THE SUMMARY OF Ph. D. DISSERTATION

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Title Development of the Practical Numerical Schemes for Moving Interfaces Using a Finite Element Method

Abstract

In this thesis, numerical schemes based on a finite element method are developed to investigate various interface phenomena including the jump conditions and deformations of gas-liquid, solid-liquid interfaces. Some of the analyses are conducted under the electromagnetic field to evaluate the effect of control with the Lorentz force, and the non-gravity field, that is similar to the condition of a space laboratory. The moving interfaces are often controlled for the industrial needs, and the effect of surface tension appears clearly when the materials are grown in space. Because of the difficulty of the experiment on the interfaces set in special surroundings, it is worth developing the practical numerical schemes satisfying accuracy, economy, universality, and stability. The following is the composition of this study.

Chapter 1 is an introduction which describes the background and purpose of this thesis first. The outlines of the interface problems are summarized, and some of the conventional researches relating to the moving interfaces are presented to clarify the position of this study.

In Chapter 2, a numerical scheme of the Marangoni convection is developed with a finite element method. Since the jump condition on a free surface is described as the jump quantity of the stress vector, it is successfully introduced into the boundary integral term added in the weak form of the Navier-Stokes equation formulated in accordance with the weighted residual method. After that, the space-discretized equation considering the Marangoni effect is obtained by the Galerkin method. In order to verify the present scheme, numerical analysis is carried out with the same condition of the experiment presented by Metzger et al, and the numerical results are compared with the experimental ones qualitatively and quantitatively.

The purpose of Chapter 3 is to develop a numerical scheme satisfying both accuracy and economy by coupling a level set method with an adaptive mesh refinement (LSM-AMR) to calculate the problems on large deformation of a free surface. In the explanation of this scheme, it is emphasized that the level set function and the smoothing band width are effectively utilized for the guide and the threshold of grid refinement or coarsening, respectively. In addition, the algorithm of the AMR in which a quadrangle grid is divided into four pieces in two dimensional calculation is also described in detail. After that, the numerical analyses of a collapse of a water column, a drop oscillation, and a drop rising in non-gravity are performed by using the present scheme. The effectiveness of this scheme is proved from the viewpoint of accuracy and economy as well as good agreement with other numerical and experimental results. On the other hand, some comments in terms of parameters for AMR and its limitation are made to clarify a range for effective use of the present scheme.

In Chapter 4, a numerical scheme dealing with the interaction between the flow and electromagnetic fields is developed to calculate the melt flow with a deformed free surface controlled by the electromagnetic force under the AC magnetic field. In the computation of the electromagnetic field, a boundary element method is adopted to the infinite gas area to treat the open boundary. While, a finite element method is done to the calculation domain formed by grids. These discretized equations are finally combined into Hybrid FEM-BEM. At this time, the physical quantities of two dimensional electromagnetic field are calculated with the vector potential method. In the computation of the flow field, a level set method is used to handle large deformation of a free surface. Then, numerical analysis of a conducting drop oscillation in non-gravity is carried out by using the present scheme to show its effectiveness.

In Chapter 5, a new numerical scheme is developed by applying the ALE method to the deformation problem of the solid-liquid interface in solidification and melting. The analytical object is the FZ crystal rod set in low gravity. In the present scheme, the difference between heat flux of solid and that of liquid at the nodes on the interface is calculated with the interpolation from an element value to a node one to obtain the interface velocity explicitly from the jump condition. Although the governing equations are discretized implicitly when the ALE method is applied to the moving interface problem, the computation speed is kept fast in this study by adopting the explicit iterative method with a predictor. After that, heat and fluid flow analysis in the FZ crystal rod is performed by using the present scheme, and the solid-liquid interface shape is investigated by varying gravitational acceleration and free surface condition. Moreover, the flow control effect with the DC magnetic fields and the resultant variation of the interface shape are examined by changing magnetic flux density.

In Chapter 6, the conclusions obtained here are summarized with the description of the characteristics and application limits of the present schemes. In addition, some further improvements are indicated for the future work.