accord with the interface as shown in **Fig.3**. The gravity level in the bore was upward maximum of about 2.8 G, downward maximum of about 4.8 G, and there was a large gradient.

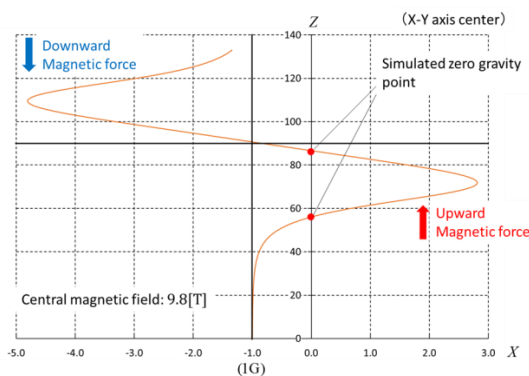


Fig. 2: Gravity level inside the bore of superconducting electromagnet at the central axis when the central magnetic field is 9.8 Tesla.

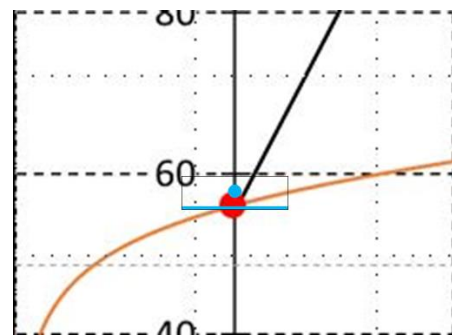
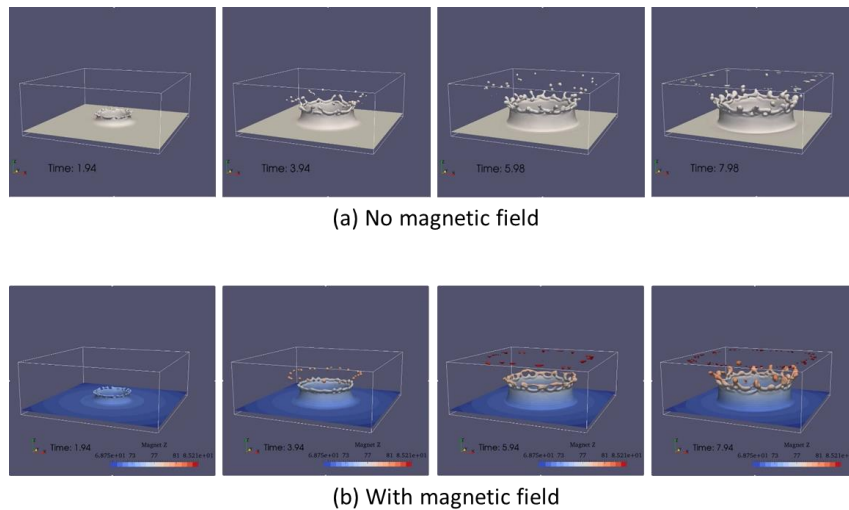


Fig. 3: Placement of the container. (Real scale)

**Fig. 4:** Computational result.

The computational results are shown in **Fig. 4**. The color of (b) in **Fig. 4** represents the magnitude of the upward magnetic force. The central magnetic field is 9.8 Tesla. In the two results, the volume error during implementing computation was 0.02% or less, which resulted from taking advantage of the characteristics of the CLSVOF method. In the case with magnetic force, it can be seen that the droplet is separated due to the influence of the upward magnetic force and that it reaches the upper wall more quickly than the case without magnetic field. This is because the gradient of the magnetic field is large in the container and the magnetic force exceeds the gravity considerably in most part of the container.

5. Summary

We succeeded in real scale computation of the gas-liquid two-phase fluid inside the superconducting electromagnet and speeding up the computation. However, the region of the pseudo microgravity environment with the superconducting electromagnet modeled this time was very narrow. There was the incline of the big magnetic field in the computation domain, and the liquid greatly caught the influence of the magnetic power at the upper part of the computation domain. We would like to compute different models including the effect of wettability and conduct computation close to the result of real phenomena.

6. References

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