APPLICATIONS OF LORENTZ FORCE TECHNIQUES FOR FLOW RATE CONTROL IN LIQUID METALS

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Abstract: Lorentz force velocimetry (LFV) is based on the electromagnetic induction of braking force acting on an electrically conductive fluid, which moves through a static magnetic field. Two such methods are presented here. First, time-of-flight LFV allows determining the flow rate of liquid metal by two flow meters placed at a predetermined distance by finding the time delay between their signals. Secondly, Lorentz torque velocimetry is a technique, which uses an electromagnetic pump with a torque sensor connected to the pump's shaft. Simultaneous pumping and measurement of the torque allows controlling the flow rate.

1. Introduction

Flow rate measurements in aggressive and hot fluids like liquid metals is a complicated task. Liquid metals are not transparent to allow usage of optical methods and chemical corrosion makes it impossible to employ mechanical probes. Therefore the most promising methods for liquid metal flow rate control are contactless techniques, a big branch of which is based on principles of magnetohydrodynamics [1]. Lorentz force velocimetry (fig 1) is such non-contact method based on electromagnetic principles.

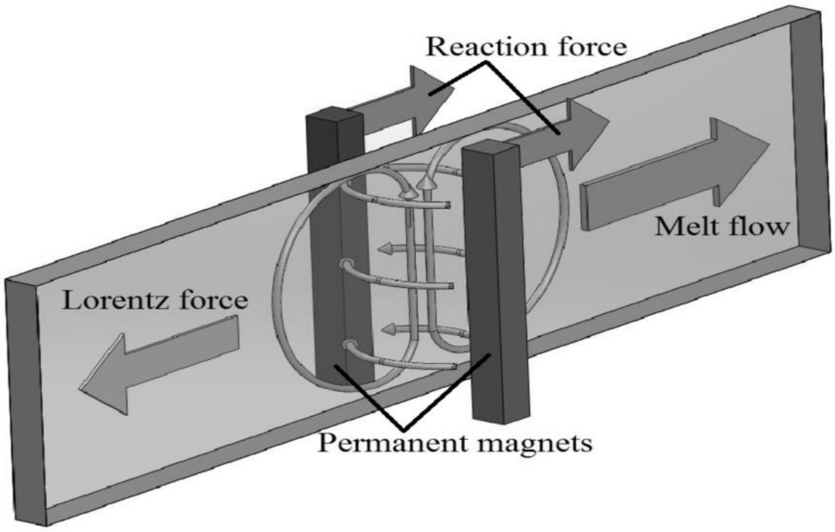


Figure 1: Electrically conductive liquid moves with velocity v through magnetic field of permanent magnets; magnetic field penetrates moving liquid and their interaction creates eddy currents inside the liquid, which give rise to Lorentz force F_L ("braking force"); resulting force of reaction F_R=-F_L acts on permanent magnets and can be measured

When an electrically conducting fluid moves across magnetic field lines, which are created by a permanent magnet, the induced eddy currents lead to a Lorentz force, which brakes the flow. The Lorentz force density is roughly [2]:

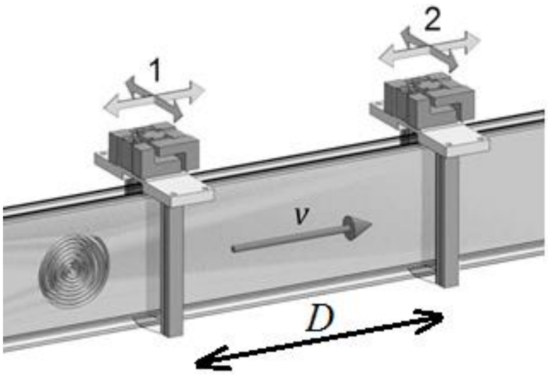
$$F_L \sim \sigma v L^3 B^2, \tag{1}$$

where σ is the electrical conductivity of the fluid, B is the magnitude of the magnetic field and L is the characteristic length of system. Magnetic field B and the moving, conducting medium interact in such a way as to restrain the relative motion of the field and the medium [3]. Magnet system and force sensor form a so-called Lorentz force flow meter. Because the force depends on velocity, it provides a velocity dependent signal for flow meter applications.

When Lorentz force appears within the liquid, according to Newton's third law, reaction force appears, which acts on the source of flow disturbance – the permanent magnet. For measuring of the value of force $F_{R,}$ which is equal to Lorentz force and opposite in direction, different ways are used. The devices that are applied to measure the Lorentz force can be constructed in two ways [2]. They can be designed as static flow meters where the magnet system is at rest and one measures the force acting on it. Alternatively, they can be designed as rotary flow meters where the magnets are arranged on a rotating wheel and the torque is a measure of the flow velocity [4]. We present examples of both methods here - Time-of-flight LFV [5] and Lorentz torque velocimetry (LTV) – flow control by the system of electromagnetic pump and torque sensor.

2. Experimental setup and results

Time-of-flight LFV (fig 2a,b) allows measurement of the flow rate in liquid metal and is unaffected by physical properties of fluid or by outer conditions. As the time-of-flight principle is based on cross-correlation measurements, two flow meters are mounted on a channel at a certain distance D to each other.



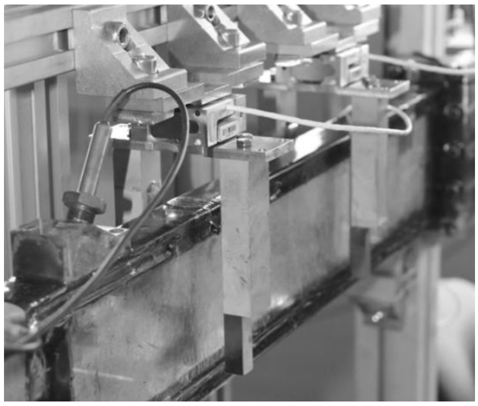


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Figure 2: Principle scheme of time-of-flight LFV (a) and the photo of the device (b)

A closed rectangular channel is used for the experiment. The channel with cross-section 80 mm x 10 mm is filled with the alloy GaInSn in eutectic composition. This allows conducting of model experiment at room temperature. The magnet system consists of permanent magnets with magnetic induction of 450 mT at the surface and two-component strain gauge sensors, which are mounted to record the force that the fluid exerts on the magnet system. Experiment procedure results in evaluating the transit time τ (time-of-flight) of any vortex structure that is present in the flow needed to pass through the distance D to obtain the volumetric flow rate Q_V is then given by the relation:

$$Q_V = vA = kD/\tau, \tag{2}$$

where A – cross-section area of the channel, k – experimental coefficient of proportionality. To increase both the rate and the intensity of such vortex structures and likewise the rate of usable signals, vortices can be generated by two different methods: mechanically – by immersing a solid body in the channel, or electromagnetically – by formation of magnetic obstacles [6] within the fluid as a result of static or time-dependent magnetic field. In other words according to time-of-flight LFV, velocity is estimated by measuring the traveling time τ for the vortex to cross a predefined distance D between flow meters.

Measurements of time shift τ are based on obtaining a cross-correlation function of two force signals (fig 3a,b), which are registered by magnetic measurement systems as a result of disturbance by the passing vortex (in fluid experiment) or copper plate (in dry experiment).

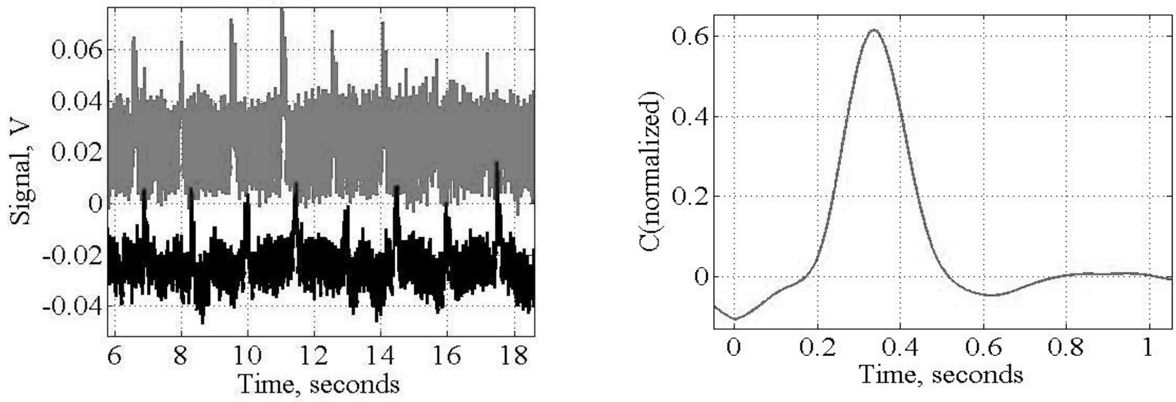

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Figure 3: Raw signal of time-of-flight LFV (dry tests) with several peaks, caused by serial copper plate movement through magnetic field of first flow meter (grey curve) and second flow meter (black curve) (a) and normalized cross-correlation coefficient C of the signals (b)

To ensure correct working of flow meters it is necessary to provide dry tests in which solid material – copper plate – was used instead of moving vortex. Because σ of solid conductor is about twenty times higher than σ of the melt, the Lorentz force induced by its movement is likewise twenty times higher (according to (1)) and it is possible to observe clear peaks on both signals even without additional filtering. The main goal of dry tests is to register signals that prove operating performance of measurement scheme. When plate is moved serially through the magnetic field of both flow meters with a known velocity and two peaks are observed in each trial.

Another method – LTV [7] – includes applying electromagnetic pump as flow-controlling and as flow-measurement device simultaneously.

Figure 4a shows the principal scheme of such a pump. The pump consists of a pair of metal disks, on each of which a total of 20 finger-type permanent magnets are mounted. The disks are arranged on a shaft that is connected to an electrical motor. By controlling the motor power, we can control the rotation frequency n of the shaft. The rotation of permanent magnets generates a time-dependent magnetic field acting on liquid within the gap between the two rotating disks. In turn, the rotary field gives rise to Lorentz force that pumps the liquid and acts on the pump shaft as a back reaction. A strain gauge torque sensor is mounted on the shaft to measure the torque that is exerted on liquid.

Using such an arrangement, the volumetric flow rate Q_V can be estimated by the relation:

$$Q_V = kT/(\sigma B^2 Ll) \qquad (3)$$

where T is the measured torque, l its lever, and k is the device factor. This factor depends on a number of specific experimental parameters like the aspect ratio of the flow channel, the actual geometric arrangement of the permanent magnets, among others. Hence, the specific value of k has to be obtained for each experimental setup by a calibration procedure. Within our experiment, two methods – ultrasonic Doppler velocimetry and local velocimetry by Vives-probe [8] – were used as standards to measure velocity value; the results show strong temperature-dependent behaviour of k, which indicates necessity of qualitative temperature control of liquid in the experiment.

For obtaining specific value of *l*, one needs to conduct simultaneous measurement of Lorentz force F_L and torque T for various rotation frequencies in order to find the functional relation T/F_L. However, calibration of the device using liquid metal is complicated, time-consuming and expensive. Therefore we perform a dry calibration procedure. The main idea of dry calibration is to model the liquid by a solid electrically conducting non-magnetic material like solid aluminium bars. In this case F_L can be measured by commercial strain gauge force sensors and the ratio of torque to force could be easily calculated.

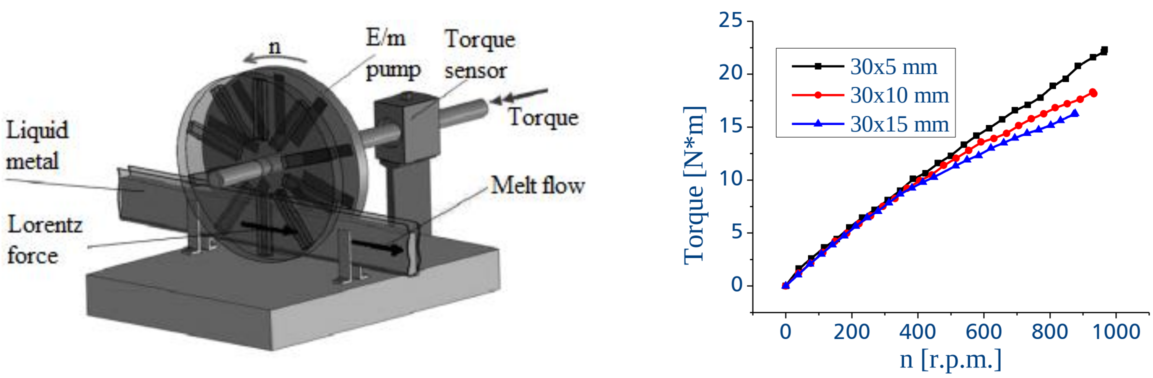

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Figure 4: Working principle (a) and Lorentz torque measurement result of dry calibration (b) of LTV flow control. Electromagnetic pump pushes liquid and, hence is a subject to a reaction torque (b) that was measured by torque sensor.

Figure 4b shows the resulting torque acting on the shaft as measured by the torque sensor. In the graph we use a scaled representation of the measured value. The re-scaling has been performed to eliminate the inherent dependence of the data on the width of the aluminium bars. In detail we use the scaling:

$$T_{SC}=T(H/W), \qquad (4)$$

where H and W denote the distance between wheels and the width of the aluminium bar, respectively. The motivation for this re-scaling stems is explained below.

As a rule Lorentz force and produced by it torque increase with increasing of cross-section of the conductive material because with a change of a plate's width as a consequence two parameters are changing: the volume of a conductive material that is influenced by magnetic field, and its electric resistance to induced eddy current, as well as the gap between wheels of e/m pump. Besides, magnetic field distribution in between of wheels is not homogeneous: it decreases from walls to the middle of gap. Hence magnetic field, which passes through thick plate, has higher value than through thin one.

The difference between scaled values of measured torque under high rotation frequency of the e/m pump is caused mainly by change of magnetic Reynolds number Re_m (fig 5a) for aluminium bars. An increase of width results in an increase of the magnetic Reynolds number Re_m given by the relation by $Re_m=\mu\sigma vL$, where μ is the magnetic field constant. This increase is due to the increase of the electromagnetic interaction length L. As it is known from MHD, larger values of Re_m result in stronger induced magnetic fields that fight against the applied primary field [9]. This give rise to a weakening of the overall magnetic field that contributes to the Lorentz force. Therefore lower values for T are observed in cases of thicker plates. For liquid experiment the obtained values of Re_m are ten times less than dry calibration results because of difference between σ of aluminium ($3{,}5\cdot10^7$ S/m) and GaInSn ($3{,}5\cdot10^6$ S/m). Hence the dependence between Re_m and the scaled pump power in case of liquid is linear, while for aluminium the ratio has curvilinear contour [9].

According to fig 5b, the lowest reachable value of *Re* is proportional to $5 \cdot 10^3$. The experimentally registered *Re* is higher than its critical value for channels, hence only turbulent flow can be provided within the experiment.

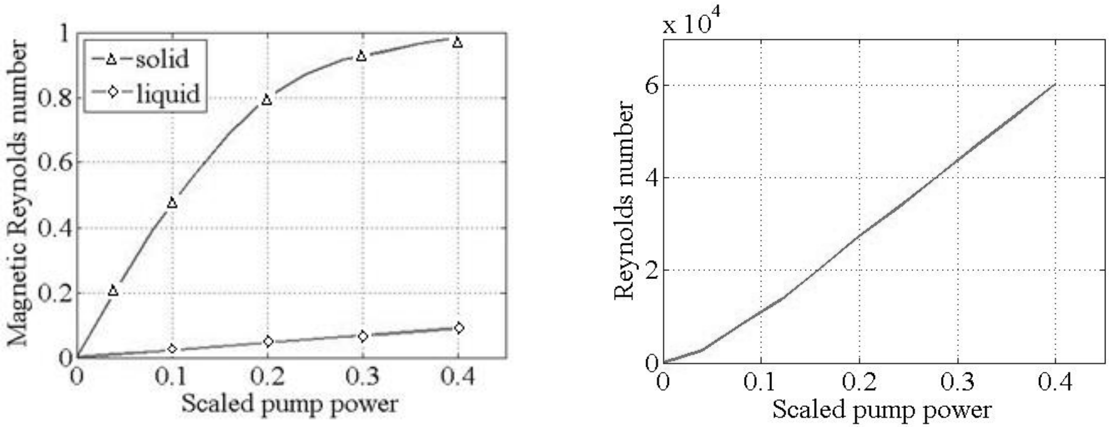

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Figure 5: Obtained by LTV values of the magnetic Reynolds number Re_m for solid (aluminium bars) and liquid (GaInSn) materials (a), and reachable values of Reynolds number *Re* (b) in the experimental channel

3. Conclusion

The model experiments described here demonstrate that time-of-flight LFV and LTV are feasible non-contact electromagnetic techniques for measuring and control of volumetric flow rates in turbulent liquid metal flow. The first technique is based on cross-correlating the force data registered by the two flow meters. Due to this it is independent of any fluid properties and the magnetic field distribution. The second method allows complete control of the flow rate of the fluid.

The experiment shows that both methods must be properly calibrated by applying additional measurement techniques and controlled temperature regime. The ratio between time shift and characteristic flow time strongly depends on the separation distance of the flow meters and presumably, on the geometry of the obstacle, which is submerged into the flow or created in contactless way in order to produce detectable vortex structures. In addition an optimal data processing technique for fluid time-of-flight results is necessary to obtain precise value of volumetric flow rate within the channel.

4. References

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