Investigations and Experiments of Sophisticated Magnet Systems for a first Lorentz Force Velocimeter for Electrolytes

WERNER¹, M. and HALBEDEL¹, B.

¹ University of Technology Ilmenau – Department of Inorganic-nonmetallic Materials
Gustav-Kirchhoff-Straße 6 – 98693 Ilmenau – Germany
Email: mi.werner@tu-ilmenau.de

Abstract: This paper describes the design process of a first magnet system for the so called “Lorentz force velocimetry” in electrolytes. FEM optimizations were used to find the optimal geometry for a basic magnet design, which provides the highest possible Lorentz force within a strict limited mass of 1 kg. This magnet system was assembled using a layered carbon fiber bracket and characteristically described by a 3D pattern magnetic field measurement. Furthermore the influence of the wall thickness and the channel cross section onto the final realizable Lorentz force were investigated using FEM simulations too.

1. Introduction and background

Since 1832 the electromagnetic interaction between a magnetic field and a moving conductive object is well known by Michael Faraday’s “Experimental Researches in Electricity” [1]. Nowadays this theory is industrially used e.g. in food and wastewater industries as magnetic inductive flowmeters. These devices can handle fluids up to temperatures of 250 °C and conductivities down to some mS/m. For temperatures higher than 250 °C there are no similar methods possible, due to the corrosion of the electrodes in the fluid. More than 170 years after Faraday a team of scientists under supervision of Prof. A. Thess is using an improved method of this interaction to measure flow velocities in hot and high conducting fluids, like metal melts too. In [2] this technique, called “Lorentz force velocimetry” (short LFV), is presented as absolutely contactless and offers therefore a method to measure the flow velocity of such hot fluids. Instead of analyzing the induced voltages here the forces, acting on the magnet system, are detected, which arise by interaction of the eddy currents with the applied basic magnetic field (see Figure 1)

Figure 1: Principle of LFV (primary magnetic field, eddy currents due to motion of the fluid and braking Lorentz forces)

In general the same method can be used for electrolytes, e.g. glass melts or acids, although the conductivities and therefore the arising Lorentz forces are up to 6 orders of magnitude smaller than in metal melts. One key point in this further research on LFV is the development and structural optimization of sophisticated magnet systems, which provide a suitable magnetic field
structure with as much as possible average flux density and within a strict limited amount of weight [3]. With these optimized magnet systems the forces can be increased again to become easier to measure with available high precision force measurement systems.

At the moment there is only one analytical solution for the arising Lorentz force on a dipole magnet source over an infinite plate [4]. For more complex magnet systems or specific channel geometries the exact solution by hand is not possible. Therefore parameterized FEM simulations must be used for influence studies and optimizations of the magnet system and the channel geometries. Anyway this theory gives an important correlation: For electrolytic flows with small magnetic Reynolds numbers \( (R_m < 1) \) the Lorentz force density \( f \) is linear depending on the conductivity \( \sigma \) and the velocity \( v \) of the moving object.

The first investigations have shown that for the prototypic LFV only permanent magnet systems with high grade magnetic materials of neodymium iron boron (NdFeB) without iron yokes are suitable at the moment. The main reason for that is the goal to measure continuous flow rates, which does need constant magnetic fields too. In the direct comparison of a constant “magnetic-field-strengths to system-weight”-ratio an electrical driven coil is disadvantageous. Furthermore every contact to a coil – whether electrical or cooling – must be realized without influencing the tiny Lorentz force (see [3]), which are expected to be in the region of \( 10^{-5} \) N. These contacts are not needed in a permanent magnet system.

2. Presentation of the problem

In the short future a first experimental setup for LFV investigations on electrolytic flows will be build up at the University of Technology in Ilmenau. For this prototype a magnet system is needed to perform first measurements on a cold electrolyte. Here salt water with conductivities up to \( \sigma = 6 \, S/m \) is planned. The flow velocities in the channel shall be adjustable up to \( v = 5 \, m/s \). The first test channel geometry cross section will be rectangular with \( A_{\text{channel}} = 50 \, mm \times 50 \, mm \).

The turbulent flow at \( v = 5 \, m/s \) is conditioned along the channel to provide well defined fluidic profiles within the test section part. Considering the magnetic Reynolds number \( (R_m \approx 2 \times 10^6) \) and the Hartmann number \( (Ha < 0.05) \) it becomes clear that the fluid-magnetic interaction is weak, which means there is only a small mechanical influence of the magnetic field onto the fluid profile and there is no magnetic field deformation due to the secondary magnetic field of the eddy currents in the fluid [5]. In the case of a plug profile, which is expected at the inlet of the planned test section, the fluid therefore can be simulated as a solid bar with the conductivity of salt water and a cross section of the planned channel. With this approximation no dynamic fluid simulation is necessary to predict the generated Lorentz forces, which reduces the simulation time significant. In [3] the simulation procedure of LFV was validated on a real solid body experiment. Here considerable agreements between simulations and measurements could be achieved. So it is proven that a prediction and comparison of the arising Lorentz forces for different magnet system designs and furthermore there optimization within an acceptable amount of time is possible with these simulations.

3. Channel investigations

To produce as high as possible Lorentz forces at small velocities the exact channel geometry is an important parameter for the magnet system optimization. For the planned prototype the influence of the wall thickness onto the Lorentz force was investigated. Therefore a basic magnet system was used, which shall be called “standard” system from now. It consists of two permanent magnets with the same direction of magnetization – perpendicular to the channel – (see Figure 2). So the magnetic flux is perpendicular to the fluid motion too. Each magnet has a length of
\( l = 40 \text{ mm} \), a thickness \( b = 30 \text{ mm} \) and a height of \( h = 44.4 \text{ mm} \). Here \( l \) is the length in moving direction of the bar (x), \( b \) is the thickness in magnetization direction (y) and \( h \) is the height perpendicular to the moving direction (z). The salt water bar (\( A_{\text{Bar}} = 50 \text{ mm x 50 mm} \)) was moved parallel to the ground through the magnets (x). The magnetic properties are assumed to be linear with coercivity force \( H_c = -900 \text{ kA/m} \) and remanence \( B_r = 1.38 \text{ T} \), which is comparable with standard neodymium iron boron material of grade N48. The distance \( \delta \) between each of the magnets and the constant fluid body was varied in order to determine the dependency of the Lorentz force on this gap. Figure 2 right shows these Lorentz forces normalized to their maximum at the smallest distance of \( \delta = 2 \text{ mm} \). It turns out, that for larger \( \delta \) the force decreases significant. At \( \delta = 10 \text{ mm} \) the force is factor 0.3 of the force for \( \delta = 2 \text{ mm} \), which is a loss of approximately 70 \%. Therefore thin walls for the channel designs are essential for effective LFV. Based on this result the prototype channel was planned with a wall thickness of 2 mm plus 1 mm additional air gap on each side to ensure the free movement of the magnet system (\( \delta = 3 \text{ mm} \)).

![Figure 2: Simulated situation for distance investigation and result for normalized Lorentz force at different distances](image1)

Another general point of interest is the influence of the channel cross section aspect ratio (\( ar = \text{height/width} \)) onto the producible Lorentz force, although the geometry of the planned first prototype is fixed at \( A_{\text{channel}} = 50 \text{ mm x 50 mm} \) (\( ar = 1 \)). The magnet geometries of a “standard” system were optimized onto highest possible forces for different channel aspect ratios. The cross section area is kept constant every time, in order to realize the same volume flows in every channel. Furthermore the mass of magnetic material is kept constant at \( m_{\text{NdFeB}} = 800 \text{ g} \) and the distance between the magnets and the fluid is constant \( \delta = 3 \text{ mm} \). The magnetic properties are the same like in the simulation before. The implemented “pattern search” optimization algorithm in the commercial software MAXWELL was used. The resulting forces were again normalized onto the maximum of the simulated forces at the channel cross section of \( A_{\text{channel}} = 20 \text{ mm x 125 mm} \) with the aspect ratio \( ar = 6.25 \) (see Figure 3).

![Figure 3: Maximal normalized forces in relation to the channel width at constant magnet mass and volume flow through the channel (pictures illustrate the optimal magnet geometries)](image2)
It is obvious that the forces on the channels with higher aspect ratios are larger. Because of the constant weight these magnet systems can be seen as more effective (higher force-to-weight-ratio). This is an important aspect for the practical realization of LFV, because higher efficiency means a more accurate flow measurement too.

4. Design and realization of a “standard” magnet system

For the mentioned experimental setup in Ilmenau a “standard” design should be used first. In order to find the optimal geometries of the magnets for this LFV assembly on electrolytes the following conditions had to be considered: The whole magnet system must be less than 1 kg over all mass, due to the dead load limit of the planned force measurement device. The weight of the bracket for the magnet fixation was restricted to 150 g. The distance between the two magnets was set to \( d = 56 \text{ mm} \), due to the cannel width of \( 50 \text{ mm} \), 2 mm wall thickness and 1 mm additional air gap on each side (see chapter 3). The conductivity of the planned salt water was assumed to be \( \sigma = 4 \text{ S/m} \) and the velocity to \( v = 5 \text{ m/s} \). For simulation and optimization the commercial software MAXWELL was used again. The chosen optimizer was the “Quasi Newton” type here, which is feasible for optimizing goal functions with maximal 2 parameters and low noise in the Parameter dependencies, which can be expected in this problem. Here the parameters were chosen to be the thickness \( b \) and the length \( l \). It turns out that there are various geometries, which produce nearly the same Lorentz force. The optimal thickness \( b \) is in a range of \( 28 \text{ mm} < b < 30 \text{ mm} \) and the best length \( l \) is in a range of \( 37 \text{ mm} < l < 40 \text{ mm} \). The optimum varies, due to discretization errors in the simulation and depends strongly on the mesh resolution. Because the differences in the expected Lorentz forces within this plateau were within 1 % tolerance, one geometry was chosen due to fabricating issues. The ordered magnets finally have the dimensions \((l \times b \times h)\) \(40 \text{ mm} \times 30 \text{ mm} \times 47 \text{ mm} \) out of material of grade N52, which carries higher energy than the simulated material and generates therefore higher Lorentz forces. This does not influence the geometrical optimum. Simulating the attracting force between these two magnets gives \( F_{\text{att}} \approx 30 \text{ N} \), which must be compensated by the fixating bracket. Here carbon fiber composite materials were used. They are lightweight and robust.

A simple bracket was designed using a comparison of analytical calculated bending stresses with the empirical realizable tensile strength of the carbon fiber matrix, given by the distributor of the carbon fiber layers. In general a 1 mm thick bracket is enough to fix the magnets, but because of the ideal assumptions in this analytical solution and the necessity of a bracket with very high stiffness, the thickness was increased to 10 mm. A simplified structural mechanic simulation in ANSYS gives a deformation, by the magnetic attraction force, of 50 \( \mu \text{m} \) for the ends of the bracket, which is acceptable because of the additional 1 mm air gap.

Figure 4: Assembled standard magnet system for first LFV on electrolytes and measured magnetic field inside
This bracket has a total mass of $m_{\text{bracket}} \approx 150$ g, which meets the required value. The bracket was built up out of approx. 70 layers of uniaxial carbon fiber with a mass of 80 g/m² and a thickness of $d_{\text{layer}} = 0.12$ mm. After hardening of the epoxy material at room temperature the magnets were glued into the bracket and mechanically protected by some additional layers of carbon fiber material. The result was a “standard” magnet system of 1008g overall mass. The magnetic field in the channel region was measured using a 3D pattern measurement system of linear positioning stages and a hall probe (see Figure 4 right). The difference of the measured field with the simulated field was within 1 % using the characteristic values $B_r = 1.4462$ T and $H_c = -1110$ kA/m given by the producer of the magnets. With this magnet system a Lorentz force of $F_{\text{Lorentz}} \approx 34 \, \mu$N can be expected under the mentioned simulated standard conditions.

4. Outlook

It is planned to use the realized magnet system on the prototype – once it is ready for measurements – and to prove the force predictions for different fluid profiles. To design a completely optimized magnet system, the bracket and therefore the carbon-fiber layered structure has to be improved too. Here the mass of the bracket can be optimized significant. Furthermore another kind of magnet system design will be assembled, which bases on J.C. Mallinsons idea of one sided fluxes [6]. These structures – nowadays known as Halbach arrays – allow a magnet system design with factor 3 higher Lorentz forces at same magnet system mass. Here the assembling of the arrays is a challenge, which has to be dealt with.

5. Conclusion

The first investigations on LFV for electrolytes predict a measurable Lorentz force in the order of magnitude of $10^{-5}$ N, which has to be measured accurately for flowmeter purposes. In order to increase these forces, the magnet system has to be as close as possible to the fluid, which requires thin walls along the measurement section. Furthermore it turns out, that LFV is much more effective on channels with high aspect ratios, due to the fact, that higher flux densities can be realized there. A first LFV measurement device for electrolytes is still in construction. The “standard” magnet system for this prototype was optimized, built up and characterized by magnetic field measurements.

6. References


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