MHD ANALYSIS

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ISSUES

• Effectiveness of SiC$_f$/SiC as electrical/ thermal insulator

• Some thoughts on openings in the FCI

• MHD pressure drop in ITER TBM

• Flow and heat transfer in the concentric pipe

• Other issues
Effectiveness of SiC$_f$/SiC as electrical/thermal insulator

- 2-D MHD and 3-D heat transfer analysis were performed for the reference blanket module for the FCI with two types of pressure equalization openings: PEH or PES for $\sigma = 5\text{-}500\ (\Omega\text{m})^{-1}$ and $k = 2\text{-}20\ W/\text{m}\cdot\text{K}$.

- The results have been summarized in two papers:

- **Main conclusions are:**
  - 5 mm FCI with $\sigma=20\text{-}50\ S/\text{m}$ reduces $\Delta P$ by $\sim 10^2$;
  - No heat escape from Pb-17Li core was observed at $k=2\ W/\text{m}\cdot\text{K}$, $\sigma=20\text{-}50\ S/\text{m}$.
  - Rough estimate for energy distribution is 40% in He and 60% in Pb-17Li.
- $\sigma$ affects not only the heat flux through the FCI but also $\Delta T$ across the FCI, and the liquid metal – Fe wall temperature. Reducing $\sigma$ results in smaller MHD pressure drop, but causes higher $\Delta T$ and higher interface temperature. The effect of $k$ is just thermal insulation.

Radial temperature variations in the vicinity of the front wall at the flow exit calculated at $k = 2$ W/m-K (a); $\sigma = 20$ (\Omega m)$^{-1}$ (b).

- Present conclusions from the MHD analysis can easily be extrapolated to the ITER TBM, since conditions are pretty much the same

- Heat transfer for ITER TBM will require special considerations, since conditions are different: lower thermal loads, unsteady regime, low/high performance regimes. The same codes can be used.
Induced magnetic field distribution in the domain with PES.

Flow in the gap (PEH): Hartmann gap (a); side gap (b).

Velocity profiles in the reference MHD flow: PEH, $\sigma = 500 \, (\Omega m)^{-1}$ (a); PEH, $\sigma = 5 \, (\Omega m)^{-1}$ (b); PES, $\sigma = 500 \, (\Omega m)^{-1}$ (c); PES, $\sigma = 5 \, (\Omega m)^{-1}$ (d). The velocities are scaled with the mean velocity in the bulk flow.

Temperature field ($^\circ C$) at $\sigma = 20 \, (\Omega m)^{-1}$ and $k = 15 \, W/m-K$. The domain includes the bulk flow, gap, FCI and the ferritic wall. T is shown in the cross-sectional plane at the flow exit (a), and in the poloidal-radial plane at $Z = 0$ (b).
Some thoughts on openings in the FCI

- Increasing the opening area will result in better pressure equalization, but higher MHD pressure drop and heat/tritium leakage. The effect of openings on the pressure equalization has not been justified yet. What is the opening area that assures good equalization effect without serious impact on the MHD pressure drop and with reasonable heat/tritium leakage?

- Pressure is equalized via two mechanisms: fluid flow (1); electric current flow (2). Unlike fluid, electric currents can flow not only through the openings but also through the FCI. This may result in better pressure equalization:

\[
\nabla^2 p = S_p^V + S_p^J
\]

\[
S_p^J = \frac{\partial}{\partial x} \left( j_z B_y^0 - j_y B_z^0 \right) + \frac{\partial}{\partial y} \left( j_x B_z^0 - j_z B_x^0 \right) + \frac{\partial}{\partial z} \left( j_y B_x^0 - j_x B_y^0 \right)
\]

- Over the fully developed flow section, both pressures are the same. Both core and gap flows are driven by the same pressure head.

- It appears that requirements for openings are not so severe as it was thought before. Nevertheless, the effect of openings on the pressure equalization should be accessed.
### MHD pressure drop in TBM

<table>
<thead>
<tr>
<th>Flow</th>
<th>$\Delta P$, MPa (high performance)</th>
<th>$\Delta P$, MPa (low performance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front channels</td>
<td>$0.177 \times 10^{-3}$</td>
<td>$2.12 \times 10^{-3}$</td>
</tr>
<tr>
<td>Return channels</td>
<td>$0.224 \times 10^{-3}$</td>
<td>$2.69 \times 10^{-3}$</td>
</tr>
<tr>
<td>Concentric pipe (internal, uniform B-field)</td>
<td>$7.1 \times 10^{-3}$</td>
<td>$0.085$</td>
</tr>
<tr>
<td>Concentric pipe (annulus, uniform B-field)</td>
<td>$0.0132$</td>
<td>$0.158$</td>
</tr>
<tr>
<td>Concentric pipe (internal, fringing B-field)</td>
<td>$0.027$</td>
<td>$0.329$</td>
</tr>
<tr>
<td>Concentric pipe (annulus, fringing B-field)</td>
<td>$0.027$</td>
<td>$0.329$</td>
</tr>
<tr>
<td>Inlet manifold</td>
<td>$0.032$-$0.064$</td>
<td>$0.39$-$0.77$</td>
</tr>
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<td>$0.032$-$0.064$</td>
<td>$0.39$-$0.77$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.138-0.202</strong></td>
<td><strong>1.68-2.45</strong></td>
</tr>
</tbody>
</table>

- Calculations of $\Delta P$ include numerical simulation, analytical solutions, and empirical correlations.
- Flow turns at the top and bottom of the TBM occur in the plane perpendicular to the magnetic field. Corresponding losses are small.
- The total $\Delta P$ is mostly contributed by the flows in the manifolds and in the concentric pipe over the fringing magnetic field zone. Such pressure losses can’t be reduced by insulation.
- Uncertainty in $\Delta P$ is related to manifold flows.
Flow and heat transfer in the coaxial pipe

- Calculations were performed for a rectangular duct flow of the same structure.
- Therefore, current and velocity distributions shown in the picture are qualitative.
- Currents in the top and bottom sections of the annulus (I and II) almost do not interact with the magnetic field. As a result, most of the flow is localized within these two sections. Flow in the side sections is reduced.
- Core flow is almost uniform.
- The effect of such a flow on heat transfer is being accessed.
- The goal of the analysis is to see if the interface temperature is below the corrosion limit.
Other issues

• The model currently used is incomplete. Heat transfer will be strongly affected by natural convection and 2-D MHD turbulence.

• The increase of effective thermal conductivity due to 2-D MHD turbulence is by more than one order of magnitude. There will be reduction of the side-wall jets due to turbulent diffusion.

• Natural convection (circulation) velocity is much higher than the operation velocity. The flow will most likely be turbulent even though the magnetic field is strong. This will result in a pretty uniform temperature distribution in the radial direction.

• Significant progress has recently been achieved as a result of cooperation with Prof. Rene Moreau (Grenoble, France).
Example: 2-D turbulence

- Zero-equation turbulence model has been derived for 2-D MHD turbulence
- Comparisons were performed between pure laminar (left) and turbulent (right) flows
- Turbulent flow demonstrates significant reduction of the side-wall jets
- MHD pressure drop is approximately the same in these two flows
- Effective thermal conductivity in the turbulent case is about 10 times higher