Experimental and numerical investigation on particle-induced liquid metal flow using Lorentz force velocimetry

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Abstract
The dynamics of electrically non-conducting particles in liquid meal flow are of interest in a number of metallurgical processes. For instance, during continuous casting of steel, proper removal of slag particles interacting with mold flow is crucial for the quality of the product. However, as such flows are very complex, analyzing single effects are almost impossible. Therefore, we investigate experimentally a simplified configuration where spherical particles of known size are pulled in the vertical direction with a controlled speed at a given position through a liquid metal column initially at rest. As a test melt we use the alloy GaInSn in eutectic composition which is liquid at room temperature. The displacement flow induced by the particle movement is measured using Lorentz force velocimetry. This method is based on recording the flow-induced force acting on an externally arranged permanent magnet. In the present paper we extend earlier work by analyzing not only the drag force in the direction of the particle movement but also the lift force acting in the horizontal direction. Moreover, we use an improved signal processing routine that allows us to perform measurements at higher particle Reynolds numbers. The experimental results are in both quantitatively and qualitatively agreement with the predictions of numerical simulations using the commercial code ANSYS/FLUENT.

Key words: liquid metal, Lorentz force, particle-induced flow

Introduction
Lorentz force velocimetry (LFV) is a non-contact electromagnetic flow measurement technique in electrically conducting fluids like liquid metal melts [1]. The measurement principle is based on the interactions of a moving melt with a magnetic field, i.e. on the effects of magnetohydrodynamics (MHD) [2]. When the melt enters into a magnetic field, it will slightly bend the field lines in the direction of its movement. As a result, electrical eddy currents are induced. These eddy currents interact with the magnetic field generating flow-braking Lorentz forces within the melt. Physically, these Lorentz forces are the restoring forces of the bent magnetic field lines when considered to behave as elastic strings. The magnitude $F_L$ of the Lorentz force is proportional to the melt velocity $u$ according to the relation

$$ F_L \sim \sigma u B^2 V, \quad (1) $$

where $\sigma$ is the electrical conductivity of the melt, $B$ the magnetic flux density and $V$ a characteristic volume corresponding to the volume penetrated by the magnetic field. In LFV, we measure the counter force which is acting on the magnet system that generates the field and which is pointing in the direction of the melt flow. The respective measuring device is called Lorentz force flowmeter (LFF) which basically consists of a magnet system and an attached force sensor. In case the flowrate of the melt is of interest, the magnet system consists of an array of permanent magnets in such a way that the magnetic field penetrates the entire cross-section of the flow. On the other hand, if local velocities shall be measured, the magnetic system consists of a single tiny permanent magnet. As the LFF is arranged outside of the melt domain, LFV can be considered to be a non-contact electromagnetic method.

In this paper we apply this technique to the case when melt flow is induced by spherical solid and non-conducting particles of known size pulled with a constant speed $u$ through a liquid metal column initially at rest. Using this simplified configuration we are able to investigate purely the displacement flow induced by the rising particles. This model experiment shall be the first step on the way of applying LFV to more complex cases like detection of gas bubbles or particle-flow in metallurgical applications. We extend previous work [3], [4] by not only recording the drag force induced by the displacement flow but also the lift force acting in the horizontal direction. Furthermore, we describe a new data processing scheme that allows us to perform measurements at higher particle Reynolds numbers.

The present study is organized as follows. First, we describe the improved experimental set-up and explain the new features of the data processing method employed. Secondly, we present some selected results obtained using these new techniques. Next we compare the experimental findings with the predictions of numerical simulations. Finally, we shall give a short summary of the main conclusions.
Experimental set-up
The experimental set-up is shown in Fig. 1. It consists of a vessel made of plexiglass of size $60 \times 60 \times 400 \text{ mm}^3$ having a wall thickness of 8 mm. The vessel is filled with liquid metal GaInSn which is liquid at room temperature. The spherical particle is made of plastic, i.e. it is electrically non-conducting, and has diameter of $d = 6 \text{ mm}$. The particle is fixed on a thin fishing line of thickness 0.1 mm in order to fix its lateral position at a distance of 10 mm away from the left side-wall. During an experimental run the fishing line is pulled through the top and bottom holes of the vessel. The pulling velocity of the sphere is controlled by an additional linear driver, which provides speeds in the range of 0 to 200 mm/s. The highest speed corresponds to a particle Reynolds number of $\text{Re} = 3600$, where $\text{Re} = \frac{ud}{\nu}$, $u$ is the pulling speed and $\nu$ is the kinematic viscosity of the melt.

![Fig. 1: Sketch of the experimental set-up](image)

Our LFV consists of a $12 \times 12 \times 12 \text{ mm}^3$ permanent magnet (NdFeB 42) which is installed in 1 mm distance from the outer wall of the vessel. It is arranged in such a way that the magnetic field lines are pointing into the horizontal direction. The magnetic flux density of the magnet is about $B = 575 \text{ mT}$ at its surface. However, this value decreases rapidly with increasing distance from the surface. Within the melt domain, we measure values of $B = 98 \text{ mT}$ at distance 9 mm corresponding to the inner vessel wall, and $B = 10 \text{ mT}$ at distance 19 mm, i.e. the position of the fishing line. Hence, according to Eq. (1) we expect magnitudes of the Lorentz forces in the range of micronewtons. Such tiny forces can only be measured by special sensors. We use an Interference-Optical-Force-Sensor (IOFS) to measure either the x- or z-component, corresponding to the lift or the drag component of the Lorentz force induced by the displacement flow of the melt around the particle, respectively. The sensor measures the displacement of an elastic body under the load to the force by interferometric means and converts the signal into a voltage in the range of nanovolts. Finally, using the calibration curve of the sensor, the voltage is converted into a certain force value.

The flow chart of our data processing is shown in Fig. 2. Our improved procedure can be described as follows. The dynamic characterization of the IOFS force sensor corresponds to the frequency response of the second order transfer function. Using the given eigenfrequencies of the sensor of 16 Hz when arranging in the z-direction and of 14 Hz when arranged in the x-direction, respectively, we define the transfer function $G(s)$ and then use the inverse function $G(s)^{-1}$ to compensate the measurement data. Thus, we eliminate the dynamic effects of IOFS sensor. Afterwards, a low pass filter is applied to denoise the signal. Additionally, a synchronized Ultrasonic Doppler Velocimetry (UDV) measurement is applied to provide the accurate time when the particle is passing the magnet. We record it as the reference zero-time for the LFV measurement. Using this sensor and data processing we can conduct measurement up to particle Reynolds number of 2000. By that, we can extend the range of Re by a factor of about 4.

Numerical simulation
For the numerical simulation we use the commercial CFD software ANSYS/FUENT and its MHD extension. Here we modify a numerical scheme developed for the simulation of Argon bubbles rising in a GaInSn column initially at rest. Details of the scheme are given elsewhere [6], [7]. Here, we replace the free-slip velocity condition at the bubble interface by a no-slip condition at the surface of the rigid particle. The code solves the incompressible Navier-Stokes equations that are extended by the Lorentz force density $f_L$ defined by the relation

$$f_L = j \times B.$$  \hspace{1cm} (2)
Here, \( j \) denotes the eddy current density. It can be calculated via Ohm’s law given by
\[
 j = \sigma [-\nabla \Phi + u \times B],
\]  
(3)
where \( \Phi \) the electrical potential, and \( u \) is the velocity vector. The set of equations is closed by calculating \( \Phi \) upon applying the charge conservation law, i.e.
\[
 \nabla \cdot j = 0
\]  
(4)
to Eq. (3). Finally, for \( B \) we take an analytical representation for a cubic permanent magnet [7]. Hence, we solve the MHD equations in the limit of small magnetic Reynolds number when the effect of the induced magnetic field can be neglected. Vessel walls and sphere are taken as electrically non-conducting. Fluid properties are those of GaInSn.

The simulations are carried out as follows. The sphere is fixed in space and vessel, melt, and magnet all of which are moved with a constant velocity \(-u\) downwards. In order to resolve the boundary layer with at least 10 nodes, a Reynolds number dependent mesh is used around the sphere, see Fig. 3. The code is validated for the pure hydrodynamic case of flow around a sphere. Here we compare our calculated drag coefficient with experimental data [8]. In each case errors are less than 8%.

As an example, Fig. 4 shows the flow field around the sphere at a Reynolds number of \( Re = 300 \). The plot refers to reference time zero, i.e. when the magnet on the left wall is at the same height with the sphere. We observe that boundary layer separation occurs at about 80° on the right hand side. This value is in excellent agreement with purely hydro dynamical experiments. However, on the left hand side, separation occurs at about 90°. We attribute this stabilizing effect to the presence of both, a near wall on the left and the MHD interactions.

**Results and comparison**

![Drag and lift force for Re = 200.](image)

![Drag and lift force for Re = 2000.](image)
Figs. 5 and 6 show some selected results of our experiments and the supporting numerical simulations. Here, Fig. 5 refers to a Reynolds number of Re = 200. In this case the flow is steady. The upper graph (a) shows the measured drag force (black curves) together with the predictions of the simulation as a function the normalized position t u/d. Here, t u/d = 0 refers to reference time zero. The lower graph (b) shows the measured lift force and the respective results of the simulation. As expected from Eq. (1), the forces are in the range of some microneutrons. We observe that in the experiments, the drag force can only be measured within an accuracy given by the two black curves, i.e. the repeatability of the experiment is limited at relatively small Reynolds numbers. However, the overall agreement with the results of the simulation is remarkably good, especially in the downstream area t u/d > 5. In the region -5 < t u/d < 5, i.e. when the magnet is close to the sphere, the signals look more complex. We first find a slight increase of the drag when the sphere approaches the magnet, then a drop to almost zero at reference time zero and another sharper increase when the sphere leaves the magnet. The simulations predict a continuously increasing rag in this region. We may attribute this difference to both the restrictions of the experimental set-up in measuring such tiny forces and the assumptions made in the simulations. However, we can clearly see from Fig. 5 (b) that the agreement of experiments and simulations is excellent with respect to the lift force. In the region -5 < t u/d < 5 we observe first an increase reaching a maximum at about t u/d = -1.5, then a decrease to zero at t u/d = 0, then a further decrease to a minimum with negative lift, and finally a relaxation to zero in the wake region. Moreover, we can observe that the repeatability of the experiment concerning lift force is also excellent. Hence, in possible applications of analyzing particle dynamics using LFV, recording the lift force is favorable.

Fig. 6 shows the results for a Reynolds number of Re = 2000. In this case the flow is transient. Again, the upper graph shows the measured and the calculated drag forces while the lower graph shows the respective lift forces. As the flow is transient, we have added the results of 4 numerical runs with slightly different initial conditions. We observe that the repeatability of the experiments are much better than in the low-Reynolds number flow as the forces are significantly higher. Moreover, the overall agreement between the experimental findings and the predictions of the simulations become likewise much better. However, in the region -5 < t u/d < 5 the measurement and the calculation differ again, as already observed in the case Re = 200. In the experiments we find even negative drag forces at zero position while the simulations predict positive values. More experimental runs and simulations are needed to explain this difference. However, as for the low-Re case, the agreement between experimental findings and numerical prediction is again excellent. We can conclude that the lift force is more reliable for particle detection in the entire range of Reynolds numbers investigated.

Summary and conclusions
In this study we have investigated experimentally and numerically the application of Lorentz force velocimetry for analyzing particle dynamics in liquid metal flow. We consider the simplified case when non-conducting spherical particles are pulled at a prescribed speed from bottom to top of the test melt GaInSn initially at rest. We measure and simulations become likewise much better. However, in the region -5 < t u/d < 5, i.e. when the magnet is close to the sphere, the signals look more complex. We first find a slight increase of the drag when the sphere approaches the magnet, then a drop to almost zero at reference time zero and another sharper increase when the sphere leaves the magnet. The simulations predict a continuously increasing rag in this region. We may attribute this difference to both the restrictions of the experimental set-up in measuring such tiny forces and the assumptions made in the simulations. However, we can clearly see from Fig. 5 (b) that the agreement of experiments and simulations is excellent with respect to the lift force. In the region -5 < t u/d < 5 we observe first an increase reaching a maximum at about t u/d = -1.5, then a decrease to zero at t u/d = 0, then a further decrease to a minimum with negative lift, and finally a relaxation to zero in the wake region. Moreover, we can observe that the repeatability of the experiment concerning lift force is also excellent. Hence, in possible applications of analyzing particle dynamics using LFV, recording the lift force is favorable.

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