MHD Analysis of Dual Coolant Pb-17Li Blanket for ARIES-CS

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A dual coolant Pb-17Li (DCLL) blanket concept has been selected as reference design for the ARIES-CS compact stellarator power plant study. This configuration is characterized by helium cooled first wall and ferritic steel structures, and a self-cooled breeding zone. Flow channel inserts (FCIs) made of silicon carbide (SiC) composite are placed in the PbLi channels, serving both as thermal and electrical insulator. The goal is to optimize the Pb-17Li inlet and outlet temperatures for high power cycle efficiency while accommodating the material temperature limits, providing reasonable flow distribution and maintaining an acceptable pressure drop.

A numerical study of magnetohydrodynamic (MHD) flows in the poloidal channels that distribute the liquid metal in the breeder units has been carried out to assess the performance of such a concept with regard to the above mentioned goals and constraints. The analysis considers the electrical coupling between adjacent poloidal ducts and the influence of various parameters such as the electric conductivity of the SiC insert and the orientation of the magnetic field.

I. INTRODUCTION

Different blanket concepts have been proposed in the conceptual study of the compact stellarator power plant ARIES-CS. A suitable blanket design should assure reasonable performance, moderate development risk and extrapolation of present knowledge. After evaluating the pros and cons of various designs a dual coolant blanket concept with He-cooled ferritic steel structures and a self-cooled breeding zone with slowly flowing PbLi has been assumed as a reference design.¹

The choice of the breeding blanket concept plays an important role in optimizing the performance and the configuration of a stellarator for a future power plant. The design of blankets based on the use of liquid metals has to take into account a number of feasibility issues related to magnetohydrodynamics (MHD). If the breeding liquid metal flows in direction perpendicular to the applied magnetic field, strong MHD effects occur that lead to an increased pressure drop compared with hydrodynamic flows. This results in larger mechanical stresses and increased pumping power. The interaction between the electrically conducting fluid and the confining magnetic field influences the flow distribution and affects the flow partitioning in the parallel poloidal ducts, which distribute the PbLi into the breeder units. Moreover, the MHD velocity profile affects the heat transfer between wall and bulk flow and influences tritium permeation due for instance to the formation of stagnant zones.

In order to minimize the MHD effects, in the present DCLL blanket concept low conductivity silicon carbide inserts are arranged inside the ducts to electrically insulate the breeding region from the walls. Moreover, since the inserts have a low thermal conductivity, they act also as thermal insulation. This allows the PbLi exit temperature to reach higher values resulting in increased power conversion efficiency.

The present study has the purpose to quantify the effects of the interaction of the breeding liquid metal with the external magnetic field in poloidal channels. Key MHD issues, like flow distribution and pressure losses, are discussed taking into account the electrical flow coupling between the poloidal ducts and the effect of the low electric conductivity of the flow channel inserts. The obtained results are used to highlight the possible technical problems and to evaluate the feasibility of the present blanket configuration with respect to the aforementioned MHD issues.

II. PROBLEM SPECIFICATION

II.A. Geometry

In the present study it is assumed that the poloidal ducts are long enough to assure that in most part of the channels fully developed flow conditions are established. The geometric features, the dimensions and the material properties are chosen according to the last review of the reference design for ARIES-CS.²

Fig. 1a shows a partial view of the PbLi flow path inside the distributing poloidal ducts. The liquid metal enters the blanket module through the annular region between two concentric circular pipes, flows upwards in parallel poloidal channels arranged in a row along the first
At the top of the breeder unit, according to a two-pass poloidal configuration, the PbLi turns by 180° and moves downwards in a second row of ducts aligned with the back plate (BP). The liquid metal exits the module by flowing through a concentric inner pipe. The typical size of a blanket module (2 m tor x 2 m pol x 0.63 m rad) is compatible with a modular replacement through a number of maintenance ports using articulated booms.

Almost square and the gap between the FCI and the wall is very small compared with the width of the central region.

Poloidal channels have common conducting walls through which an exchange of currents is possible, which couples electrically adjacent fluid domains. This phenomenon known as multichannel effect may affect the velocity distribution, the pressure drop and flow partitioning. We observe that in this geometry the poloidal ducts are arranged in such a way that channels with co-current flow are electrically coupled through walls perpendicular to the magnetic field, called Hartmann walls (grid plates) and they are aligned in a row. This latter is then coupled with counter-current flow domains through a wall parallel to the applied field, named side wall (separation plate). The global flow structure is then a result of radial and toroidal electrical coupling, taking into account that the inserts reduce the coupling intensity.

Since each wall contains helium cooling channels their real thickness \( t_w \) has been reduced for the MHD analysis depending on the volume of helium flowing in the ducts in order to obtain an electrical conductance comparable to the real one. Hence, an effective wall thickness \( t_w_{\text{eff}} \) has been defined as \( t_w_{\text{eff}} = t_w (1 - \varepsilon) \), where \( \varepsilon \) is the volume fraction of helium in the considered wall.

Primary mechanical stresses in the FCI are minimized by connecting the outer gap and the inner flow region by means of a slot made for equalizing the pressure in the two subdomains. In the present study, this pressure equalization opening has been positioned at the Hartmann wall. This choice has been made since calculations for the case with the slot at the side wall show that at this location it would cause locally a strong reversed flow. These results are in agreement with the ones available in literature.

II.B. Governing equations

The equations describing the steady state laminar, incompressible, viscous, MHD flow are written in dimensionless form so that the relative importance of the various forces acting on the flow can be inferred by the size of multiplying non-dimensional groups. These dimensionless equations consist of conservation of momentum, mass and charge and Ohm’s law:

\[
\frac{1}{N} \left( \nabla \cdot \mathbf{v} \right) = -\nabla p + \frac{1}{Ha} \nabla^2 \mathbf{v} + \mathbf{j} \times \mathbf{B},
\]

\[
\nabla \cdot \mathbf{v} = 0, \quad \nabla \cdot \mathbf{j} = 0, \quad \mathbf{j} = -\nabla \phi + \mathbf{v} \times \mathbf{B}.
\]

In these equations the variables \( \mathbf{v} \), \( p \), \( \mathbf{j} \), \( \mathbf{B} \) and \( \phi \) denote the velocity, the pressure, the current density, the magnetic field and the electric potential, scaled by the reference quantities \( v_o \), \( \sigma_o B_o L \), \( \sigma_o B_o L \), \( B_0 \) and \( v_o B_0 L \), respectively. Here, the half width of one channel,
measured along the toroidal direction, is chosen as characteristic length \( L \) (\( L = 11.65 \text{ cm} \)) and the average velocity in a cross-section of the duct is taken as velocity scale \( v_0 \) in such a way that the non-dimensional average velocity is 1. The quantity \( B_0 \) is the magnitude of the imposed magnetic field. The fluid properties, namely the density \( \rho \), the electric conductivity \( \sigma \) and the kinematic viscosity \( \nu \) are assumed to be constant.

The dimensionless groups governing the problem are the Hartmann number \( Ha \) and the interaction parameter \( N \),

\[
Ha = \frac{\sigma B_0}{\nu} \quad \text{and} \quad N = \frac{\sigma B_0^2}{\rho v_0^2}.
\]

The square of the Hartmann number characterizes the ratio of electromagnetic to viscous forces, and the interaction parameter gives a measure of the ratio of electromagnetic to inertial forces.

As boundary conditions at the fluid-wall interface the no-slip condition is applied (\( \nu = 0 \)) and the continuity of wall-normal component of current density and electric potential (\( j_n = j_{nn}, \phi = \phi_0 \)) has to be satisfied.

### III. Results

The present study is performed by using a modified version of the code CFX 5.6, where MHD equations are implemented by means of user-defined subroutines.\(^4\)

The results presented first in this section are obtained for the most conservative case that has been analyzed with a relatively high value of the electric conductivity of the flow channel inserts, \( \sigma_{CF} = 500 \ \Omega^{-1}\text{m}^{-1} \). This case is presented in detail since it is useful knowing the effects of poor insulating properties of the insert related for instance to a partial deterioration of insulation during operation. In the first section a pure toroidal magnetic field has been considered and the influence of the electric conductivity of the inserts has been investigated since it may vary depending on the techniques used for fabricating the fiber reinforced SiC composite. In the last section results for an inclined magnetic field are described.

### III.A. Pure toroidal magnetic field

#### III.A.1. Electric potential and current density

Let us consider first the distribution of electric potential \( \phi \) in the ducts. In Fig. 2 the electric potential is plotted along the radial direction, namely along a line connecting the back plate (BP) to the first wall (FW), in the middle of the central ducts (see Fig. 1b). In this diagram the potential in the gaps is not visible due to their small size.

The electric potential is nearly constant through the walls and a strong gradient occurs across the flow channel inserts. The amount of current that flows tangentially inside the insert is negligible compared with that crossing it. In the center of the ducts the potential distribution is locally deformed. This inflection point is caused by the presence of the pressure equalization slot of the insert close to the Hartmann wall. The discontinuity in the electric conductivity, represented by the opening, leads to the development of an internal parallel layer that spreads into the fluid along magnetic field lines. Therefore this distortion in the potential profile propagates along the entire magnetic field line that passes through the slot and links the Hartmann wall and the opposite side of the insert.

The analysis of the current distribution shows that there is no exchange of current across the separation plate (SP), between the two rows of ducts. This observation is supported by the presence of critical points, produced by the current vector field, located at the intersections between the separation plate and the grid plates (Fig. 3). These saddle points indicate how the currents coming radially from the grid plates redistribute tangentially in toroidal direction along the separation wall, flowing towards the Hartmann walls (grid plates) where the highest current density is observed.

It is possible to conclude that, as a result of the presence of the inserts and the particular arrangement of the ducts the resulting electric coupling is weak and a rather uniform partition of the flow in the poloidal ducts is expected.

#### III.A.2. Flow distribution

In Fig. 4 the non-dimensional velocity is plotted as a function of the radial coordinate in the middle of the central ducts, in the domain enclosed by the insert (dashed line in Fig. 3). We will refer to this region as the bulk, core flow or internal duct.
The velocity distribution indicates that the presence of the internal layer, which develops from the pressure equalization slot, determines a local velocity deficit in the center of the ducts observable along the entire field line crossing the opening.

Fig. 3. Current streamlines and critical point showing the distribution of currents from radial to toroidal direction in the separation plate and the j-streamline deformation due to the presence of the slot.

The increased velocity along the FCI at walls parallel to the magnetic field is related to the imperfect insulating properties of Hartmann walls. The side walls do not affect strongly the flow since, due to the presence of the FCI, they behave as almost insulating. This is confirmed by the fact that, in the absence of the insert the electrically conducting side walls would lead to the formation of velocity jets with a higher maximum value close to the common, internal wall (SP). In this case instead the maximum velocity at the insert is comparable at each side wall and this rise of the velocity can be regarded as a deformation of the core flow. A detailed numerical study has been further performed showing that increasing the size of the pressure equalization slot leads to an enlargement in radial direction of the region where the velocity deficit occurs.

Fig. 5 shows the flow distribution in the side gaps formed between the inserts and the separation plate. The velocity profile is almost parabolic and the maximum velocity is less than half of that in the internal ducts. In the gaps near the back and the first wall a similar velocity distribution can be observed.

In the gaps close to the Hartmann walls perpendicular to the magnetic field, at some distance from the pressure

Fig. 4. Non-dimensional velocity plotted along the radial direction in the central internal ducts, for \( Ha = 5000 \) and \( \sigma_{FCI} = 500 \, \text{Ω}^{-1}\text{m}^{-1} \).

equalization slot, the velocity distribution has the characteristics of the classic Hartmann flow with uniform core velocity and thin boundary layers with strong velocity gradients. Analogously, in the internal ducts the velocity profile along magnetic field lines is characterized by a constant core value and thin viscous boundary layers near the inserts in which the velocity decays exponentially. In the core the velocity is only a function of the radial coordinate.

Fig. 5. Non-dimensional velocity plotted along the radial direction in the side gaps formed between side plate and inserts, for \( Ha = 5000 \) and \( \sigma_{FCI} = 500 \, \text{Ω}^{-1}\text{m}^{-1} \).

**III.A.3. Variation of FCI electric conductivity**

By comparing the results obtained for various values of the electric conductivity of the flow channel inserts it is observed that, with decreasing the conductivity \( \sigma_{FCI} \), the velocity reduces in all external subdomains, and in the internal duct cores the flow tends towards a more uniform distribution. In Fig. 6 the non-dimensional velocity in the side gaps adjacent to the separation plate is plotted along the radial direction for various \( \sigma_{FCI} \).
Fig. 6. Non-dimensional velocity plotted along the radial direction in the side gaps between side plate and inserts, for \( Ha = 5000 \) and various \( \sigma_{FCI} \).

It is interesting to notice that the changes of the velocity profile by reducing the electric conductivity of the insert from \( \sigma_{FCI} = 100 \, \Omega^{-1} \text{m}^{-1} \) to \( \sigma_{FCI} = 50 \, \Omega^{-1} \text{m}^{-1} \) are quite modest. This can indicate that the insulating properties of the FCI are already sufficiently good, so that a further reduction of \( \sigma_{FCI} \) would not seriously affect the flow anymore at this Hartmann number.

III.A.4. Pressure drop and flow channel inserts

As stated before, for the design of liquid metal blankets the knowledge of the pressure drop due to MHD phenomena is a fundamental and critical requirement. In the following the difference between the pressure distribution in electrically conducting and insulating ducts is presented, in order to show the importance of the flow channel insert as technical and design solution.

In the general case the MHD pressure gradient for strong magnetic fields can be expressed as \( \frac{\Delta p}{\Delta x} = - \left( \rho v \nu / L^{2} \right) k Ha^{2} \), where \( k (Ha, N, c, ...) \) stands for a pressure drop coefficient that may depend on all the parameters affecting the flow like the magnetic field represented by the Hartmann number \( (Ha) \), inertial forces given by the interaction parameter \( (N) \) and wall conductivity expressed by the conductance ratio \( (c) \). This latter measures the ratio of the electric conductivity \( \sigma_{w} \) of the wall with thickness \( t_{w} \) to the conductivity \( \sigma \) of the fluid, \( c = \sigma_{w} L / \sigma_{w} L / \sigma \). The term in bracket, \( \rho v \nu / L^{2} \), is the viscous hydrodynamic pressure scale. The previous formula shows that the MHD pressure drop exceeds the hydrodynamic one by a factor \( k Ha^{2} \).

For fusion relevant conditions \( (Ha^{2} << c << I) \) we have \( k = c \) in conducting channels, i.e. the pressure gradient becomes proportional to the square of the Hartmann number, which is the dimensionless measure of the applied magnetic field. Instead in insulating channels \( k = Ha^{-1} \) and the pressure gradient scales only linearly with the applied magnetic field \( (Ha) \), \( \frac{\Delta p}{\Delta x} = - (\rho v \nu / L) Ha \). Therefore, providing adequate insulation in the poloidal channels allows reducing the pressure drop according to the previous formulas.

Flow channel inserts used for this purpose prevent the current circuit from closing inside the electrically conducting duct walls leading to a reduced total current induced in the fluid and as a consequence a decreased MHD pressure loss.

In Fig. 7 the non-dimensional pressure drop is plotted as a function of the electric conductivity of the insert \( \sigma_{FCI} \).

Fig. 7. Non-dimensional pressure drop as a function of the FCI electric conductivity \( \sigma_{FCI} \) for \( Ha = 5000 \).

According to the described geometry and the PbLi physical properties the value of the magnetic field corresponding to \( Ha = 5000 \) is about 1.6 T. Assuming an average velocity of \( 0.1 \, \text{m} \, \text{s}^{-1} \), a pressure loss of \( \frac{\Delta p}{\Delta x} = 1.1 \times 10^{-5} \, \text{MPa} \, \text{m}^{-1} \) for \( \sigma_{FCI} = 100 \, \Omega^{-1} \text{m}^{-1} \) is found. By increasing the Hartmann number a further reduction of the predicted non-dimensional MHD pressure drop is expected.

III.B. Inclined magnetic field

Let us consider a slightly inclined magnetic field. The results discussed here are obtained for \( B_{rad} = 10\% \, B_{tor} \) and \( \sigma_{FCI} = 500 \, \Omega^{-1} \text{m}^{-1} \).

The velocity distribution shows the presence of internal layers aligned with the magnetic field. In Fig. 8 the contour plot of the electric potential is displayed to highlight the inclination of the distribution according to the magnetic field orientation. The maximum velocity, previously observed in the middle of the side walls, is shifted towards one of the corners of the lateral toroidal walls. The location of the maximum velocity is marked by the crosses in Fig. 8.
A more accurate description of these results will be given in a separated scientific report.

Fig. 8. Contour plot of the electric potential for \( \sigma_{\text{FCI}} = 500 \ \Omega^{-1}\text{m}^{-1} \), \( Ha = 5000 \) and \( B_{\text{int}} = 10\% B_{\text{avg}} \). The crosses mark the position of the maximum velocity at toroidal walls.

**IV. CONCLUSIONS**

The fully developed MHD flow in six poloidal channels has been investigated numerically for a fixed Hartmann number \( Ha = 5000 \). Results are given for flow distribution and pressure drop considering the effects of electrical coupling between adjacent domains and the influence of the electric conductivity of the inserts used to electrically insulate the ducts.

The fact that the velocity distribution in radial direction does not show a strong asymmetry may indicate that the side walls behaves as almost insulating even for the most conservative case with \( \sigma_{\text{FCI}} = 500 \ \Omega^{-1}\text{m}^{-1} \). Therefore the characteristics of the lateral walls (back plate, separation and first wall) could influence the flow distribution in a slight way. The presence of the reduced velocity in the internal layer, which develops along the field lines passing across the pressure equalization slot, may lead to a local increase of the temperature that has to be taken into account.

The electric potential and current density distributions highlight the absence of an exchange of current through the separation plate. This indicates that the particular arrangement of the poloidal channels with co-current flow in ducts coupled at Hartmann walls and counter-current flow in the ones joined at side walls, and the use of the insulating inserts leads to a weak electric coupling and a quite uniform partitioning of the flow in the ducts.

If the Hartmann number is increased, the layers become thinner but it is expected that, by improving the insulation quality according to the rise of the magnetic field, a similar flow distribution remains and the scaling laws will still be valid.

Further studies may be required to complete the analysis of MHD effects in the DCLL blanket concept. For instance 3D calculations should be performed to predict the pressure drop in the region where the fluid expands from the circular pipe into the poloidal ducts. These zones are expected to cause strong MHD effects and associated pressure losses that cannot be eliminated by insulations, since they are due to currents closing inside the fluid.

Considering the poloidal length of the ducts, the inserts will be likely divided in various pieces overlapping at some point along the axis of the channel. The flow behavior in these areas may be interesting to analyze. Moreover, the inserts are placed loosely in the ducts and therefore the study of the effects of the size of the gap can represent a further interesting topic.

In the case of toroidal field it could be interesting to verify also the validity of the assumption of laminar flow. The presence of instabilities in the side layers cannot be excluded and they would lead to the appearance of vortices.

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