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Liquid metal flat jet transformation under influence of transverse magnetic field

N Pyatnitskaya[1,2], N Luchinkin[1], I Belyaev[2], Yu Kolesnikov[3], D Krasnov[3], Ya Listratov[1,2], O Zikanov[4] and E Sviridov[1]

[1] Moscow Power Engineering Institute, Krasnokazarmennaya 14, 111250, Moscow, Russia
[2] Joint Institute for High Temperature RAS, Izhorskaya 13 Bd.2, 125412, Moscow, Russia
[3] Technische Universitat Ilmenau, PF 100565, 98684 Ilmenau, Germany
[4] University of Michigan - Dearborn, Dearborn, MI 48128-1491

PyatnitskayaNYu@gmail.com

Abstract. The article is devoted to an experimental study of a submerged flat jet flow in a transverse magnetic field. Two different approaches to the experimental study of jet flows are described. Detailed information about the experimental program and measuring methods presented here. The flow of a flat jet 6 mm high in a square channel with a side of 56 mm is considered. The channel is positioned so that the plane of the jet is perpendicular to the magnetic field induction. The results of measuring velocity profiles and waveforms by swivel-type probe with potential sensor are presented. Effects that can be interpreted in different ways are found: strongly unstationary flow regimes, mean flow reorganization, and development of near-wall jets. Additional experiments are prepared to obtain more detailed information about the restructuring and development of the jet. In particular, continuous measurements along the channel will be made in the presence of a slight main flow.

1. Introduction

Liquid metals are considered as prospective coolants for fission and fusion reactors on account of their combination of excellent thermal properties, high boiling point, and tritium production capability (for example Pb-Li eutectic). At the same time, significant engineering problems are caused both by relatively little experience with them (compared to more traditional liquids) and by their properties (high thermal and electrical conductivity). Due to the importance of studying MHD phenomena because of its significant influence on heat transfer and hydrodynamics in the thermonuclear reactor blanket, there are large-scale research programs involving facilities in which conditions are close to real in tokamak reactors [1-2].

The formation of thin shear layers, vortices, or jets of various types during the flow of an electrically conducting liquid in a magnetic field [3] is one of the features of MHD flows. Of particular interest are jet flows that occur in various technical applications, such as sudden expansions or mixing, heating or cooling heat carriers. A round submerged jet [4, 5] in a magnetic field is a canonical configuration, traditionally considered as one of the main objects illustrating the influence of the magnetic field on hydrodynamic structures. As such, the jet combines the effects of global flow transformation and mass transfer with local effects of free shear layer transformation. A flat submerged jet is another canonical configuration [6]. The main feature of a flat jet and its main difference form a round jet is the almost instantaneous formation of thin shear layers in a plane parallel to the magnetic field. As described, for example, in [7], these layers penetrate deep into the flow while remaining extremely thin (with a thickness of about 1/Ha). Thus, a submerged jet can be considered as an optimal configuration in the sense that it allows us to study the internal shear layers formed in many MHD systems, and, at the same time, is implemented in a laboratory experiment.

2. Experimental program and measurement methods

Figure 1 shows the configuration under study. This is a flat submerged jet, the plane of which is perpendicular to the lines of the magnetic field. This configuration is of interest due to the most significant interaction of magnetic field on a jet, which experimentally provides many opportunities for improving measurement techniques and verification of numerical simulation codes.

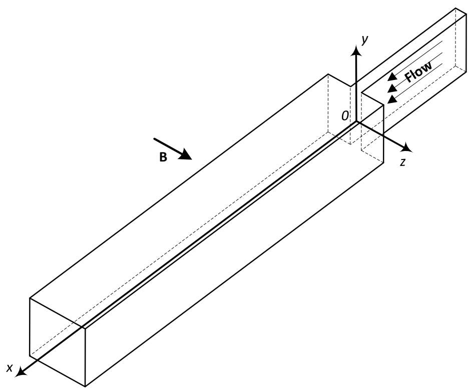

Figure 1. Configuration of the studied flow.

Studying the flow of a submerged jet of liquid metal in a magnetic field is a challenging task from the experimental point of view. It is necessary to measure the average and fluctuating characteristics of the flow at different stages of the flow evolution. We suggest two stages of experimental studies.

The first stage is based on the implementation of the simple channel flows with the possibility of handling invasive measurements, for example, probe measurements, in different sections of the experimental duct. In this case, several sensors can be used at once along the channel length, which registers both spatial and temporal correlation of the process at different stages of flow evolution. Hence, this approach requires a very specialized measurement technique.

For the second stage, on the contrary, a more complex design of the experimental section is required. The possibility of exploring different areas here is provided by a movable construction that generates a jet. Also, to smooth out the input effects and possible instabilities, a protectorate flow, called below “satellite flow”, is implemented.

2.1. Test section and probe method

Figure 2 show the test section a) and its installation on facility RK-3 [8] b) in the gap of the electromagnet. The test section is a square channel with a side of 56 mm and a length of 0.5 m. The mercury flow enters the study area through the jet formation section. The channel is positioned so that the plane of the jet is perpendicular to the magnetic field lines.

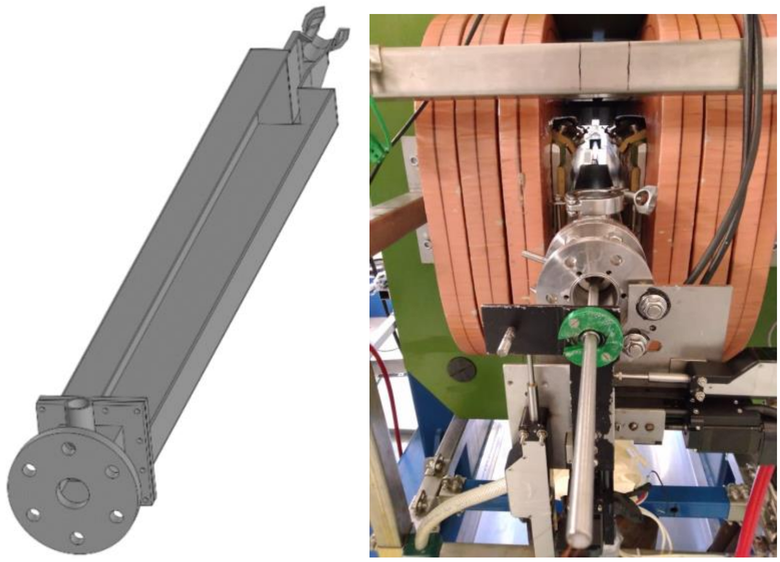

Figure 2. Test section in isometry and its installation on facility RK-3 (HELMEF).

A scanning swivel-type probe [9] (Figure 2 a)) with sensor (figure 2 b,c)) at the tip is inserted through a bellows joint into the tested section towards the flow. The swivel-type probe is an unequal lever. The short arm of the lever is connected to the coordinate mechanism, which allows one to move the sensor over the pipe section. The length of the probe rod is chosen in such a way so that the rod length is 15–20 times larger than the section of the channel. Thus, when the rod is rotated, the thermo-couple moving along the radius remains in almost the same plane perpendicular to the axis of the channel.

As the sensor [9], various combinations of thermocouples are usually used [10], but for our case with isothermal liquid metal flow we used four cooper electrodes, located in two planes on each other. Taken together, they represent a conductive sensor that measures two different components of velocity. The electrodes are glued or welded into a capillary with a larger diameter and covered with a layer of light-curing varnish

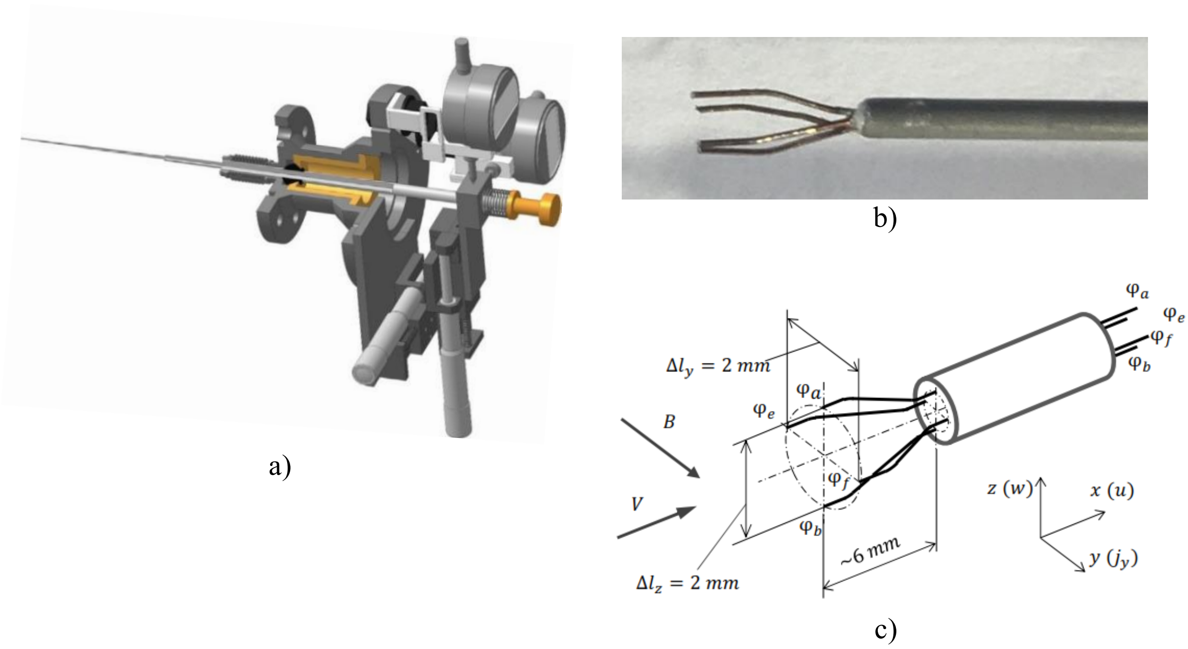

Figure 3. a) Swivel-type probe for measuring into the flow, b) conducting sensor mounted on the probe tip and c) principal scheme of sensor.

Each pair of copper electrodes measures one component of the velocity using an electromagnetic method. The method is based on Ohm's law for a moving conductive liquid:

$$\frac{j}{\sigma} = -grad\varphi + \boldsymbol{U} \times \boldsymbol{B}, \quad (1)$$

After a series of conversions for the velocity component u we get

$$u = \frac{(\varphi_a - \varphi_b)}{c\Delta l_z B}, \quad (2)$$

where the coefficient c is related to the effect of induced currents (if Ha>100 then $c\approx 1$, if Ha<100 then $c<1$).

With a weak magnetic field, this method is less reliable, because the calculation of the velocity from the voltage signal becomes very sensitive to a certain geometry and magnitude of the magnetic field. This sensitivity is expressed as coefficient c in (2). For this reason, the first stage of experiments does not involve measurements in a weak magnetic field.

2.2. Experimental results

The figure 4 shows the cross section of the test site with the jet orientation and electrodes location (a, b, c, d) relative to the magnetic field. At the first stage beginning of experimental program sensor have been positioned to form two pairs of electrodes providing measurements of longitudinal velocity.

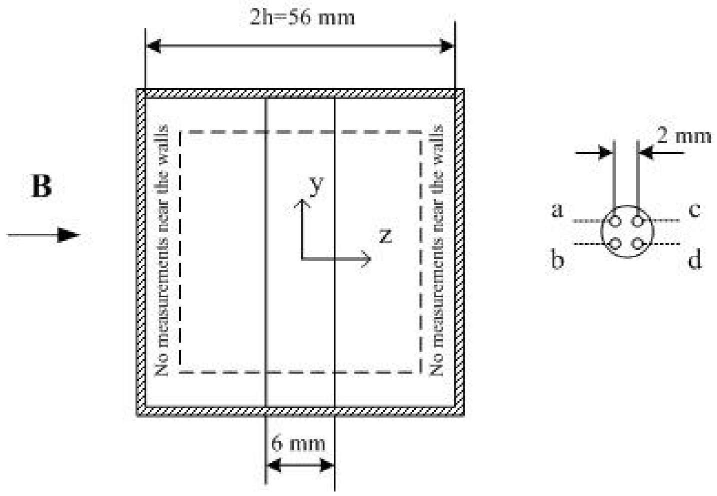

Figure 4. Cross-section of the test site and electrodes combination.

Voltages of $V_{ab}=\varphi_a - \varphi_b$ and $V_{cd}=\varphi_c - \varphi_d$ has been measured simultaneously at 1000 Hz rate using two NI PXI 4071 multimeters.

Figure 5 shows the measurement signal of the sensor in a still mercury. Solid lines show the points of switching on and off the magnetic field, dotted - time ranges of the sensor movement in the direction of the y and z axes.

Measurements in a weak magnetic field are not indicative, because with this design of the experimental section and the absence of a satellite flow, an unstable jet flow is formed. The jet will form the attached vortexes, "stick" to the walls and morph with small changes in the magnetic field. This flow cannot be used for code verification due to its extreme sensitivity to non-idealities of geometry.

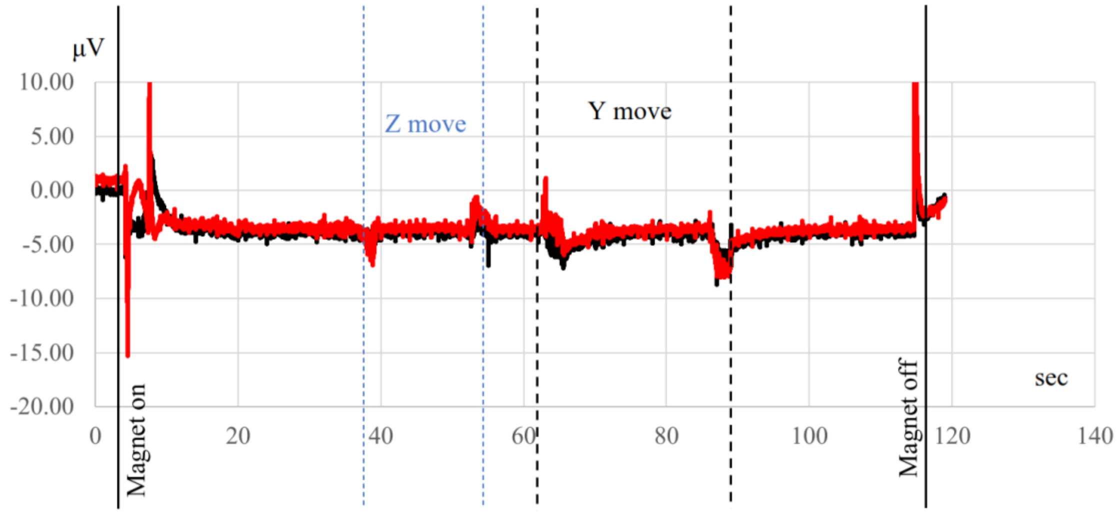

Figure 5. Probe readings in a still mercury (u=0) at the magnet switching-on to 1.5 Tesla and probe movement

Effect of decreasing flow gradients in the direction of the transverse magnetic field is one of the most important regularities in the transformation of flow in two-dimensional in plane perpendicular to the field. This is clearly manifested in the expanding flow in the direction of the magnetic field, including the sudden expansion of the flat jet.

In this case, arising electric current, interacting with the magnetic field, creates a component of the vortical Lorentz force parallel to the field. In turn, it leads to destructurisation of the initial flow and formation of highly unstable flat jet flows near the walls parallel to the field. This occurs more pronounced, the higher magnitude of the magnetic field. Figure 6 demonstrates two jets, near walls parallel to the field, interacting already on the distance x=115 mm. The high level of intensity of the velocity fluctuations shown in figure 7, is caused by the velocity gradients with inflection points in profiles in the given cross section and by the perturbations incoming from the initial cross sections, where a fundamental transformation of the flow occurs. The dotted line in the figures 6-7 indicates the average input velocity $\bar{u} = 0{,}027\ m/s$.

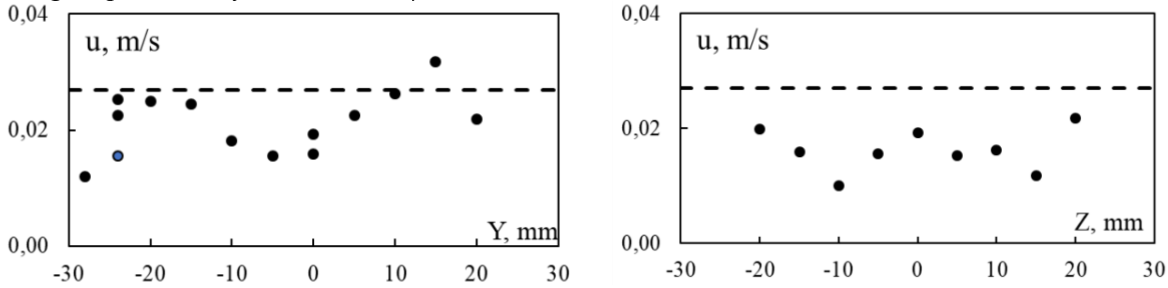

Figure 6. Flow rate 5 l/min, Magnet field 1.5 Tesla, Cross-section is 115 mm (~ 4h from the inlet of the jet), $Ha_h = 985$, $Re_h = 7{,}5 \cdot 10^3$. Signal to noise ratio (SNR) at lowest reading (SNR>50).

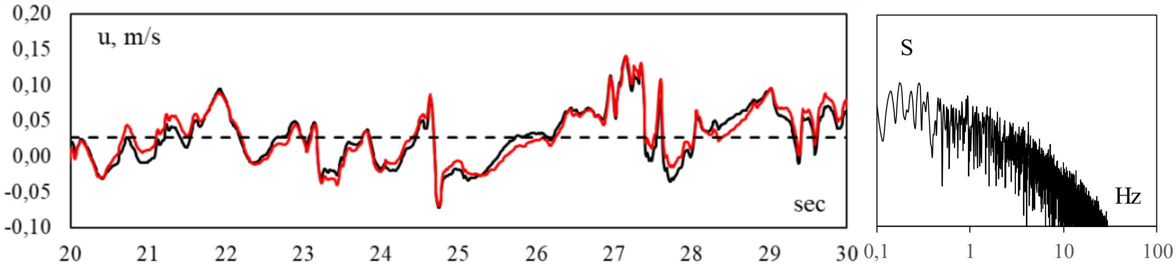

Figure 7. Velocity waveforms in the center of the channel.

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The M-shape of velocity profile can be caused by two reasons:

- Separation of instabilities during jet transformation under the influence of a magnetic field caused by a channel specific or input effects;
- Evolution of the jet into near wall structures (parallel to the magnetic field).

Measurements in only one section of the channel are insufficient, since the main transformation of the jet and major evolution of instabilities occurs at smaller distances from the beginning. It is necessary to carry out measurements closer to the beginning of the jet formation, where the above effects are more pronounced. The uncertainty in the occurrence of such structures leads us to the next stage of research.

3. Second stage of the experiments

The next case under consideration will be the satellite flow of a heated jet in the same channel geometry (figure 8). To study different areas of jet development, the design forming the jet can move along the flow. The site provides a coupling for changing a flat jet to a round one, as well as two honeycombs located at a certain distance from each other to stabilize the satellite flow. The main loop and the jet formation loop are connected to the installation independently for the possibility of heating the jet separately from the main stream. The value of the heat flow in this case should be such that the influence of thermogravitational convection can be negligible. Thus, the temperature will act as a passive scalar, which can be addressed as a "marker" in the flow for using microthermocouple sensors.

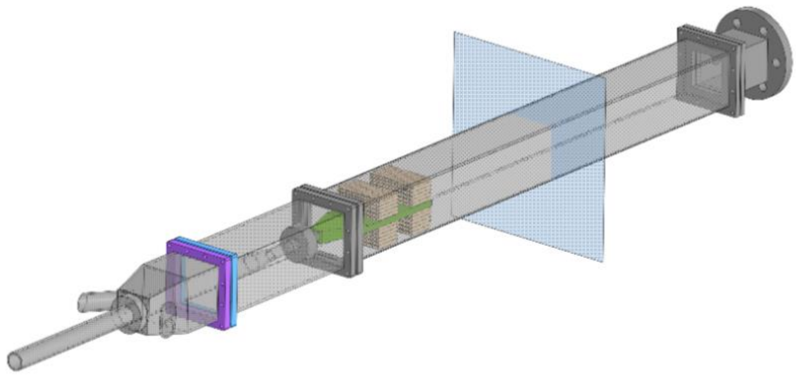

Figure 8. Test section for second stage of experimental program

4. Conclusions

A flat submerged jet flow in a transverse magnetic field directed perpendicular to the flow plane is under investigation. The jet in such conditions is a convenient model problem because of significant impact created by the magnetic field. The configuration was studied experimentally using a scanning probe technique and local measurements of the electric potential. This approach allowed to create ideas about the distribution of the local velocity in the flow and determine the statistical characteristics of the flow.

The flow in a strong magnetic field is found to be essentially unsteady, and long-term measurements are required. We observed the transformation of the initial jet into two extremely unstable jets near walls parallel to the magnetic field.

The discovered flow characteristics are of significant interest from a fundamental point of view due to their complexity. The next stage of the experimental study is planned, in which the design of the experimental section will allow continuous measurements along the channel in the presence of a satellite flow. Direct numerical simulations by verified codes can provide a more detailed and complete analysis of the flow studied experimentally and provide information that principally cannot be extracted from the experiment.

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References
[1] Huang Q and Zhu Z 2020 FDS Team. Development and experiments of LiPb coolant technologies for fusion blanket in China *International Journal of Energy Research*.
[2] Courtessole C. Smolentsev S, Sketchley T and Abdou M 2016 MHD PbLi experiments in MaPLE loop at UCLA *Fusion Engineering and Design* **109** pp 1016-1021
[3] Davidson P A 1995 Magnetic damping of jets and vortices *Journal of Fluid Mechanics* **299** pp 153-186.
[4] Kim J and Choi H 2004 Large eddy simulation of magnetic damping of jet Int. *Congress of Th. And Appl. Mech*.
[5] Kim J and Choi H 2009 Large eddy simulation of a circular jet: effect of inflow conditions on the near field // Journal of Fluid Mechanics. **620** p 383
[6] Stanley S A and Sarkar S 2000 Influence of nozzle conditions and discrete forcing on turbulent planar jets *AIAA journal* **38(9)** pp 1615-1623
[7] Moreau R 1990 *Magnetohydrodynamics* (J: Springer) p 320
[8] Belyaev I A, Biryukov D A, Pyatnitskaya N Yu, Razuvanov N G, Sviridov E V and Sviridov V G 2019 A technique for scanning probe measurement of temperature fields in a liquid flow *Thermal Engineering* **66(6)** pp 377-387
[9] Belyaev I A, Sviridov V G, Batenin V M, Biryukov D A, Nikitina I S, Manchkha S P, Pyatnitskaya N Yu, Razuvanov N G and Sviridov E V 2017 Test facility for investigation of heat transfer of promising coolants for the nuclear power industry *Thermal Engineering* **64(12)** pp 841-848
[10] Belyaev I A, Razuvanov N G, Sviridov V G and Zagorsky V S 2017 Temperature correlation velocimetry technique in liquid metals *Flow Measurement and Instrumentation* **55** pp 37-43