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Institute of Electrical and Electronics Engineers

Lattice Boltzmann Method Analyzing Helium Bubbles Motion in Liquid Helium

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***Abstract*—To estimate the cooling capability of liquid helium in a superconducting magnet, it is indispensable to analyze the liquid helium flow and the bubble motion. However, it is almost impossible to understand them by means of the experiment or the numerical calculation based on Navier-Stokes equations. Therefore, we have developed the lattice Boltzmann method to analyze the liquid helium flow and/or the bubble motion in superconducting magnets.**

In the analysis, the temperature distribution in liquid helium together with the convection was calculated. Then helium vapor bubbles were formed on the heat transfer surface where the temperature was higher than the boiling point. The buoyancy of bubble was taken into account and results in the aggregation of the bubbles. The heat flow in liquid helium could also be calculated. The applicability of this method to the stability analysis of superconducting magnet is also discussed.

***Index Terms*—Buble, lattice Boltzmann method, liquid helium, superconducting magnet.**

I. Introduction

Analysis of the complex flow of liquid helium is not only challenging but also an important task in order to evaluate the cryogenic stability of a superconducting magnet. For example, the multiphase turbulent flow is difficult to analyze by conventional numerical calculations based on Navier-Stokes equations. Therefore, the development of new calculation methods of complex flow is needed. In a previous paper [1], we investigated the cooling capability and the stability of superconducting magnets by analyzing the convection of liquid helium in the superconducting magnet. However, the bubble formations in liquid helium were not considered and only the sub-cooled regime was studied.

In the present paper, we consider the void formation of liquid helium and treat the combined model of bubble formation and convection. In the calculation, we apply the lattice Boltzmann method which is suitable for the analysis of the complex heat transfer problems [2]. The multiphase model of lattice Boltzmann method forms the nonidentical spatial distribution (phase distribution) of the number density of the particles and its boundary (interface) self-systematically by introducing the repulsive interaction between the particles. Various methods have been developed in order to realize this repulsive force effect. Shen-Chen model [3], one of the methods which adds the fluctuation term of the number density of particles by the repulsive interaction into the equilibrium distribution function and performs BGK (Bhantnagar, Gross, Krook approximation) collision operation was used. In Shen-Chen model, change of momentum which each component obtains by interaction is reflected by the local velocity when calculating the local equilibrium distribution function of a collision term of the lattice BGK model. First, a particle distribution function is defined as every fluid component s, and the fundamental equation of a lattice BGK model as follows is performed for every fluid component.

$$f_i^s(x+c_i,t+1) = f_i^s(x,t) - \frac{f_i^s(x,t) - f_i^{s(eq)}(x,t)}{\tau_s}, \quad (1)$$

where s and i is $1,\ldots,S$ and $0,\ldots,6$ and in this calculation we decided S $=$ 2 since we considered two-phase flow. Although a local equilibrium distribution function $f_i^{s(eq)}$ is calculated using local velocity u when the particle distribution function is inputted at a lattice point generally, in this model, it is calculated using velocity u_s^{eq} which is obtained by the momentum described as follows after interacting with each component.

$$\rho_s(x)u_s^{eq}(x) = \rho_s(x)u'(x) + \tau_s\frac{dp_s}{dt}(x), \quad (2)$$

where $\rho_s = \sum_i f_i^s$ is fluid density of every component s, u' is the average flow velocity of the whole component at the time of an input, and is given by the following equation.

$$u' = \frac{\sum\limits_s \frac{\rho_s u_s}{\tau_s}}{\sum\limits_s \frac{\rho_s}{\tau_s}} \quad (3)$$

Furthermore, dp_s/dt of the 2nd term of the right-hand side of (2) describes the change of the total momentum obtained as a result of the interaction between the fluid component s and the other component s$'$ at the surrounding space $x+c_i$, and generally is given by the following equation.

$$\frac{dp_s}{dt}(x) = -\psi_s(x)\sum_{s'=1}^{S} g_{ss'}\sum_{i=0}^{6}\psi_{s'}(x+c_i)c_i, \quad (4)$$

where c_i is the translation velocity shown in the distribution function f_i, and $x+c_i$ is the nearest-neighboring site from coordinate x. The calculation method of this interaction is shown in Fig. 1. The calculation of phase separation was performed by applied for the components 1 and 2. In (4), $\psi_s = \psi_s(\rho(x))$ represents the practice fluid density of component s, and In order to

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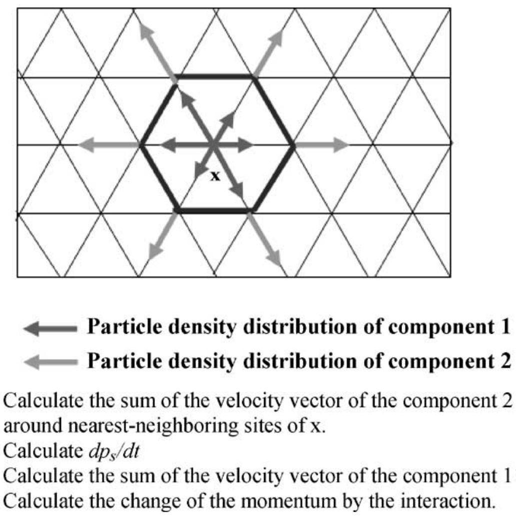

Fig. 1. Changing momentum of component 1 by interaction.

reproduce the spontaneous phase separation phenomenon of one component and two fluid system as liquid and gas, it is given as $\psi = \rho_0[1 - \exp(-\rho/\rho_0)]$. In order to reproduce phase separation of two immiscible component system, is given as $\psi_s = \rho_s$. We applied, $\psi_s = \rho_s$ and $g_{ss'}$ is a constant matrix which controls the intensity of the interaction between component s and s′, and is able to control the interfacial tension between fluid component and wetting as its development.

II. Calculation Method

If we try to analyze the state of large system with real CIC conductor, the arrangement of the strand wires is complicated, that the calculations become difficult. So, we analyzed the local area generating the following states that are important to evaluate cooling stability; disturbance generating, joule heat generation by the temperature rise in a conductor, heat transfer to a coolant, generating of quench, and void formation. Cooling stability is evaluated by computer simulations in the above mentioned calculation systems.

The analysis procedures simulating the convection by heat generation are described in the previous paper [1]. We analyzed the separation of liquid and gas of two immiscible components system by using Shen-Chen model [3] for multiphase fluid. Two kinds of particles are considered, particles 1 (helium molecules in the gas phase) and particles 2 (in the liquid phase), and the calculation field was discrete with a 2-dimensional hexagonal lattice with size of unit length 1, and the velocity was also discrete.

The effect of gravity was introduced into calculations by adding the particle density at a constant rate. The phase separation was realized by introducing the interaction between particle 1 and particle 2 shown in Fig. 1. Initial numerical densities of particle 1 and particle 2 are set to 0.2 and 0.8 per unity lattice point, respectively, and total density is 1.

Fig. 2 shows the geometry of calculation system. The bounce-back boundary condition is introduced into the surrounding walls. The number of lattice points of calculation system (a) is set to 100 × 100 point grid (18.9 × 18.9 mm; a length of a point grid corresponds to 0.189 mm), and the effect of gravity is not considered. Thereby, we confirm that

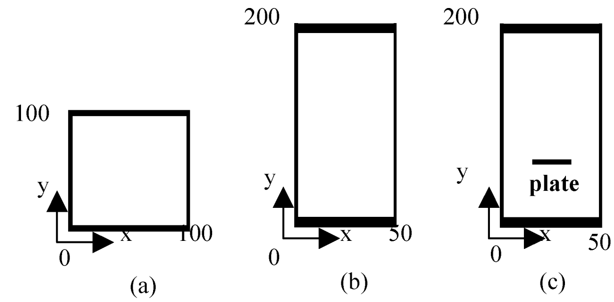

Fig. 2. Calculation system of multiphase model.

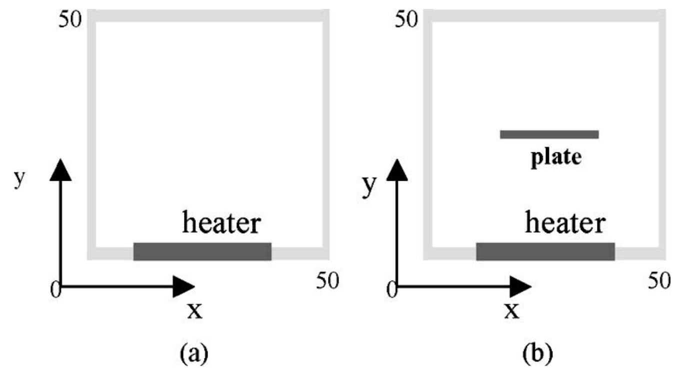

Fig. 3. Calculation system of combining model.

the phases of particles 1 and 2 are separated with time. The number of lattice points of the calculation system (b), (c) was set to 50 × 200 point grid size (9.4 × 37.8 mm). The effect of gravity was considered in those cases, and the rise of helium bubbles by the effect of the buoyancy was simulated. In the calculation system (c), the plate was inserted in x = 20–30 and y = 50, and we simulated the process of generated helium bubbles captured at the plate.

In the model which combines the analysis of the convection and the two-phase fluid of gas and liquid mixing, a total of four kinds of particles of the red and blue particle for the convection model [1], and the particle 1 (gas phase) and 2 (liquid phase) for two-phase fluid model are used. The procedure of calculation is given as followed.

1) The temperature of all lattice points is calculated by the density ratio of red particles and blue particles.
2) Two-phase fluid model is calculated at the lattice points where the temperature becomes higher than the constant value.
3) The calculation of the translation and collision for red and blue particles and particles 1 and 2 are independently carried out.

The calculation system is set to a 2-dimensional hexagonal lattice as similar as the analysis of the liquid-gas mixed flow. The calculation of the effect of the gravity was introduced into blue particles [1] and particles 2 (liquid phase). The initial density of both red and blue particles is set to the unity, and those of particles 1 and 2 are set to 0.2 and 0.8, respectively. The calculation systems of the combined model are shown in Fig. 3. The heater is set at x = 10–40 and y = 0. At the heater different from the wire used by the convection model [1], all the

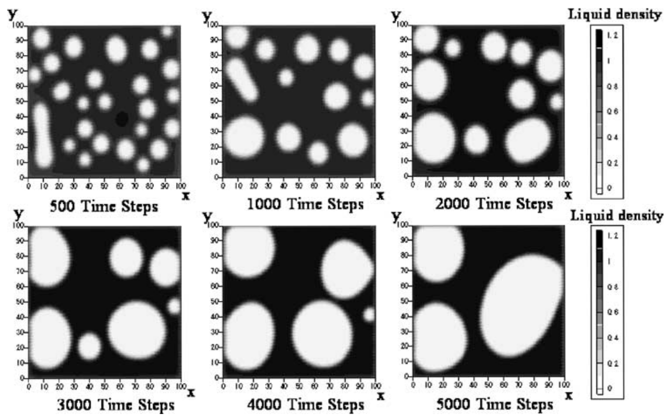

Fig. 4. Density distribution of liquid helium.

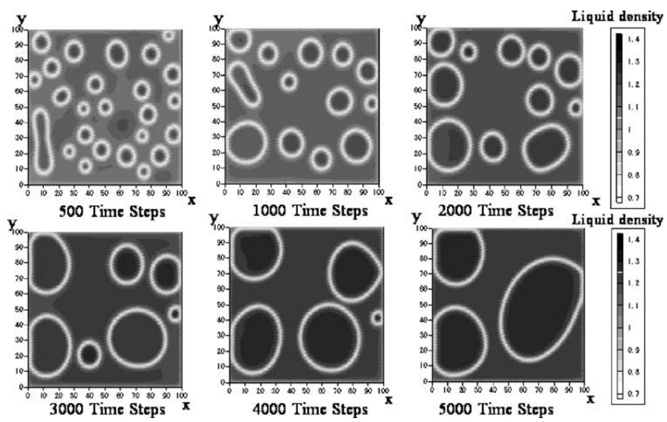

Fig. 5. Total density distribution of liquid and gaseous helium.

blue particles that went into the heat source changed to red particles and bounced off. In the calculation system (b), the plate was set in the position $x = 15–35$ and $y = 30$, and the process of the convection vanished by the plate and the behavior of the bubbles were compared.

III. Results and Discussion

The two-phase separation is considered using Shen-Chen model. We took $\tau = 0.55$ time step (one time step corresponds to 1.1 μs) which is single-time relaxation coefficient, equivalent to the viscous coefficient $5.0 \times 10^{-6}\ \mathrm{Pa \cdot s}$ of liquid helium. The heat transfer is not considered in this multiphase fluid model. Fig. 4 shows the result of the calculation system in Fig. 2(a). This figure is the time evolution of the density distribution of liquid helium. The small density parts, that is to say, the white regions in this figure are gas. With the progression of phase separation with time, gas becomes bigger.

Fig. 5 shows the total density distribution of particles 1 (gas phase) and particles 2 (liquid phase). The parts of the small density whose shapes are rings were seen in this figure, and these were interfaces generated by two kinds of particles. This indicates that the interface between gas and liquid is generated normally. Next, the effect of the gravity was considered in this two-phase fluid system. Fig. 6 shows the results of the calculation in Fig. 2(b). The white parts (gas) goes up and gets bigger with time. Furthermore, Fig. 7 shows the results of the system inserting a plate at $x = 20–30$ and $y = 50$ as shown in Fig. 2(c).

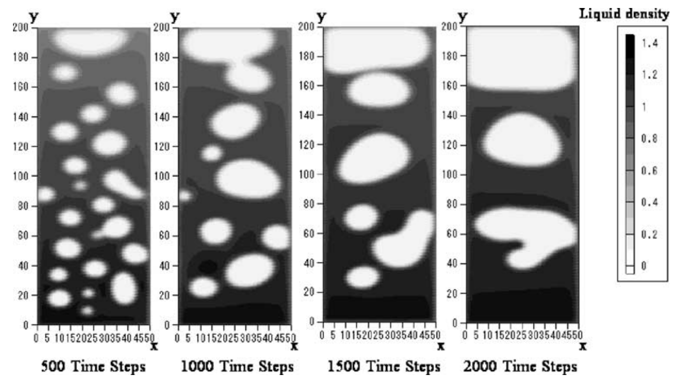

Fig. 6. Density distribution of liquid helium introducing the effect of gravity.

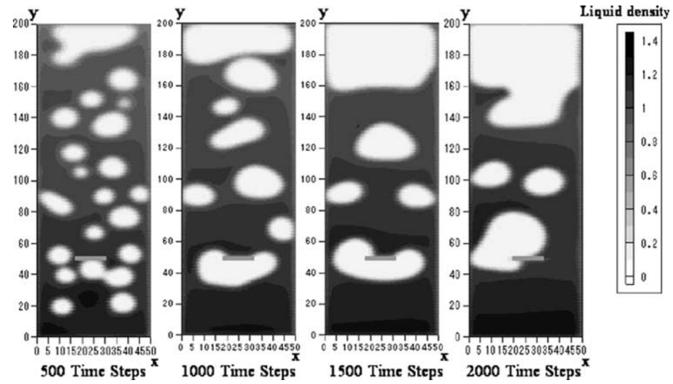

Fig. 7. Density distribution of liquid helium introducing the effect of gravity with a flat plate.

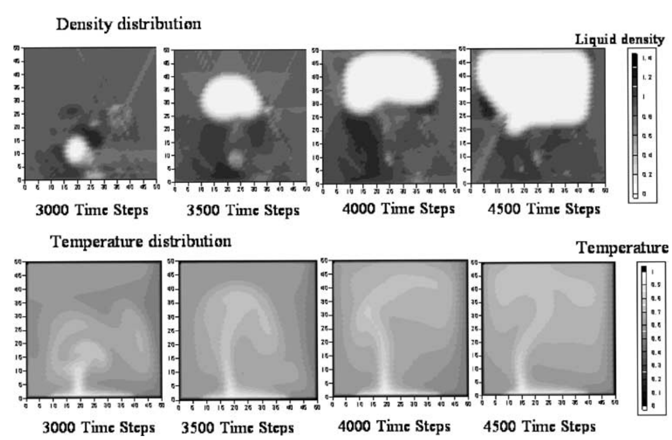

Fig. 8. Density distribution and temperature distribution of liquid helium by using combining model.

It was found that the rising of the gas parts was decreased by an insertion of plate and remained on that area. Therefore, by introducing the dynamic change of gas into the convection model, when void appears, the heat propagation can be analyzed, and the various behaviors of liquid helium can be calculated.

The combined model of the convection and the two-phase fluid of gas-liquid mixing are calculated. A series of instability states, such as generation of convection and void after generating the heat at the wire, which occurs within the superconducting magnet, could be analyzed. Fig. 8 shows the temporal evolution of the density distribution of particle 2 (liquid phase) and the temperature distribution of red and blue particles. The

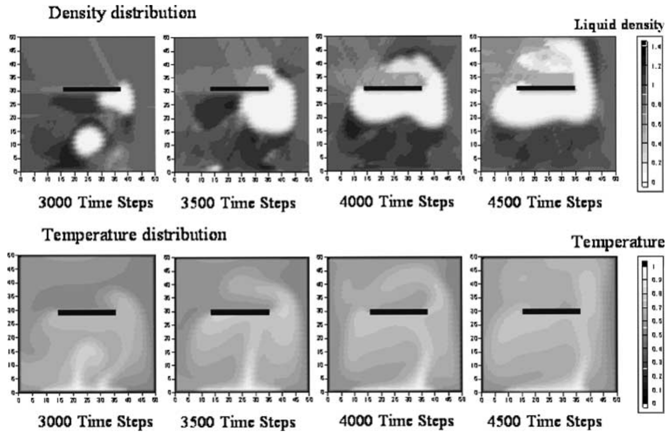

Fig. 9. Density distribution and temperature distribution of liquid helium by using combining model with a flat plate.

temperature of liquid helium rises due to the convection over the time. As the temperature of liquid helium rises, the generated vapor bubbles grow and go up.

Fig. 9 shows the time evolution of the density distribution of particle 2 (liquid) and the temperature distribution of red and blue particles in Fig. 3(b). The temperature in the region between a plate and a heater rise locally since the plate is (liquid phase) and the temperature distribution of red and blue obstructive. Consequently, generation of the bubbles in the region between a plate and a heater is remarkable. Moreover, it is found that the rising up of bubbles was decreased by the insertion of a plate. By this generation of void, it is thought that the heat transfer to liquid helium from a heater becomes smaller.

IV. Conclusions

We developed new method to analyze the helium bubble formation. The combined calculation, in which both of convection and bubble formation were considered, enabled the analyze of the following maters: heat conduction of wires, convection of liquid helium, and generation of voids. By using this calculation technique, the evaluation of cooling stability of the system, which is close to an actual condition, can be estimated.

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