Applied Electromagnetics and Mechanics
T. Takagi and M. Uesaka (eds.)

Modeling of liquid walls in APEX study

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Abstract. Liquid wall concept has a significant place in the Advanced Power Extraction (APEX) study. In the present paper, different approaches for modeling liquid wall magnetohydrodynamics (MHD) and heat transfer in APEX have been presented. Turbulent flows of low-conductivity liquids, such as molten salts (Flibe), are analyzed using a two-equation turbulence model and DNS. The analysis of liquid metal (LM) flows under strong reactor magnetic field uses different 1.5-D, 2-D and 2.5-D models for laminar flows based on the Navier-Stokes-Maxwell equations.

1. Introduction

In fusion applications, electrically conducting mediums such as liquid metals are traditionally assumed to be the best working fluids. Due to their high electrical conductivity, liquid metals have strong MHD interaction, which manifests itself through different effects. Among these, the most important manifestation is the flow "laminarization" (suppression of turbulence) by a strong magnetic field. With the exception of some specific situations, no turbulence models are needed for LM MHD flows in fusion devices.

Along with liquid metals, molten salts are being carefully studied as a practical candidate for fusion applications [1]. For example, a 2 cm thick flow of Flibe moving poloidally along the reactor First Wall (FW) from the chamber top to the bottom with a velocity of 10 m/s is used in one of the designs of the APEX study [1]. Unlike liquid metals, such flows do not experience significant MHD forces and remain turbulent because electrical conductivity of molten salts is relatively low, about 10^4 times less than that of liquid metals. However, under a reactor strong magnetic field, turbulence pulsation in low-conductivity fluids can be partially suppressed with an accompanying reduction in heat transfer.

Accordingly to significant differences in the behavior of these fluids under fusion reactor conditions, different approaches are needed. In the APEX study, "K-ε" two-equation turbulence model extended to MHD flows and DNS are used for modeling of low-conductivity fluid flows. Laminar models based on the Navier-Stokes-Maxwell equations are applied to the analysis of LM flows. Both approaches require the induced currents and the free surface location to be calculated simultaneously with other flow quantities.

The paper describes general approaches used in the APEX study, while particular analyses for ARIES RS and NSTX reactors are given in [1-5]. Other results will be given in the extended paper.

2. Low-conductivity fluid modeling

"K-ε" turbulence model extended to MHD free surface flows has been used. The key features of the model are shown below. Assuming low magnetic Reynolds number and applying Reynolds averaging to the Navier-Stokes-Maxwell equations with the conventional closure approximations, one can derive the following equations for the turbulent kinetic energy, K, and the dissipation rate per unit mass, ε:

$$\frac{\partial K}{\partial t}+\left\langle v_j\right\rangle\frac{\partial K}{\partial x_j}=\underbrace{v_t\left(\frac{\partial v_i}{\partial x_j}\right)^2}_{\text{Production}}+\underbrace{\frac{\partial}{\partial x_j}[(\nu+\frac{\nu_t}{\sigma_K})\frac{\partial K}{\partial x_j}]}_{\text{Diffusion}}-\underbrace{\varepsilon-\varepsilon_{em}^{K}}_{\text{Dissipation}}; \qquad (1)$$

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$$\frac{\partial \varepsilon}{\partial t}+\langle v_j\rangle\frac{\partial \varepsilon}{\partial x_j}=C_1\frac{\varepsilon}{K}v_t\left(\frac{\partial v_i}{\partial x_j}\right)^2+\frac{\partial}{\partial x_j}[(v+\frac{v_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}]-C_2\frac{\varepsilon}{K}\varepsilon-\varepsilon_{em}^{\varepsilon}. \tag{2}$$

All terms and coefficients in (1-2) are standard except of ε_{em}, which stands for the Joule dissipation. The closure for the electromagnetic terms for two directions of the applied magnetic field, wall-normal and spanwise, was obtained as follows [2]:

$$\varepsilon_{em}^{K}=1.9\exp\{-1.0N\}\frac{\sigma}{\rho}B_0^2K\,;\ \varepsilon_{em}^{\varepsilon}=1.9\exp\{-2.0N\}\frac{\sigma}{\rho}B_0^2\varepsilon, \tag{3}$$

where N is the Stuart number built through the twice characteristic flow thickness; σ is the electrical conductivity; ρ is the density and B_0 is the applied magnetic field.

When developing the turbulence closure, the DNS data were used. These data indicate a redistribution of turbulence by the field that can be seen through the distributions of turbulent vortices and streaky structures in the near-wall region.

The turbulence model (1-3) along with the flow equations for mean quantities has been used in the analysis of Flibe liquid walls and Flibe evaporation into the ARIES RS reactor vacuum chamber [1,2,3].

3. Liquid metal modeling

LM MHD flows are analyzed using different laminar models in the 1.5-D, 2-D and 2.5-D approximation based on the Navier-Stokes-Maxwell equations:

$$\frac{\partial \vec{V}}{\partial t}+(\vec{V}\cdot\nabla)\vec{V}=-\frac{1}{\rho}\nabla p+\nu\Delta\vec{V}+\vec{f}_t+\frac{1}{\rho}\vec{j}\times\vec{B}; \tag{4}$$

$$\nabla\vec{V}=0;\ \nabla\vec{j}=0; \qquad (5), (6)$$

$$\vec{j}=\frac{1}{\mu_0}\nabla\times\vec{B}; \tag{7}$$

$$\frac{\partial \vec{B}}{\partial t}=\frac{1}{\sigma\mu_0}\Delta\vec{B}+\nabla\times(\vec{V}\times\vec{B}). \tag{8}$$

The equations are simplified using the inductionless approximation. The numerical procedure for solving (4-8) implements Volume of Fluid (VOF) method or mapping for tracking free surfaces [4]. The models have been applied to calculations of free surface flows in ARIES RS and NSTX reactors [1,4,5].

4. Acknowledgment

This work was performed under U.S. Department of Energy Contract DE-FG-03-86ER-52123.

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