Flow velocimetry for weakly conducting electrolytes based on high resolution Lorentz force measurement

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Abstract  We demonstrate that a flow velocity measurement can be transformed into a non-invasive force measurement by metering the drag force acting on a system of magnets that is arranged around a flow channel. This method is called Lorentz force velocimetry and has been developed in the last years in our institute. It is a highly feasible principle for materials with large conductivity like liquid metals. To evolve this method for weakly conducting fluids like salt water or molten glass the drag force measurement is the challenging bottleneck. Here forces of $10^{-8}$ and less of the weight force of the magnet system have to be resolved in the rather noisy environment of the flow channel. In this paper different force measurement techniques get tested and compared.

1. Introduction

Flow measurement devices are used in a variety of industrial applications. In some industries the working fluids are hot, corrosive or abrasive. However, conventional measurement systems do not withstand such rough environments due to the necessarily direct contact of the measurement probe with the fluid or the pipe walls.

In order to avoid these interactions a novel contactless flow measurement method, called Lorentz force velocimetry (LFV), has been developed. The method works on the principle of measuring the Lorentz force acting on a magnet system when it is exposed to the flow of an electrically conducting fluid. Possible applications include but are not limited to flows of hot, aggressive or non-transparent materials, like highly aggressive chemicals, glass and salt melts.

The method of LFV has been extensively investigated, but, up to the present day, only for molten metals which have a high electrical conductivity. As Thess et al (2006) have pointed out, the Lorentz forces generated by the flow depend linearly on the conductivity of the fluid. While the conductivity of molten metals is typically of the order of $10^6$ S m$^{-1}$, the conductivity of electrolytes is only of the order of 1 S m$^{-1}$. Consequently the forces of LFV on electrolyte flows are $10^6$ times smaller than those in the LFV of molten metals, namely of the order of micronewtons. The main experimental challenge of this work is to prove, despite the force resolution difficulties, that LFV can indeed be applied to electrolyte flows.

2. Experiment

In the first setup the drag force is acting on the magnets that are hanging as a pendulum with 0.5 m long wires on a mounting. The magnet system (b) had a total mass of $m = 1.286$ kg and was made of two NdFeB permanent magnets. Here the displacement in the range of a few μm can be detected with a laser interferometer and another optical positioning sensor (Fig. 1). Faucet water has been used as working fluid because its electrical conductivity can be easily adjusted by adding salt (NaCl). Depending from the conductivity (varied from 0.03 Sm$^{-1}$ up to 14 Sm$^{-1}$) Lorentz forces up to about 80 μN have been measured. The force signal was proportional to the fluid velocity. For detailed information see Wegfrass et al (2012).

For the second setup the magnet system is attached to a state of the art electromagnetic force compensation balance (EFC) and a new developed magnet system. The high resolution EMC balance with the magnet system is placed along the 1.5 m long test section (c) with a rectangular cross section of 50 mm × 50 mm. The frame of the balance system (d) is mounted on large granite plate (e) in order to damp vibrations. For
that reason its aluminum frame stands on a separate concrete basement. Further components of the water channel are the nozzle, a slowdown tank with temperature control (f), the continuously adjustable pump(a) and a commercial magnetic flow meter as a reference. The velocity in the channel can be adjusted between 0.2 m/s$^{-1}$ and 5 m/s$^{-1}$. The highest electrical conductivity of the model fluid (salt water) was 20 S/m$^{-1}$. The fluid in the channel was cooled by an external cooling system; hence the conductivity of the salt water changes with the temperature. The extra-long test section of the water channel allows the validation of the Lorentz force velocimetry principle at different flow profiles of the duct flow (Fig. 2).

The geometrical optimization of several parameterized standard magnet system principles were performed using a coupling between numerical finite element simulations with a downhill simplex optimization routine under consideration of the mass limit of 1 kg imposed by the force measurement system. The almost perfect utilization of the disadvantageous stray field of the usual (standard) permanent magnet system (see Fig. 3) by using a combination of so called Halbach arrays instead increases the generated Lorentz force significant (Werner et al 2012).

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**Fig. 1** Schematic illustration of channel 1 with flow channel (a), system of magnets (b), laser interferometer (c), mounting and wires (d) and massive granite table (e).

**Fig. 2** Schematic illustration of channel 2 with pump (a), nozzle (b), test section / duct (c), mounting for Lorentz force velocimeter (d), mechanical decoupling (e) and relax vessel (f).
The balance is used in an unusual orientation: It is turned by 90 degrees to measure the horizontally acting Lorentz force. For different electrical conductivities (varied from 0.03 Sm⁻¹ up to 20 Sm⁻¹) and different fluid velocities (0.2 m s⁻¹ to 3 m s⁻¹) the resulting Lorentz forces have been measured. Additionally the position of the force measurement system was varied (five equidistant places along the full duct length). As a fluid we have used salt water again.

To remove long term drifts (e.g. temperature changes) the force signal has been detrended. Averaging over 1200 samples with a sampling rate of 20 Hz allows to reduce the standard deviation to a minimum. The optimal interval length of this moving average filter was determined before numerically with some test-measurements. In addition to that we have developed new systematic noise reduction methods to increase the resolution of both force measurement techniques by a factor of ten or larger.

![Fig. 4](image-url) **Fig. 4** (a) Principle of the usual (standard) magnet system on the rectangular test channel as applied in Wegfrass et al 2006; (b) Principle of the five-piece Halbach array system on the rectangular test channel; (c) Picture of the assembled Halbach array magnet system with the carbon fiber bracket.

### 3. Results

Both force measurement techniques can be used to detect Lorentz forces in the range of µN. The response time of the pendulum setup is larger due to a small attenuation coefficient. The step-response oscillation is damped by e in about 30 seconds. The EFC balance is at least ten times faster. Hence it is feasible for faster changes in the flow rate but it also is more sensible to environmental noise. For use in industrial applications the commercial EFC balance is the superior choice due to its faster operation. In terms of sensitivity our in-house indirect force measurement technique - the pendulum setup with the laser interferometer - is on par with the commercial solution and it is a highly feasible and in comparison a simple construction if only slow flow accelerations need to be resolved.

The proportionality between the electrical conductivity and the Lorentz force has been verified experimentally just as the proportionality between Lorentz force and flow velocity (Fig. 3). With respect to the flow profile (implemented by different sensor positions along flow channel) no significant change has been detected. This means this flow profile sensitive measurement method is feasible at least for typical fluid velocity profiles that occur in a pipe and in a duct (Fig. 4). Both measurement systems are quite sensible to environmental disturbances. The explained correlation of a long term drift in the force signal and the room temperature can be explained by thermal expansion due to an oscillating room heater temperature that heats the setup only from one side. This causes a (small) tilting of the aluminum frame on which the force sensor is mounted. Due to the large ratio of the weight force of the magnets (about 10 N) and the Lorentz forces (µN range) even very small tilting angles effect a recognizable change in the force signal.
Fig. 3 Lorentz force over fluid velocity for different electrical conductivities (position 1).

Fig. 4 Measured Lorentz force from different flow profiles along the test section of the salt water channel.

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References

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