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Experimental study of liquid metal magnetohydrodynamic flows near gaps between flow channel inserts

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Abstract

The flow of the electrically conducting lead lithium, foreseen in liquid metal blankets as breeder and coolant, under the influence of the plasma-confining magnetic field induces electric currents that create strong electromagnetic Lorentz forces and high magnetohydrodynamic pressure drop. Electrically insulating flow channel inserts (FCI) may be applied for electrically decoupling the liquid metal flow from the well-conducting channel walls. This reduces currents and associated Lorentz forces that are responsible for the major contribution to pressure drop in the blankets. For fabrication reasons, it is unavoidable that gaps between inserts are present. Gaps will interrupt the electrical insulation, thus providing unwanted local short circuit for electric currents. For experimental investigations of 3D effects at junctions of FCIs, a test section has been manufactured and experiments have been performed in the MEKKA facility at the Karlsruhe Institute of Technology (KIT). The present experimental study shows the benefits of FCIs for pressure drop reduction in fully developed flows and quantifies the deterioration of pressure drop reduction by the presence of uninsulated gaps between FCIs.

Key words: magnetohydrodynamics (MHD), liquid metal experiments, flow channel inserts (FCI), MHD pressure drop
PACS:

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1. Introduction

In dual-coolant lead lithium (DCLL) blankets, foreseen in fusion power plants, the liquid metal PbLi flows at sufficiently large velocity to remove the volumetric heat generated in the fluid. In the plasma-confining magnetic field, the electrically conducting fluid flow induces currents that are responsible for strong electromagnetic Lorentz forces and high magnetohydrodynamic (MHD) pressure drop. Electrically insulating flow channel inserts (FCI) represent a feasible option for electrically decoupling the liquid metal flow from the well-conducting walls. First ideas go back at least to a patent by S. Malang (1987) [1]. FCIs reduce currents, Lorentz force and pressure drop in fusion blankets. They are required in the breeder zone of DCLL blankets [2], [3], but they could be also a promising option for manifolds and piping systems in the back supporting structure of water-cooled (WCLL) or helium-cooled (HCLL) lead lithium blankets, where the fluid velocity is of similar order of magnitude as in DCLL breeding channels.

It has been proposed to manufacture electrically insulating FCIs from ceramic materials such as fiber enforced silicon carbide [4] or ceramic foams [5]. However, experiments with the latter type of insert did not show the expected pressure drop reduction [6] and post-experimental material analyses [7] confirmed PbLi ingress through local defects of the protective CVD layer.

The problem of liquid metal infiltration into porous ceramics is avoided by using sandwich-type FCIs, where the insulating ceramics is protected from all sides by thin sheets of steel [8]. Sandwich-type FCIs are less efficient for reduction of pressure drop than ideal non-conducing ceramic inserts, because currents can close along the inner conducting steel sheet. However, if the protecting steel layer is thin, its electrical resistance is large, which limits the magnitude of induced currents. Previous experimental investigations using such FCIs showed a pressure drop reduction by a factor of nearly 9 compared to the flow in a non-insulated circular pipe [9]. Such FCIs are therefore considered a feasible option based on available materials and fabrication techniques [10], [11], [12].

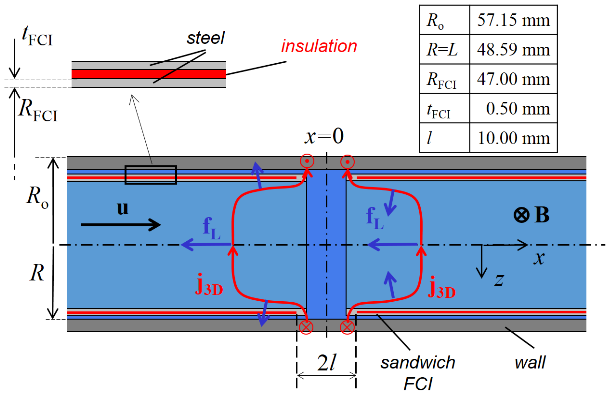
The present paper focuses on experimental studies of three-dimensional liquid metal MHD flow near gaps between FCIs with the purpose to demonstrate the benefits of the inserts for pressure drop reduction and to quantify the additional pressure drop near gaps, that has been predicted by theoretical analyses [13]. Experiments in a parameter range typical for DCLL blankets are performed in the MEKKA laboratory at the Karlsruhe Institute of Technology (KIT) for different flow rates and strengths of the magnetic field.

In the following, an introduction to the problem is given, the experimental test section is described, relevant physical parameters are introduced and scales are defined that are used for nondimensional representation of results.

2. Test section, parameters and scales

A test section with circular cross-section is used for experimental investigation of MHD pressure drop reduction by FCIs. Details of the geometry are shown in Fig. 1. The thick-walled pipe has an inner radius $R = L$ that is used as length scale for the problem. All dimensions, including the radius R_{FCI} of the inner steel layer of the FCI, can be seen from Fig. 1 and the inserted table. The thickness $t_{\mathrm{FCI}} = 0.5\,\mathrm{mm}$ of the protection sheets has been suggested e.g. in [14].

The fabrication of FCIs with circular shape required different techniques than those proposed for rectangular ducts [10]. Details of a successful manufacturing process can be found in [11]. Due to fabrication issues and in order to maintain a circular shape, a pressure equalization slot along the entire Hartmann wall has been avoided. Instead a short non-insulated fraction of the FCI is tolerated, where pressure equalization holes give access for measuring pressure distribution along the FCIs (Fig. 2).



R_o	57.15 mm
R=L	48.59 mm
R_{FCI}	47.00 mm
t_{FCI}	0.50 mm
l	10.00 mm

Fig. 1. Geometry at the junction between two FCIs.

Leakage currents are minimized since potential is zero along the symmetry plane $z = 0$, where the pressure taps are located [15]. Nevertheless, the non-insulated fraction of FCI surface might lead to some local distortion of core velocity and increase slightly the pressure drop in the FCI compare to ideal conditions. In a fusion blanket, where there is no need for pressure measurements, it would be better to use instead seamless insulation and non-interrupted outer sheets.

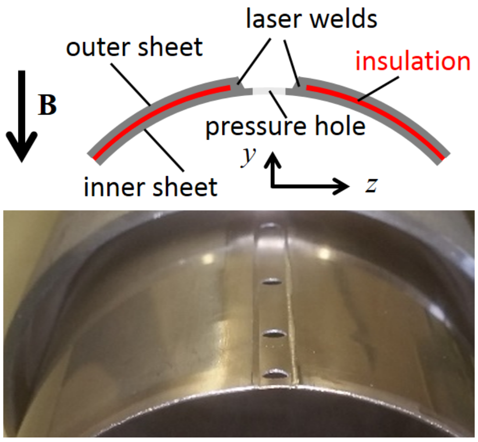


Fig. 2. View of pressure equalization holes in the FCI.

Two sandwich-type FCIs have been placed in a thick-walled circular pipe, leaving a short distance that represents the non-insulated axial gap at junctions between two FCIs (Fig. 1). Far upstream two flow straighteners have been inserted into the pipe to homogenize the inflow. The external thick-walled pipe has 30 pressure taps primarily located on the upper Hartmann wall at positions coinciding with the locations of pressure equalization holes in FCIs. Smaller axial spacing of these holes at the entrance of the flow into the FCIs and at the gap near $x = 0$ gives a higher spatial resolution at those positions, where strong 3D effects are expected. In addition, at the entrance, at the gap, and at the exit of the FCIs the pressure is recorded also at the side wall. Pressure taps are switched by a system of computer-controlled valves to an array of pressure transducers with different sensitivity in the range of a few mbar up to 7 bar.

Sodium potassium NaK is used as a model fluid and a magnetic field with maximum strength of 2.1T is provided by a normal-conducting dipole magnet in the MEKKA MHD laboratory. The magnetic gap has a rectangular cross-section and within a region of $850 \times 168 \times 483 \text{mm}^3$ the field is quite uniform with deviations from the core value smaller than 1%. The test section inserted in the magnet is shown in Fig.3.

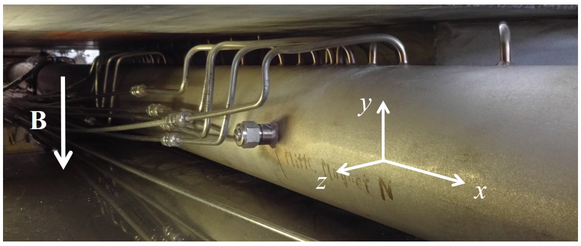


Fig. 3. Test section in the gap of the magnet.

The intensity of the flow and strength of the magnetic field are quantified by the nondimensional Reynolds and Hartmann numbers

$$Re = \frac{u_0 L}{\nu}, \qquad Ha = LB\sqrt{\frac{\sigma}{\rho\nu}}. \tag{1}$$

The parameter Re quantifies the ratio between inertia and viscous forces, and Ha^2 stands for the ratio of electromagnetic forces to viscous forces. Here, ν, ρ and σ denote the kinematic viscosity, density and electric conductivity of the fluid. The mean velocity in the bare pipe without FCI is u_0 and B stands for the magnitude of the magnetic field.

The influence of wall conductivity σ_w on MHD pipe flow is described using the wall conductance parameter c according to [16], which evaluates for the present problem and material properties at $50°C$ [17], [18] to

$$c = \frac{\sigma_w}{\sigma}\frac{R_o^2 - R^2}{R_o^2 + R^2} = 0.0727 \tag{2}$$

for the thick-walled pipe and to $c_{FCI} = 0.00476$ for the thin inner conducting sheet of the FCI.

For strong magnetic fields, the nondimensional pressure gradients ("$*$" denotes dimensional quantities) in fully established flow become

$$\frac{\partial p^*/\partial x^*}{\sigma u_0 B^2} = \frac{\partial p}{\partial x} = -\frac{c}{1+c} = -0.0678, \tag{3}$$

$$\frac{\partial p^*_{FCI}/\partial x^*}{\sigma u_0 B^2} = \frac{\partial p_{FCI}}{\partial x} = -\frac{c_{FCI}}{1+c_{FCI}}\frac{R^2}{R^2_{FCI}} \tag{4}$$

for the flow in a pipe [19] and in an infinitely long FCI, respectively. The factor R^2/R^2_{FCI} accounts for the fact that the mean velocity is slightly higher in the insert than in a pipe without FCI. For derivation of (4) we assume that the flow rate in the thin annular gap between FCI and wall is negligible in comparison with that in the core [20]. This yields $\partial p_{FCI}/\partial x = -0.00508$.

3. Experimental results

Prior to experiments with FCIs the pressure gradient of fully developed MHD pipe flow without FCIs has been measured along three different axial positions $\Delta x_{1,2,3}$. Results shown in Fig. 4 show quite good agreement with theoretical predictions (3) and confirm thereby the quality of the instrumentation used. Further results for MHD pipe flow without FCI in uniform and non-uniform magnetic fields will be published in a separate paper.

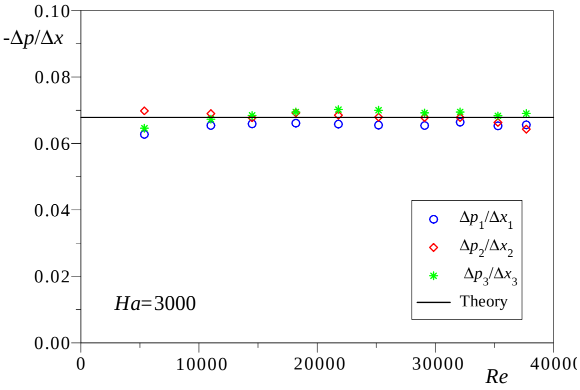


Fig. 4. Pressure gradient in the pipe without FCI compared with theoretical value according to Eq. (3).

For investigations of 3D effects near the non-insulated region at $x = 0$, the gap between FCIs has been positioned in the center of the magnet. Pressure differences with respect to the position $x = 0$ have been measured along the axis and normalized by $\sigma u_0 B^2 L$ for a common representation of results. In the following, x stands for the axial position, scaled by L. The insulations in bothe FCIs extend from $x = \pm 0.2$ up to $x = \pm 12.25$ as illustrated in subplots in Figs. 5, 6.

Results obtainned for $Ha = 3000$ are shown in Fig. 5. One can observe the great benefit from using FCIs by comparing the theoretical curves for pipe flow and assumed perfect FCI, which yield a pressure drop reduction factor of $0.0678/0.00508 = 13.3$. At some distance from the gap, here for $|x| \gtrsim 1$ the measured pressure gradients in the FCIs are close to these predictions as indicated in the figure. Experiments therefore confirm that a pressure drop reduction close to predicted values is achievable with the used sandwich-type inserts. At larger distance from the center the pressure gradient increases. This is caused by additional 3D effects, because for $|x| > 8.8$ the magnetic field is not uniform anymore and decays for larger distance from the center. Moreover, the insulation ends at $|x| = 12.24$, which leads to electrical short circuit into the thick well conducting pipe wall. 3D effects at entrance and exit of FCIs will be the subject of a separate upcoming paper and are not discussed here. At $x = 0$ some additional pressure drop $\Delta p_{3D} = 0.12$ is present due to leakage currents across the gap into the well-conducting pipe wall. Extra currents create additional Lorentz forces responsible for Δp_{3D}. There seems to be no difference in non-dimensional pressure drop near the gap for the Reynolds numbers considered, i.e. those flows are apparently inertialess.

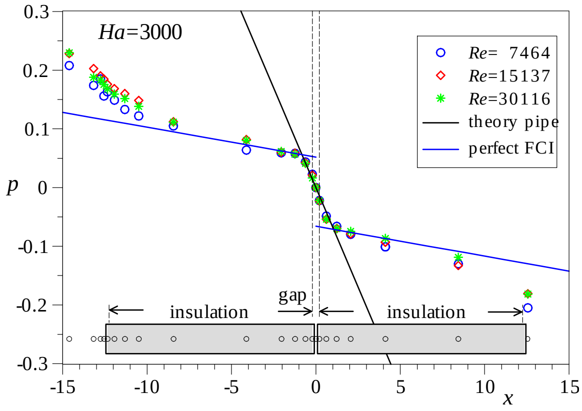


Fig. 5. 3D MHD flow at the junction between two FCIs. Pressure along the axis for $Ha = 3000$ and different Re. Positions of FCIs and pressure taps are illustrated in the sketch.

Figure 6 shows results for $Re = 15000$ and different values of Ha. We observe similar results as discussed above. It appears that there is some moderate influence of Ha on the results and that the curves are slightly shifted in vertical direction depending on Ha. However, the additional 3D pressure drop seems not much affected by this.

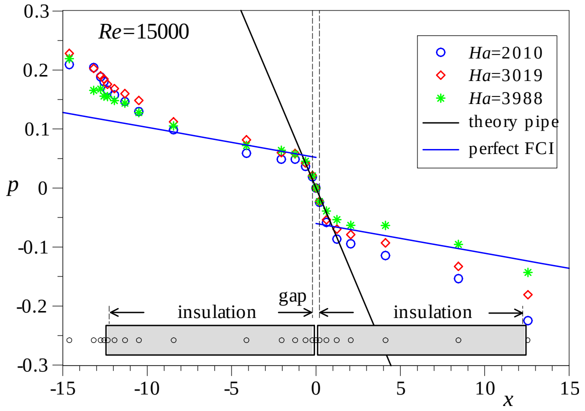


Fig. 6. 3D MHD flow at the junction between two FCIs. Pressure along the axis for $Re = 15000$ and different Ha.

4. Conclusions

Magnetohydrodynamic experiments have been performed to demonstrate pressure drop reduction capability by FCIs. According to present experiments, sandwich-type FCIs may reduce pressure drop of fully developed MHD flow by more than one order of magnitude compared to that in a thick-walled pipe. The additional nondimensional pressure drop at a gap between two FCIs has been measured to $\Delta p_{3D} = 0.12$, a value that seems not very high. Nevertheless, one should keep in mind that this pressure drop caused by one single non-insulated gap corresponds to that of a fully developed flow in an FCI over a length $\Delta l_{3D} = 14.8$.

Upscaled to reactor conditions ($L = 0.096\text{m}$, $u_0 = 0.014\text{m/s}$, $B = 5.5\text{T}$, $\sigma = 7.56 \cdot 10^5 \Omega^{-1}\text{m}^{-1}$ [3]) we find per gap $\Delta p^*_{3D} = \sigma u_0 B^2 L \cdot \Delta p_{3D} = 37\,\text{mbar}$. This is a relatively small value for the breeding channels where the velocity is low. Applied to the back supporting structure, where L and u_0 are considerably larger [3], one could conclude that the number of non-insulated gaps has to be kept at a minimum. It has to be mentioned, however, that the experiments have been performed for circular pipes and an application to the slotted geometry of the back supporting structure of the present DCLL design [14] is not straight forward.

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