CURRENT APPROACHES TO MODELING MHD FLOWS IN THE DUAL COOLANT LITHIUM-LEAD BLANKET

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Introduction. Here, we review modeling approaches developed at UCLA, and present some calculation results for MHD flows in the dual coolant lithium-lead (DCLL) blanket of a fusion power reactor [1]. In the DCLL blanket, the self-cooled breeder, Pb-17Li, circulates for power conversion and tritium breeding, experiencing MHD effects. A typical blanket channel configuration is shown in Fig. 1. A key element of the concept is the flow channel insert (FCI) made of silicon carbide composite (SiC_f/SiC), which is used as an electric insulator to reduce the impact from the MHD pressure drop, and as a thermal insulator. The FCIs are seated inside the blanket channel, without having direct contact with the ferritic channel walls. The same pressure head drives the liquid through the channel and the thin gap between the FCI and the ferritic wall. There can be openings in one of the walls of the FCI, such as a pressure equalization slot (PES), to equalize the pressure on both sides of the FCI, thus resulting in almost no primary stresses in the insert. The basic channel dimensions and other related parameters are summarized in Table 1.

The paper considers MHD effects in the flows in the reference blanket channel. First, the flows are treated as fully developed. A zero-equation turbulence model was added to incorporate 2-D turbulence phenomenon. Buoyancy effects are then analyzed using a quazi-2-D flow model. As a potential tool for simulation of complex blanket flows, newly-developed MHD software (HIMAG) is introduced.

1. Fully developed flow with FCI. A mathematical model for a fully developed flow in the blanket channel (Fig. 1) in a toroidal magnetic field, B_z^0, is

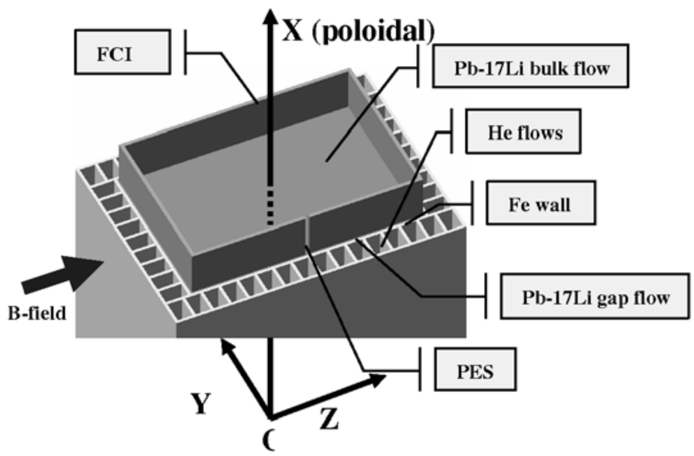

Fig. 1. Typical poloidal blanket channel with FCI and helium cooling channels. There can be openings in the FCI (a slot or holes) to equalize the pressure on both sides of the insert.

Table 1. DCLL blanket channel parameters

Poloidal length, L:	2 m	Ferritic wall thickness:	0.005 m
Toroidal width, $2b$:	0.3 m	PES width:	0.005 m
Radial depth, $2a$:	0.2 m	Magnetic field (outboard), B_z^0:	4 T
FCI thickness:	0.005 m	Pb-17Li flow velocity, U_0:	0.06 m/s
Gap width:	0.002 m	Inlet Pb-17Li temperature:	460°C

formulated in terms of the flow velocity (U) and induced magnetic field (B_x):

$$\frac{\partial}{\partial z}\left[(\nu+\nu_{tz})\frac{\partial U}{\partial z}\right]+\frac{\partial}{\partial y}\left[(\nu+\nu_{ty})\frac{\partial U}{\partial y}\right]-\frac{1}{\rho}\frac{dP}{dx}+\frac{B_z^0}{\rho\mu_0}\frac{\partial B_x}{\partial z}=0; \quad (1)$$

$$\frac{1}{\mu_0}\frac{\partial}{\partial z}\left(\frac{1}{\sigma_z}\frac{\partial B_x}{\partial z}\right)+\frac{1}{\mu_0}\frac{\partial}{\partial y}\left(\frac{1}{\sigma_y}\frac{\partial B_x}{\partial y}\right)+B_z^0\frac{\partial U}{\partial z}=0. \quad (2)$$

The model incorporates turbulence via ν_t. In a strong magnetic field turbulence is anisotropic; a closure relation is needed for ν_{ty}, while ν_{tz}=0. The following closure relation was obtained using experimental data of [2]:

$$\frac{\nu_{ty}}{\nu}=\frac{a}{b}\mathrm{Re}_*\Big[1-\exp\big\{-\sqrt{\mathrm{Ha}}\big(a/b-|y/b\,|\big)\big\}\Big]. \quad (3)$$

Here, Re_* is constructed through the characteristic velocity difference, $U_* = U_{\max} - U_{\min}$, and $\mathrm{Ha} = B_z^0 b\sqrt{\sigma/\nu\rho}$. An exponential correction is introduced to suppress turbulence production at the side walls, where the flow is supposed to be laminar. A finite-volume code has been developed to solve Eqs. (1), (2) in a "sandwich-type" domain [3]. The code includes automatically generated Hartmann number sensitive meshes, and effective convergence acceleration technique. The electrical conductivity of $\mathrm{SiC_f/SiC}$ depends on the fabrication technique. The computations were performed in a parametric form for σ_{SiC} =5–500 S/m. The velocity profile demonstrates high velocity jets near the side walls (Fig. 2). Both the jets in the bulk flow and the flow in the side gaps are reduced as σ_{SiC} decreases. There is strong reduction of the near-wall jets when the flow is treated as turbulent.

2. Buoyancy effects. The buoyancy effects on the flow are modeled in the Boussinesq approximation on the basis of a quasi-2-D model for MHD flows

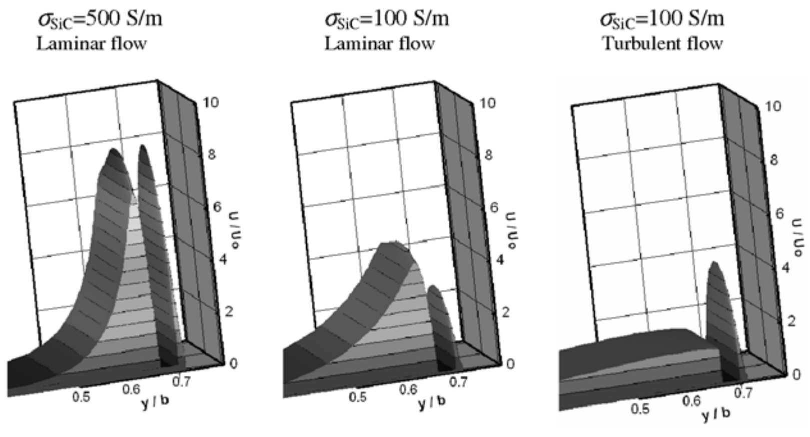

Fig. 2. Near-wall jets and flow in the gap at different SiC at Ha = 15, 900. The velocity is scaled by the mean velocity U_0.

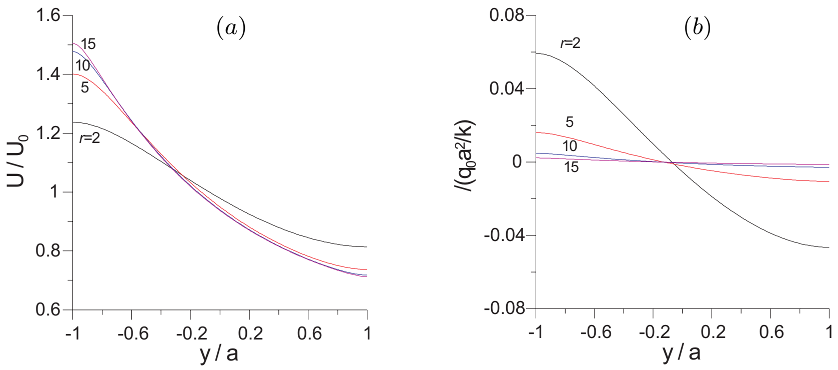

Fig. 3. Velocity (a) and temperature (b) in the mixed convection from Eqs. (4),(5).

in a strong uniform magnetic field (SM82 [4]). In the blanket, the buoyancy effects are caused by volumetric heating generated by neutrons: $q''' = q_0 \mathrm{e}^{-(y+a)/l}$. Test calculations were performed for pure natural convection flows first. As Ha grows, the flow transients from turbulent to quasi-periodic and eventually to a steady-state. The calculations match well the results in [5] except for the low Hartmann number cases, for which the code gives lower values of the Nusselt number, indicating a more stable flow behavior. For the mixed convection flows in a long vertical channel, the temperature field can be written as $T(x,y) = T_0 + \gamma x + \theta(y)$; $U = U(y)$ and $V = 0$. Then, the solution for the core variables was found analytically:

$$\theta(y) = \frac{q_0 a^2}{k}\left\{\frac{m/r}{r^2 - m^2}\left[\frac{\mathrm{e}^{-2m}\cosh\left[r(y/a+1)\right] - \cosh\left[r(y/a-1)\right]}{\sinh(2r)}\right] + \right. \\ \left. + \frac{\mathrm{e}^{-m(y/a+1)}}{r^2 - m^2} - \frac{1-\mathrm{e}^{-2m}}{2m}\frac{1}{r^2}\right\}; \tag{4}$$

$$U(y) = U_0\left[1 + r^2\frac{k}{q_0 a^2}\theta(y)\right]. \tag{5}$$

Here, $r = \sqrt{\mathrm{Gr}/[\mathrm{Re}\,(a/b)^2\,\mathrm{Ha}]}$. Other notations are standard. For the reference blanket, $q_0 = 30$ MW/m^3, $m = a/l = 1$, and $r = 75$. Eqs. (4), (5) suggest flattening of the temperature profile and increasing the difference between the velocities at the opposite walls as r grows (Fig. 3). However, such flows have not been observed in the numerical computations, since the blanket channel is not long enough, and vortex generation occurs, making the flow much more complex.

3. HIMAG code. The HyPerComp Incompressible MHD Solver for Arbitrary Geometry (HIMAG) has been developed over the past several years. At the beginning of the code design, the emphasis was on the accurate capture of a free surface in low to moderate Hartmann number flows. To pursue this goal, an unstructured grid formulation was utilized to allow any geometry of the fluid flow, and to provide adequate resolution of thin MHD boundary layers. Parallel solver implementation was used to allow large problem sizes to be solved in an acceptable amount of time. A second-order level set method was applied for tracking of the free surface. Tests were performed for free surface flows to validate the code under various conditions [7], demonstrating reasonable accuracy. A typical simulation showing a lithium jet passing through a fringing magnetic field is seen in Fig. 4. At present, efforts are directed to the code modification and benchmarking for

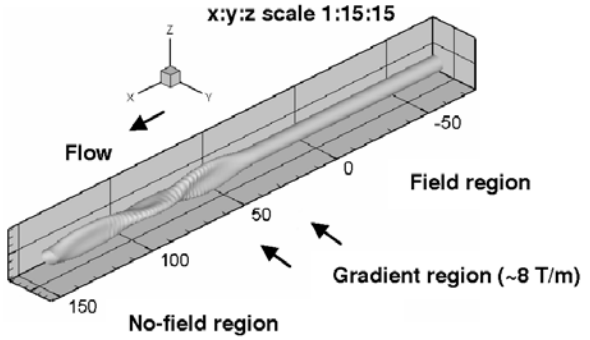

Fig. 4. Li jet with Re=5000, Ha = 100 passing through the fringing field. The jet flattens to catch more magnetic flux and then oscillates due to capillary forces.

higher Hartmann number flows in typical closed channel configurations relevant to the DCLL blanket. The code includes:

- 3-D incompressible flow solver (2d-order accurate in space and time);
- Finite volume discretization on unstructured meshes;
- Electric potential formulation;
- Four-step projection method with semi-implicit Crank-Nicholson formulation for the convective and diffusion terms;
- Multiple strategies to account for mesh skewness;
- Parallel architecture using computational cluster.

Besides the development of the solver, a significant effort is proceeding to develop an alternate approach based on the induced magnetic field, to implement semi-analytical treatment of the Hartmann layers, and to include models for buoyancy effects and turbulence. Current testing is underway to check the code validity for flows with either cross-sectional or axial currents using available analytical solutions, experimental data and results computed with other codes. Present benchmarks show reasonable accuracy when the code is applied to low and moderate Hartmann number flows. Validation of the above-mentioned improvements of the code for Ha $\sim 10^3$–10^4 is still required.

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