EXPERIMENTS ON MAGNETOHYDRODYNAMIC FLOWS IN A SUDDEN EXPANSION OF RECTANGULAR DUCTS AT HIGH HARTMANN NUMBERS

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Introduction. In current designs for liquid-metal blankets in fusion reactors the eutectic alloy PbLi serves exclusively as breeder material and the fusion heat is removed from the blanket by a separate helium cooling system. For tritium removal a weak liquid-metal flow of the order of mm/s is required in the breeder units. The units are fed through smaller pipes and expansions are therefore unavoidable. Moreover, expansions are generic elements of liquid metal circuits and perfect objects for fundamental research. They received attention in the past by a number of authors and one should recall as examples the experiments in insulating sudden expansions up to Ha $\approx$ 300 [1], [2], or MHD flows through smoothly expanding insulating [3] or conducting [4], [5] channels. For applications in nuclear fusion blankets, where Hartmann numbers may reach the order of Ha $> 10^4$ and walls are electrically conducting, experimental results for sudden expansions do not exist. Experiments on MHD flows in a sudden expansion of conducting rectangular ducts have been performed in the MEKKA laboratory of the Forschungszentrum Karlsruhe. A sketch of the experimental geometry is shown in Fig. 1. In these experiments the magnetic field was strong enough that Hartmann numbers up to Ha $\gtrsim$ 5500 could be established. The measured quantities presented here are the pressure variation along the axis of the duct and the surface potential for di.erent values of the interaction parameter and Hartmann number. These values are compared with results of an inertialess asymptotic analysis.

1. Formulation. We consider the three-dimensional, inertialess, incompressible flow of an electrically conducting viscous fluid through a sudden expansion, subject to a strong, externally applied magnetic field. The momentum

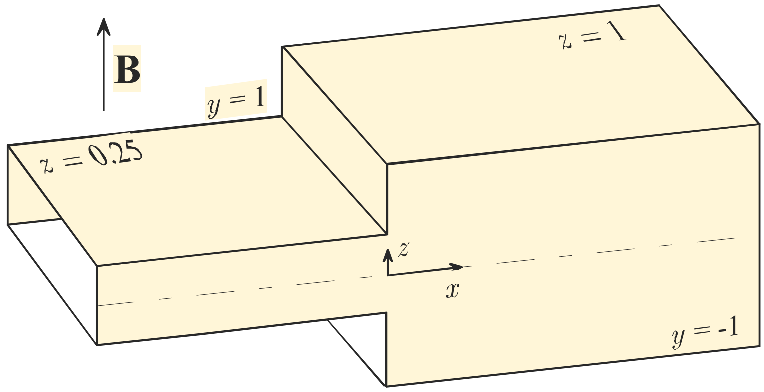

Fig. 1. Sketch of the expansion geometry.

equation and Ohms law that govern the flow are

$$\frac{1}{N}\left(\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\cdot\nabla)\mathbf{v}\right)=-\nabla p+\frac{1}{\mathrm{Ha}^2}\Delta\mathbf{v}+\mathbf{j}\times\mathbf{B},\quad \nabla\cdot\mathbf{v}=0, \tag{1}$$

$$\mathbf{j}=-\nabla\phi+\mathbf{v}\times\mathbf{B}, \tag{2}$$

with conservation of mass and charge, $\nabla\cdot\mathbf{v}=0$ and $\nabla\cdot\mathbf{j}=0$. Here, the variables $\mathbf{B}=\hat{\mathbf{z}}$, $\mathbf{v}$, $\mathbf{j}$, ϕ and p stand for the magnetic field, velocity, current density, electric potential and pressure, scaled by the reference values B_0, v_0, $\sigma v_0 B_0$, $v_0 L B_0$, and $\sigma v_0 L B_0^2$, respectively. The electric conductivity of the fluid σ, its kinematic viscosity ν and density ρ are assumed to be constant. As a universal length scale we use the constant half width $L = 47\,\mathrm{mm}$ of the duct and v_0 stands for the average velocity in the large square cross section.

The flow is governed by two nondimensional parameters, the Hartmann number and the interaction parameter,

$$\mathrm{Ha}=B_0L\sqrt{\frac{\sigma}{\rho\nu}},\quad N=\frac{\sigma L B_0^2}{\rho v_0}. \tag{3}$$

They account for the importance of electromagnetic forces to viscous forces and inertia forces, respectively. They are linked to the hydrodynamic Reynolds number as $\mathrm{Re}=\mathrm{Ha}^2/N$.

At the wall the fluid satisfies no-slip $\mathbf{v}=0$, and continuity of potential $\phi=\phi_{\mathrm{w}}$ (no contact resistance). The wall potential ϕ_{w} is determined by currents flowing in the wall. Here the essential parameter is the wall conductance ratio $c=\sigma_{\mathrm{w}}d/(\sigma L)$, were σ_{w} stands for the electric conductivity of the stainless steel wall with thickness $d=3\,\mathrm{mm}$.

2. Experimental setup. The experiments were conducted by fitting the test section into the MEKKA experimental facility of Forschungszentrum Karlsruhe. An eutectic sodium-potassium alloy $\mathrm{Na}^{22}\mathrm{K}^{78}$ is used in the liquid metal loop which allows measurements at room temperature. Fig. 2*a* shows the test section during preparation. One can see the sudden expansion in which the smaller duct is yet uncovered, while the large rectangular duct is already covered by insulating plates which are fitted by a large number (> 300) of spring-loaded electric potential probes for measurements of surface potential. These plates improve in addition the mechanical strength of the thin-walled metallic structure. The photograph shows some of the 16 pipes for pressure di.erence measurements. They

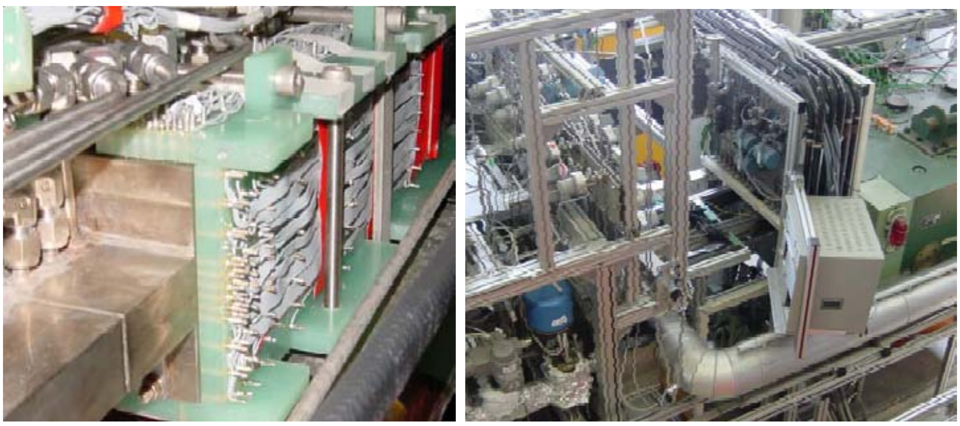

Fig. 2. Test section during preparation (*a*), view on the magnet containing the test section (*b*).

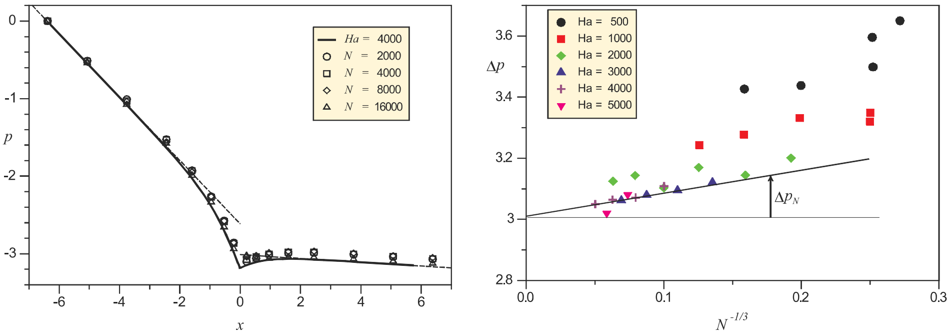

Fig. 3. Pressure along the expansion for Ha = 4000 (*a*) and pressure difference $\Delta p = p(x = -6.38) - p(x = 6.38)$ for various Ha and N (*b*).

are connected to a valve system for switching the pressure lines to four unipolar capacitive pressure transducers of di.erent sensitivity. On Fig. 2*b* one can see the movable liquid metal compact loop and the dipole magnet in which the test section is completely inserted.

The magnet can reach a 2.1 T transverse uniform magnetic field in a volume of 170 mm×480 mm×800 mm, while the test section has a 600 mm long instrumented part. The fluid is circulated through the test section by electric pumps. The flow rate is measured by a gyrostatic- and an electromagnetic flow meter. A more detailed description of the MEKKA facility, the safety- and operational conditions has been given previously in [6].

The data acquisition system for surface potential-difference measurements basically consists of a 320 channel low nose ($< 1\,\mu$V) relay multiplexer and a very sensitive voltmeter (resolution 10 nV). The voltmeter has multiplexed 20 differential input channels in one step. The measuring time (integrating time) for each potential value was in the range of 2 s The control of the multiplexer, voltmeter, pressure valves and reading of measured data is organized by a computer.

3. Results. Fig. 3*a* shows a typical example of pressure measurements. The measured data far upstream ($x < 0$) and downstream ($x > 0$) from the expansion approaches perfectly the predicted pressure gradients for fully developed MHD flows. This indicates that the entrance and exit lengths of the experiment are su.ciently long to reach (with the used flow homogenizes at $x \approx \pm 13$) fully established conditions within the uniform part of the magnetic field. Near the expansion the pressure drops more rapidly due to threedimensional recirculating electric currents, associated with additional Joule dissipation. A small fraction of this extra pressure drop is recovered behind the expansion in the downstream duct. The total pressure drop Δp between the two measuring points at $x = \pm 6.38$ is displayed in Fig. 3*b*). For the parameters shown, we observe a weak linear dependence of the inertial fraction of pressure drop Δp_N on $N^{-1/3}$. For higher Ha the results seem to converge to the line indicated in the figure. The results suggest a behavior of the inertial pressure drop like $\Delta p_N \approx 0.75 N^{-1/3}$.

Measurements of surface potentials are shown for the side wall in Fig. 4. The figure gives just a first qualitative impression that there is good agreement between theoretical and experimental data. A more detailed comparison is impossible in this short paper but will be published in a detailed experimental article.

4. Conclusions. Experiments on MHD flows in conducting sudden expansions of rectangular ducts confirm inertialess asymptotic predictions for large Hartmann numbers Ha and interaction parameters N. For Ha $\lesssim 2000$ one can observe a small increase of the total pressure drop Δp with decreasing Ha. The

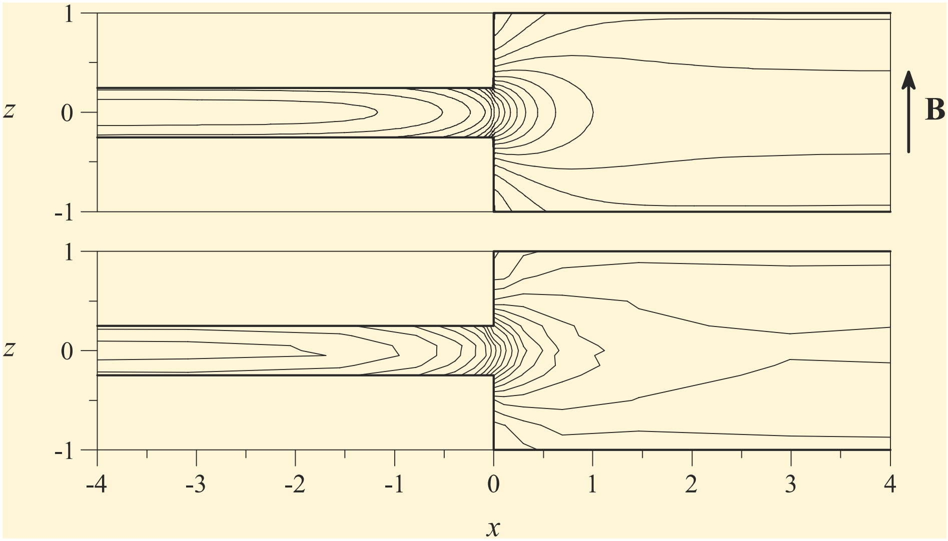

Fig. 4. Isolines of potential on the side wall of the expansion for Ha = 4000, $N = 2000$. Qualitative comparison of theoretical predictions (upper) with measurement (lower figure).

inertial fraction of pressure drop vanishes like $\Delta p_N \approx 0.75N^{-1/3}$ as $N \to \infty$. A comparison of measured and calculated surface potentials shows agreement. It is planed in subsequent experiments to investigate local flow properties by using traversable probes inside the fluid in order to get a complete picture of the expansion flow.

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