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# MHD flow in a prototypical manifold of DCLL blankets


### Abstract

An attractive blanket concept for a fusion reactor is the dual coolant lead lithium (DCLL) blanket where reduced activation steel is used as structural material and a lead lithium alloy serves both to produce tritium and to remove the heat in the breeder zone. Helium is employed to cool the first wall and the blanket structure.

Critical issues for the feasibility of this blanket concept are related to complex induced electric currents and 3D magnetohydrodynamic (MHD) phenomena that occur in distributing and collecting liquid metal manifolds. They can result in large pressure drop and undesirable flow imbalance in parallel poloidal ducts forming blanket modules. Uniform flow rate among parallel channels is required to ensure homogeneous heat transfer conditions and to minimize the occurrence of locally overheated ducts. In the present work we consider the MHD flow in a manifold where the liquid metal is distributed from a single feeding rectangular duct into three parallel vertical channels. The aim is identifying possible sources of flow imbalance and to predict velocity distribution and pressure losses in the manifold.

# MHD-Strömung in einem Flüssigmetall Verteiler für DCLL Blankets


## Zusammenfassung

Das Dual Coolant Lead Lithum (DCLL) Blanket, bei dem eine Blei-Lithium-Legierung als Brutmaterial und als Kühlmittel eingesetzt wird, ist ein attraktives Designkonzept für Fusionsreaktoren. Helium wird nur zur Kühlung der ersten Wand und der Blanketstruktur verwendet.

Kritische Punkte für die Realisierbarkeit dieses Konzepts ergeben sich aus komplexen induzierten elektrischen Strömen und dreidimensionalen magnetohydrodynamischen (MHD) Phänomenen in Flüssigmetall-Verteilern und -Sammlern. So kann es zu sehr großen Druckverlusten und unerwünschten Strömungsverteilungen in den poloidalen Strömungskanälen des Blanketmoduls kommen. Eine gleichmäßige Strömungsaufteilung zwischen parallelen Kanälen ist erforderlich, um homogene Wärmeübertragungsbedingungen zu gewährleisten und um lokale Überhitzung einzelner Kanäle zu verhindern. In dieser Arbeit betrachten wir die MHD Strömung in einem Verteiler, bei der das flüssige Metall von einem rechteckigen Kanal in drei parallele vertikale Unterkanäle verteilt wird. Mögliche Ursachen für ungleichförmige Strömungsverteilungen werden identifiziert und Geschwindigkeitsverteilungen und Druckverluste bestimmt.

# MHD flow in a prototypical manifold of DCLL blankets

## Contents

# 1 Introduction

In the framework of the European study of a DEMO fusion reactor a dual coolant lead lithium (DCLL) blanket design is under development. Reduced activation ferritic-martensitic steel is used as structural material. Helium is employed to cool the first wall and the blanket structure, and the self-cooled lead lithium breeder, PbLi, is circulated for heat removal and tritium extraction. Critical issues related to magnetohydrodynamic (MHD) interactions of the moving liquid metal with the magnetic field required for plasma confinement consist in increased pressure drops and velocity distributions that differ significantly from those expected in hydrodynamic flows. Modifications of the velocity field are caused by electromagnetic Lorentz forces that brake the core flow and result from the interaction of induced electric currents with the magnetic field. Since these forces have to be balanced by driving pressure heads, larger pressure losses occur compared to analogous hydrodynamic flows.

The non-dimensional groups relevant to MHD flows are the Hartmann number $Ha$ and the interaction parameter $N$ (see Section 3). The former one gives a dimensionless measure for the strength of the magnetic field and $Ha^2$ quantifies the ratio between electromagnetic and viscous forces. The interaction parameter $N$ describes the relative importance of Lorentz forces compared to inertia. MHD flows for fusion applications are characterized by intense magnetic fields ($Ha \geqslant 10^4$) and small or moderate liquid metal velocities ($N = 10^4 - 10^5$). Pressure drops $\Delta p$, required to balance the electromagnetic forces in the established MHD flows, are proportional to the electric current density induced in the fluid, whose magnitude is determined by the resistance of the current path. In electrically conducting ducts the resistance is often controlled by the conductivity of the walls, while in insulating channels it is given by the conductivity of very thin viscous boundary layers whose thickness reduces by increasing the magnetic field. Therefore, in the latter case the resistance is higher and a minimum current density is achieved. From analytical considerations it can be briefly said that in electrically conducting ducts $\Delta p \sim Ha^2$ and in electrically insulated channels $\Delta p \sim Ha$ (Lielausis (1975)). For that reason low-conducting flow channel inserts (FCIs) are proposed to be used in DCLL blankets e.g. inside long poloidal ducts to electrically decouple the walls from the liquid metal and hence reducing the total induced current density compared to the one in conducting channels.

Dual coolant blanket concepts have been extensively studied as part of the ARIES US project (Najmabadi, Raffray and Team (2008)) and in the European power plant conceptual study (Norajitra, Bühler, Fischer, Malang, Reimann and Schnauder (2002)). A DCLL blanket design was selected as primary US test blanket module for testing in ITER (Morley, Katoh, Malang, Pint, Raffray, Sharafat, Smolentsev and Youngblood (2008)) and in Europe as advanced blanket concept for a DEMO reactor (Li-Puma, Boccaccini, Bachmann, Noriajitra, Mistrangelo, Aiello, Aubert, Carloni, Kecskes, Kang and Morin (2013)). Although these designs are being considered since many years, several issues remain still unresolved (Smolentsev, Moreau, Bühler and Mistrangelo (2010)) and a final design has not been defined yet.

In the past studies have been performed to investigate liquid metal MHD flows in long poloidal channels as considered in DCLL blanket concepts. It has been shown that with efficient electrical insulation the MHD pressure drop in such ducts is not a critical issue (Bühler and Norajitra (2003), Smolentsev, Morley, Wong and Abdou (2008)). However, the major fraction of pressure losses arises in 3D geometric elements that distribute the liquid metal into the larger breeding zone, e.g. in expansions and bends. Here MHD interactions are intense and there are additional pressure drops due to strong Lorentz forces originating from complex electric current loops that close in the liquid metal rather than in the walls.

In the present study liquid metal MHD flows are investigated for different design options of a DCLL blanket manifold. Similar geometric set-ups have been analyzed in the past. Magnetohydrodynamic flows in a manifold feeding electrically conducting ducts have been studied by Hua and Picologlou (1991) for applications to self-cooled blankets. The occurrence of velocity jets in layers along walls aligned with the magnetic field was indicated as a source of non-uniformity of flow partitioning in poloidal parallel channels. Electrical coupling between adjacent ducts has been suggested in order to support a more uniform flow balance (Tillack and Morley (1995)). Numerical simulations and experiments have been performed at UCLA for liquid metal flows in a rectangular electrically insulating duct feeding three parallel horizontal channels (Morley, Ni, Munipalli, Huang and Abdou (2008), Messadek and Abdou (2009)) and it was observed that increasing the imposed magnetic field while keeping constant the average velocity reduces flow imbalance in parallel channels.

# 2 Problem description

The geometry considered in the present study consists of a manifold feeding an array of three parallel poloidal first-wall ducts. The liquid metal is supplied through an inlet horizontal rectangular channel that expands in toroidal direction into a larger distribution zone. The transition from radial to poloidal flow is achieved by a 90 degree elbow (Fig.1). Since a detailed design for a DEMO DCLL blanket is not available, the present analysis is based on a model geometry and main dimensions are taken according to the design described in Norajitra et al. (2002). The poloidal length of the module is about 3.5 m, while the radial depth, from the expansion to the first wall is $\sim 70\,\mathrm{cm}$, which should allow accommodating in radial direction three parallel rows of poloidal ducts. A uniform magnetic field is applied in toroidal direction. A uniform magnetic field is applied in toroidal direction.

Different design options for the manifold are considered. The aim is getting an overview of velocity and pressure distributions to reach first conclusions, based on MHD considerations, about a suitable manifold design, and identifying flow structures and geometric features that affect the liquid metal distribution in the parallel ducts. Uniform flow rate among parallel channels is required to ensure homogeneous heat transfer conditions and to minimize the occurrence of locally overheated ducts where larger thermal stresses could occur. The length of the internal walls that separate the flow domain into three channels is varied, i.e. the distance $l_s$ of the beginning of internal walls from the expansion wall is modified, and different cases have been considered as indicated by $a,...,e$ in Fig.1(a). Two possible expanding zones are compared, a sudden expansion (Fig.1(a)) and a continuous enlargement (Fig.1(b)). A geometry similar to the latter one has been proposed for the US ITER TBM Smolentsev, Moreau and Abdou (2008).

# 3 Mathematical formulation

Purely pressure driven MHD flows, as considered in the present study, are governed by the Navier-Stokes equations and by equations for conservation of mass and charge that in non-dimensional form read as

$$\frac{1}{N}\frac{D\mathbf{v}}{Dt} = -\nabla p + \frac{1}{Ha^2}\nabla^2\mathbf{v} + \mathbf{j}\times\mathbf{B}, \tag{1}$$

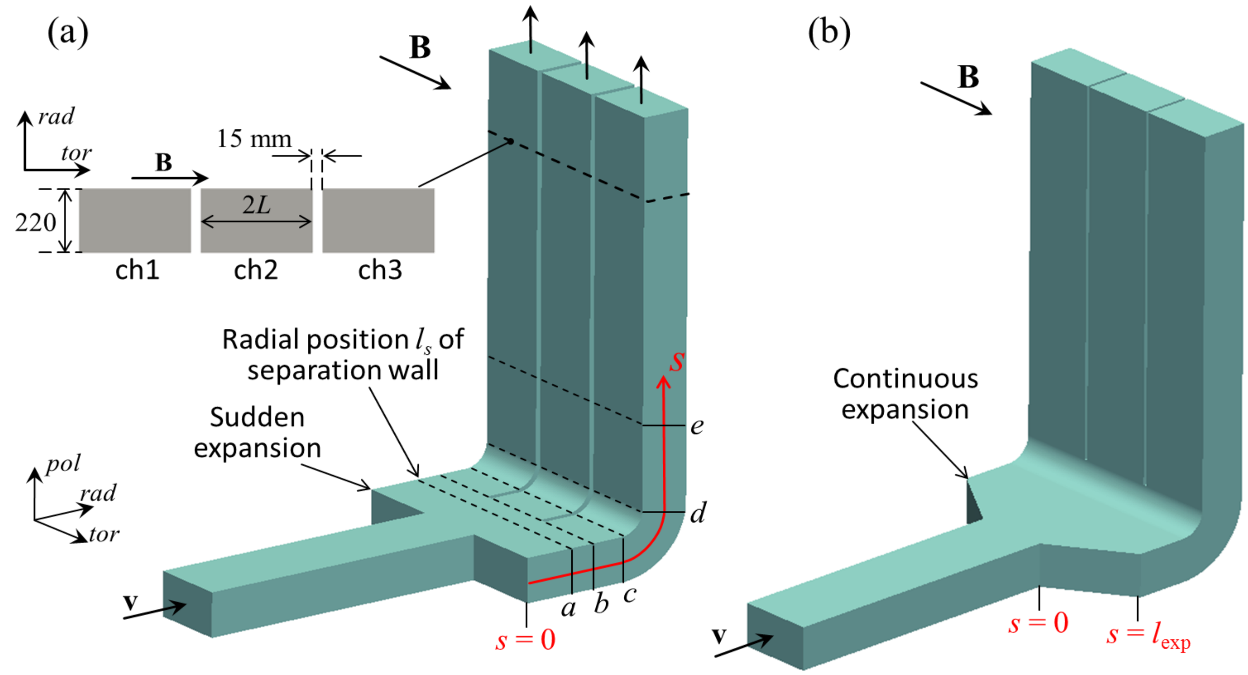


Figure 1: Geometries used for the numerical simulations. Different positions for the beginning of the internal separation walls are considered (marked by $a$,..., $e$). Two designs for the expansion region are compared, a sudden expansion (a) and a continuous enlargement (b).

$$\nabla \cdot \mathbf{v} = 0, \qquad \nabla \cdot \mathbf{j} = 0, \tag{2}$$

where $\mathbf{v}$, $p$, $\mathbf{j}$ and $\mathbf{B}$ indicate velocity, pressure, current density and magnetic field normalized by $u_0$, $\sigma u_0 B^2 L$, $\sigma u_0 B$ and $B$, respectively. As a characteristic velocity $u_0$ we choose the average value in the inlet feeding duct, the scaling dimension $L = 0.1725\,\mathrm{m}$ is half of the toroidal size of a poloidal channel (Fig.1(a)). The electric current density $\mathbf{j}$ is determined by the dimensionless Ohm's law as

$$\mathbf{j} = -\nabla\phi + \mathbf{v} \times \mathbf{B}, \tag{3}$$

where $\phi$ represents the electric potential scaled by $u_0 B L$.

The dimensionless parameters in (1) are the interaction parameter and the Hartmann number:

$$N = \frac{\sigma L B^2}{\rho u_0}, \qquad Ha = LB\sqrt{\frac{\sigma}{\rho\nu}}.$$

The physical properties of the liquid metal alloy PbLi, density $\rho$, electric conductivity $\sigma$ and kinematic viscosity $\nu$, are taken at a reference temperature of $450\,^\circ\mathrm{C}$.

Fully developed flow profiles are imposed at the entrance of the feeding duct for velocity and electric potential. At the three outlets the pressure is fixed to a constant value. At the fluid wall interface the flow satisfies the no-slip condition, $\mathbf{v} = 0$, and in a generic problem, where walls have arbitrary electric conductivity, continuity of wall-normal currents and electric potential is applied

$$j_n = j_{n,w} \text{ and } \phi = \phi_w. \tag{4}$$

For this first numerical analysis it is assumed that perfect electrical insulation is provided by using flow channel inserts, i.e. no electric currents flow into the walls, $\partial\phi/\partial n|_w = 0$, and currents close their paths through fluid cores and boundary layers. The layers at walls parallel to the magnetic field are called side layers and their thickness scale as $\delta_s \sim Ha^{-1/2}$. The ones along walls where the magnetic field has a normal component are the Hartmann layers and they are thinner, $\delta_{Ha} \sim Ha^{-1}$. Since the thickness of the layers decreases for larger Hartmann numbers and the resolution of velocity gradients in these thin regions requires a minimum number of nodes, it follows that simulations of MHD flows in electrically insulating geometries exposed to intense magnetic fields is extremely demanding from a computational point of view.

# 4 Numerical results

Simulations are carried out by using finite volume methods and applying an electric current density conservative scheme as proposed in Ni, Munipalli, Morley, Huang and Abdou (2007). The numerical code has been developed in the open source package OpenFOAM and predicts accurately three dimensional incompressible, viscous flows of electrically conducting fluids exposed to strong magnetic fields (see Mistrangelo and Bühler (2011)).

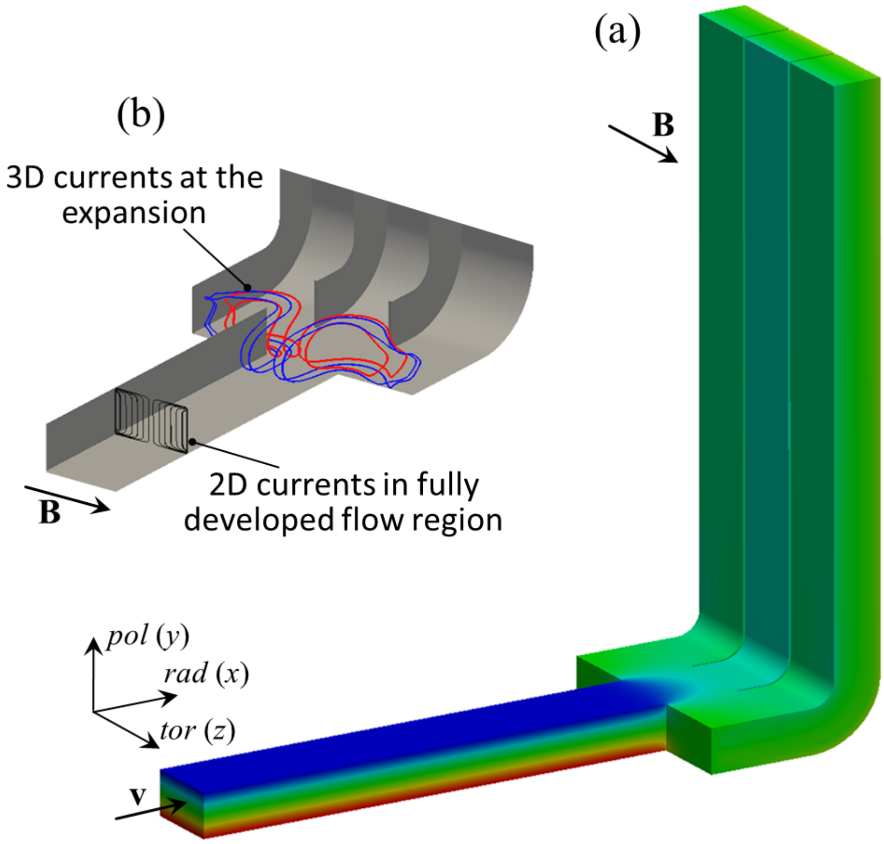


Figure 2: (a) Electric potential distribution on the surface of the manifold system for the flow at $Ha = 1000$ and inlet average velocity of about 0.05 m/s. (b) 2D current streamlines are plotted in the inlet duct and 3D current loops across the sudden expansion.

We discuss in the following numerical results for a reference MHD flow at $Ha = 1000$ and $Re = 6.2 \cdot 10^4$, which corresponds to an inlet average velocity $u_0$ of about $0.05\ \mathrm{m/s}$. For these flow conditions inertia effects are expected to be significant. In a DEMO reactor $Ha$ will be more than one order of magnitude larger. Nevertheless the value chosen for the present study is quite large so that typical phenomena expected for strong fields should be already well observable.

For the description of the results the coordinate $s$ is introduced, which varies along the central line of the geometry, as shown in Fig.1(a). The sudden expansion is located at $s = 0$ and the beginning of the internal separating walls at $s = l_s$. In the first examples the distributing region consists of a rectangular channel that expands abruptly along magnetic field direction and $l_s = 0.235\,\mathrm{m}$ and $0.335\,\mathrm{m}$ (cases $a$ and $b$ in Fig.1(a)).

In Fig.2(a) the electric potential distribution is shown on the surface of the manifold system. In almost the entire inlet duct the electric potential does not vary in axial direction and electric current paths are contained in 2D cross-sectional planes, which is typical for fully developed flow conditions. Characteristic 2D current streamlines are shown in Fig.2(b) in the feeding channel. Near the expansion a streamwise potential gradient occurs, which drives electric currents that close inside the fluid, as displayed in Fig.2(b). These 3D current loops are depicted also in Fig.3 together with contours of electric potential on the plane $z = 0$. The geometry is rotated to better appreciate similarities with the study of MHD flows in ducts that expand along magnetic field direction (see e.g. Bühler (2008), Mistrangelo (2011)). However, due to the presence downstream of the elbow more complex 3D current paths establish behind the expansion.

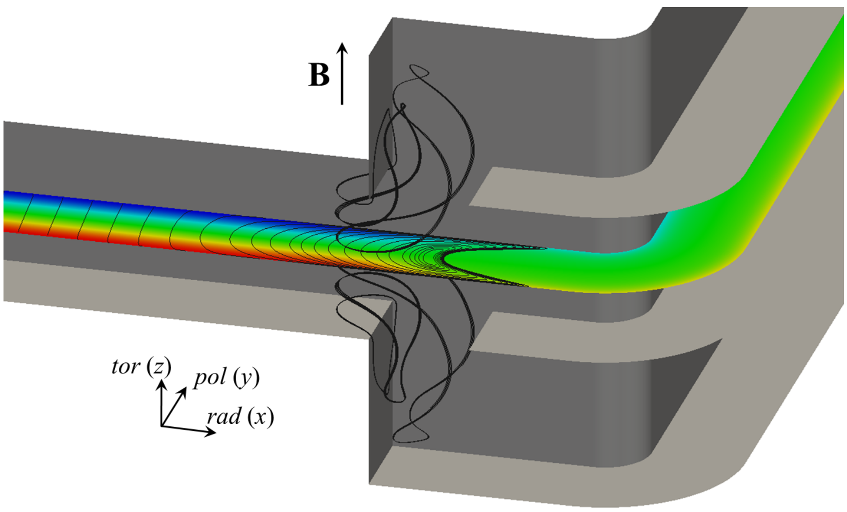


Figure 3: Contours of electric potential on the plane $z = 0$ and current streamlines across the sudden expansion. Far upstream the current recovers a 2D distribution in $y - z$ planes, i.e. no axial component is present. Results for $Ha = 1000$ and $l_s = 0.235\,\mathrm{m}$ (case $a$).

In the core flow across the cross-section enlargement poloidal currents interact with the toroidal magnetic field resulting in streamwise Lorentz forces ($f_x = j_y B$) that slow down the liquid metal in the middle of the channel (see velocity profiles for $s/L \geqslant 0$ in Fig.5). Electromagnetic forces created by radial currents ($f_y = -\, j_x B$) push the fluid PbLi towards the side walls parallel to the magnetic field, as shown in Fig.4 by contours of electric potential (a) and contours of velocity magnitude (b) plotted on the middle symmetry plane of the manifold at $z = 0$. Here velocity streamlines are also visualized. It can be seen how the fluid tends to avoid the core, where a strong electromagnetic braking is present, preferring the side layers as flow path. A detailed physical explanation of this phenomenon can be found in Bühler (2008) for the case of electrically conducting expansions. As a consequence of the action of electromagnetic forces the flow distribution is strongly modified compared to the fully developed flow conditions in the feeding channel where a slug-type velocity profile is present. This is shown in Fig.5 where the scaled streamwise velocity $u/u_0$ is plotted along the vertical coordinate $y$ at various positions $s/L = const$. After the expansion, i.e. for $s/L > 0$, the highest velocity is localized in the side layers along walls parallel to $\mathbf{B}$ (see velocity profile at $s/L = 1.74$). The local increase of the velocity in the core is related to the vicinity of the internal separating walls ($l_s/L = 1.94$) that determine a further redistribution of the fluid.

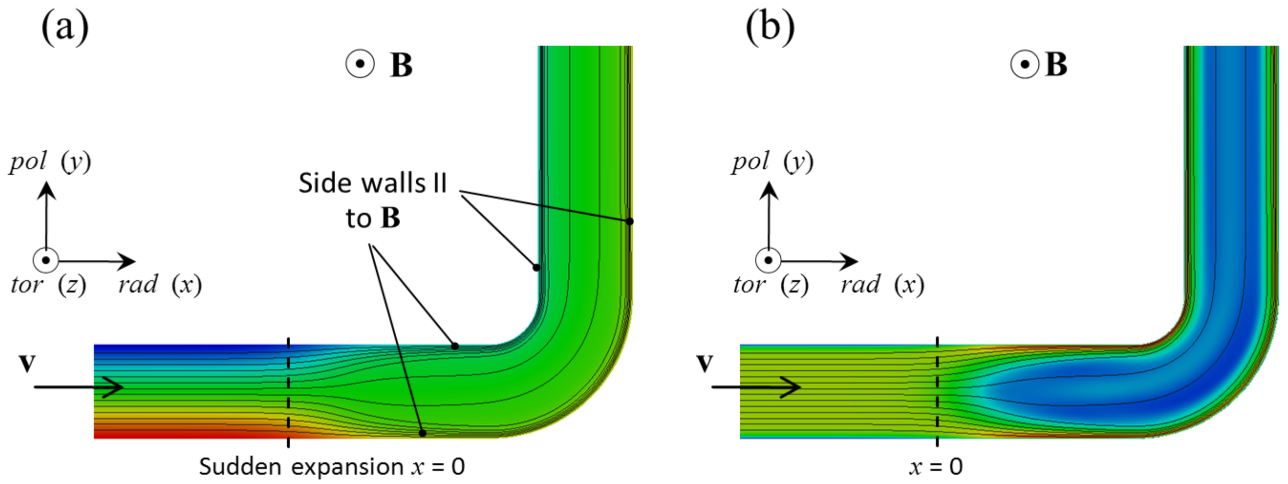


Figure 4: (a) Electric potential distribution and (b) contours of the velocity magnitude on the symmetry plane at $z = 0$. The velocity streamlines clearly show the redistribution of the flow behind the sudden expansion.

An approximate map can be drawn on the inlet cross-section that indicates in which poloidal outlet channel (ch1, ch2, ch3) the fluid will preferentially flow. In other words the entrance position of the fluid in the feeding duct determines where the liquid metal will distribute behind the expansion. The map is shown in Fig.6(a) and the main types of velocity streamlines are plotted in Fig.6(b).

All the streamlines emerging from the horizontal symmetry line (dashed line in Fig.6(a)) flow almost unperturbed in the core of the central channel (blue streamlines in Fig.6(b)). Fluid particles that enter through the central grey band that extends till the side walls move downstream into the central duct ch2, creating a sort of streamline tube. Lines seed close to the Hartmann walls ($\perp$ $\mathbf{B}$) form narrow recirculations near the expansion wall and then they continue in the lateral channels (green streamlines in ch1 and ch3). An exception is represented by particles entering near the duct corners (red lines), which will flow close to the Hartmann walls of the central duct. Fluid coming from regions between the central band and the Hartmann walls flows in the lateral channels creating recirculations. An intense mixing occurs at the entrance

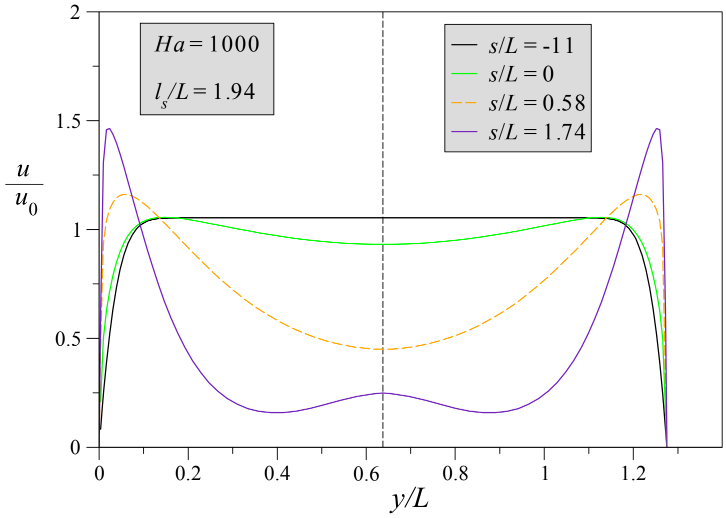


Figure 5: Profiles of the scaled axial velocity $u/u_0$ at different streamwise positions $s/L = constant$. Results are obtained for case $b$ (see Fig.1).

of the side ducts and immediately behind the sudden expansion. In Fig.6(c) the occurrence of vortical flow structures is displayed. By increasing the imposed magnetic field the region with reversed flow tends to be confined to thin boundary and internal layers at the expansion. No closed recirculations have been identified. It should be noticed that in cases $a$ and $b$ described above, where the radial length of the distributing zone is relatively short, the flow partition in the parallel ducts is strongly determined by the 3D effects at the sudden expansion, since the fluid has no possibility to further redistribute before entering the poloidal channels. The influence of the internal walls on flow partition is summarized and discussed later (see Fig.8).

Figure 7 displays velocity distributions at different locations $s = const$. Upstream at some distance from the expansion the velocity profile in the inlet duct exhibits typical features of fully developed MHD flows in electrically insulating rectangular ducts. It is characterized by a uniform core and by thin boundary layers (see profile at $s/L = 0$ in Fig.5). By approaching the expansion the velocity in the side layers increases and the core flow is deformed and slowed down (velocity distributions at $s/L \geqslant 0$ in Fig.5). The liquid metal flows in the central duct with higher velocity compared to the one in the lateral channels and in the side layers a significant overspeed is still present after a long flow path. In the side layers a significant overspeed is still present after a long flow path. Distortions reduce further downstream when the flow recovers fully developed velocity profiles. Due to the relatively large inlet velocity and the moderate magnetic field inertia forces play an important role in determining the flow structure after the expansion.

In Fig.8 the flow rate in the three parallel ducts is plotted as a function of the distance $l_s$, i.e. for different cases as indicated in Fig.1(a). It can be observed that there is an optimized position at which the flow imbalance among poloidal channels tends to zero. If the radial length of the distribution region is too short (cases $a$ and $b$) there is a noticeable flow rate imbalance between lateral and central ducts. The 3D MHD phenomena caused by the expansion of the liquid metal along the magnetic field direction determine a significant redistribution of the flow with high velocity jets at the walls parallel to $\mathbf{B}$ and vortices behind the expansion wall. If there

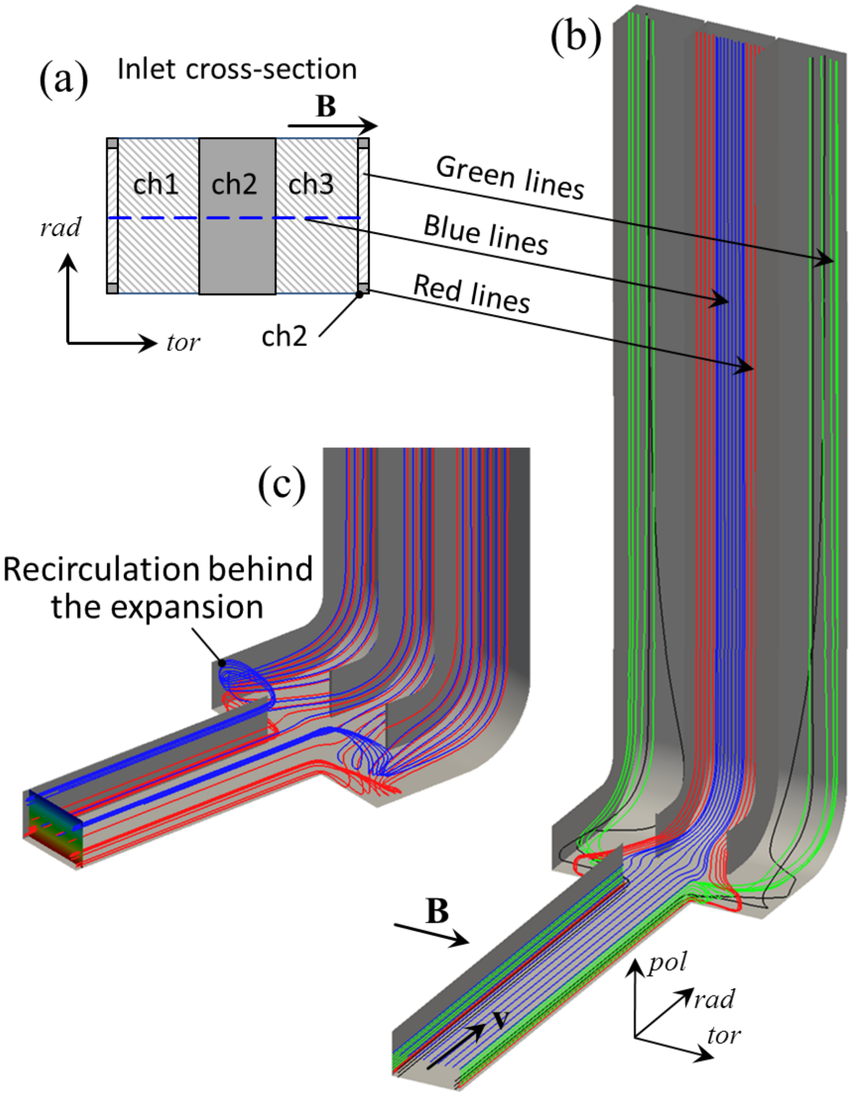


Figure 6: (a) Approximate map on the inlet cross-section indicating into which outlet channel the fluid will move. (b) Velocity streamlines originating from different areas of the inlet cross-section. (c) Streamlines show the recirculation behind the expansion.

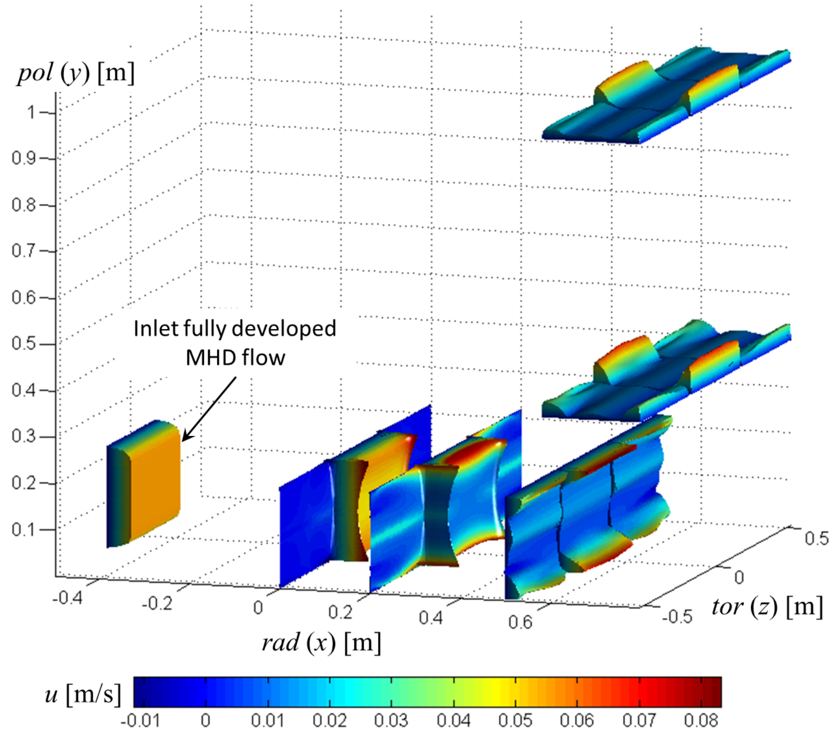


Figure 7: Axial velocity distribution at different cross-sections at $s = const$ for the flow at $Ha = 1000$ and $l_s = 0.335\,\mathrm{m}$ (case $b$ in Fig.1(a)).

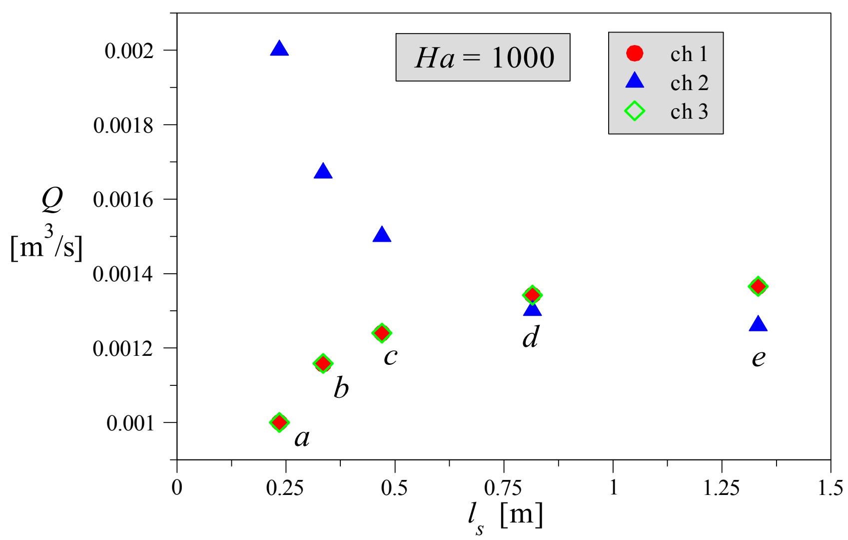


Figure 8: Volumetric flow rates $Q$ in the three poloidal outlet channels as a function of the distance $l_s$ between expansion wall and beginning of separating walls. The position $l_s = 0.47\,\mathrm{m}$ (case $c$) corresponds to the beginning of the 90 degree elbow and $l_s = 0.815\,\mathrm{m}$ (case $d$) to its end. The flow rate in ch1 and ch3 is the same.

is enough space after the expansion, before the separation into three ducts, a more homogeneous partition is observed (see Fig. 8 for flow rates and Fig.9 for velocity streamlines in the limiting case $e$).

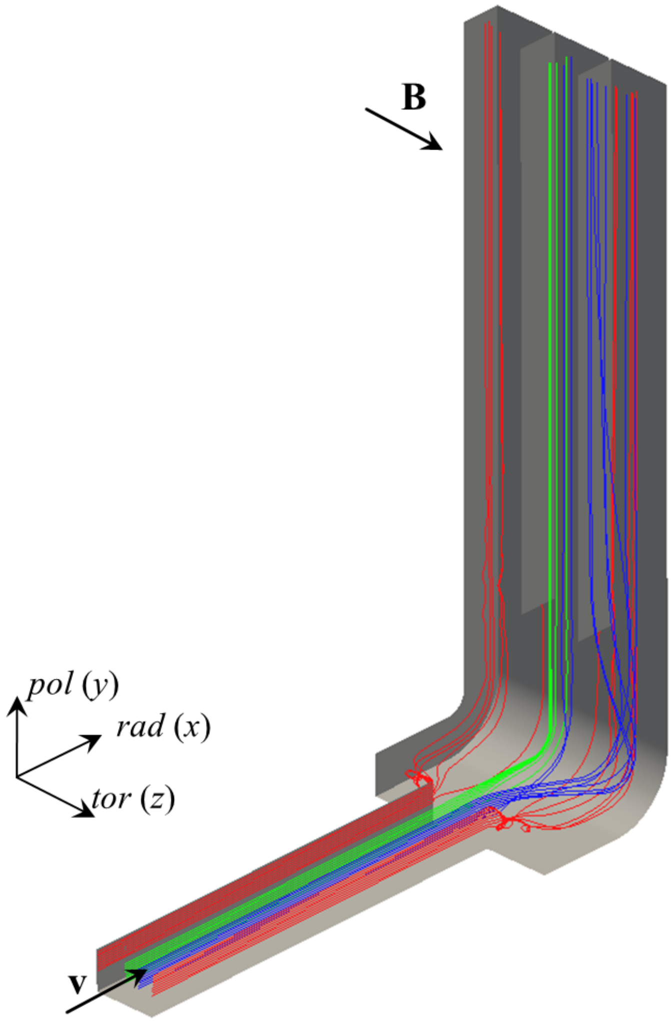


Figure 9: Velocity streamlines for case $e$. A large distributing zone exists since the internal walls are present only in the vertical part of the manifold.

From the engineering point of view it is important to predict not only the velocity distribution but also the pressure head required to drive the flow and to establish the desired flow rate. In Fig.10 the normalized pressure is plotted along the scaled coordinate $s/L$ for case $b$. Fully developed MHD flows are established at some distance from the expansion and from the bend both in the inlet channel and in the poloidal ducts as indicated by the constant pressure gradients. Precise quantification of pressure drops should be performed in a next step when more information about the design are available. However, it is important to identify the geometric features that can increase the total pressure losses in order to provide recommendations for design development. In general in a blanket module the total pressure drop caused by MHD phenomena is the result of the contributions of flows in various components, such as flows in long poloidal ducts, in the inlet and outlet manifolds, in access ducts located in regions where the magnetic field is nonuniform or in geometric elements where the liquid metal changes flow direction compared to magnetic field orientation. In the present example, the total pressure drop in the liquid metal distributing system includes the part in the inlet duct and in the poloidal channels where the flow is fully developed ($\nabla p \simeq -\rho\nu\bar{u}/L^2 Ha$ for $Ha \gg 1$, where $\bar{u}$ is the average velocity in the duct considered (Shercliff (1953))) and the one related to electromagnetic forces created by induced 3D electric currents across the expansion. In Fig.10 a pressure recovery can be observed behind the sudden expansion due to the presence of accelerating axial Lorentz forces. Moreover, it can be noticed that there are different pressure conditions at the entrance of channel 1(3) and channel 2.

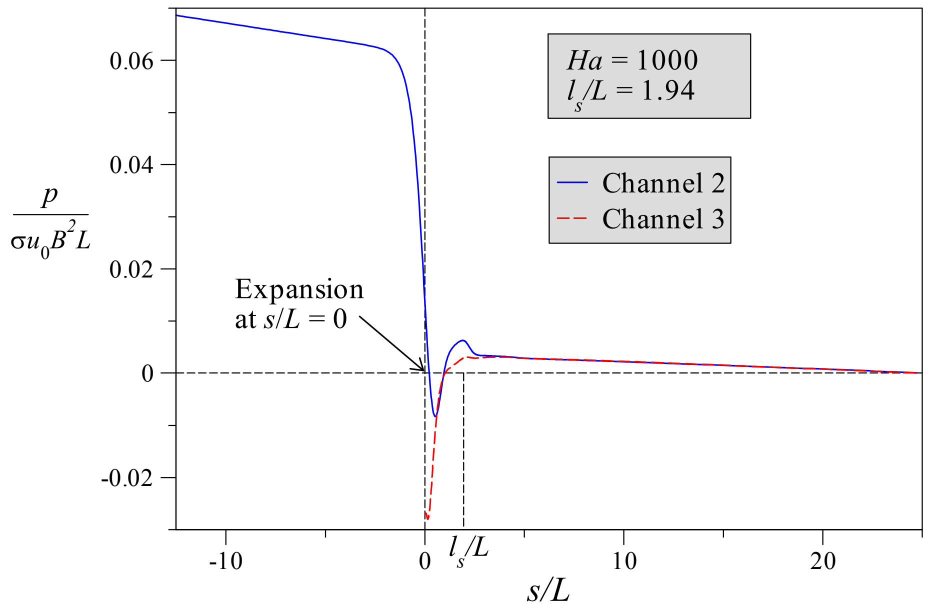


Figure 10: Distribution of the normalized pressure along the scaled coordinate $s/L$ for case $b$. The pressure profile in channel 1 coincides with the one in channel 3.

In Fig.11 the distribution of the pressure along $s/L$ is displayed for two additional limiting cases: in case $a$ the internal walls start closer to the expansion and in case $e$ the division into three channels occurs much later in the poloidal portion of the manifold system (see Fig.1(a)). It can be observed that for case $a$ the pressure gradient at the exit of channels 2 and 3 do not coincide. This is an indication of the larger mass flow rate in the middle duct (ch2) as shown in Fig.8.

An alternative design for the manifold system has been additionally considered with a continuos expansion as displayed in Fig.1(b). Streamlines are plotted in the new geometry in Fig.12 showing that the fluid tends to follow the inclined walls for $0 < s < l_{exp}$. The flow detaches when the walls become again perpendicular to the magnetic field ($s > l_{exp}$). It can be noticed that behind the expansion the core velocity is very small and the fluid flows preferentially towards the side walls parallel to the magnetic field as shown by contours of velocity magnitude plotted on the symmetry plane $z = 0$ and in a $yz-$ cross-section. The occurrence of recirculation is then shifted downstream compared to the case of an abrupt expansion. This affects velocity and

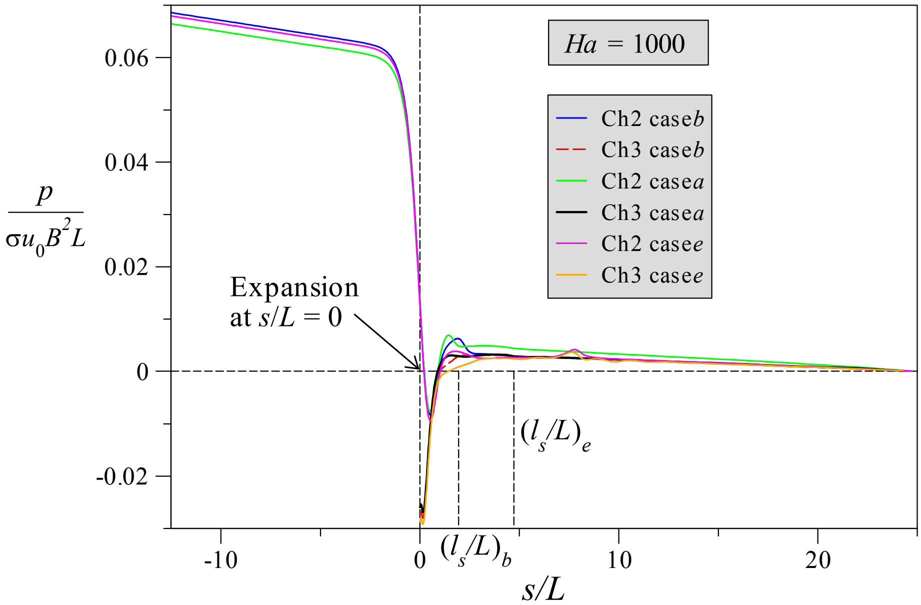


Figure 11: Distribution of the normalized pressure along the scaled coordinate $s/L$ for various cases as shown in Fig.1(a).

pressure distributions at the entrance of the poloidal ducts and therefore the flow partitioning in these channels.

Previous studies of MHD flows in continuous enlargements of electrically conducting rectangular ducts showed that in this modified design a reduced pressure loss occurs compared to the sudden expansion (Bühler (2007), Bühler (2008)). This is due to the fact that the influence of the viscous internal layer that forms at the expansion are less important for longer expansion lengths $l_{exp}$. Moreover, in case of continuos expansions with large $l_{exp}$ the 3D current loops are long and the related resistance of the circuit is high. For these conditions the effects of the induced currents on the additional MHD pressure drop remain small. This can be observed in Fig.13 where the scaled pressure is plotted along the coordinate $s/L$ for a sudden and a continuous expansion. It can be noticed that in the two cases the pressure profiles in the outlet ducts almost coincide while in the feeding channel the pressure in the case of a continuous expansion is reduced by a factor two. Therefore, it seems worthwhile investigating further this alternative design in particular considering the significant influence of this geometry on the total pressure drop in the distributing system.

It can be concluded that the velocity profile behind the expansion and the pressure distribution at the inlet of the poloidal ducts, which depend on both $Ha$ and $Re$, determine, together with the position $l_s$ of the separating walls, how the flow distributes among parallel channels.

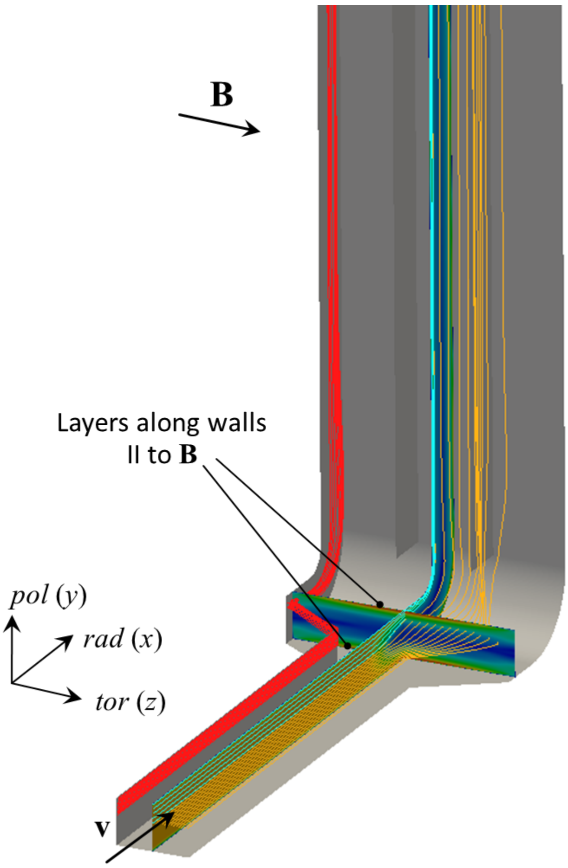


Figure 12: Contours of the magnitude of the velocity on two planes and streamlines. High velocity jets form close to the walls parallel to the magnetic field. The fluid entering the feeding channel in the core region is found in the side layers $\|$ to $\mathbf{B}$ behind the expansion.

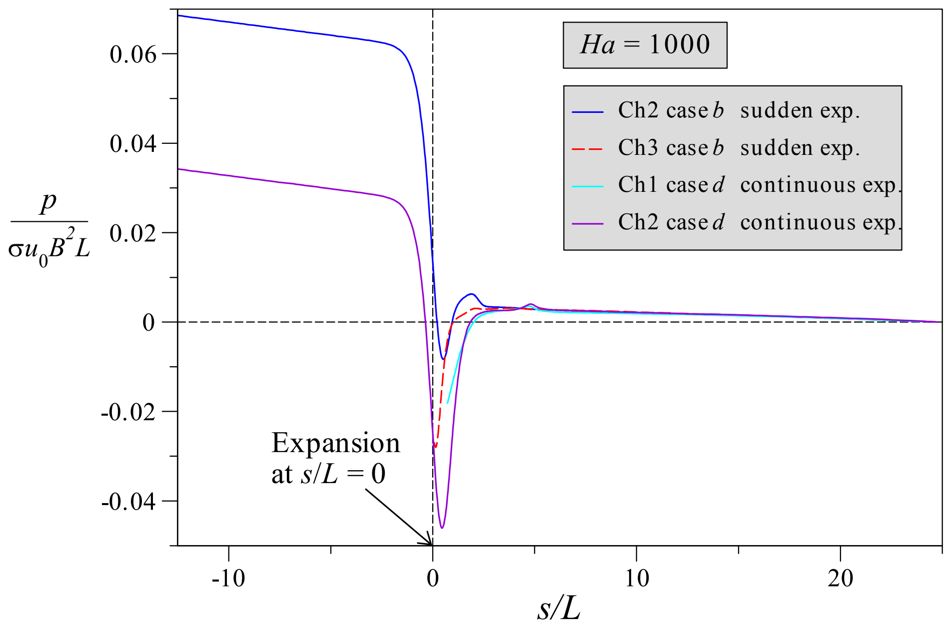


Figure 13: Distribution of the normalized pressure along the scaled coordinate $s/L$ for a sudden and a continuous expansion (see Fig.1). The pressure profile in channel 1 coincides with the one in channel 3.

# 5 Conclusions and future work (R&D)

Numerical simulations have been performed to investigate MHD flows in model geometries of a liquid metal manifold for a DCLL blanket. Results obtained in the present study showed that flow partitioning in poloidal ducts is affected by the length $l_s$ of the distributing region between the expansion and the entrance of the poloidal ducts, by 3D MHD pressure drops and by the velocity distribution behind the cross-section enlargement. The shape of the expansion (continuous or sudden expansion) has a significant impact on the MHD pressure losses in the manifold system. For that reason ongoing parametric analysis performed by means of an asymptotic technique ($Ha >> 1$ and $N >> 1$) will be used to obtain scaling laws for MHD pressure drops as a function of the expanding length $l_{exp}$ of the manifold and to extrapolate the results to the range of very large Hartmann numbers.

Another geometric feature that could affect pressure and velocity distribution in the manifold system is the way in which the considered poloidal ducts are connected to the other channels in the module. It has been observed that the development length of the flow in the vertical channels is pretty large and therefore the knowledge of the design length of the parallel ducts is needed to understand if fully developed flow conditions are reached at the channel exit.

In Bühler and Norajitra (2003) first estimates for MHD pressure drop in DEMO DCLL blanket have been done and it was highlighted that, available empirical formulations for 3D MHD pressure drops were not derived for geometries comparable to the manifold design. Therefore the contribution of 3D flows in this component remains the main uncertainty and further investigations are necessary for new proposed designs. The impact of 3D MHD effects on pressure and velocity distribution has to be still thoroughly studied. Three dimensional MHD flows that play a fundamental role in determining additional pressure drops are those in manifolds (Bühler and Norajitra (2003)), in non-uniform magnetic field, at junctions between FCIs (Bühler and Mistrangelo (2013)), near gaps or holes for pressure equalization (Smolentsev, Morley and Abdou (2006), Mistrangelo, Raffray and Aries Team (2007)). Asymptotic analyses of MHD flows near junctions of flow channel inserts highlighted the importance of getting reliable inputs from the design team in order to estimate pressure drops caused by 3D induced currents due to the noticeable influence of geometric data on the results.

The previous observations clearly show that knowledge about the design are essential to quantify pressure drop and flow imbalance in a manifold system. If on one hand MHD investigations are required to provide recommendations for design development, on the other hand at least basic indications about available space in the reactor, dimensions and general layout are mandatory to obtain meaningful estimates and not only qualitative description of flow behavior in the manifold. The geometry used for the present analysis has been already fully parametrized so that modifications can be easily applied.

Future work includes a systematic analysis of 3D MHD pressure drop as a function of the proposed design options. Since in the DCLL blanket concept the impact of MHD issues on the design feasibility is strictly related to the possibility of realizing flow channel inserts with sufficiently low electric conductivity, the influence of imperfect insulation on velocity and pressure distribution should be studied as well. Moreover, the possibility of leakage currents could lead to flow electric coupling in parallel channels that although weak cannot be fully excluded or neglected.

Recent simulations showed the importance of mixed magneto-convection in the DCLL blanket (Smolentsev, Vetcha and Moreau (2012)). Buoyancy phenomena can increase the effective heat transfer coefficient resulting in higher heat losses from the PbLi flow into the cooling helium and this would degrade blanket thermal efficiency. Therefore the presence of volumetric heating and first-wall heat flux should be also modelled.

Laboratory mock-up experiments could provide valuable data for code validation in case of complex 3D MHD flows.

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