Experimental study of the MHD flow in a prototypic inlet manifold section of the DCLL blanket

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Abstract: This paper presents preliminary experimental results on Magnetohydrodynamic (MHD) flow in a prototypic distribution and collection manifold relevant to the Dual Coolant Lead Lithium (DCLL) blanket concept. A series of experiments is carried out in order to understand the mechanisms that determine the division of flow from a single supply channel to three parallel channels stacked in the direction the magnetic field lines. For values of the interaction parameter $N > 90$, the flow is found to be uniformly distributed among the parallel channels (with less than 5% flow unbalance). For lower values of N, the ratio between the outer to the central channels flow rates is found to follow a scaling law $N^{1/3}$ for $N \leq 60$ and $N^{1/4}$ for $60 < N \leq 90$.

1. Introduction

The performance and the structural integrity of liquid metal based fusion blanket systems are strongly dependent on the type of MHD flows that are established. The MHD flow patterns and their associated transport properties that result from the interaction between the pressure-driven flow, the plasma-confining magnetic field and the neutronic heating, control indeed many parameters such as the operating temperature, the pumping power, thermal-mechanical loads, corrosion *etc*. A recent review on the DCLL MHD and thermal related issues is given in [1].

In the DCLL blanket concept, where PbLi serves as a tritium production/transport media and as a coolant, relatively high velocities (~ 0.1m/s in the breeding/cooling channels) are required in order to achieve a nominal output temperature. To keep the MHD pressure drop at an acceptable level and to minimize heat leakages from the liquid to the Helium cooled ferritic structure, Flow Channel Inserts (FCI) made of poor thermal and electrical conductor materials like Silicon Carbide (SiC) are considered. Their role is to decouple electrically and thermically the liquid metal from the rest of the structure.

In the current DCLL design, a minimum of three breeding/cooling channels is required for structural reasons. Flow distribution among these channels becomes then an important element of the design as small changes in flow conditions may lead to strong flow imbalance resulting in overheating of channels with slower flow.

In order to understand the mechanisms that determine the division of flow from a single supply channel to a series of parallel blanket channels, a prototypic manifold experiment has been constructed. Its main goals are

i) Provide detailed information about the flow structure and the main scaling laws associated with each flow pattern.

ii) Answer the question about the effectiveness of flow channel inserts in reducing pressure losses in the inlet/outlet manifold section.

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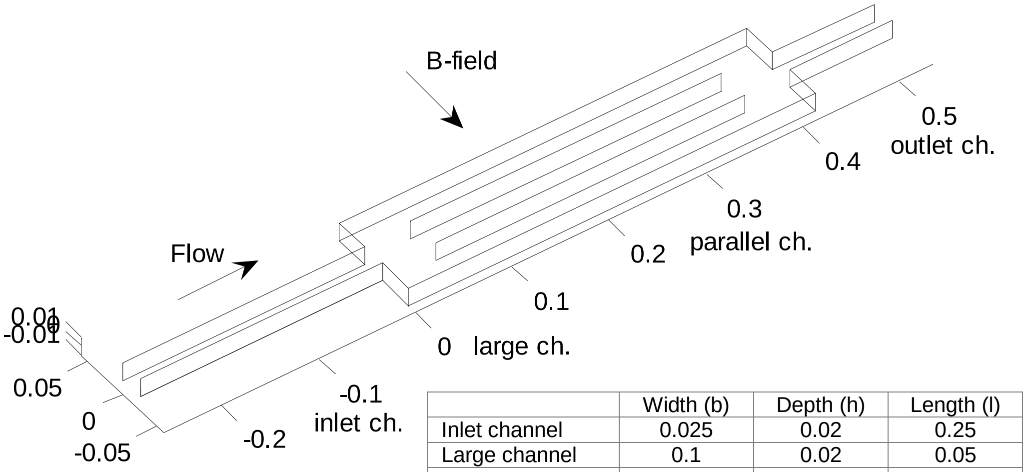
iii) Provide a reference database for validation of theoretical and numerical models.

In this paper, only data regarding flow rates are presented. Pressure drop and velocity field measurements are currently underway and will be reported in future papers.

2. Experimental set-up

2.1 Geometry

The test section, whose geometry is depicted on Fig. 1, consists of a set of three parallel rectangular channels stacked in the direction of the magnetic field lines. The flow is supplied by a single channel that expands abruptly (from 1 to 4) to match the total cross section of the manifold channels, and is collected downstream by a symmetrical contraction/single channel element. All channel walls are fabricated from Acrylic to simulate the insulating characteristics of the SiC flow channel inserts. An identical test section, made out of conducting walls is being now fabricated, and comparison of the flow properties from both test sections will help answer the question about the effectiveness of the SiC FCI in reducing the overall pressure losses.



	Width (b)	Depth (h)	Length (l)
Inlet channel	0.025	0.02	0.25
Large channel	0.1	0.02	0.05
Parallel channels	0.03	0.02	0.32
Outlet channel	0.025	0.02	0.105

Fig. 1: Geometry and key dimensions of the manifold experiment (in [m])

The working fluid, mercury, is circulated using a conducting MHD pump that is integrated to the manifold as shown on Fig. 2c. The whole set-up sits in the uniform field region of the magnet which is approximately $0.8 \times 0.2 \times 0.15$m. The studied flow is therefore decoupled from any three dimensional effects associated with the frigging field regions. A summary of the experimental and blanket relevant parameters is given in table 1. Although the blanket Hartmann number $Ha = B(b/2)\sqrt{\sigma/\rho\nu}$ can't be matched in our experiments, the Reynolds number, $Re = v_0 h/\nu$ can be adjusted to match either the interaction parameter $N = Ha^2/Re$, or the ratio Ha/Re (the symbols B, σ, ρ, ν, v_0, b and h denote the magnetic field intensity, the fluid electrical conductivity, the fluid density, the fluid kinematic viscosity, a typical fluid velocity, the width of the large channel and the channels depth respectively).

	B-field [Tesla]	inlet velocity [m]	Ha	Re	N
ITER blanket	4	0.3	7500	$2{\cdot}10^5$	280
Experiment	1.8	0.02 to 0.6 m/s	2430	$4{\cdot}10^3$ to $1.2{\cdot}10^5$	34 to 10^3

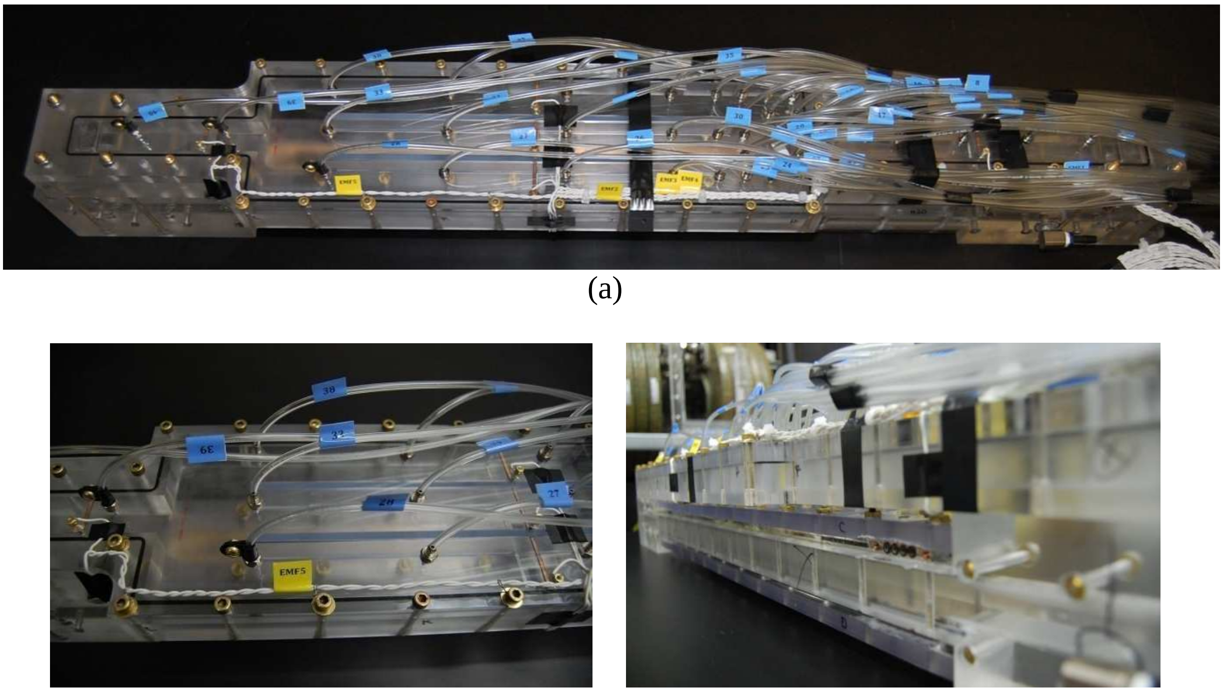
Table 1: relevant flow parameters

2.2 Diagnostic

In order to obtain detailed information about the flow structure, global and local flow quantities are measured. As shown on Fig. 2a, a large number of pressure taps have been machined on the manifold top wall of. Their positions allow us to determine pressure drop distributions in the direction parallel and perpendicular to the main flow direction. All pressure taps are connected to a single differential pressure sensor.

Flow rates are measured using inductive velocimetry technique. The integration of Ohm's law expressed in the B-field lines direction, $\partial\phi/\partial z = j_z/\sigma - v_x B$, along the two axes perpendicular to the flow direction, y and z, leads to a simple proportionality relationship between the mean velocity v_m and the electric potential drop $\Delta\phi$ across the channel depth: $\Delta\phi/h = v_m B$; this integration is equivalent to stating that the influence of the velocity profile shape on the potential readings is cancelled out by matching the electrode dimensions to the full width of the channel [2] (Fig 2b).

Finally, velocity profiles are measured using ultrasound Doppler velocimetry. Simultaneous measurements of the three velocity components along the emitting probe axis of a 4-probe system are now being tested.



(a)

(b)

(c)

Fig. 2: Photographs of the manifold test section
(a) general view of the manifold experiment
(b) close-up view showing the electrodes in each channel (1 pair per channel)
(c) Side view of the conducting MHD pump and the manifold section

3. Results and discussion

As previously mentioned only data concerning flow distribution are presented. Pressure and velocity field results will be reported later. We denote Re_r, Re_c and Re_l the Reynolds numbers associated with the right, central and left channels respectively. Fig. 3 displays their evolution as a function of the inlet Reynolds number Re for different values of Ha. In order to cover both inertial and inertialess flow regimes, the inlet mean velocity and the magnetic field intensity were varied from 0.02 to 0.6m/s and from 0.3 to 1.8T, respectively (which corresponds Re and Ha ranging from $4 \cdot 10^3 - 1.2 \cdot 10^5$ and $421 - 2430$ respectively). Note that the actual values of the field intensities at the electrodes were measured in order to accurately derive the mean velocities in every channel.

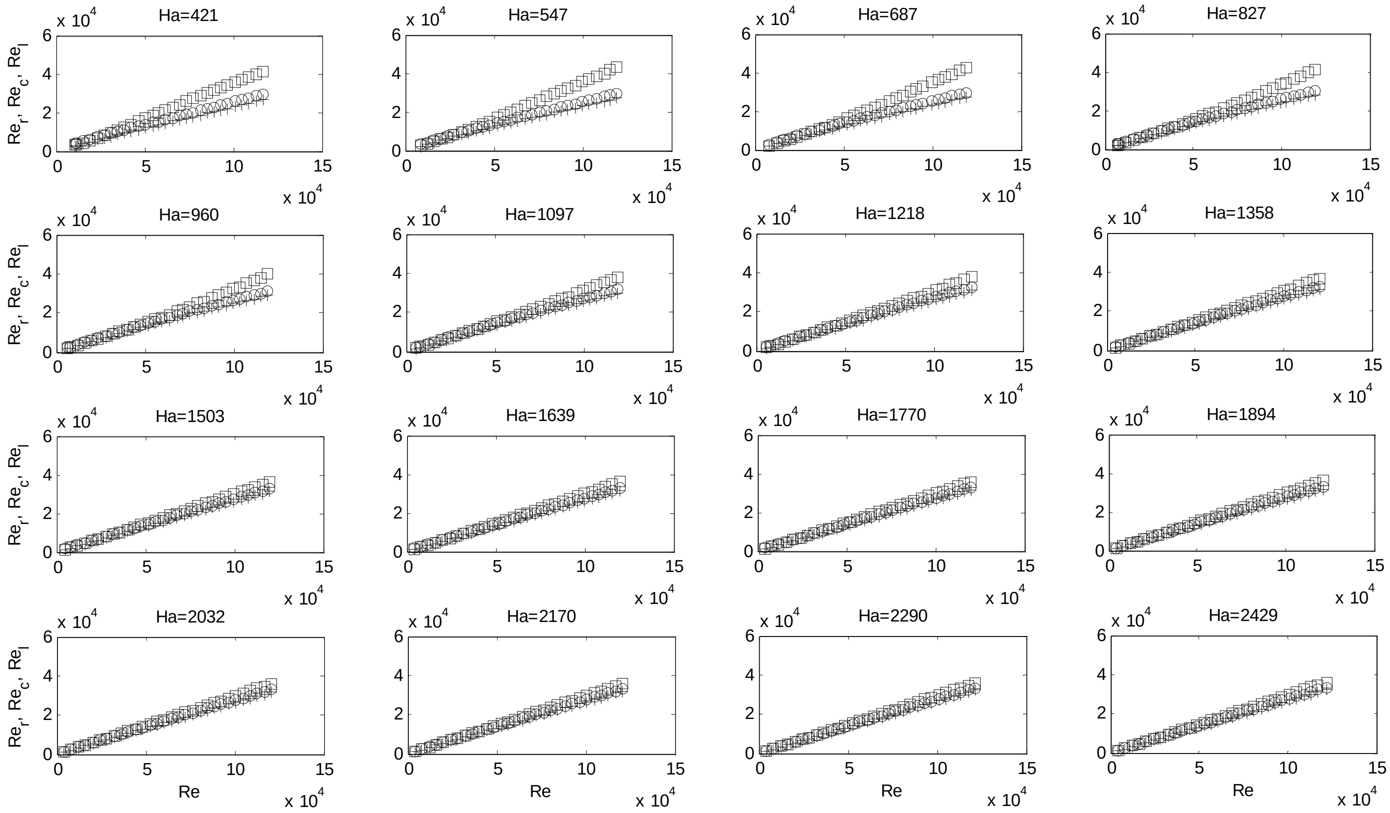


Fig. 3: plots of the evolution of Re_r (○), Re_c (□) and Re_l (+) as a function of Re

A clear tendency towards a uniform flow distribution among the parallel channels is observed when Ha increases and/or Re decreases. For an inlet velocity of 0.32 m/s ($Re \simeq 6 \cdot 10^4$), which is the typical inlet velocity of a supply pipe in the blanket, the relative difference of flow rates between the right and the central channel $(Re_c - Re_r)/Re_c$ drops from 0.24 to 0.05 when the field intensity goes from 0.3 to 1.8 T ($Ha \simeq 550 \div 2430$). In other words, the central channel may carry at the most 5% more flow rate than the outer channels when the field intensity becomes high enough.

Fig. 4 shows compensated log-log plots of the quantity Re_r/Re_c as a function of the interaction parameter N, revealing two scaling laws: $Re_r/Re_c \propto N^{1/3}$ for $N \leq 60$ and $Re_r/Re_c \propto N^{1/4}$ for $60 < N \leq 90$. An inertialess flow regime for which Re_r/Re_c does no longer depend on N seems to be reached for $N > 90$. This important result means that if N is the right parameter that governs the flow (which needs to be confirmed by the pressure and velocity distribution data), a similar manifold geometry will ensure a uniform PbLi distribution among the poloidal channels of the blanket.

We believe that at least three concurrent mechanisms are responsible the flow division:
i) the pressure drop in each parallel channel versus the overall pressure drop of the system: because the pressure drop scales differently in 3D flow regions like in the expansion and contraction than it does in the parallel channels, it may exist flow conditions (most likely at small Ha and small Re), for which the flow becomes very sensitive to small pressure drop

differences among the channels, which will lead to a strong non symmetrical and non uniform flow distribution.

ii) the flow properties in the expansion and contraction elements: due to the change of the axial velocity at the expansion/contraction regions, axial electric currents appear and are responsible for additional pressure drop and for a strong modification of the flow structure [3]. The velocity profile in the expansion determines how the flow will be distributed among the channels.

iii) the tendency towards a two-dimensionalization of the flow in the expansion region [4]: one can show that for fusion relevant conditions (*i.e.* high Ha and high N), the time needed to establish a quasi-2D flow $\tau_{2d} = (\rho/\sigma B^2)(b^2/l_\perp^2)$ in the large channel region, is much shorter than the time $\tau_c = L/U$ needed by the fluid to travel from expansion to the parallel channels (b, $l_\perp$, L and U stand for the distance between the Hartmann walls in the large channel, a typical transverse size of an eddy, the distance between the expansion and the parallel channel and a typical fluid velocity in the expansion). This mechanism may explain the good flow balancing observed at high N.

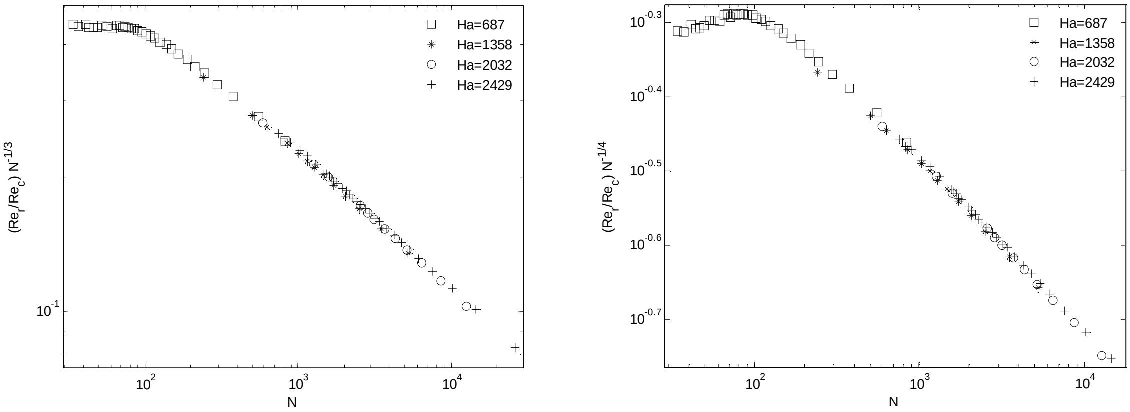


Fig. 4: Log-log plots of the quantities $Re_r/Re_c \times N^{-1/3}$ (left) and $Re_r/Re_c \times N^{-1/4}$ (right) as a function of the interaction parameter N

4. Conclusion

Experiments in a prototypic three-channel manifold system have been carried out in order to address the issue of flow distribution of PbLi in the DCLL blanket. Measurements of flow rates were performed for values of Re and Ha ranging from $4 \cdot 10^3 - 1.2 \cdot 10^5$ and $421 - 2430$ respectively. For values of the interaction parameter $N > 90$, the flow is found to be uniformly distributed among the parallel channels (with less than 5% flow unbalance). An inertial flow regime characterized by a N^m type law is also observed. Measurements of pressure drop and velocity distributions are underway and are expected to provide a more detailed picture of the flow structure in order to understand what mechanisms control these types of flows.

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