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EXPERIMENTAL STUDY OF MHD FLOWS IN A PROTOTYPIC INLET MANIFOLD SECTION OF THE DCLL TEST BLANKET MODULE

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This paper presents preliminary results on a magnetohydrodynamic (MHD) flow in a prototypic distribution and collection manifold relevant to the Dual Coolant Lead Lithium (DCLL) blanket concept. A series of experiments has been 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. First flow rate data show that for a relatively high interaction parameter ($N > 90$), a uniform flow distribution is achieved 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 N^m type scaling law, with $m = 1/4$ for $60 < N < 90$ and $m = 1/3$ $N < 60$.

1. Introduction. The performance and the structural integrity of liquid metal based fusion blanket systems are strongly related to the type of MHD flows that are established. The magnetohydrodynamic 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 medium and as a coolant, relatively high velocities ($\sim 0.1\,\mathrm{m/s}$ 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 electrically and thermally decouple 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 a strong flow imbalance resulting in overheating of channels with a 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 sections;

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

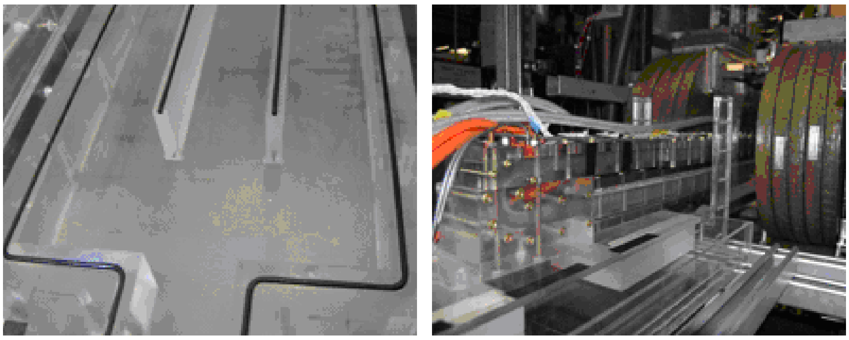

Fig. 1. Manifold geometry showing the feeding channel, the expansion and the manifold channels (left). Manifold and integrated MHD pump assembly ready to be inserted in the magnet gap (right).

2. Experimental set-up. The test section consists of a set of three parallel rectangular channels stacked in the direction of the magnetic field lines (Fig. 1 left). The flow is supplied by a single channel that expands abruptly (from 25 mm to 100 mm) 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.

The working fluid, mercury, is circulated using a conducting MHD pump that is integrated to the manifold as shown in Fig. 1, right. 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 flow in the manifold 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 typical fusion Hartmann numbers $\mathrm{Ha} = (1/2)bB\sqrt{\sigma/\rho\nu}$ cannot be matched in our experiments, the Reynolds number $\mathrm{Re} = (v_0 h)/\nu$ can be adjusted to match either the interaction parameter $N = \mathrm{Ha}^2/\mathrm{Re}$ or the ratio Ha/Re (the symbols B, σ, ρ, ν, v_0, b and h denote magnetic field intensity, fluid electric conductivity, fluid density, fluid kinematic viscosity, a typical fluid velocity, the width of the large channel and the channels depth, respectively).

2.1. Diagnostics. Flow rates are derived from electric potential drop measurements between electrodes imbedded in the side walls (see Fig. 1). The integration of Ohm's law expressed in the magnetic field lines direction (z-axis), $\partial\phi/\partial z = j_z/\sigma - v_x B$, 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: $\Delta\phi/h = v_\mathrm{m}B$; 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. 2).

Table 1. Key dimensional and non dimensional parameters.

	B-field [T]	inlet velocity [m/s]	Ha	Re	N
ITER TBM	4	0.3	7500	$2{\cdot}10^5$	280
Experiment	1.8	0.02–0.6	2430	$4{\cdot}10^3 - 1.2{\cdot}10^5$	34–1000

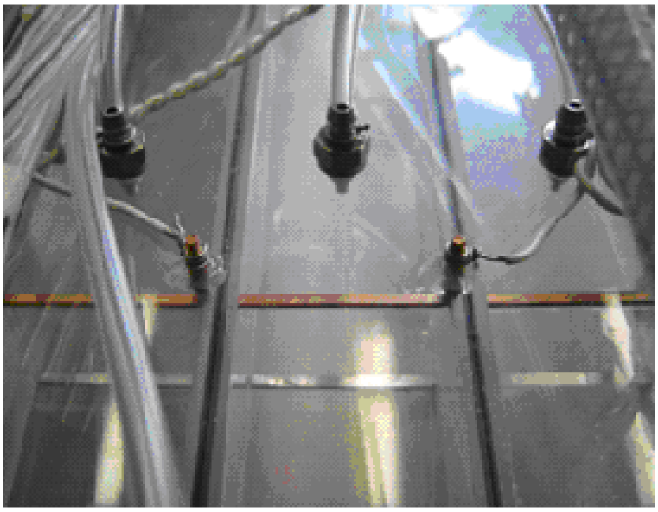

Fig. 2. Copper electrodes used to measure flow rates in each channel.

3. Flow distribution. In this section we present results of flow rate measurements corresponding to different MHD flow regimes. Pressure drop and velocity field data will be reported later. We denote $\mathrm{Re_r}$, $\mathrm{Re_c}$ and $\mathrm{Re_l}$ the Reynolds numbers associated with the right, central and left channels, respectively.

The evolution of $\mathrm{Re_r}$, $\mathrm{Re_c}$ and $\mathrm{Re_l}$ as a function of the inlet Reynolds number Re is plotted for some values of Ha (Fig. 3). Both inertial and inertialess flow regimes are covered. Note that the actual values of the field intensities at the electrodes were measured in order to accurately derive the mean velocities in each channel.

For relatively high interaction parameters ($N > 90$), the flow rates in all channels are found to be almost identical, thus N-independent. For $N \leq 90$,

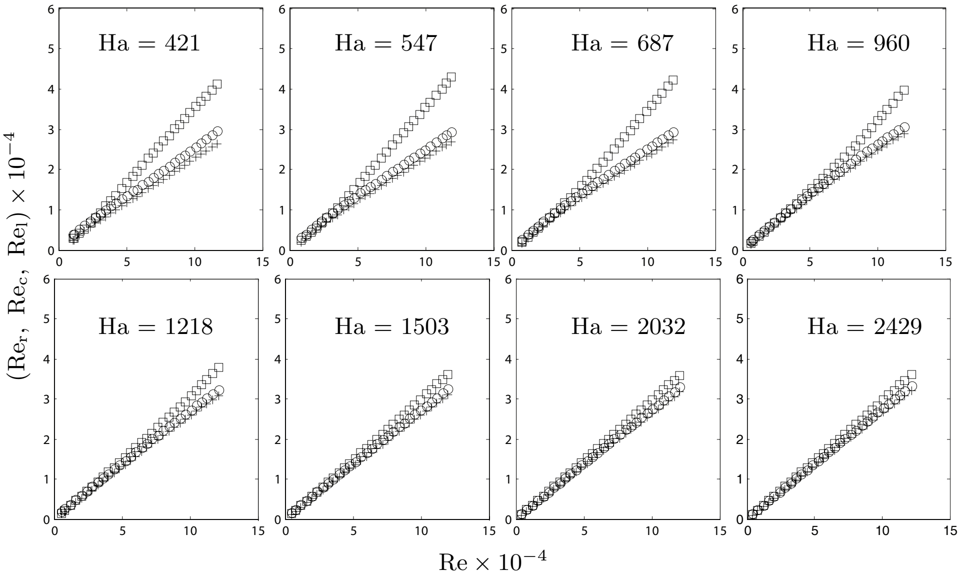

Fig. 3. Evolution of $\mathrm{Re_r}$, $\mathrm{Re_c}$ and $\mathrm{Re_l}$ versus Re for different values of Ha. '+' Left channel, '□' central channel, '○' right channel.

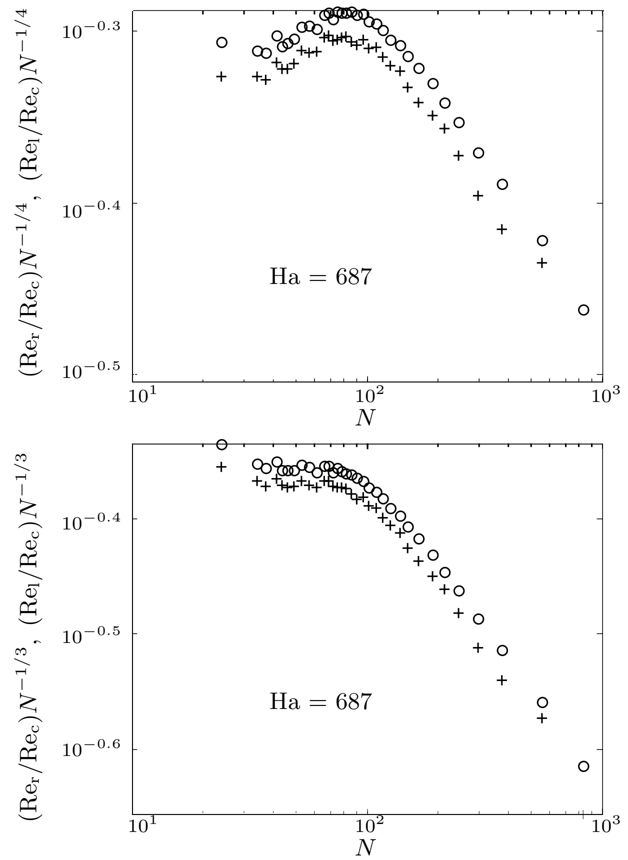

Fig. 4. N^m-type scaling laws for the quantities $\mathrm{Re_r}/\mathrm{Re_c}$ and $\mathrm{Re_l}/\mathrm{Re_c}$. '+' Left channel, '∘' right channel.

inertial effects become more important and the flow rate in the central channel increases with N while, by mass conservation, the flow rate in the two other channels decreases. This inertial regime seems to be characterized by two scaling laws: $\mathrm{Re_r}/\mathrm{Re_c} \propto N^{1/4}$ for $60 < N \leq 90$ and $\mathrm{Re_r}/\mathrm{Re_c} \propto N^{1/3}$ for $N \leq 60$ (Fig. 4). It is important to point out that a similar scaling for the Ludford layer thickness, namely, $\delta_{\mathrm{Ludford}} \propto N^{-1/3}$ could be derived when the flow is dominated by an inertial-electromagnetic balance [3].

A systematic flow asymmetry between the left and right channels is observed for the whole range of Ha and Re numbers. Indeed, the quantities $\dfrac{\mathrm{Re_r}}{\mathrm{Re_c}}$ and $\dfrac{\mathrm{Re_l}}{\mathrm{Re_c}}$ plotted in Fig. 4 do follow the same scaling laws, but their absolute values are quite different. This systematic asymmetry is more pronounced at low Ha (∼ 400) and it is still present at higher Ha (∼ 2400).

The physical arguments that explain the asymmetric separation of internal hydrodynamic flows in the vicinity of an abrupt change in test-section geometry (see, for instance, [4]) do not apply to our flow, at least for high Ha flow regimes, since the coherent structures responsible for that flow asymmetry are strongly damped out due to Joule dissipation.

In order to quantify the flow imbalance between the central channel and the two other channels, the quantity $\alpha = \dfrac{2\mathrm{Re_c} - \mathrm{Re_r} - \mathrm{Re_l}}{\mathrm{Re_c}}$ has been plotted as a

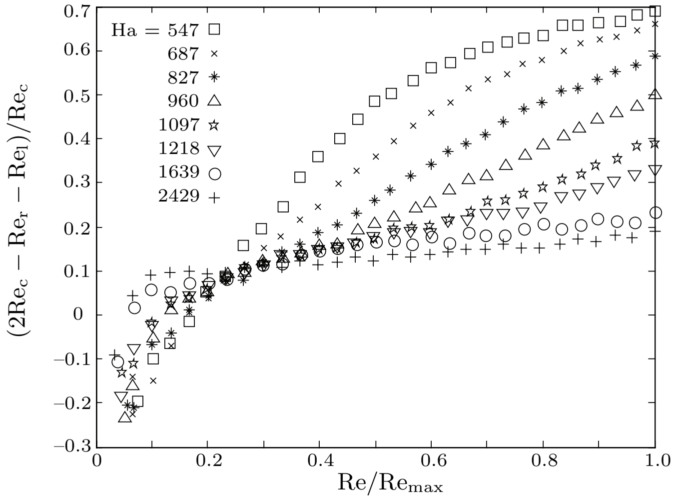

Fig. 5. Evolution of the relative cumulative flow imbalance $2\mathrm{Re_c} - \mathrm{Re}_r - \mathrm{Re_l}/\mathrm{Re_c}$ as a function of $\mathrm{Re}/\mathrm{Re_{max}}$.

function of $\dfrac{\mathrm{Re}}{\mathrm{Re_{max}}}$ (Fig. 5). For $\dfrac{\mathrm{Re}}{\mathrm{Re_{max}}} < 0.1$, the flow rate in the central channel is surprisingly much lower that the flow rate in external channels. For higher Re, the flow carried by the central channel becomes more important, up the 35% more than the left or right channel. Notice that the change of sign of α is a clear indication that at least two concurrent mechanisms are responsible for the flow division (Fig. 5).

Although the physics of such flows is quite complex, the above observations lead us to think that three basic mechanisms are responsible for the flow balance/imbalance and asymmetry:

i) *pressure drop:* for small Ha and N, the pressure drop in the parallel channels and the one associated with the expansion and contraction are of the same order, so that any small pressure drop difference between the channels may lead to a strong flow imbalance and asymmetry;

ii) *flow properties in the expansion and contraction elements:* due to the change of the axial component of the velocity at the expansion, axial electric currents appear and are responsible for additional pressure drop and for a strong modification of the flow structure [3]. New 'initial' flow conditions are set in the Ludford layer and, depending on the balance between inertial and electromagnetic forces, the flow balance may or may not be affected;

iii) *two-dimensionalization:* at Ha and high N, the flow at the onset of the parallel channels is likely to be quasi two-dimensional, leading therefore to a uniform flow distribution. The average relative flow imbalance for Ha = 2429 is of the order of 5% (Fig. 5). For lower values of Ha, the flow remains 3D to weakly 3D.

4. Concluding remarks. Experiments in a prototypical 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). From a fusion application stand point, this is an important result since it shows that even in a simple rectilinear manifold geometry, a good flow balance can be achieved providing that a two-dimensional flow regime can be reached before the flow is distributed.

Finally we observed that the inertial flow regime is characterized by a N^m type law. Measurements of pressure drop and velocity distributions are being performed in order to provide a more detailed picture of the flow structure and help understanding what mechanisms control these type of flows.

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