Validation of COMSOL Multiphysics® for Magnetohydrodynamics (MHD) Flows in Fusion Applications

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Introduction

- MHD instabilities in liquid metal (LM) flows in a fusion reactor blanket associated with the mixed-convection phenomena have recently been recognized to be dominant, critically important to any LM blanket concept.
- Understanding and quantifying these effects is absolutely necessary to design a feasible LM blanket.
- The existing MHD codes lack the ability to capture such phenomena at high Ha, Re, and Gr numbers or this ability has not been demonstrated.
- Therefore, we initiated an effort to build and test a new computational methodology (physical/mathematical model, boundary conditions, numerical methods) to particularly address a class of time-dependent MHD flows with volumetric and surface heating.
- We selected COMSOL as the starting code for building 3-D MHD capability because it is a commercial 3-D multi-physics solver with many advanced capabilities.

Governing equations and Dimensionless parameters

- Flow equations: \( \nabla \cdot (\rho \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{f} \)
- Electric potential equation: \( \nabla^2 \phi = \nabla \cdot (\mathbf{u} \times \mathbf{B}) \)
- Ohm’s law: \( \mathbf{J} = \sigma (-\nabla \phi + \mathbf{u} \times \mathbf{B}) \)
- Heat transfer equation: \( \rho C_p \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \nabla \cdot (\mathbf{K} \nabla T) \)

Reynolds number (Re) Hartmann number (Ha) Grashof number (Gr)/Rayleigh number (Ra)

<table>
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<tr>
<th>Re: Ratio of inertia to viscous force</th>
<th>Ha²: Ratio of Electromagnetic to viscous force</th>
<th>Gr or Ra: Ratio of buoyancy to viscous force</th>
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<td>COMSOL</td>
<td>ALEX Experiment</td>
<td>HIMAG Code</td>
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Validation procedure and Results

- We follow the validation approach proposed in 2014 by Smolentsev et al [1].
- First, fully developed laminar MHD flows were computed and the results compared with the analytical Shercliff [2] and Hunt [3] solutions at high Ha up to 15,000 for electrically conducting and insulating ducts.
- Second, the COMSOL capability to address developing MHD flows was tested against available experimental data for 3D laminar steady MHD flows in a non-uniform transverse magnetic field [4].
- As a final test, two unsteady MHD flows were computed and the results compared against available 3D numerical data: (1) MHD flow in a horizontal cavity with volumetric heating [5] and (2) periodic MHD flow in conducting duct with thin electrically conducting walls [6].

1. Simulation of Shercliff, and Hunt flows

![Fig.1 Velocity distribution for Hunt flow at Ha = 15000 with electrically insulating on side wall and 0.01 of conducting ratio on Hartmann wall](image)

2. 3D laminar pipe MHD flow with fringing magnetic field

![Fig.2 Comparisons of non-dimensional pressure gradient distribution at point a, along flow direction with Ha = 2900 and Re = 15574](image)

3. Unsteady natural convection MHD flow in a cubic enclosure with volumetric heating. All walls are adiabatic except for top isothermal wall.

![Fig.3 Axially averaged temperature distribution along vertical axis with Ha = 200 and Ra = 1e6 (steady)](image)

4. Simulation of Kelvin-Helmholtz instability on isothermal flow generated naturally by high flow jet in an electrically conducting duct.

![Fig.5 Base velocity profile in a conducting](image)

Concluding Remark and Future Work

- All computations have demonstrated good qualitative and in most of the cases fair quantitative match with the available experiment, analytical and numerical data.
- It suggests that COMSOL can serve as a good CMHD tool along to analyze multi-physics effects in MHD flows for fusion applications.
- As a next step, we will apply our numerical methodology to analyze critical MHD instabilities under experimental and real blanket conditions.

References