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# Numerical simulations of 3D magnetohydrodynamic flows in dual-coolant lead lithium blankets

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**Abstract**

In the dual coolant lead lithium blanket (DCLL) the liquid metal PbLi is used as coolant to remove the volumetrically generated heat. This requires higher flow velocities than in separately cooled blanket concepts, where the liquid metal serves exclusively as breeder, neutron multiplier and shield against high neutron radiation. The relatively fast movement of the electrically conducting fluid in the strong magnetic field confining the fusion plasma induces electric currents, which are responsible for strong Lorentz forces, high magnetohydrodynamic (MHD) pressure drop, and substantial modifications of velocity profiles compared with hydrodynamic flows. In order to support the design activities of a DCLL blanket, 3D numerical MHD simulations for one column of such a blanket module have been performed. The simulations take into account, that currents may close along the inner conducting sheet of sandwich-type flow channel inserts, that are foreseen for pressure drop reduction. The applied numerical code has been carefully validated. It applies for magnetic fields of arbitrary orientation and is capable of simulating the liquid metal MHD flow in the blanket in the parameter range relevant for fusion applications.

*Key words:* numerical simulations, magnetohydrodynamics (MHD), dual-coolant lead lithium blanket (DCLL), flow channel inserts (FCI), MHD pressure drop
*PACS:*

## 1. Introduction

The majority of blanket concepts for a fusion power plant proposed over the past years employ liquid metal in order to meet the requirements for power extraction, tritium fuel sustainability, and radiation shielding. The flow of the electrically conducting liquid metal in strong magnetic fields, as it is the case for a fusion reactor environment, induces electric currents, which, in return, interact with the magnetic field resulting in strong Lorentz forces, large magnetohydrodynamic (MHD) pressure drop, flow pattern modification and therefore massively affects heat and mass transfer.

One liquid metal blanket concept investigated in the frame of EUROfusion is the dual coolant lead lithium (DCLL) blanket [1], in which the liquid metal PbLi serves as breeder, as neutron multiplier, as shield against high neutron radiation and as coolant. For efficient heat removal, the liquid metal has to flow at significantly higher velocity than in helium cooled (HCLL) or water cooled (WCLL) lead lithium blanket concepts, so that MHD effects become dominant. The design of a DCLL blanket module is shown in Fig. 1(a). The liquid metal enters the blanket structure radially at the bottom, flows in a poloidal channel along the plasma-facing first wall, makes an U-turn at the top and flows down in a second poloidal duct before it leaves the module through the back plate. Along its path, schematically depicted in Fig. 1(b), the fluid absorbs the heat and transports it out of the blanket.

In order to mitigate partially the high MHD pressure drop in DCLL blankets, it has been pro-

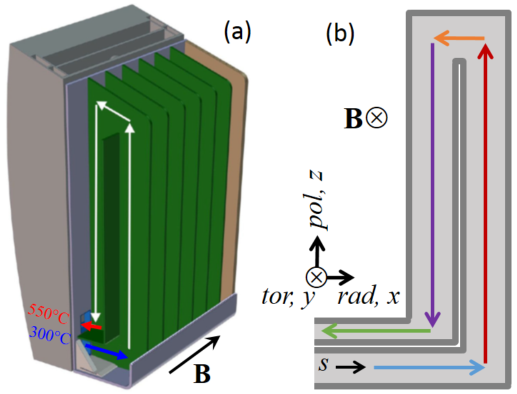


Fig. 1. Design of a DCLL blanket module [2] (a) and principle sketch of flow path (b).

posed to reduce current density in the fluid by decoupling electrically the liquid metal from the well-conducting blanket structure by so-called flow channel inserts (FCIs) [3], [4]. To prevent liquid metal infiltration into the potentially porous insulating ceramics of FCIs, the latter is enclosed and protected from all sides by thin sheets of steel to avoid direct PbLi-ceramic contact. Although the steel layers are thin, they represent closure paths for induced currents with implications on the MHD flow in the blanket ducts. For that reason, reliable predictions of MHD flows in fusion blankets have to take those conducting sheets into account. The present work presents results of numerical simulations of pressure driven MHD flow in DCLL blanket ducts as shown in Fig. 1. Pressure drop and flow distribution in an entire column of a DCLL blanket are determined for fusion relevant parameters.

## 2. Formulation

The viscous incompressible flow of an electrically conducting fluid such as PbLi in a uniform constant magnetic field is described by a balance of momentum, conservation of mass and by Ohm's law

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{v}=-\nabla p+\rho\nu\nabla^2\mathbf{v}+\mathbf{j}\times\mathbf{B}, \quad (1)$$

$$\nabla\cdot\mathbf{v}=0,\ \text{and}\ \mathbf{j}=\sigma\left(-\nabla\phi+\mathbf{v}\times\mathbf{B}\right). \quad (2)$$

Here $\mathbf{v}, \mathbf{j}, \mathbf{B}, p$ and $\phi$ denote velocity, current density, applied magnetic field, pressure and electric potential. The fluid properties density $\rho$, kinematic viscosity $\nu$ and electric conductivity $\sigma$ are taken for an average fluid temperature of $425°C$ and assumed to be constant. The Poisson equation

$$\nabla^2\phi=\nabla\cdot(\mathbf{v}\times\mathbf{B}) \quad (3)$$

determines the electric potential such that conservation of charge $\nabla\cdot\mathbf{j}=0$ is satisfied. The computational domain for the fluid is bounded by the interface with the wall, at which the no-slip condition $\mathbf{v}=0$ applies. The domain in which $j$ and $\phi$ have to be determined extends further into the wall with conductivity $\sigma_w$ up to an outer insulating boundary, where wall normal currents vanish $j_n=-\sigma_w\partial_n\phi=0$. The insulating outer surface corresponds either to the external surface of a duct or to the interface with the insulating ceramic layer of the FCI. A perfect electrical contact is assumed at the fluid-solid interface, which results in continuity of wall-normal currents $j_n=j_{nw}$ and potentials $\phi=\phi_w$.

The physical parameters characterizing the flow are the Hartmann number and the Reynolds number,

$$Ha=BL\sqrt{\frac{\sigma}{\rho\nu}},\quad Re=\frac{u_0L}{\nu}, \quad (4)$$

where $L$ and $u_0$ denote a typical length scale and velocity. $Ha^2$ and $Re$ stand for the ratio of electromagnetic to viscous forces and inertia to viscous forces, respectively. In the present work $L=0.0808$m stands for half the duct size measured in toroidal direction and $u_0$ is the average velocity at the inlet.

The conductance of the thin steel layer of sandwich-type FCIs can be taken into account in numerical simulations by either applying the thin wall condition proposed in [5], or by numerically resolving the thin conducting sheets by a computational mesh. The numerical method used in the present work implements Eqs. (1) - (3) with finite volume techniques for fluid and wall domains and consists of an extension of the hydrodynamic open source code OpenFOAM [6] for MHD applications [7]. The code has been further developed in recent years and thoroughly validated.

## 3. Validation example

While the code had been validated in the past as proposed e.g. in [8] against analytical solutions and experimental data for MHD flows in rectangular ducts where one pair of walls is aligned with the magnetic field, applications for fusion blankets will be more general and involve multi-component fields, not necessarily aligned with the duct walls. Therefore, a supplementary series of new validation simulations has been performed for MHD flows in ducts, subject to an inclined magnetic field as shown in Fig. 2.

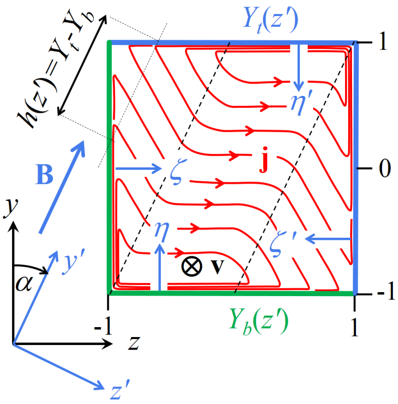


Fig. 2. Sketch of cross-section geometry and current paths for MHD flows in a strong inclined magnetic field.

The duct walls are parallel to $yz$ coordinates and the magnetic field is oriented along the $y'$ direction that is inclined with respect to $y$ by an angle $\alpha$. An exact analytical solution for insulating walls has been derived for comparison with numerical results for moderate Hartmann numbers. Later our attention was drawn to a paper by Eraslan (1966) [9], in which an exact solution is derived in a similar way. For that reason further details are skipped here. For comparison of results for higher Hartmann number an asymptotic solution has been used based on ideas presented by Chang and Lundgreen (1961) [10]. These authors find that the core velocity $u_c$ in insulating ducts of arbitrary shape is uniform along magnetic field lines and proportional to the duct height measured along field lines, i.e. $u_c = u_c(z') \sim h(z') = Y_t - Y_b$. Here $Y_t$ and $Y_b$ are the $y'$ coordinates of the top and bottom duct contour (see Fig. 2). As a result, the velocity in our case becomes constant in the central core where $h = const$. It decays linearly towards the external corners. The mentioned asymptotic analysis [10], valid for $Ha \to \infty$, has been extended by boundary layer corrections in the viscous Hartmann layers, where the local wall-normal coordinates, scaled by the corresponding thickness of the layers $\delta_\eta = 1/\cos(\varphi)\, Ha$ and $\delta_\zeta = 1/\sin(\varphi)\, Ha$ are denoted by $\eta$ and $\zeta$, respectively (see Fig. 2). This leads to viscous corrections of velocity as

$$u = u_c - \left(u_t e^{-\eta'} + u_b e^{-\eta} + u_b e^{-\zeta} + u_t e^{-\zeta'}\right), \quad (5)$$

where $u_t$ and $u_b$ denote core velocity evaluated at $Y_t$ and $Y_b$.

Results from Eq. (5) have been used to validate the numerical code for different $\alpha$ and $Ha$. The numerical domain was meshed using a hexahedral grid with 100x100 cells. A grading was applied that provides sufficient grid points to the boundary layers. The duct walls were implemented as electrically insulating.

Velocity profiles obtained by numerical simulations are compared with the asymptotic solution in Fig. 3 for $Ha = 1000$. We observe a very good agreement in almost the entire cross section and in particular inside the viscous Hartmann layers, as shown e.g. by the enlarged view in the subplot. The sharp change of slope visible in the asymptotic solution at the edges of the inner core i.e. along the field lines that pass the duct corners are due to the fact that viscosity has been neglected in the core of the flow. The numerical solutions correctly account for viscous effects also at the edges of the cores. The numerical code has been successfully validated for flows up to $Ha = 50000$ and deviations for pressure gradients are smaller than 0.3%.

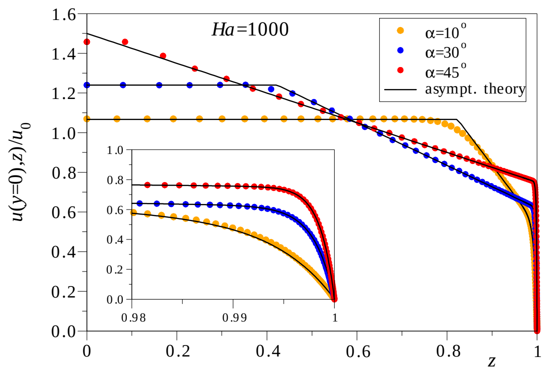


Fig. 3. Comparison of numerical results for velocity profiles $u(y=0,z)/u_0$ for different inclination angles $\alpha$ of the magnetic field with asymptotic solutions valid for $Ha >> 1$.

## 4. MHD flow in a DCLL blanket module

The numerical model used in the following is based on the physical and geometrical data of the most recent DCLL design in which thin sandwich-type FCIs are foreseen for electrical decoupling [4]. In these first simulations it is assumed that the entire inner surface of the module is covered by an FCI with no holes or gaps through which currents could leak into the blanket walls. As a consequence, the numerical domain consists of the fluid region inside the FCI and the inner conducting sheet with thickness $t_w = 0.5$mm [4]. Since the gaps between FCIs and the thick duct walls do almost not contribute to the flow rate and pressure drop [11] they have been neglected in the present analysis.

The DCLL blanket geometry displayed in Fig. 1(a) has been introduced in Sect. 1. The numerical model is based on the geometry schematically shown in Fig. 1(b) and uses structured hexahedral cells with non-uniform spacing for higher resolution of boundary layers and the conducting sheet of the FCI. The cross-section of each duct is resolved by a $70 \times 70$ grid and the wall domain contains 5 grid points in wall-normal direction. A cell refinement towards bends and U-turn as well as in wall-normal direction is applied, in order to resolve vortices at sharp-edged corners and the very thin viscous boundary layers. This results in an overall model size of about $5.7 \cdot 10^6$ cells. The lengths of entrance and exit ducts have been extended compared with the original design in order to impose fully established entrance conditions and reasonable convective parallel outflow.

The objective of numerical simulations is to determine MHD flow in the DCLL blanket under fusion-relevant conditions [4] up to magnetic fields of 4.1T i.e. up to $Ha = 8000$. The mean entrance velocity has been chosen similar as in [4] to $u_0 = 2$cm/s which corresponds in our scaling to $Re = 10932$. For the first simulations we assume that the magnetic field has a toroidal orientation. More general orientations of the magnetic field and buoyancy effects caused by volumetric heating will be considered in separate papers. Simulations have been executed on the MARCONI supercomputer in Italy.

Figure 4 shows contours of electric potential and velocity streamlines in the model geometry at $y = 0$ for moderate $Ha = 500$ and high $Ha = 8000$. It can be seen that the entrance and exit ducts are long enough that the assumed fully developed flow conditions apply. 3D effects are present near bends and U-turn, but the flow approaches quite rapidly fully establishes conditions in the poloidal channels. Streamlines follow approximately lines of constant electric potential. Flow separations and recirculations visible for $Ha = 500$ behind the bends are suppressed for higher magnetic fields and not visible anymore for $Ha = 8000$. Despite the high Reynolds number, the flow remains stable and laminar for the parameters considered.

A velocity profile of the poloidal flow in the cross-section AA′ is shown in Fig. 5. Both poloidal duct flows exhibits cores with uniform velocity, thin Hartmann layers at walls perpendicular to the magnetic field and velocity-jets along the walls that are parallel to **B**, as expected for MHD flows in conducting ducts.

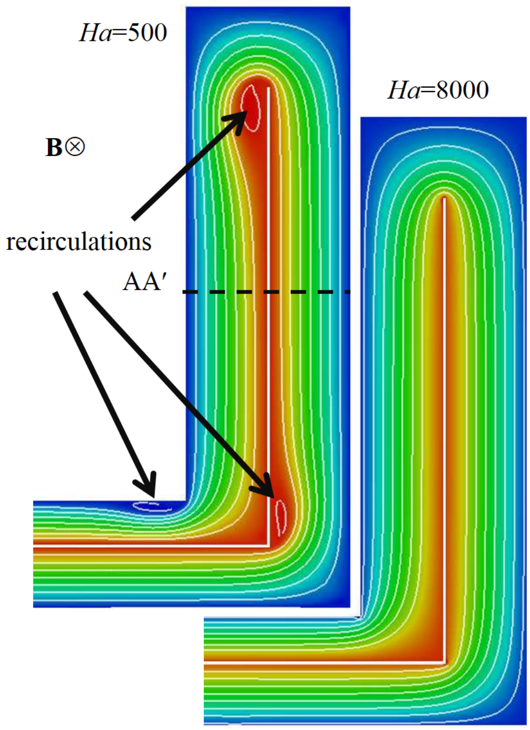


Fig. 4. Contours of potential and streamlines in a DCLL blanket for $u_0 = 2$cm/s, for $Ha = 500$ and $Ha = 8000$.

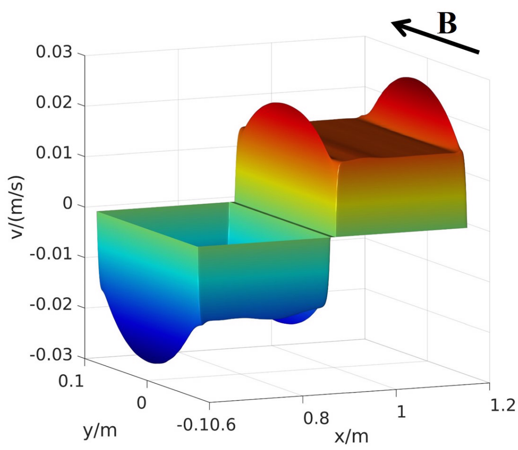


Fig. 5. Poloidal velocity profile in cross-section AA′ for $Ha = 500$ and $u_0 = 2$cm/s.

The pressure distribution along a center line of the blanket module is shown in Fig. 6 for $Ha = 8000$ and two velocities $u_0 = 1\text{cm/s}$ and $u_0 = 2\text{cm/s}$. The data confirms previous observations, that the flow approaches rapidly fully established conditions after passing 3D geometric elements. It can be further seen that bends and U-turns do not substantially contribute to the total pressure drop. Immediately after passing 3D elements the pressure gradient practically coincides with that of an asymptotic analysis for fully developed flows as indicated in the figure.

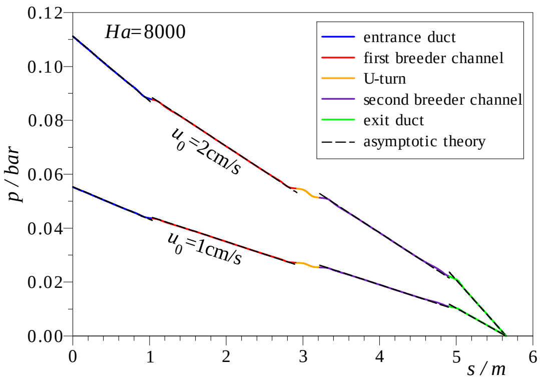


Fig. 6. Pressure as a function of a coordinate $s$ along the flow path in the center of the channels.

Simulations have been performed for various Hartmann numbers $500 \leq Ha \leq 8000$ and for two inlet flow rates. The total pressure drop $\Delta p$ between entrance and exit is displayed in Fig. 7. In the logarithmic scale of the plot all values collapse perfectly to straight lines confirming $\Delta p \sim u_0 B^2$, the typical scaling for inertialess MHD flows for strong magnetic fields. It can be seen that this scaling applies also for moderate fields at least down to $Ha = 500$. Nonlinearities in equations leading to the observed recirculations do not affect pressure drop at a visible magnitude.

## 5. Conclusions

A series of numerical simulations has been performed for a 3D MHD flow in ducts of a DCLL blanket with flow channel inserts, taking into account the conductance of FCIs, flow velocities, and the toroidal magnetic field up to fusion relevant conditions. The validation data base for the numerical code has been extended by an example for MHD flows in rectangular ducts with walls inclined with respect to the orientation of the magnetic field. An excellent agreement with asymptotic solutions has been found for the performed benchmark calculations up to $Ha = 50000$.

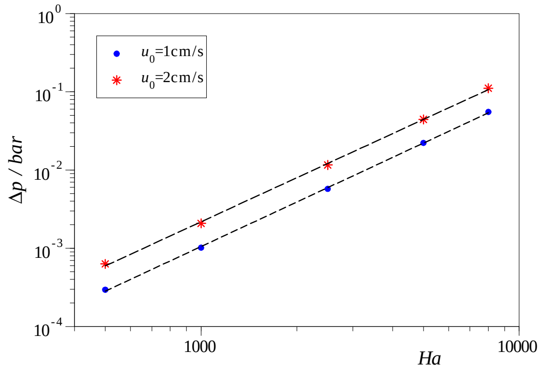


Fig. 7. Total pressure drop as a function of $Ha$ for two flow rates $u_0 = 1\text{cm/s}$ and $u_0 = 2\text{cm/s}$.

Numerical simulations for liquid metal flow in a DCLL blanket show that the flow approaches rapidly fully established conditions after passing 3D geometric elements such as bends or U-turns. Flow separations and recirculations present at moderate magnetic fields are suppressed for higher Hartmann numbers at fusion-relevant parameters. The pressure drop in radial and poloidal ducts coincides almost with that of an assumed fully developed flow and could, for engineering purposes, be estimated as well by asymptotic correlations available from literature. The 3D elements do not contribute significantly to pressure drop, because the flows turning in radial-poloidal planes perpendicular to $\mathbf{B}$ do not affect MHD pressure drop [12]. The present results should be considered as a first step for predicting liquid metal flow in DCLL blankets. In order to complement the present work, future simulations will account in addition for inclined fields, heat transfer and strong buoyancy effects for which the laminar flow might become unstable or even turbulent.

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