Lorentz force velocimetry using small-size permanent magnet systems and a multi-degree-of-freedom force/torque sensor

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Abstract

Lorentz force velocimetry is a contactless velocity measurement technique for electrically conductive liquids like molten steel. In this technique, a localized static magnetic field is applied on a flowing metal melt generating eddy currents and, therefore, a flow-braking Lorentz force within the fluid. Hence, due to Newton's third law, a force of same magnitude acts on the magnet system which is connected to a force sensor. According to the principles of magnetohydrodynamics, this force is proportional to the velocity of the liquid metal. Depending on the volume subset of the flow which interacts with the magnetic field lines produced by permanent magnets, we have local Lorentz force velocimetry (LFV) or Lorentz force flow meter. In the case of the Lorentz force flow meter, the magnetic field lines penetrate the entire cross-section on the flow given access to flow rate information. In regard to local LFV, significantly smaller magnets are used for local velocity measurements. This paper presents the possibility of increasing the spatial resolution of the model experiment and acquiring more information of the flow, e.g. local velocity gradient, by introducing a novel arrangement of small-size permanent magnets connected to a multi-degree-of-freedom force/torque sensor.

Key words: velocity measurement, liquid metal, contactless

Introduction

In local LFV, owing to the rapid decay of magnetic fields, a localized magnetic field distribution in the liquid metal is archived by using magnets comparatively smaller that the cross-section of the flow. The permanent magnet is connected to a sensitive force sensor and a qualitative assessment of the velocity distribution of the liquid metal can be obtained. In this case, the Lorentz force F_L is proportional to the velocity V, to the applied magnetic field B_0 to the power of two and to electrical conductivity σ of the liquid metal [1]:

$$F_L \sim V \sigma B_0^2 \qquad (1)$$

This technique has already proven to identify obstacles and the wake behind them in a rectangular duct with an accuracy of 3 cm with a 1 cm cubic magnet [2]. The reference measurement device was a 1D interference optical force sensor reaching a resolution of 0.3 μN at experimental conditions. In this experiment, just one force component acting on the magnet can be measured simultaneously, i.e. the Lorentz force in the streamwise direction. However, velocity profiles of liquid metal in industrial applications are not simple 1D flows but mostly 3D having low and high scale turbulent structures. For that purpose, we are introducing a new concept of local Lorentz velocimetry in which the permanent magnet is connected to a multi-degree-of-freedom force/torque sensor and the common cubic magnet is replaced by an arrangement of permanent magnets (Table 1). In this case, we are experimentally investigating the effect of different magnetic field distributions on the Lorentz force. As a first step, the magnets are compared based on the model experiments at the experimental facility GALINKA (Fig.1). The reference 1D force measurement system is used for this purpose having GaInSn in eutectic composition as a test fluid [2].

Table 1: Permanent magnet systems used for a parametric study investigating the influence of their geometry on the Lorentz force in local LFV. The volume and material are held constant, and therefore, their mass is nearly the same for an accurate comparison. The magnetization direction is perpendicular to the widest surface of the magnet.

			
Type	cubic	Cross-shaped magnet arrangement	Cross-shaped magnet
Material	N52	N52	N52
Volume	1000 mm^3	(8 mm * 5 mm * 5 mm) * 5 = 1000 mm^3	1000 mm^3
Mass	7,55 ± 0,01 g	7,51 ± 0,01 g	7,53 ± 0,01 g

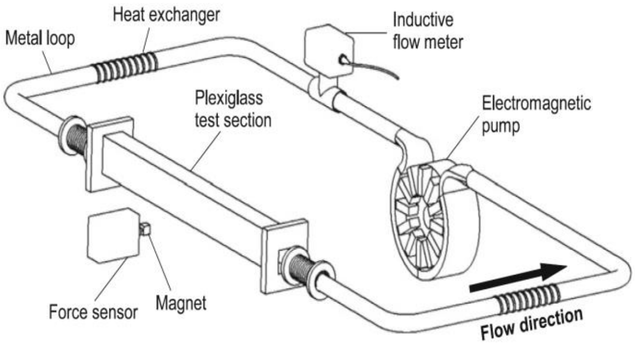

Fig. 1: Experimental facility GALINKA. The liquid metal loop consists of stainless steel pipes and an 80cm long plexiglass rectangular duct (50mm x 50mm). The GaInSn is driven by an electromagnetic pump and flows though the test section, where the force sensor is placed beside and measures the resulting streamwise force acting on the magnet.

Fig 2. Set-up for parametric study investigating the influence of different geometries of permanent magnet systems on the Lorentz force. Their volume (*1000 mm^3*) and the flow rate (*Re* ≈ 7000) of GaInSn are held constant. On the figure the magnet is placed in *y* = -25 mm and moves vertically (double sided arrow) until reaching the top wall of the duct (*y* = 25 mm).

Problem description

As explained before, as a contactless measurement technique, local LFV allow us to obtain local velocity information of electrical conductive liquids. In this approach, the volume subset of the liquid that interacts with the magnetic field has to be considerably smaller that the cross-section of the flow. However, by decreasing the size of the magnet, the force reduces as well making its measurement a big challenge to present techniques. Having as reference the 10 mm cubic magnet used in [2], we propose a cross-shaped magnet and a cross-shaped magnet arrangement while maintaining the volume and the material of the magnet system constant. We are going to investigate the influence of the change of the magnetic field distribution on the Lorentz force at the liquid metal loop GALINKA (Fig.1). An electromagnetic pump drives GaInSn in eutectic composition through stainless steel pipes. Just before the liquid metal enters the plexiglass test section, it flows across a honeycomb (D_h = 3 mm, L = 160 mm) that works as an hydraulic resistance and a typical turbulent flow is achieve. The wall thickness of the duct is 5 mm and has a rectangular cross-section of 50x50 mm^2. At the beginning of each experiment, the center of the permanent magnet is placed on the bottom of the wall at *y* = - 25 mm (y^* = -1) and its outer surface is placed almost touching the wall at *z* = 0 mm (Fig. 2). Then, the magnet is moved upwards to *y* = 25 mm (y^* = 1) in 2.5 mm steps. In each step we record the average value of the force, obtaining access to velocity information of the liquid metal inside the duct. Finally, the distance between the outer surface of the magnet and the test section is changed from *z* = 0 mm (almost touching the wall) to *z* = 6 mm with a 1 mm step size. As a result, we have an insight on how the Lorentz force depends on the position of the magnet system in *y* and *z* directions.

Results

The results of the parametrical study are summarized in Fig 3. According the force signals, a higher symmetry of the velocity profile with the proposed honeycomb was seen in comparison with the ones obtained by Heinicke in [2]. Here, a shorter one (L = 60 mm, D_h = 3 mm) was used at the same experimental conditions. Nevertheless, there is still a discrepancy between the force measured at the bottom duct (y^*= -1) and the top of the duct (y^* = 1). This effect can be explained due to the fact that, there is a minor misalignment of the surface of the duct and the vertical movement of the magnet. As a result, the magnet is slightly closer to the wall at y^* = 1 than at y^* = -1 which corresponds to an increment of the force. As a next step, we are going to introduce a corrector factor of the force as function of the distance that will minimize this effect. Finally, a visible improvement of the force was not seen by using the proposed cross-shaped permanent magnet systems in comparison with the reference 10 mm cubic magnet. Possible causes of these results may be explained owing to the rapid decay of the magnetic field with the distance. As a consequence, the effect on the magnetic field distribution is negligible for different geometries of magnet systems at distances higher that 5 mm for a 1000m^3 magnet.

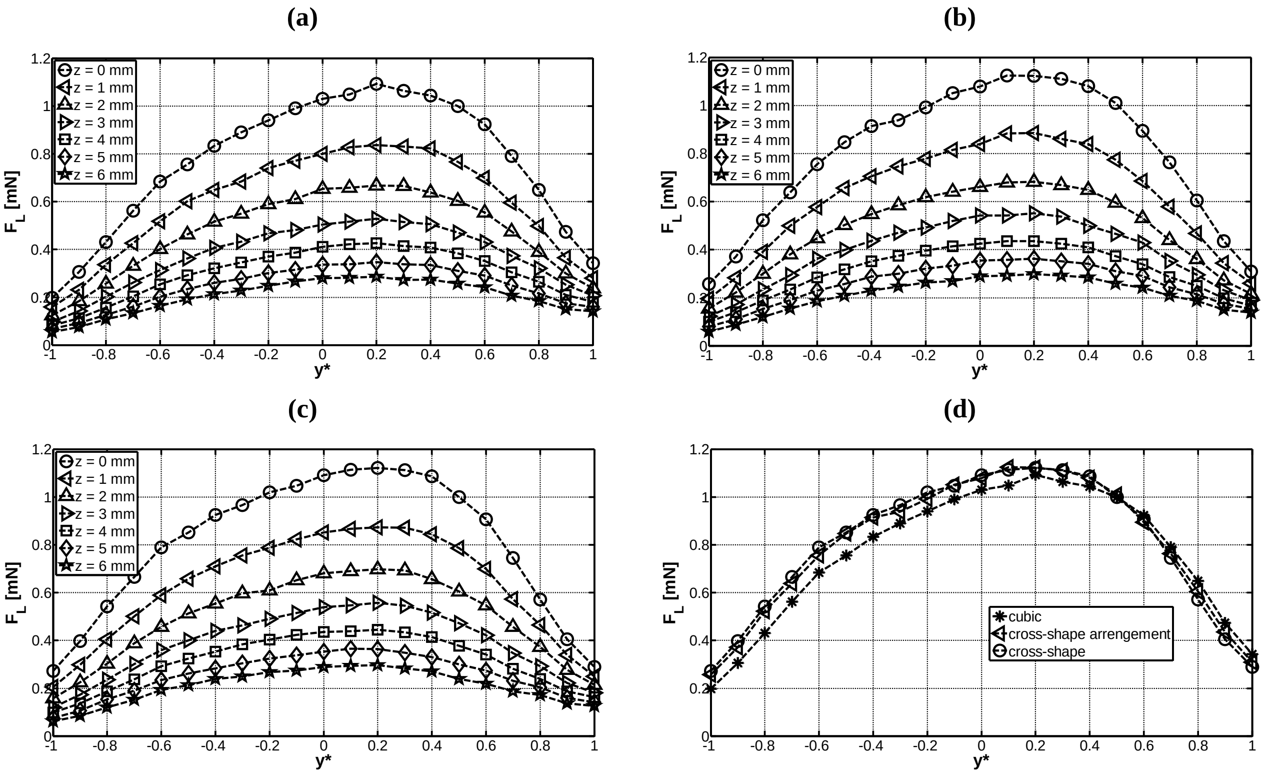

Fig 3. Results of parametric study investigating the effect of different magnetic field distributions on the Lorentz force using a cubic **(a)**, a cross-shaped magnet arrangement **(b)** and a cross-shaped magnet **(c).** All magnet systems share the same volume ($1000m^3$) and material (N52). The center of the magnet moves from the bottom (y^* =-1) to the top (y^* =-1) of the duct in 2.5 mm steps. The outer surface of the magnet is located almost touching the surface of the duct (z = 0 mm) and then is increased in 1 mm steps. The results show a clearly more symmetrical turbulent velocity profile based on the Lorentz force measurements in comparison with the ones obtained in [2]. There is still some discrepancy of the value of the force at the bottom and top of the duct (y^* =-1 and y^* = 1) which is expected to be the equal. The fact that on the bottom of the duct we have higher force can be explained by the slightly misalignment of the duct. As a result, the magnet is closer to the liquid metal on the top than on the bottom of the duct. A comparison of all magnets is shown in **(d)** at z = 0 mm presenting no noticeable difference between them. Galinstan in eutectic composition is flowing through the rectangular plexiglass duct (50mm x 50 mm) at a $Re \approx 7000$.

Conclusions

Based on the results of local LFV presented in this paper, a far more symmetrical velocity profile was seen at the rectangular test section of GALINKA using the proposed honeycomb. This fact implies that we may have successfully obtained a typical turbulent velocity profile in the duct. Now we are performing velocity measurements using Ultra Doppler Velocimetry (UDV) in order to validate our results. Even though there was no noticeable difference between the Lorentz force signals using the new permanent magnet systems, we cannot conclude if there is or not any advantage. For this purpose, we are going to test at first the multi-degree-of-freedom sensor and the magnet systems using a rotating electrically conductive disk achieving a higher control and accuracy of the measurements. In this case, we are able to have a better insight of the forces and torques acting on the magnets by a given velocity profile and velocity gradient.

Acknowledgment

Financial support from LIMTECH Alliance of Helmholtz Society and the Deutsche Forschungsgemeinschaft DFG within the RTG Lorentz Force Velocimetry and Eddy Current Testing under Grant GRK 1567/1 is gratefully acknowledged.

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