Numerical Simulation of MHD Free Surface Liquid Metal Flows for Nuclear Fusion Applications

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論 文 内 容 の 要 旨

Thesis Summary

Nuclear fusion is a promising alternative energy source, with the potential to provide the world with virtually unlimited energy without adverse climatic or environmental impacts. Despite these theoretical prospects, several significant technical challenges remain, putting into question the practicality and commercial viability of this technology. Most prominent among these technical challenges is the problem of designing plasma-facing components (PFCs) that can withstand the extreme heat and particle loads anticipated in reactors of practical scales. The PFC designs presently used in research reactors will not be adequate to handle the tremendous heat fluxes which are anticipated in future DEMO and commercial Tokamaks. At such extreme heat loads, solid components experience excessive melting and evaporation, compromising their structural integrity and adversely impacting plasma confinement. To address the shortcomings of solid PFC designs, several alternative concepts that utilize a flowing liquid metal surface have been proposed. Liquid metal PFCs, however, introduce several technical challenges. This is because the operation of such devices gives rise to complicated phenomena spanning multiple disciplines of physics, most notably the interaction of electromagnetic fields with electrically conductive fluids, or magnetohydrodynamics (MHD).

The complicated interactions and extreme physical parameters associated with the phenomena do not lend themselves well to theoretical analysis and experimental study. Numerical simulation is a powerful tool that enables researchers to study such complex phenomena and assess the viability of different designs. To date, most numerical studies of fusion-related liquid metal flows focused on internal magnetohydrodynamic flows in ducts. Free surface flows add a layer of complexity to such phenomena, requiring additional careful treatment. However, most previous numerical studies of such problems employed simplified, steady, or two-dimensional models that may overlook crucial features of the flow.

In this work, a fully 3-dimensional and transient numerical tool for the simulation of free surface, thermo-MHD phenomena is developed in the framework of the finite volume method and implemented using the OpenFOAM open-source toolkit. The goal of this development is to create a tool that aids in the design of liquid metal PFCs. In the developed solvers, the solution of the electromagnetic equations is carried out in a coupled manner, both in the fluid and solid domains. The MHD forces exerted on the flow are computed using

the inductionless approximation that utilizes the electric potential as a solution variable. Furthermore, a solver that utilizes the magnetic vector potential is developed to include the effect of the induced magnetic field.

This thesis is organized in 3 parts, as follows:

1. Introduction:
   Chapter 1, Introduction: the background of the problem that motivated this work is discussed, including a literature review of previous relevant experimental and numerical studies.
   Chapter 2, Mathematical model: A detailed description of the mathematical model employed to describe magnetohydrodynamics, free surface flows and heat transfer is given, including a discussion of approximations used and boundary conditions.

2. Development and validation:
   Chapter 3, Numerical method: The numerical solution methodology is discussed, including a description of implementation and domain coupling procedure.
   Chapter 4, Validation: In this chapter, the developed solvers are validated for a number of relevant physical phenomena by comparing to analytical solutions and experimental measurements. This includes internal flows in ducts under the influence of strong uniform and variable magnetic fields. Validation is also carried out for internal, thermo-MHD flows, free surface flows with complicated free surface interactions and a first of its kind validation study of free surface MHD flows.

3. Applications:
   Chapter 5: Applications: in this chapter, the developed set of tools are used to simulate practical problems related to the use of liquid metals in fusion reactors. This includes a numerical study of a scheme to decrease the pressure drop due to a magnetic field gradient. Furthermore, the behavior in the fast-flowing film divertor is simulated, revealing interesting features that cannot be produced by reduced-order models. Finally, the divertorlets liquid metal plasma-facing component concept, which utilizes a relatively slow flow is simulated. Simulations yield good matching with experimental observations and reveal the effect of the electrical conductivity of the boundaries on the device performance.

This thesis is concluded with a summary of findings and details regarding outlook and future work, including additional physics and numerical improvements.