

CONFERENCE PRE-PRINT**EXPERIMENTAL RESEARCH ON MAGNETOHYDRODYNAMIC (MHD) FLOWS IN LIQUID METAL COOLING SYSTEMS FOR FUSION REACTORS**

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Abstract

This paper presents an experimental research program investigating magnetohydrodynamic (MHD) flows of liquid metals under strong transverse magnetic fields, relevant to cooling systems in fusion reactors. The studies are conducted on the HELMEF facility using mercury as a working fluid and magnetic fields up to 2.7 T. The research focuses on several fundamental flow configurations. A key finding is the identification of Magneto-Convective Fluctuations (MCF) in mixed convection within vertical ducts, where a transverse magnetic field suppresses small-scale turbulence but leads to large-scale, high-amplitude temperature and velocity fluctuations, posing risks of thermal cycling. The effectiveness of vortex promoters to disrupt these quasi-two-dimensional structures and enhance heat transfer is demonstrated. Furthermore, the behaviour of free vertical convection around a heating element is analysed, showing that local heat transfer can be described using classical Nusselt and Rayleigh numbers with an axial formulation. Experiments on submerged jets reveal a complex, non-monotonic disintegration process in a magnetic field, characterized by jet flattening and unsteady vortex formation. Finally, the paper outlines methodologies for studying transient MHD phenomena, such as those induced by pulsed currents or magnetic fields, simulating plasma disruption events. The results provide crucial phenomenological data and validation for numerical models aimed at ensuring the thermohydraulic stability and safety of liquid metal components in fusion energy systems.

1. INTRODUCTION

Several projects for thermonuclear installations and hybrid facilities (thermonuclear neutron sources) consider liquid lithium or lead-lithium eutectic usage as a coolant and a tritium production source. Liquid metals and salt melts are significantly electrically conductive media. In the case of thermonuclear devices with magnetic and magnetically inertial plasma confinement the operation of these media will occur in the presence of strong magnetic fields, which requires the study of thermal hydraulics in configurations as close in geometry as possible to realistic devices

JIHT RAS and MPEI conducts research by studying the characteristics of basic geometries – forced flow in ducts and pipes, jet behaviour, flows around obstacles, flows in combined channel systems and free convection under the combined influence of both strong magnetic fields and high heat fluxes.

2. METHOD OF RESEARCH

Fluctuations of flow and temperature that develop naturally under the influence of a magnetic field and a strong thermal load [1]. As a criterion, it is proposed to use the intensity of the resulting fluctuations of velocity or temperature in the form of a standard deviation. Strong temperature fluctuations in the reactor heat exchange path are highly undesirable, as they can create local overheating points, lead to thermal cycling loads, provoke corrosion and shorten the service life of the equipment.

The research team has at its disposal magnets capable of creating stationary magnetic fields of up to 2.7 T [2]. Experimental facility is shown in fig.1. Available parameters of experiment are given in Table 1.

Usage of mercury gives the highest value of Grashof number (one or two orders of magnitude higher than with other metals). Mercury, therefore, allows to perform heat transfer experiments at the lowest heat fluxes and liquid metal volumes.

Studies of the flow structure are carried out by scanning submersible probes, which make it possible to reconstruct three-dimensional fields of average and fluctuating temperature and fields of average longitudinal velocity. The experiments are conducted in a fully automated mode, which minimizes errors and allows for the acquisition of extensive experimental data.

TABLE 1. HELMEF Parameters

Parameters	Values
Heating rate	0-100 kW/m ²
Magnetic field	2.7 T (30 mm gap) 1.8 T (60 mm gap) 1.65 T (110 mm gap)
Channel size	Pipes - diameter 19 mm or 40 mm Ducts - 16 x 56, 56 x 56, mm x mm
Liquid metal	Mercury [3]
Temperatures	20-180, °C

Due to the poor wetting of stainless steel by mercury and the small thickness of the channel walls, wall conductivity can be neglected. For investigating systems with realistic wall conductivity, a method for forming intermediate copper coatings has been developed. Mercury experiments are conducted with strict adherence to necessary personnel and environmental protection protocols, with waste disposed of by licensed specialized organizations.

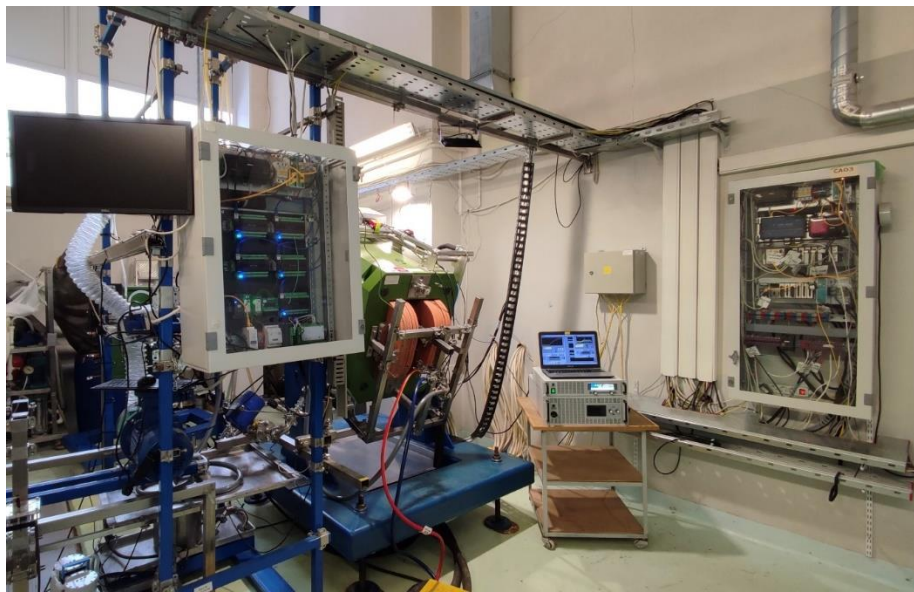


Fig.1. HEattransfer of Liquid Metals Experimental Facility (HELMEF)

3. RESULTS

The presented experimental data were obtained during experiments conducted on the facility using unified approaches, methods, and equipment. A brief review cannot encompass all existing knowledge of the processes under consideration.

3.1. Mixed Convection and Magneto-convective fluctuations

One of the primary and, accordingly, long-developed research topics is the problem of mixed convection of liquid metal in pipes and channels. It is known that the interplay of heating characteristics, flow direction, and spatial orientation relative to the gravity vector generates substantially different flow patterns [1]. Much depends on whether the flow is opposed [4] to or aligned [5] with the gravitational force. Flows in horizontal channels also possess their own distinct features [6]. The following features are common. As is well known, a magnetic field suppresses classical isothermal turbulence, with only the largest disturbances able to overcome its influence. The resulting disturbances manifest as vortices with axes aligned with the magnetic induction vector, while the entire flow in the channel tends to become two-dimensional along the magnetic field direction.

The control complexes of dimensionless parameters are defined, which make it possible to describe the changes under the influence of a magnetic field. It is shown that it is necessary to analyse not just the dimensionless criteria

Ha, Re, Gr, but such dimensionless complexes as $Ri=Gr/Re^2$, $Rh^{-1}=Ha/Re$ [1,7]. Dimensionless criteria are formulated as follows:

$$\text{Nusselt number: } Nu = \frac{q \cdot d}{\lambda(T_w - T_{bulk})},$$

$$\text{Grashof number: } Gr = \frac{g\beta d^4 q}{\lambda \nu},$$

$$\text{Dimensionless temperature fluctuation intensity } \sigma_T^* = \sigma_T \cdot \lambda / (qd),$$

$$\text{Reynolds number } Re = U_o \cdot d / \nu,$$

$$\text{Hartman number } Ha = Bd\sqrt{\sigma/\mu},$$

, where q – heat flux $W/(m^2)$, d – characteristic channel size (pipe diameter or radius, duct doubled short side or half of short side, see [1,4,5,7] for discussion), λ – mercury thermal conductivity, T_w – heated wall temperature, °C; T_{bulk} – bulk flow temperature, °C, g – acceleration of gravity; β – volumetric expansion, $1/^\circ C$; ν – kinematic viscosity, q – heat flux $W/(m^2)$; λ – mercury thermal conductivity, $W/(m \cdot K)$; U_o – mean flow velocity, m/s; B – magnetic field induction, T; σ – mercury electrical conductivity, $1/(Ohm \cdot m)$; μ – mercury dynamic viscosity Pa·s.

A common feature is the formation of large-scale fluctuating disturbances with amplitudes exceeding those observed in analogous flows without magnetic field influence. It is proposed [7] to term such flow patterns as magneto-convective fluctuations (MCF).

A schematic example of MCF formation for one-sided heating under downward flow conditions is shown in Fig. 2a. The superheated region formed at the wall detaches into the main flow, generating a significant temperature spike. The mechanism behind this detachment was also termed the "elevator mode" and described in reference [8]. Such pulsating flows create a risk to the channel's structural integrity as they impose additional low-frequency thermomechanical loads. Based on two-dimensional numerical modelling, reference [8] proposed a universal boundary between stable flow regimes and the MCF regime (Fig. 2b). In our experiments with downward flow in a 56x16 mm channel with one-sided heating, we were also able to identify the region of MCF existence.

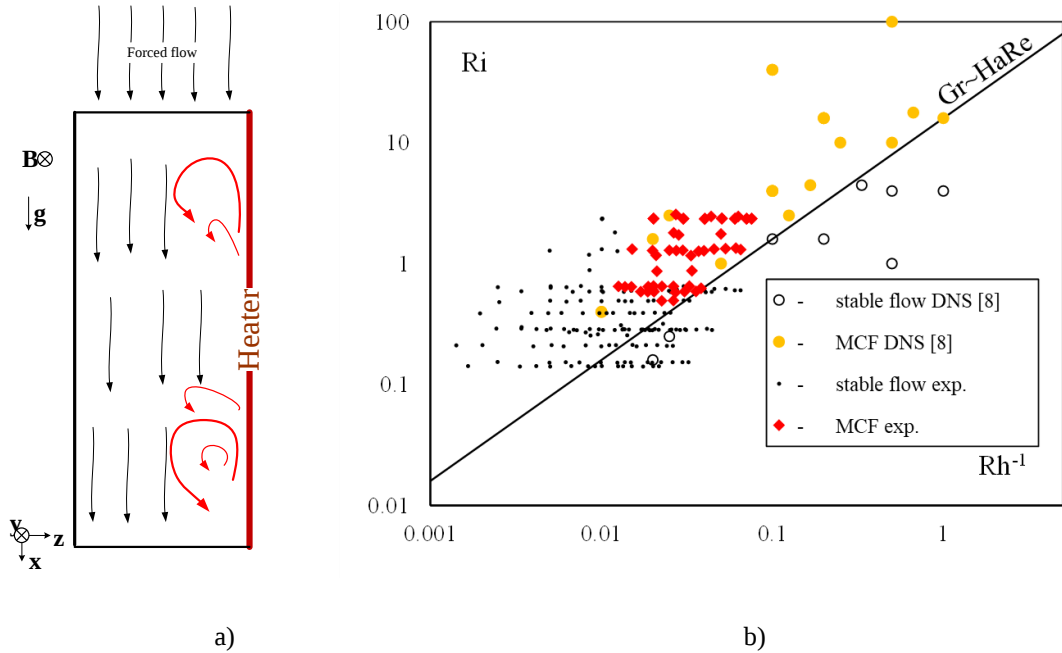


Fig.2. Principal configuration of magneto-convective fluctuations (MCF) formation under the influence of magnetic field (a) and experimental results of local heat transfer depending on Stuart number.

Information on heat transfer coefficients is equally important. In experiments under a magnetic field, we observed a reduction in the dimensionless heat transfer coefficient (Nusselt number) to 60% of its value without a magnetic field (fig.3).

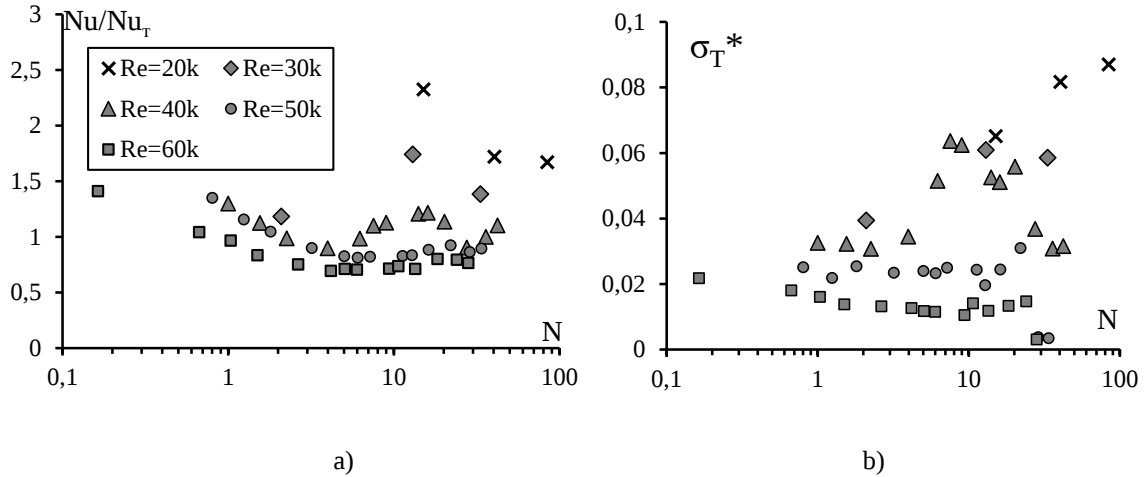


Fig.3. Relative local heat transfer (a) and normalized temperature fluctuation intensity (b) at wall of one-sided heated duct with mercury downflow. The measurements were obtained in the stabilized flow region at the center of the heated wall.

However, in certain regimes with MCF, the heat transfer coefficients recovered and even exceeded the values observed without magnetic field influence. Correlating the heat transfer coefficients with the observed temperature fluctuation intensities reveals that the influence of MCF alone is insufficient to restore the heat transfer coefficients.

3.2. Enhancement of forced convection in magnetic field

As a potential solution to the MCF issue and a means to enhance the efficiency of liquid metal systems, the application of stationary passive flow disturbers to forced flow was investigated.

A schematic diagram is shown in Fig. 5a. The flow is disturbed by a rod aligned with the magnetic field. Detaching behind the obstacle, the flow forms a channel-confined analogue of a Kármán vortex street. The experiments successfully created and detected the influence of vortex promoters at a significant distance downstream from the initial point of impact [9].

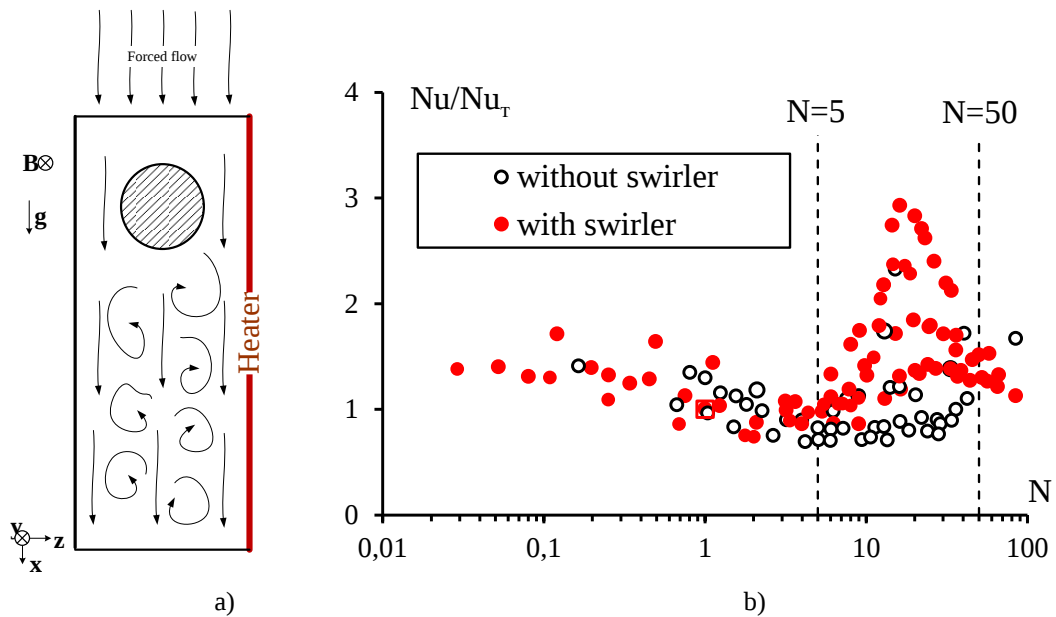


Fig.4. Principal configuration of vortex promoter affecting the duct flow under the influence of magnetic field (a) and experimental results of local heat transfer depending on Stuart number.

The generated vortices replace the small-scale turbulence suppressed by the magnetic field and, within a certain range of Stuart numbers, not only restore the heat transfer coefficients suppressed by the magnetic field but also enhance heat exchange.

Figure 5b presents data on local heat transfer coefficients for a fixed Grashof number and a Reynolds number range from 20000 to 60000. The influence of the vortex promoter also significantly reduces the region of MCF existence. In particular, within the investigated range of operating parameters, the application of the vortex promoter completely suppressed the formation of MCF, even in the case of the most energetically significant disturbances generated in the system with asymmetric heating [10].

At low flow rates, the use of vortex promoters is expected to require more frequent installation of the disturbing devices. It is clear that such disturbance leads to an increase in hydraulic resistance, which will likely be comparable to the observed heat transfer enhancement.

3.3. Vertical natural convection in magnetic field

Free vertical convection around a heat-generating element located within a cavity filled with liquid metal represents a fundamental geometry for addressing the challenge of thermal stabilization, for example, in chemical reactors. This same geometry can also be attractive for creating hybrid modules in fusion devices. In this case, convection will occur under the influence of a magnetic field, which, to first approximation, is transverse to both the heating element and the cavity. The complexity in understanding and modeling such a system lies in the presence of several interconnected processes that form the complex flow (Fig. 4a). In the initial stage (L2), the flow begins its motion driven by the buoyancy force, while the magnetic field acts to flatten the velocity profile along the magnetic field direction. In the developed flow region (L3), a quasi-stable flow is established. Flow reversals occur in regions L1 and L2. Furthermore, for a correct resolution of the problem, it is necessary to account for both the complexity of forming superheated layers near the heater and the specific features of MHD flows in the regions near the external channel walls. The problem becomes even more complex, considering that even in relatively strong magnetic fields, the flow often remains time-dependent, exhibiting a tendency to form large-scale vortices with axes aligned with the magnetic field vector.

Recent experiments (fig 4b) indicate that this rather complex system can be analyzed using classical relationships between the local Nusselt number and the Rayleigh number. It is necessary to use axial formulations of these criteria with a characteristic dimension defined as the height from the onset of heating.

$$Nu_A = \frac{q \cdot z}{\lambda(T_w - T_{cold})}$$

, where q – heat flux $W/(m^2)$; z – axial length, m; λ – mercury thermal conductivity, $W/(m \cdot K)$; T_w – heater temperature, $^{\circ}C$; T_{cold} – cold wall temperature, $^{\circ}C$.

$$Ra_A = \frac{g\beta z^4 q}{\lambda \nu} Pr$$

, where g – acceleration of gravity; β – volumetric expansion, $1/^{\circ}C$; Pr – mercury Prandtl number; ν – kinematic viscosity.

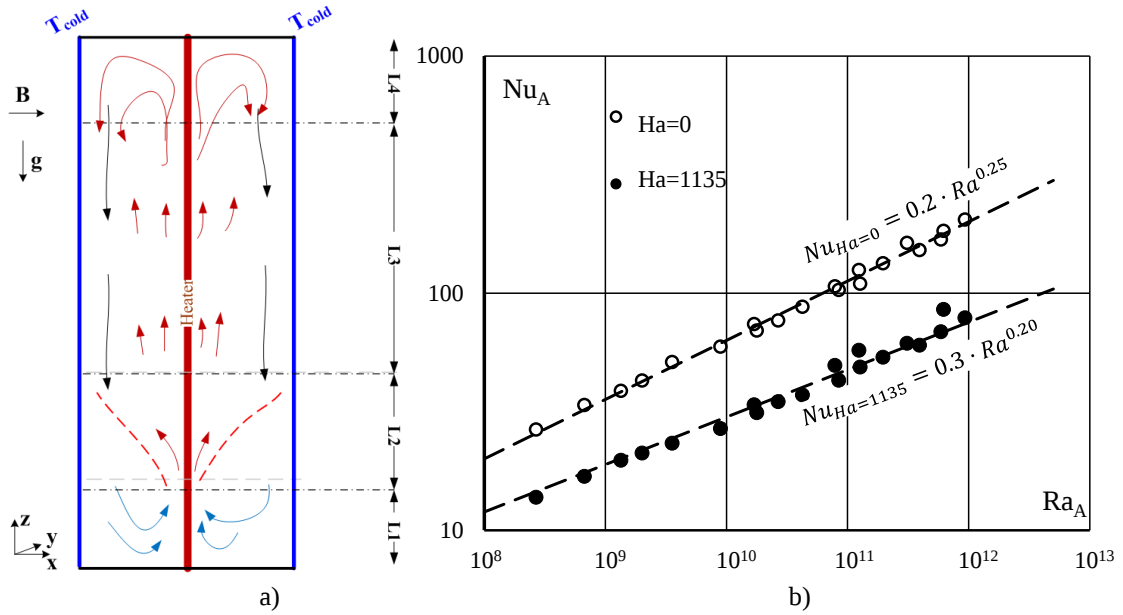


Fig.4. Principal configuration of vertical natural convection under the influence of magnetic field (a) and experimental results of local axial heat transfer depending on axial Rayleigh number.

3.4. Jet-flow in magnetic field

The design of actual flow elements in cooling systems involves the creation of local contractions and expansions. Abrupt expansions can also be used for fluid mixing, component blending, and other specific tasks. It is known that jets entering a liquid volume tend to lose stability and become turbulent easily. It is also known that the application of a magnetic field causes the jet to elongate along the magnetic field direction (fig. 5a), leading to its rapid decay.

Experiments on a 6mm round jet entering a 56x56 mm rectangular channel revealed that the jet disintegration process in a transverse magnetic field is highly unsteady [11]. The suppression of the jet exhibits a non-obvious dependence on the magnetic field strength. The competition between instability loss and jet flattening leads to a non-monotonic change in the velocity fluctuation intensity of the jet. Specifically, several stages of jet disintegration can be identified, including the formation of a statistically symmetric, flattened central jet or the rapid development of a macrovortex occupying the entire channel cross-section.

The complexity of the studied system provides an effective means for verifying the most advanced numerical simulation methods [12,13]. Similarly, planar jets create systems that are no less complex to analyze [14].

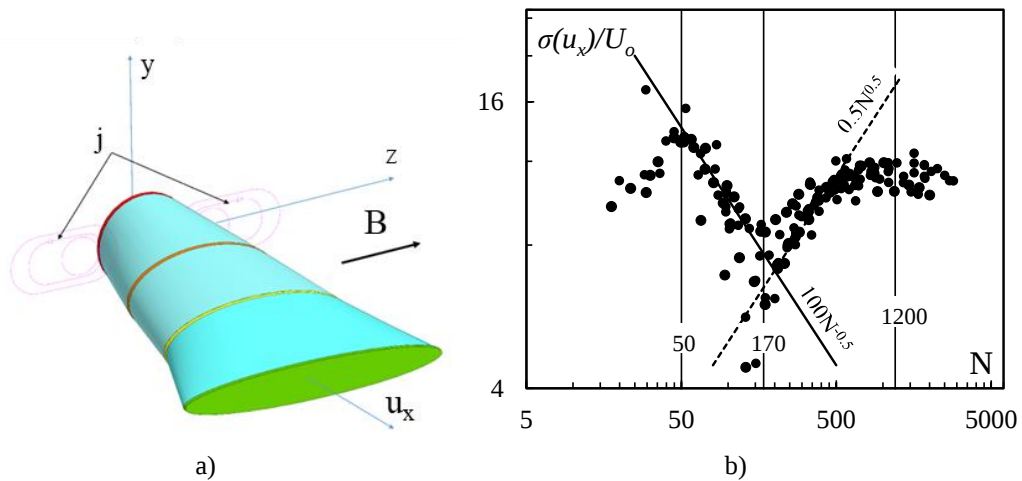


Fig. 6. Principal configuration of jet annihilation under the influence of magnetic field (a) and experimental results on intensity of longitudinal velocity fluctuation over Stuart number.

3.5. Pulsed magnetic field and electrical disruptions through liquid in magnetic field

Unsteady magnetohydrodynamic (MHD) processes in a conducting continuum media, arising from plasma disruptions in tokamaks, represent a critical safety concern for future fusion reactors, particularly during transient events with characteristic timescales of 0.1-100 ms. The absence of a clear phenomenological model and reliable diagnostic methods for key parameters—such as flow velocity, pressure dynamics, and induced current density—hinders progress in this field. Numerical simulation methods are developing to correctly describe flows with [15]. As in the cases described earlier, the formation of large-scale disturbances in the liquid metal volume is expected, for which a correct understanding must be based on experimental data.

As simplified laboratory research systems, it is proposed to consider a horizontal cavity filled with mercury under a strong static transverse magnetic field, studying the impact of a longitudinal electric current pulse (Fig. 7a) or a longitudinal magnetic field pulse (Fig. 7b).

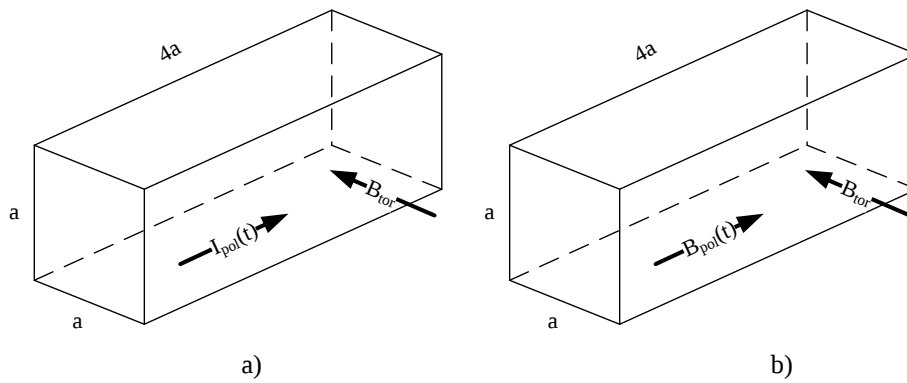


Fig. 7 Principally studied configurations of electric disruption through liquid metal (a) and pulse of magnetic field (b)

To accomplish the selection of diagnostic sensors, estimates of expected fluid pressures and flow velocities were conducted, based on simulations of either a 1.5 kA current pulse or a 0.8 T magnetic field pulse within a uniform 1.7 T transverse magnetic field [16].

The functionality of piezoelectric pressure sensors in strong magnetic fields was confirmed, and a combined measurement system utilizing fiber-optic sensors was proposed to enhance reliability amidst strong electromagnetic interference.

CONCLUSION

The developed experimental approach enables the acquisition of data on the phenomenology of liquid metal systems under strong magnetic fields in a controlled laboratory experiment. Approaches have been established to describe previously unreported and unforeseen hydrodynamic phenomena, such as magneto-convective fluctuations and jet disintegration in a magnetic field. Confirmation and quantitative assessment of the effectiveness of vortex promoters on forced flow have been provided. Experimental methods are being developed to study the effects of electric current breakdowns and pulsed magnetic fields on liquid metal systems.

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