3D Thermo-fluid MHD simulation of single straight channel flow in LLCB TBM

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Introduction

The LLCB blanket Concept is one of the prominent Concepts to breed the required tritium and achieve efficient heat removal for the Indian Demo reactor.

The capability of this concept will be validated experimentally by introducing a test blanket module (TBM) in ITER.

The design of TBM has to simulate the DEMO condition at ITER.

In this TBM, pressurized helium is used to remove the heat from walls and Pb-Li is used to extract heat from the breeder zones.

The flow of Pb-Li inside the channel can be significantly modified due to MHD effects.

A numerical approach is established to capture this flow modification at higher Hartmann number (~25000).
As a first step, a single straight flow channel is considered (2\textsuperscript{nd} flow channel).

Steady state fully developed laminar flow condition is assumed for the incompressible fluid.

The inlet temperature is considered as 368 °C.

Both conducting and insulating walls are studied.

Temperature dependent thermo-physical properties of the fluid are considered.

Toroidal width of the channel is 424 mm.
Problem Description: Nuclear Heat Load

<table>
<thead>
<tr>
<th>Zone Name</th>
<th>Dimension (mm)</th>
<th>Volume (m³)</th>
<th>Nuclear Heat Deposition (kW)</th>
<th>Heat Load (MW/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial</td>
<td>Toroidal</td>
<td>Poloidal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB-1</td>
<td>11</td>
<td>424</td>
<td>1455</td>
<td>0.00678612</td>
</tr>
<tr>
<td>FMS-3</td>
<td>5</td>
<td>424</td>
<td>1455</td>
<td>0.0030846</td>
</tr>
<tr>
<td>Alumina-3</td>
<td>0.2</td>
<td>424</td>
<td>1455</td>
<td>0.000123384</td>
</tr>
<tr>
<td>PbLi-2</td>
<td>50</td>
<td>424</td>
<td>1455</td>
<td>0.030846</td>
</tr>
<tr>
<td>Alumina-4</td>
<td>0.2</td>
<td>424</td>
<td>1455</td>
<td>0.000123384</td>
</tr>
<tr>
<td>FMS-4</td>
<td>5</td>
<td>424</td>
<td>1455</td>
<td>0.0030846</td>
</tr>
<tr>
<td>CB-2</td>
<td>15</td>
<td>424</td>
<td>1455</td>
<td>0.0092538</td>
</tr>
<tr>
<td>Right plate</td>
<td>30</td>
<td>506</td>
<td>1455</td>
<td>0.0220869</td>
</tr>
<tr>
<td>Left plate</td>
<td>30</td>
<td>506</td>
<td>1455</td>
<td>0.0220869</td>
</tr>
</tbody>
</table>
Numerical Model: *Basic hydrodynamics + MHD*

**Continuity (Mass Conservation):**
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0
\]

**Navier Stokes Equation (Momentum Conservation):**
\[
\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U} \mathbf{U}) = \nabla \cdot \mathbf{F} - \nabla p + \rho g + \mathbf{J} \times \mathbf{B}
\]

**Maxwell’s Equation**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Differential Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauss’s law</td>
<td>(\nabla \cdot \mathbf{B} = 0)</td>
</tr>
<tr>
<td>Faraday’s law</td>
<td>(\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0)</td>
</tr>
<tr>
<td>Ampère’s law</td>
<td>(\nabla \times \left( \frac{\mathbf{B}}{\mu_m} \right) = \mathbf{J} + \left{ \varepsilon \frac{\partial \mathbf{E}}{\partial t} \right} )</td>
</tr>
<tr>
<td>Ohm’s law</td>
<td>(\mathbf{J} = \sigma (\mathbf{E} + \mathbf{U} \times \mathbf{B}))</td>
</tr>
</tbody>
</table>
**Numerical Model: Induction and Potential based model**

**Induction Formulation:**

The magnetic induction equation that is derived from the Maxwell’s equations

\[ \frac{\partial B}{\partial t} + \nabla \cdot (BU) = \frac{1}{\mu_m \sigma} \nabla \cdot (\nabla B) + (B \cdot \nabla)U \]

The current density is computed from Ampere’s law as:

\[ j = \frac{1}{\mu} \nabla \times \vec{B} \]

**Potential Formulation:**

**Current Conservation:**

\[ \nabla \cdot \mathbf{J} = 0 \]

**Modified Ohm’s Law:**

\[ \mathbf{J} = \sigma (-\nabla \varphi + \mathbf{U} \times \mathbf{B}) \]

**Electric Potential Equation:**

\[ \nabla \cdot [\sigma (\nabla \varphi)] = \nabla \cdot [\sigma (\mathbf{U} \times \mathbf{B})] \]
## Numerical Model: Boundary Condition

<table>
<thead>
<tr>
<th>Boundary Condition</th>
<th>Magnetic Induction Method</th>
<th>Electric Potential Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid outer boundary when the fluid flows inside a conducting solid</td>
<td>$\mathbf{B} = \mathbf{B}_0$</td>
<td>$\frac{\partial \varphi}{\partial n} = 0$</td>
</tr>
<tr>
<td>Fluid boundary when the surrounding solid is a non-conducting wall</td>
<td>$\mathbf{B} = \mathbf{B}_0$</td>
<td>$\frac{\partial \varphi}{\partial n} = 0$</td>
</tr>
<tr>
<td>Fluid boundary when the surrounding solid is a perfectly-conducting wall</td>
<td>$\frac{\partial \mathbf{B}}{\partial n} = 0$</td>
<td>$\varphi = \varphi_0$</td>
</tr>
<tr>
<td>Fluid boundary when the surrounding solid is a partially-conducting thin wall</td>
<td>$\frac{\partial \mathbf{B}}{\partial n} = \frac{\mathbf{B}}{\mathbf{c}_w}$, $\mathbf{c}_w = \frac{\sigma_w t_w}{\sigma a}$</td>
<td>$\mathbf{J} \cdot \mathbf{n} = \nabla \cdot (\mathbf{c}_w \nabla_t \varphi_w)$</td>
</tr>
<tr>
<td></td>
<td>$\mathbf{c}_w = \frac{\sigma_w t_w}{\sigma a}$</td>
<td></td>
</tr>
</tbody>
</table>
Energy Conservation:

\[ C_p \left[ \frac{\partial (\rho T)}{\partial t} + \nabla \cdot (\rho \mathbf{UT}) \right] = \nabla \cdot (k \nabla T) \left[ \frac{\partial (\ln \rho)}{\partial (\ln T)} \right] \rho \left[ \frac{\partial p}{\partial t} + \mathbf{U} \cdot \nabla p \right] + S_v + S_T + \frac{\mathbf{J} \cdot \mathbf{J}}{\sigma} \]

where \( C_p \) = specific heat at constant pressure

Terms on the RHS:

The 1st term represents heat conduction,

The 2nd term work done by fluid expansion,

3rd term viscous dissipation,

4th term heat sources (e.g., heat generation),

The 5th term is the Joule heating.
Code Validation: *Benchmarking with Hunt’s case*

**Schematic of Hunt’s Case**

- **Hartmann No**: 25000
- **Hartmann Wall**: \( \sigma_{hw} = \infty \)
- **Side wall**: \( \sigma_{sw} = 0 \)

<table>
<thead>
<tr>
<th></th>
<th>Induction</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analytical</strong></td>
<td>Umax (m/s)</td>
<td>Umax (m/s)</td>
</tr>
<tr>
<td></td>
<td>22.6887</td>
<td>22.5817</td>
</tr>
<tr>
<td><strong>Code</strong></td>
<td>22.37</td>
<td>22.5817</td>
</tr>
<tr>
<td><strong>Error (%)</strong></td>
<td>1.405</td>
<td>0.472</td>
</tr>
</tbody>
</table>

- **Uc (m/s)**
- **Umax/Uc**

- **Simulation (dots)**
## Code Validation: Benchmarking with Hunt’s case

<table>
<thead>
<tr>
<th>Hartmann No</th>
<th>Hartmann Wall</th>
<th>Side wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>15000</td>
<td>$\sigma_{hw}=0$</td>
<td>$\sigma_{sw}=0$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Umax (m/s)</th>
<th>Uc (m/s)</th>
<th>Umax/Uc</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Induction</strong></td>
<td><strong>Analytical</strong></td>
<td><strong>Code</strong></td>
<td><strong>Error (%)</strong></td>
</tr>
<tr>
<td>Induction</td>
<td>0.18127</td>
<td>0.18127</td>
<td>1</td>
</tr>
<tr>
<td>Analytical</td>
<td>0.180738</td>
<td>0.180738</td>
<td>1</td>
</tr>
<tr>
<td>Error (%)</td>
<td>0.293</td>
<td>0.293</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Potential</strong></td>
<td><strong>Analytical</strong></td>
<td><strong>Code</strong></td>
<td><strong>Error (%)</strong></td>
</tr>
<tr>
<td>Potential</td>
<td>0.1856</td>
<td>0.186443</td>
<td>1.0045</td>
</tr>
<tr>
<td>Code</td>
<td>0.1856</td>
<td>0.186443</td>
<td>1.0045</td>
</tr>
<tr>
<td>Error (%)</td>
<td>2.389</td>
<td>2.854</td>
<td>0.450</td>
</tr>
</tbody>
</table>

Code results are in fairly good agreement with analytical results for the range of Hartmann no.s 15000-30000.

Both Induction and Potential methods gives rise to nearly similar results.

CPU time requirement is more for potential case (particularly insulating walls)
At first, the code is used to generate a velocity profile for the rectangular TBM channel (424×50 mm²) considering temperature ~368 °C.

This velocity profile is used at the inlet of the channel.

Conducting and insulating wall cases are solved for Hartmann no. 25000 and 30000.

In the presence of the given heat load condition, both momentum and energy equations are solved to get velocity and temperature profile along the flow direction.

Temperature dependent thermo-physical properties of the fluid are used.
Evolution of velocity profile (Conducting channel)

Profile across side walls

Profile across Hartmann walls

Slight change in profile is attributed to change in properties with temperature. No significant change for $Ha=25000$ and $30000$. 
Evolution of velocity profile (Insulating channel)

Profile across side walls

Profile across Hartmann walls

Here also change in profile is attributed to change in properties with temperature. No significant change for $Ha=25000$ and $30000$. 
Evolution of Temperature (Conducting channel)

Temperature °C

Poloidal Length (m)

Radial Length (m)

Temperature (C)

Toroidal Length (m)

Breeder

Pb-Li

FMS
Evolution of Temperature (Insulating channel)

- Pb-Li
- FMS
- Coating
- Breeder
Effect of change in breeder thermal conductivity

With increase in breeder thermal conductivity breeder temperature reduces, but the core temperature remains unchanged.
Summary

A numerical approach has been established to carry out thermo-fluid MHD analysis for LLCB TBM.

The code validation has been successfully done by comparing the results with existing analytical results for a 2D square channel. The results from both electric potential method and magnetic induction method have also been compared.

As a first step, the code has been used to solve the MHD flow in a straight single channel of LLCB TBM in the presence of two adjacent breeders, under steady state flow condition.

Both velocity and temperature profile have been generated for insulated and conducting channel walls.

All temperatures are found to be well within the operational limit.