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Magnetohydrodynamic flow in the

Dual Coolant Blanket

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Abstract

The magnetohydrodynamic flow in the improved Dual Coolant Blanket is analyzed with focus on velocity distribution and pressure drop for a fully developed flow in the long poloidal rectangular channels. The fluid in the channels is insulated from the electrically conducting walls by means of ceramic flow channel inserts for pressure drop reduction. It is found that the pressure drop for the poloidal flow is low even if the insulation provided by the insert is not perfect. The distribution of velocity in a laminar regime is not optimal for heat transfer if the electric conductivity of the insert is too high. Then most of the fluid is carried along the side walls in jets with high velocity. Such flows tend to develop instabilities associated with intense mixing.

Three-dimensional effects near expansions and contractions cause a major fraction of the total pressure drop. Results for flows in these geometric elements have been obtained by using empirical correlations which had been derived for different geometries. More detailed analysis would require 3D inertial computations which are foreseen in future. For validation experiments are recommended.

Magnetohydrodynamische Strömungen im Dual Coolant Blanket

Zusammenfassung

In diesem Bericht werden magnetohydrodynamische Strömungen im verbesserten Dual Coolant Blanket untersucht. Von besonderem Interesse sind dabei die Verteilung der Geschwindigkeit und der Druckverlust in den langen poloidalen Rechteckkanälen. Das Fluid in diesen Kanälen ist von den elektrisch leitenden Wänden durch keramische Strömungskanaleinsätze isoliert, um den Druckverlust zu reduzieren. Der Druckverlust in den poloidalen Kanälen ist selbst bei einer nicht perfekten Isolation klein. Die Geschwindigkeitsverteilung ist jedoch, in Bezug auf die abzuführende Wärme, nicht optimal, falls die elektrische Leitfähigkeit der Strömungskanaleinsätze zu groß wird. In einem solchen Fall wird der größte Teil des Fluids entlang der Seitenwände in Jets mit relativ hohen Geschwindigkeiten geführt. Solche Strömungen neigen gewöhnlich zur Ausbildung hydrodynamischer Instabilitäten, was dann wiederum eine intensive Vermischung zur Folge hätte.

Der größte Anteil am Gesamtdruckverlust entsteht im Bereich von Expansionen und Kontraktionen. Zur Ermittlung dieser Anteile wurden empirische Korrelationen angewandt, die für andere Geometrien entwickelt wurden. Detailliertere Rechnungen erfordern trägheitsbehaftete 3D Rechnungen, die für ähnliche Anwendungen geplant sind. Zur Validierung werden Experimente empfohlen.

Magnetohydrodynamic flow in the Dual Coolant Blanket

Contents

1 Introduction

The idea of using liquid metals as breeding material and removing a major fraction of heat by a separate helium cooling has been presented some years ago by Malang, Bojarsky, Bühler, Deckers, Fischer, Norajitra and Reiser (1993). In their proposal the authors assumed that an electrically insulating coating covers the duct walls so that magnetohydrodynamic pressure losses are minimized to those in insulating ducts. It has been shown that the pressure drop in such a blanket concept is not a crucial issue. Moreover, it has been shown in the summary report compiled by Malang and Schleisiek (1994) that even with the technology of conducting flow channel inserts pressure drop in the blanket stays within design limits. These flow channel inserts consist of an insulating layer that is protected from the corrosive liquid metal by thin sheets of stainless steel. The steel layers are electrically conducting, but as long as they are thin the pressure drop is acceptable.

Now in the improved Dual Coolant Blanket concept it is proposed to use a silicone carbide composite material as insulating insert. This material seems to be compatible with the liquid breeder *PbLi* (see e.g. Pérez, Giancarli, Molon and Salavy (1995), where SiC is used as structural material). The electrical conductivity of SiC is very low. Values for the electrical conductivity of the insert material $\sigma_i = 4 \cdot 10^{-5} \frac{1}{\Omega\,\mathrm{m}}$ are given by Pérez et al. (1995), while more recently a value of $\sigma_i = 10^2 - 10^3 \frac{1}{\Omega\,\mathrm{m}}$ for SiC has been reported (M. C. Billone, 1998, included in Raffray, Jones, Aiello, Billone, Giancarli, Golfier, Hasegawa, Katoh, Kohyama, Nishio, Riccardi and Tillack (2001)). These values are several orders of magnitude lower than that of the fluid at 600 °C, $\sigma = 7.2 \cdot 10^5 \frac{1}{\Omega\,\mathrm{m}}$ (Malang and Tillack (1995)) and promise small MHD pressure drop. There are indications that a fiber enforced SiC composite has a conductivity different from that of the pure material. Recently Scholz, dos Santos Marques and Riccardi (2002) published values $\sigma_i = 22 - 650 \frac{1}{\Omega\,\mathrm{m}}$ depending on the fabrication technique of composites. The low value has been measured for materials produced by polymer impregnation pyrolysis and the high value holds for materials made by chemical vapor infiltration. Although these authors show that the insulation properties of SiC composites improves during moderate irradiation one should be aware that the electrical resistivity of SiC under fusion relevant irradiation is still unknown until present day.

In previous reactor studies usually blanket elements extended over the whole poloidal length. This was initially also the case for the Dual Coolant Blanket considered in the preparatory work (PPA 2.5.2) by Norajitra, Bühler, Fischer, Kleefeldt, Malang, Reimann, Schnauder, Aiello, Giancarli, Golfier, Poitevin and Salavy (1999). In the present design the whole blanket is divided into a number of smaller modules which allow easier replacement by remote techniques. Moreover, the blanket exerts lower electromagnetic forces during plasma disruptions and builds up lower thermal stresses during operation. Figure 1 shows how the blanket modules may be arranged in a Tokamak. With the larger number of blanket modules their length decreased in comparison with the earlier design. Therefore the pressure drop in the blanket modules is expected now to be smaller. On the other hand the larger number of modules requires more connections to the supplying lines. These connections, called the access tubes, are now smaller in dimensions caused by the new design which considers the supplying lines as permanent full life-time components, while only the smaller blanket modules are foreseen for replacement. Because of the high velocities in these access tubes they cause now a major fraction of the pressure drop, especially at the expansions and contractions to the full blanket dimensions.

Each blanket module consists of a number of poloidal rectangular boxes which are filled with the liquid lead lithium breeder. All walls of the blanket are cooled by a high-pressure helium flow in small channels which are integrated in the walls. The cooling of the walls ensures acceptable temperature of the wall even if the liquid breeder is at higher temperatures. The major fraction of heat released by nuclear volumetric heating in the liquid breeder is convected with the liquid metal flow and transported out of the reactor for conversion into electric power. The magnetohydrodynamic pressure drop of that flow is kept low by using insulating inserts which are fabricated from ceramic composite material SiC/SiC. Since the ceramic has low thermal conductivity the inserts act not only as electrical but also as thermal insulation. The latter effect allows for higher liquid metal temperatures than the uninsulated steel could withstand and premises thus best thermal efficiency of the whole power plant.

The major part of this report focusses on the magnetohydrodynamic flow in the poloidal boxes but additionally estimates are given for the expected additional pressure drop in strong expansions and contractions trough which the blanket is fed and drained.

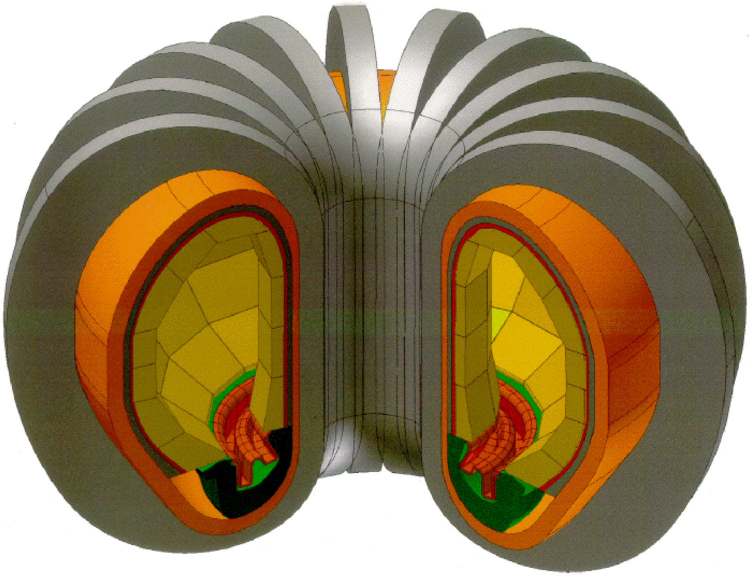

Figure 1: View on Dual Coolant Blanket modules in a fusion Tokamak

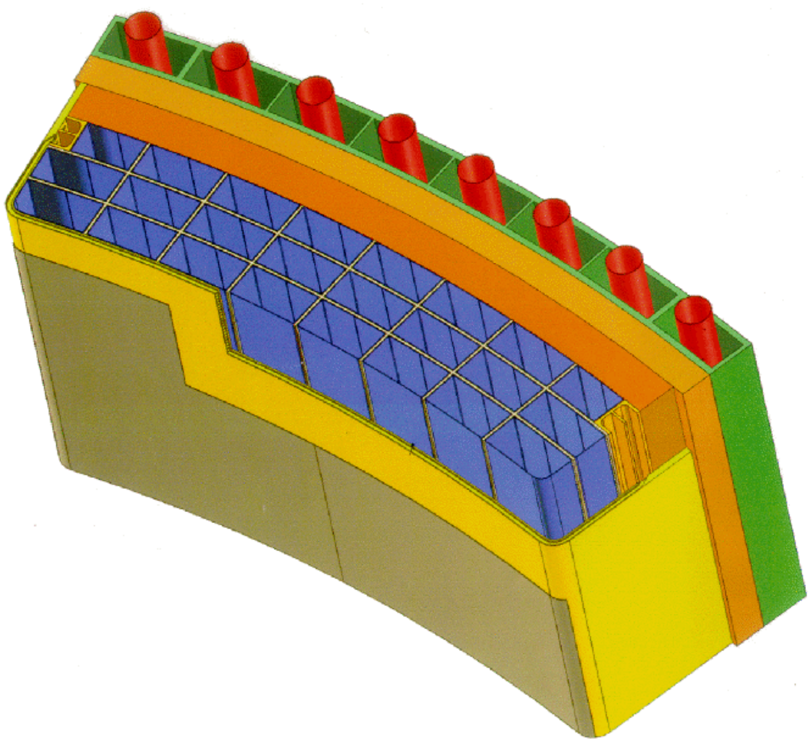

Figure 2: Sketch of a Dual Coolant Blanket

2 Formulation

The geometry of a typical duct in the Dual Coolant Blanket is shown in figure 3. The cross section has a rectangular shape. The liquid metal flows, electrically insulated from the conducting walls, inside the SiC insert. There may be a small gap between the insert and the conducting steel wall which is filled with the fluid. In all domains occupied by the fluid thin viscous layers develop for strong fields. At walls perpendicular to the magnetic field such layers are called the Hartmann layers, while layers parallel to the magnetic field are known as side layers or as parallel layers. These layers match the solutions in the cores with the no-slip condition at the rigid insert and at the conducting wall.

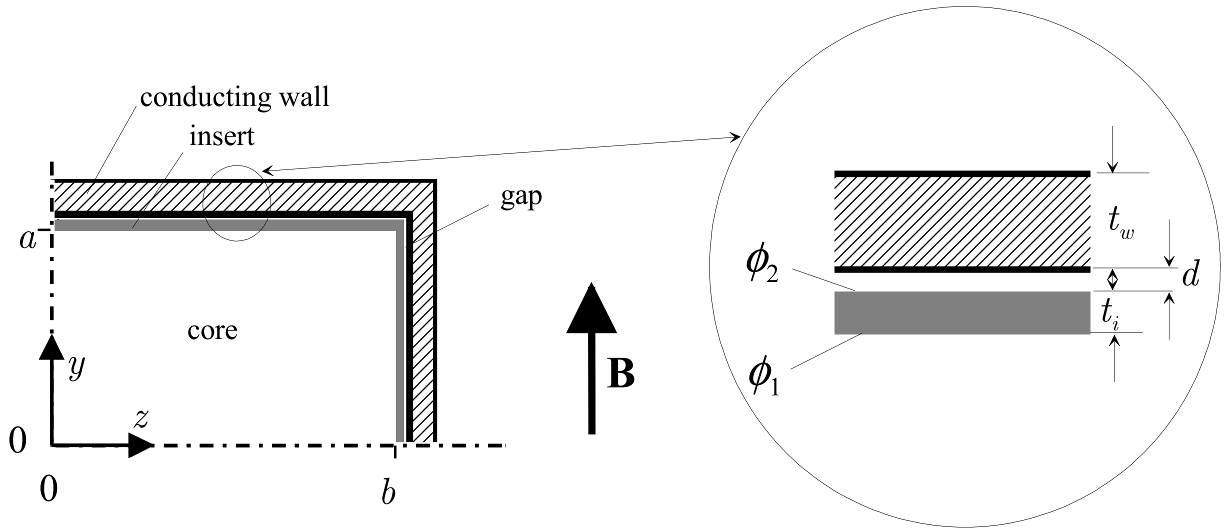

Figure 3: Sketch of a quarter of a rectangular duct typical for the Dual Coolant Concept.

The fully developed laminar incompressible flow of the liquid metal with constant density ρ, kinematic viscosity ν, and electric conductivity σ, confined by the SiC insert is governed by the equations for momentum along the axis, here the x-direction. For a nondimensional uniform transverse magnetic field $\mathbf{B} = \hat{\mathbf{y}}$ we have

$$Ha^{-2}\nabla^2 u + K = j_z, \tag{1}$$

and Ohm's law becomes

$$j_y = -\partial_y \phi, \tag{2}$$
$$j_z = -\partial_z \phi + u. \tag{3}$$

Conservation of electric charge requires

$$\partial_y j_y + \partial_z j_z = 0. \tag{4}$$

In the equations displayed above u, K, j, and ϕ denote the velocity, the pressure gradient, the current density and potential, scaled by the reference quantities, the average velocity

u_0, $\sigma u_0 B^2$, $\sigma u_0 B$, and $u_0 aB$, respectively and

$$Ha = aB\sqrt{\frac{\sigma}{\rho\nu}} \tag{5}$$

is the Hartmann number. The square of Hartmann number characterizes the ratio of electromagnetic and viscous forces. A typical scale of the duct geometry is a, a length scale that may be conveniently chosen as the half width of the duct, measured along the magnetic field lines.

It is assumed that the poloidal extension of the blanket is large enough that in most part of the blanket fully developed flow will establish. The kinematic boundary conditions are as usual in hydrodynamic flows. At the walls there is no-slip

$$u = 0. \tag{6}$$

If there is a large liquid-metal filled gap between the insert and the conducting wall the above equations apply as well for the flow within the gap. If the gap width is small, then the fluid is practically at rest.

It is further assumed that the inserts are good insulators, say they do not carry a significant amount of current in the tangential direction compared to the current flow within the Hartmann layers. Nevertheless, it is known that the wall material is not a perfect insulator. This is taken into account by the fact that currents may cross the thin insert and enter the liquid-metal filled gap and the wall.

$$j_n = -\frac{1}{\kappa}\left(\phi_2 - \phi_1\right). \tag{7}$$

Here, the subscripts 2 and 1 denote the potential at the insert, of the fluid in the gap and in the channel, respectively. The parameter

$$\kappa = \frac{\sigma t_i}{\sigma_i a} \tag{8}$$

denotes the wall-normal electric resistance of the poorly conducting insert, with thickness t_i and conductivity σ_i (compare e.g. Bühler and Molokov (1993)). It can be seen that κ may become small if $t_i \ll a$, a fact that becomes important when very thin layers (coatings) are considered. Instead of using κ we introduce the wall-normal conductance parameter

$$s = \frac{1}{\kappa}. \tag{9}$$

The currents which enter the wall create there a distribution of wall potential ϕ_w that is, according to the thin-wall condition (see e.g. Walker (1981)), determined by

$$j_n = -c\nabla^2\phi_w. \tag{10}$$

The tangential conductivity of the walls, inserts and gaps may be characterized by the wall conductance ratios

$$c_w = \frac{\sigma_w t_w}{\sigma a}, \quad c_i = \frac{\sigma_i t_i}{\sigma a}, \quad c_g = \frac{d}{a}, \tag{11}$$

respectively, which is a good approximation for thin walls, thin inserts and thin gaps.

3 Analysis

3.1 Rectangular ducts without insulating inserts

The MHD flow in rectangular ducts without insulation has been studied widely in literature. It is known that the velocity in the core is uniform

$$u = u_c = constant. \tag{12}$$

The flow exhibits thin viscous boundary layers of exponential type near the walls that are perpendicular to the field, called Hartmann walls. These viscous layers are known as the Hartmann layers and their thickness scales as $\delta \sim Ha^{-1}$. Near the side walls which are parallel to the field lines another type of boundary layer develops. The so-called side layers scale in thickness as $\delta \sim Ha^{-1/2}$. These layers may carry a significant fraction Q_s of the total flow rate

The pressure drop is obtained by the condition for volumetric flux

$$Q = \underbrace{Q_s}_{\text{side layer}} + \underbrace{\int_{-b}^{b}\int_{-1}^{1} u_c dydz}_{\text{core}} = 4b. \tag{13}$$

Now b stands for the half width of the duct scaled by the Hartmann length a. One obtains the result for the pressure gradient as

$$K = \frac{1}{\frac{1}{k} + \frac{1}{3cb}}, \tag{14}$$

where the first term in the denominator ($k = \frac{c}{1+c} + \frac{1}{Ha-1}$) results from the flow in the core and the second term from the flow in the side layers. For details see e.g. Walker (1981) or Tillack and McCarthy (1989).

3.2 Rectangular ducts with insulating inserts

It can be seen from the sketch in figure 3 that between the poorly conducting insert and the wall there exists a liquid-metal filled gap. One can argue that the pressure drop in the gap is very high so that the flow rate and associated velocities are small in comparison with the flow in the insulated duct. With this assumption the problem reduces to that treated by Bühler and Molokov (1993). The results are briefly outlined below and applied to the present problem.

For the case that the inserts carry some small amount of current in the tangential direction and assuming a stagnant liquid in the gap of thickness d one could define an effective tangential wall conductance ratio as

$$c = c_w + c_i + c_g. \tag{15}$$

The governing equations then can be solved by asymptotic techniques valid for high Hartmann numbers, $Ha \gg 1$, and one finds finally

$$u = u_c(z)\left\{1 - \exp\left[Ha\left(|y| - 1\right)\right]\right\}, \tag{16}$$

where the core velocity $u_c(z)$ is given according to Bühler and Molokov (1993) by

$$u_c(z) = K\left\{(Ha-\eta)\frac{\cosh(\beta z)}{\cosh(\beta b)} + \eta\right\}, \tag{17}$$

with coefficients

$$\beta = \sqrt{\frac{cHa+1}{c\kappa}}, \quad \eta = \frac{c+1}{c+Ha^{-1}}, \tag{18}$$

The velocity profile is nearly uniform along magnetic field lines and exhibits thin viscous boundary layers of exponential type near the walls that are perpendicular to the field, called Hartmann walls. The velocity outside the viscous Hartmann layers, i.e. in the core, depends on z only. There is the possibility of higher velocities near the sides, where the magnetic field is tangential to the so-called side walls. It has been shown by Bühler and Molokov (1993) that for high enough insulation, the side layers do not affect the pressure drop or the flow rates in the core of the duct.

The pressure drop is obtained by the condition for volumetric flux

$$\int_{-b}^{b}\int_{-1}^{1} u\,dy\,dz = 4b. \tag{19}$$

One obtains the result for the pressure gradient as

$$K = \frac{\beta b}{(Ha-\eta)\tanh(\beta b) + \eta\beta b}. \tag{20}$$

3.3 Circular pipes

Circular pipe flow occurs in the present design in the inner part of the coaxial arrangement of the ducts supplying PbLi to the blanket modules and in the coaxial connections to these pipes (access tubes). Unfortunately there exists so far no solutions for poorly conducting inserts. Correlations for pressure drop are known for perfectly insulating circular pipes for which the pressure gradient takes values as

$$K = \frac{3\pi}{8Ha}. \tag{21}$$

For electrically conducting pipes with $c \gg Ha^{-1}$ a relation exists in the form

$$K = \frac{c}{1+c}. \tag{22}$$

There exists also a correlation that connects smoothly these two ideal cases. The latter one is a lengthy expression and is not explicitly given here. For more details the reader is referred to the summary given by Müller and Bühler (2001) or to the original papers like, Shercliff (1953), Shercliff (1962), Chang and Lundgren (1961).

3.4 Three-dimensional effects

Three dimensional effects play an important role in the Dual Coolant Blanket concept because the pressure drop in the ducts fitted with insulating inserts is relatively small compared with the pressure drop that is expected near the strong expansions and contractions when the fluid leaves or enters the access tubes. The central connecting pipe (radial access tube) with the large number of holes seems to be not the optimum design since it creates a strongly three-dimensional motion. Details of the geometry can be seen on Fig. 5. It should be checked if there exists a possibility that one can avoid the perforated part completely. This would allow the fluid to enter immediately a tube through a larger cross section. However, in any case, the connecting pipe forms an abrupt contraction that causes strong 3D effects with associated pressure drop. Exact correlations for 3D pressure drop in such geometries are not available. Nevertheless, simple arguments allow us to judge about the order of magnitude of such pressure drops. The pressure drop is mainly created by the fact that due to axial differences in electric potential additional current paths are possible which are responsible for additional Lorentz forces. It is assumed here that the dimensions, along which the 3D currents penetrate into the liquid metal, are of the same order as the radius of the access tube. This leads to an equivalent conduction ratio of $c \approx 1$. Three-dimensional effects are now estimated by assuming a fully developed flow in a circular pipe with $c = 1$ over a length of a, where a now stands for the radius of the access tube. This yields a pressure drop due to the contracting flow as

$$\Delta p_{3D} = \frac{1}{2}\sigma u_0 B^2 a \tag{23}$$

The insulation does not help to eliminate 3D effects because currents shortcut in the liquid metal and not only along the walls. Moreover, the velocities in the current blanket design are very high which leads to relatively small interaction parameters. Inertia effects may therefore contribute additionally to the 3D pressure drop. Stieglitz, Barleon, Bühler and Molokov (1996) showed for a bend flow that the inertial contribution may reach the same order of magnitude as the inertialess estimates.

Experimental observations for MHD pressure drop in 3D elements can be correlated by the empirical relation

$$\Delta p_{3D} = \zeta \, \frac{1}{2}\rho u_0^2, \text{ with } \zeta = f\left(N, Ha\right), \tag{24}$$

where ζ is the coefficient of local MHD resistance (Dem'yanenko, Karasev, Kolesnichenko, Lavrent'ev, Lielausis, Murav'ev and Tananaev (1988), Grinberg, Kaudze and Lielausis (1985), Tananayev, aitov, Chudov and Shmatenko (1989)) that depends on the geometry and on the orientation of the magnetic field. Here,

$$N = \frac{\sigma a B^2}{\rho u_0} \tag{25}$$

stands for the interaction parameter. For the geometries investigated in these references, ζ was found in the inertial regime as $0.25 < \zeta/N < 2$. Both relations for 3D pressure drop, i.e. Eqs. (23) and (24) are equivalent for $\zeta = N$, a value that could be taken in lack of better knowledge. Note, the upper limit for ζ/N observed in these experiments depends also on Ha and N so that at the fusion relevant Hartmann numbers even larger values are possible. On the other hand several references report values of $\zeta/N < 0.3$ especially for large interaction parameters, i.e. $N \gg 1$. For all these reasons we chose for the present estimates $\zeta = 0.5N$ but recommend for precise values more detailed analyses and experiments for the present geometry.

3.5 Results

Results displayed in the following, have been derived for the geometry of the Dual Coolant Blanket. According to the geometry described above and liquid metal properties according to Tab. 1 one can evaluate the nondimensional parameters governing the flow. They are for the present design of a Dual-Coolant Blanket for the duct near the first wall of the outboard blanket ($B = 5\,\mathrm{T}$)

$$Ha = 22.7 \cdot 10^3, \quad c = 1.7 \cdot 10^{-2}, \quad \kappa = 43.5 \tag{26}$$

There are uncertainties for the conductivity of the inserts. For a conservative estimate of pressure drop a value of $\sigma_i = 500 \frac{1}{\Omega\,\mathrm{m}}$ has been chosen. The liquid metal properties are taken at an average temperature of $T = 580\,^\circ\mathrm{C}$, using the polynomial dependences on temperature as published by Jauch, Karcher, Schulz and Haase (1986). For the present design one finds pressure gradients of $K = 8.3 \cdot 10^{-4}\,\mathrm{MPa/m}$ and $K = 4.4 \cdot 10^{-4}\,\mathrm{MPa/m}$ for the duct near the first wall and for the rear channels, respectively. In these ducts the average velocity is close to $u_0 = 0.07\,\mathrm{m/s}$ and $0.04\,\mathrm{m/s}$. This yields for a blanket of total length of roughly $2\,\mathrm{m}$ a total pressure drop of $\Delta p = 2.5 \cdot 10^{-3}\,\mathrm{MPa}$, a value which is very small. The present calculation applies for the straight channels. The bends at the top or bottom of the blanket turn the flow in a plane perpendicular to the magnetic field lines. Such flows do not cause higher MHD pressure drop than the flow in a straight duct of same average length Molokov (1995).

Table 1: Properties of PbLi

density	ρ	=	$10.45\,(1 - 161 \cdot 10^{-6} T/\mathrm{K})$	$\mathrm{kg/m^3}$	$508\,\mathrm{K} < T < 625\,\mathrm{K}$
electric resistivity	$\rho_{el} = \sigma^{-1}$	=	$(102.3 + 0.0426 T/\mathrm{K}) \cdot 10^{-8}$	$\Omega\,\mathrm{m}$	$508\,\mathrm{K} < T < 933\,\mathrm{K}$
dynamic viscosity	$\eta = \rho\nu$	=	$0.187 \cdot 10^{-3} \exp\left(\frac{11640}{8.314\,T/\mathrm{K}}\right)$	$\mathrm{Pa\,s}$	$508\,\mathrm{K} < T < 933\,\mathrm{K}$

Since there exists an uncertainty concerning the electric conductivity of the insulating inserts we show velocity profiles for different values of σ_i in Fig. 4. If the insert provides high insulation, $\sigma_i \lesssim 1 \frac{1}{\Omega\,\mathrm{m}}$, the velocity is almost uniform in the whole cross section. For conductivity values as proposed by Scholz et al. (2002), where $\sigma_i = 22 \frac{1}{\Omega\,\mathrm{m}}$ (material made by polymer impregnation pyrolysis), the velocities near the sides remain moderate. For higher conductivities one finds an increase of velocity when approaching the side walls which are parallel to the applied magnetic field. The magnitude of nondimensional velocity at the side wall may reach relatively high values depending on

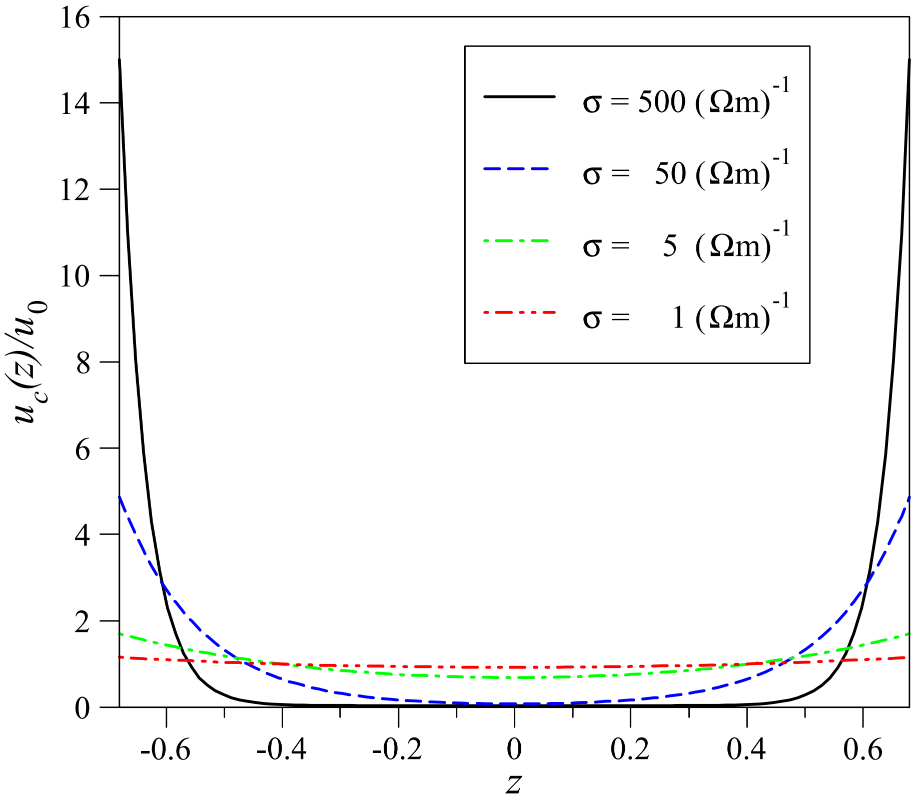

Figure 4: Core velocity in a rectangular duct. It is assumed that the duct wall has an effective thickness for electric conductance of 2 mm. The duct is insulated by a SiC/SiC insert of 5 mm thickness.

the insert conductivity. Such strongly expressed velocity profiles can not be excluded with the present knowledge about the insulation properties of the SiC material. The increased velocities near the side walls, especially near the first wall, increase the heat transfer in regions of high volumetric power density. The very low velocity near the duct center may be unfavorable for heat transfer reasons for which a uniform velocity profile would be desirable. On the other hand, rectangular ducts allow for MHD instabilities that promote a vortex motion with main vorticity aligned with the B- field. Such vortices could homogenize the average velocity and temperature field without increasing the pressure drop too large. The answer to this question requires more detailed nonlinear calculations and experiments are required that are beyond the scope of the present laminar study. Nevertheless, the idea of vortex generation near the side walls is reasonably supported by the analytical work performed by Ting, Walker, Moon, Reed and Picologlou (1991a), by experiments of Ting, Walker, Moon, Reed and Picologlou (1991b), or by more recent experiments performed by Burr (1998) and should be kept in mind for future research. In principle there exists also the possibility to reduce the duct dimensions in order to achieve more uniform velocity profiles. This option, however, would increase pressure drop and moreover increase also the fraction of steel and SiC in the blanket and should be considered only if other means fail.

A similar analysis can be performed for the duct at the bottom that supplies PbLi to the front channel. For the rectangular geometry of 350 mm ×50 mm, a mean velocity of $u_0 = 1.4$ m/s and for conducting walls with thickness of $t_w = 2$ mm Eq.(14) applies and we find a pressure drop of $\Delta p = 7.5 \cdot 10^{-2}$ MPa for a liquid metal at temperature $T = 460\,^{\circ}$C. If this duct is supplied with an insulation of 5 mm thickness the velocity increases slightly but the pressure drop reduces to about $\Delta p = 2.3 \cdot 10^{-3}$ MPa. The insulating insert reduces the pressure drop by more than one order of magnitude. This simple example demonstrates that electrical insulation should be preferred in order to obtain reasonable values for pressure drop.

Similar conclusions can be made for the flow in the supplying pipes in the back of the blanket and for the coaxial connection between the blanket module and those pipes (access tubes). Results are summarized and added to the Fig. 5. Unfortunately there exist no correlations comparable with those shown in Eq. (20), which account for the pressure drop in conducting circular pipes with insulating inserts. The values specified in the figure for circular pipes are obtained for perfectly insulating walls (and for conducting walls, value in brackets). In the case of conducting walls a certain fraction of the exterior fluid has been considered for an effective electrical conductance. The pressure drop for flows in pipes with insulating inserts would be in between these values. A comparison with a square duct of same cross section as the central pipe, fitted with an insulating insert yields a pressure drop of $\Delta p = 3.5 \cdot 10^{-3}$ MPa, which is higher by a factor of 1.7 than the pressure drop of a perfectly insulating pipe.

As described above we estimate the three-dimensional pressure drop at the abrupt contraction of the flow during the entrance to the central access tube. We assume $\zeta/N = 0.5$ according to (24). As a result we find a value of 3D pressure drop as $\Delta p_{3D} = 0.56$ MPa for a flow at $u_0 \approx 2.6$ m/s and $N = 38$. The formation of thin viscous boundary layers may change the pressure drop values but the order of magnitude should remain.

Similar arguments hold also for the flow in the 'annular' gap with strong expansion to the total toroidal length. Such a geometry is not similar to any geometry for which solutions for MHD flows are known. It could be expected that the pressure drop is of the same order of magnitude than that in the central pipe. Nevertheless, since the velocities are smaller the pressure drops (fully established annular flow and Δp_{3D}) should be smaller also. Here, for simplicity and lack of better knowledge half the value as for the contraction to the central access tube is used, i.e. $\Delta p_{3D} = 0.28$ MPa.

The calculations shown above demonstrate that the pressure drop in the whole blanket is negligible in comparison with the pressure drop near 3D elements. This is the case also for the inboard blanket. For these reasons only the 3D pressure drops at the inlet and outlet of the blanket module are shown for inboard conditions. Three-dimensional effects scale as $\Delta p_{3D} \sim u_0 B^2$ so that Δp_{3D} is larger at the inboard blanket although the velocity there is smaller. For $u_0 \approx 1.4$ m/s and $B = 10$ T we estimate the pressure drop to roughly $\Delta p_{3D} = 1.2$ MPa for the contraction and $\Delta p_{3D} = 0.6$ MPa for the expansion.

The 3D pressure drops estimated above are relatively high compared with the pressure drop in the blanket module. A simple geometric means for pressure drop reduction could be an enlargement of the access tubes. Therefore, for any further improvement of the design, one should keep this option in mind. Finally it has to be noticed that 3D pressure drops have been estimated using correlations which have been obtained tor different geometries. The ζ coefficient depends strongly on the geometry. The order of magnitude for pressure drop should be correct but in order to get more accurate estimates it is recommended to perform experiments using a realistic model geometry and flow parameters close to applications.

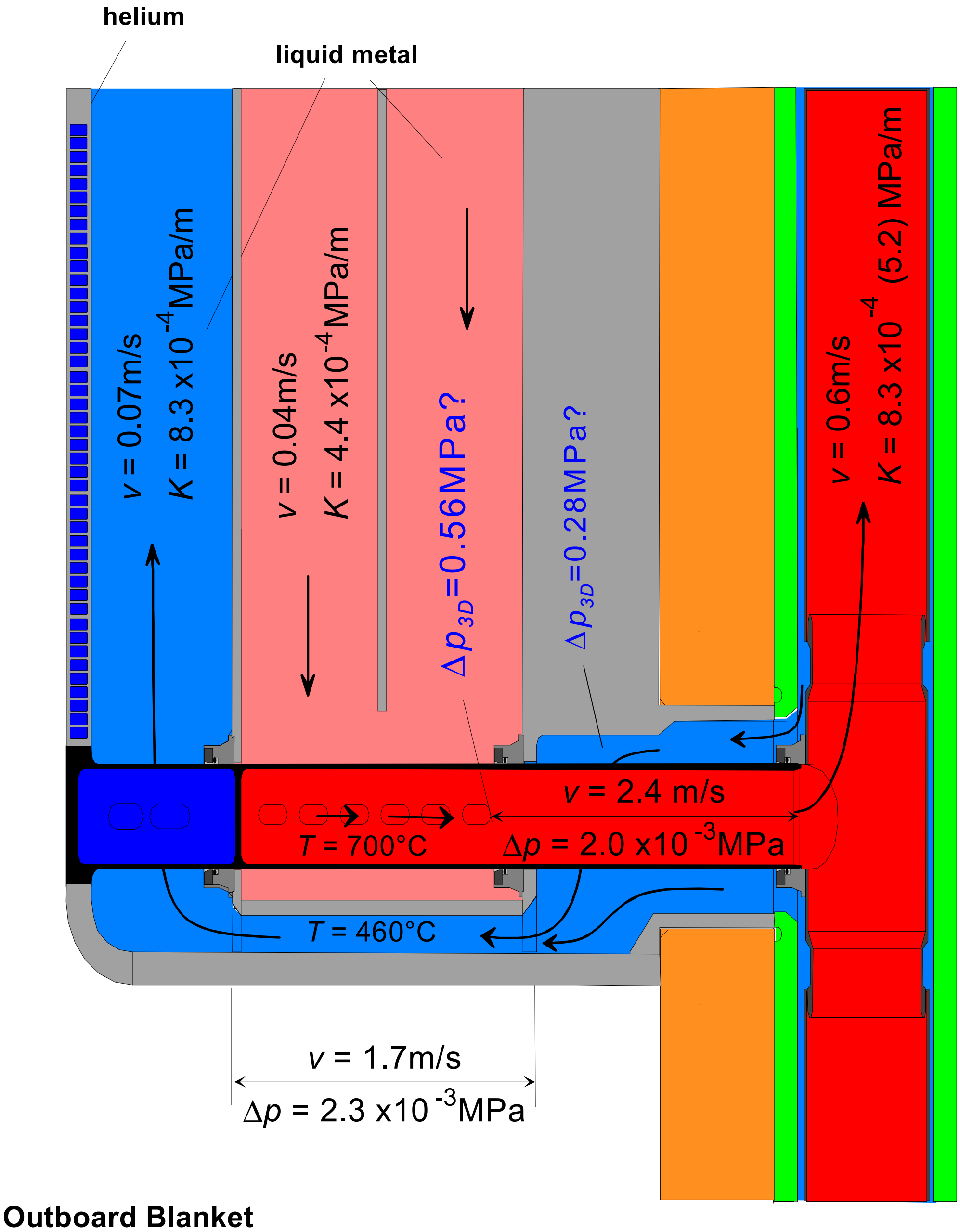

Figure 5: Summary of pressure drops in individual sub channels

4 Conclusions

The magnetohydrodynamic flow in the present design for a Dual Coolant Blanket module has been considered. Such a blanket module consists of a number of rectangular poloidal channels through which the liquid alloy PbLi is circulated. For thermal and electrical insulation all ducts are supplied with inserts made from the composite material SiC/SiC. Most of the ducts are straight rectangular ducts for which pressure drop correlations are known. As a result of the analysis the pressure drop in the blanket itself is small if all walls are covered by the electric insulation of 5 mm thickness. The pressure drop for the blanket reaches values of about $\Delta p = 8.2 \cdot 10^{-4}$ MPa for a poloidal length of 2 m. This pressure drop is really small and negligible compared with the pressure drop in the elements connecting the blanket with the rear coaxial pipes which feed and drain the blanket with the liquid metal. Some estimates demonstrate that electric insulation in these elements is unavoidable for a reasonable performance.

Three-dimensional effects at the strong contractions and expansions will cause the major fraction of pressure drop in this Dual Coolant Blanket. These crucial elements can not be analyzed by standard correlations. Estimates for the outboard blanket yield $\Delta p_{3D} \sim 0.84$ MPa and 1.68 MPa for the inboard blanket. Any more detailed analysis, however, requires exact three-dimensional modelling which is not the subject of these first estimates. Inertialess calculations in 3D seem to be possible with the numerical code described by Bühler (1995). On the other hand the velocities are relatively high in these regions so that inertia effects may become important. Modelling and computations of inertial flows in expansions will be the subject of the near term research at the *Institut für Kern-und Energietechnik* of the *Forschungszentrum Karlsruhe*. Pressure drop due to 3D effects at expansions and contractions is sensitive to the geometry. Especially larger dimensions of the access tubes could reduce the major fraction of pressure drop to lower values.

The flow in the gap between the rectangular channel and the circular pipes in the rear part of the blanket module has not been calculated in this work. If the walls are insulating and the dimensions of cross sections are reasonably chosen, these pressure drops should be much smaller than the values for 3D pressure drop at the expansions and contractions near the ends of the access tubes. If required, it is possible to perform a more detailed analysis for these geometries in future.

The MHD flow through the fringing field of the reactor causes additional drop which should be accounted for in future studies.

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