Status of DCLL Manifold Modeling

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Thermofluid/MHD issues of DCLL

In the DCLL blanket, the PbLI flows and heat transfer are affected by a strong magnetic field

**Issues:**

- Impact of 3-D effects on pressure drop & flow distribution
  - *Flows in the manifold region*
  - Flows in non-uniform, 3-component ITER B-field
  - Pressure equalization via slots (PES) or holes (PEH)
  - FCI overlap regions
  - FCI property variations
- Coupled Flow and FCI property effects on heat transfer between the PbLi and He and and temperature field in the FCI and Fe structure
- Flow distribution, heat transfer, and EM loads in off-normal conditions

**Two lines of activity:**

**Experimental database.** Obtain experimental data on key MHD flows affecting operation and performance of the blanket for which there is little/no data available.
- Flow distribution in manifolds; FCI effectiveness and 3D flow issues
- Coupled heat transfer / velocity field issues

**Modeling tools.** Develop 2D and 3D codes and models for PbLi flows and heat transfer in specific TBM/DEMO conditions. Benchmark against existing and new analytical solutions, experimental data and other numerical computations.
- **HIMAG – arbitrary geometry 3D fully viscous and inertial parallel MHD solver**
  - 2D models and codes for specific physics issues – MHD turbulence and natural convection
Numerical methods for MHD flows at low \( Re_m \)

- Consistent and conservative scheme allows us to directly simulate MHD flows with high accuracy at high Hartmann numbers
- HIMAG, a parallel code developed on an arbitrary collocated mesh implemented with the consistent and conservative scheme for incompressible fluid flows, allows us to simulate MHD flows at complicated geometry
- Both of the scheme and HIMAG are validated for MHD flows at low magnetic Reynolds number and high Hartmann numbers with good accuracy

M.-J. Ni, R. Munipalli, N.B. Morley, P.Y. Huang, M.A. Abdou, Consistent and Conservative Schemes for MHD. Part I. on a rectangular mesh, under review

M.-J. Ni, M.A. Abdou, Consistent and Conservative Schemes for MHD. Part II. A fully conservative formula of the Lorentz force on an arbitrary mesh, under review


Applied to Hunt’s case with $\text{Ha} = 1k$ and $10k$

\textbf{a}: along the middle line normal to the Hartmann walls

\textbf{b}: along the middle line normal to the side walls
ALEX Duct flow experiment (C.B. Reed et al, 1987)

Case-1
- $B_{\text{max}} = 2.08 \, \text{T}$
- $H_a = 6640$
- $N = 11061$
- $R_e = 3986$
- $U = 0.07 \, \text{m/s}$

Case-2
- $B_{\text{max}} = 1.103 \, \text{T}$
- $H_a = 3500$
- $N = 770$
- $R_e = 15909.1$
- $U = 0.2794 \, \text{m/s}$

Pressure gradient comparison between Hartmann and side-layer
Simulation of a 3D sudden expansion MHD flows
Experimentally conducted by Leo Buhler’s group

Theoretical analytical solution of pressure gradient

\[
\frac{\partial p}{\partial x} = \begin{cases} 
-0.37479 & \text{for } x < 0 \\
-0.02057 & \text{for } x > 0
\end{cases}, \quad \text{as } Ha \to \infty
\]
Application of HIMAG to Manifold Problem

$Ha$ and $Re$ based on parallel channel half-width and average velocity:

For TBM, $Ha\sim 6000$, $Re\sim 35000$, $N\sim 1028.57$

<table>
<thead>
<tr>
<th>Inlet directions</th>
<th>Insulated walls</th>
<th>Conductive walls</th>
<th>Fully cond. wall</th>
</tr>
</thead>
</table>
| **X direction**  | Ha=929.16, Re=1500, N=575.56  
Ha=929.16, Re=3000, N=287.78  
Ha=657.03, Re=1500, N=287.78 | Ha=929.16, Re=1500, N=575.56  
Ha=929.16, Re=3000, N=287.78  
Ha=657.03, Re=1500, N=287.78 | Ha=929.16, Re=1500, N=575.56 |
| **Z direction**  | Ha=929.16, Re=1500, N=575.56  
Ha=929.16, Re=3000, N=287.78  
Ha=657.03, Re=1500, N=287.78 | Ha=929.16, Re=1500, N=575.56  
Ha=929.16, Re=3000, N=287.78  
Ha=657.03, Re=1500, N=287.78 | Ha=929.16, Re=1500, N=575.56 |

- 3D complex geometry
- Strong MHD interaction
- Flow directions
- Flow rate balance
- Velocity profile
- Pressure drop
Geometry and Flow Conditions

Fully insulated wall or fully conductive wall conditions

With wall thickness included

Vertical flow inlet
Wall thickness resolved
Numerical Results of Manifold for $Ha=929.16$, $Re=1500$, $N=575.56$

Velocity profiles from inlet to outlet

The center channel has flow rate 10.8% above the uniform flow, and the side channels have -5.4% below the uniform flow.

Current distribution at the outlet shows that the flows here is fully developed

Velocity vector shows M Shape Velocity, and Vortex Parallel to the magnetic field
Parameters to be matched with experimental data

Electrical potential

3D current streamlines

Pressure distribution

3D velocity streamlines
Velocity profiles for insulated walls and partially fully conductive wall

Ha=929.16, Re=1500, N=575.56

Ha=929.16, Re=3000, N=287.78

Ha=657.03, Re=1500, N=287.78

Fully conductive walls
Ha=929.16, Re=1500, N=575.56
Flow Rate Balance between Central Channel and Side Channels

$\text{Ha}=929.16$, $\text{Re}=1500$, $N=575.56$

The center channel: **10.8%** above the uniform flow
The side channel: **-5.4%** below the uniform flow.

$\text{Ha}=929.16$, $\text{Re}=3000$, $N=287.78$

TBM, $\text{Ha} \sim 35000$, $N \sim 1028.57$

The center channel: **17.46%** above the uniform flow
The side channel: **-8.73%** below the uniform flow.

$\text{Ha}=657.03$, $\text{Re}=1500$, $N=287.78$

The center channel: **25.76%** above the uniform flow
The side channel: **-12.88%** below the uniform flow.

$\text{Ha}=929.16$, $\text{Re}=1500$, $N=575.56$

The center channel: **0.1%** above the uniform flow
The side channel: **-0.05%** below the uniform flow.

Fully conductive walls
Summary

HIMAG and the consistent and conservative scheme have been used to simulate idealized manifold geometry with different parameters and conditions.

Velocity profile, electrical potential, pressure drop (distribution) and flow rate balance continue to be studied and analyzed, and will be compared with experiment.

There exists flow rate imbalance between central channel and side channels for fully insulated walls (perfect FCI case).

- This flow rate imbalance is a function of $Ha$, $Re$ and $N$ numbers, as well as wall conditions.
- When interaction number is fixed at 287.8, increasing Hartmann (from 657 to 929) & Reynolds numbers (from 1500 to 3000) show a reduction in the flow rate imbalance. It is not clear yet how this trend extrapolates, esp for TBM at $Ha$~6000 and $Re$~350k.
- Also a perfectly conductive expansion wall can reduce the flow imbalance between the central channel and side channels. It is not clear yet how “real” conductive walls will behave.

Further calculations of manifold with “real” conductive walls resolved, and with different inlet geometry and outlet conditions are needed. Estimation of pressure drop is also needed.