Lorentz Force Velocimetry – A Contactless Technique for Flow Measurement in High-Temperature Melts

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Abstract
We describe a non-contact technique for velocity measurement in electrically conducting fluids. The technique, which we term Lorentz force velocimetry (LFV), is based on exposing the fluid to a magnetic field and measuring the force acting upon the magnetic-field-generating system. We illustrate the physical principles of LFV and report results of comprehensive laboratory experiments which characterise the sensitivity of LFV. We then present results of an industrial test of the technique in the aluminium industry which demonstrates that LFV performs well under harsh industrial conditions. We finally outline some future developments and argue that LFV, if properly designed, has a wide range of potential metallurgical applications.

Keywords: flow measurement, magnet systems, Lorentz force

Introduction
Measuring the velocity in liquid metals is a notoriously difficult problem because these materials are opaque and often hot and aggressive. Especially when liquid metals reach high temperatures, as in metallurgy, the development of reliable, robust, and contactless velocity measurement methods has far-reaching consequences. The goal of the present work is to describe a flow measurement technique in which the problem is reduced to a force measurement that does not require any mechanical contact between the measurement system and the melt. This technique is referred to as Lorentz force velocimetry (LFV) and is described in more detail in [1] and [2].

Basic principles
When a liquid metal moves across magnetic field lines as shown in Figure 1, the interaction of the magnetic field with the induced eddy currents leads to a Lorentz force with density \( f = j \times B \) which brakes the flow. The force density is roughly \( f \approx \sigma v B^2 \) where \( \sigma \) is the electrical conductivity of the fluid, \( v \) its velocity and \( B \) the magnitude of the magnetic field. This fact is well known [3–5] and has found a variety of applications for flow control in metallurgy and crystal growth [6]. Equally obvious but less widely recognized [7,8,9,10] is the fact that by virtue of Newton’s law, an opposite force acts upon the system generating the magnetic field and drags it along the flow direction as if the magnetic field lines were invisible obstacles. Although the described phenomenon occurs no matter whether the magnetic field is generated by a permanent magnet or an electromagnet, it is only thanks to the advent of powerful rare-earth permanent...
magnets and design tools for permanent magnet systems that a practical realisation of this principle has now become possible. The present communication focuses on measuring the mass or volume flux of a liquid metal flow.

Figure 2 Main types of Lorentz force flowmeters: rotary flow meter (left) and stationary flowmeter (right) applied to a flow in a circular pipe. Sketches are highly simplified; measuring systems for angular velocity (left) and angle of inclination or force (right) are omitted for clarity.

Such devices will be referred to as Lorentz force flowmeters. Figure 2 shows the core elements of the two main types of Lorentz force flowmeters. When the permanent magnets are arranged along the rim of a rotatable disk, the interaction of the liquid metal flow and the magnetic field causes torque. This torque in turn sets up a rotary motion of the disk the angular velocity of which is a measure of the liquid metal velocity. Such devices are called rotary Lorentz force flowmeters. The second type of Lorentz force flowmeters is called stationary Lorentz flowmeters, and is shown on the right-hand side of Figure 2. It consists of a magnet system which creates a magnetic field perpendicular to the direction of the mean flow. The force on the magnet system is then either measured directly (not shown) or is measured through its displacement caused by the fluid movement. We have constructed various models of both types of flowmeters and performed a comprehensive series of experiments to characterise their sensitivity. Before discussing these measurements, let us briefly derive a simple mathematical relation describing how the sensitivity of a Lorentz force flowmeter depends on its main parameters.

Consider a single small permanent magnet with dipole moment m. This magnet is located at a distance L above a semi-infinite fluid moving with uniform velocity v parallel to its free surface. The magnetic field of the dipole which we refer to as the primary field, is of the order $B \approx \mu_0 m L^{-3}$ at the surface of the fluid. Due to the fluid’s motion, eddy currents are induced in the liquid metal. Order of magnitude of these currents is $J \approx \sigma v B \approx \mu_0 \sigma v m L^{-3}$. The eddy currents are concentrated below the surface, and interact with the primary field to produce the Lorentz force which is of the order $f = JB \approx \mu_0^2 \sigma v m^2 L^{-6}$ and brakes the flow. Since the force acts on a volume $L^3$, the total Lorentz force is $F \approx fL^3$ and we have

$$F \approx \frac{\mu_0^2 \sigma v m^2}{L^3}. \quad (1)$$

According to Newton’s law, the braking force is equal to the force acting on the magnet. Hence, equation (1) is the desired relation. We can draw a number of useful conclusions from this formula. First, the force is proportional to the product of velocity and electrical conductivity. This is in contrast to electromagnetic flowmeters [7] where the induced voltage does not depend on the conductivity. Second, F grows with the second power of the magnetization (or with the second power of the electric current if the magnetic field were to be produced by an electromagnet). This is a consequence of the fact that the magnet acts simultaneously as a source of the primary magnetic field and as a sensor of the secondary magnetic field. In contrast to other contactless methods, the sensitivity of LFV can thus be increased by
increasing the strength of the magnetic field. This makes LFV potentially suitable even for low conductivity melts like glass which are inaccessible to any other non-contact electromagnetic measurement method.

Laboratory experiments

Figure 3 shows the results of a simple laboratory experiment in which the magnet system is at rest during the measurement. The magnet system is U-shaped and contains two permanent magnets connected to each other with an iron yoke. The magnet system is connected to a pendulum. We can either measure the angle of inclination of the pendulum under the influence of the flow or fix the pendulum and directly measure the force acting on the magnet. The flowmeter is applied to measure the flow rate of a turbulent flow of a Ga-In-Sn eutectic alloy at room temperature which flows in a circular pipe with an inner diameter of 35 mm and stainless steel walls. The flow is set up by an electromagnetic pump and the flow rate is determined by a commercial Faraday-type electromagnetic flowmeter. A similar result is obtained (not shown) when the angular velocity of the rotary flowmeter is measured as a function of the flow rate.

As was already pointed out by Shercliff [7], it is desirable that the output of a flowmeter be independent of the detailed shape of the velocity profile. In order to test whether this property holds for a Lorentz force flowmeter, we have performed a test in which the flow of liquid metal in a rectangular channel was obstructed at different levels. This was accomplished by using a mechanical obstacle while keeping the flow rate fixed. We found that the force is only weakly affected by the level of obstruction.

We have also designed rotary flowmeters and tested their characteristics. Selected results are reported in [1]. Similar work was independently performed and reported in [10].

Industrial tests

In order to assess whether Lorentz force velocimetry is suitable for measurements in an industrial environment, we have designed a Lorentz force flowmeter that is capable of performing flow measurements in channels with a width up to 0.5 m. The flowmeter was tested by measuring the flow of aluminium at a temperature of 800 °C in an aluminium recycling plant. Selected results of the measurements are shown in Figure 4.

Measurement A corresponds to a run in which a given amount of aluminium was discharged within a comparatively short time of approximately 20 minutes. Curve A in Figure 4 shows that the time-dependent flow rate is well detected by our flowmeter. An initial period of high velocity is followed by a period in which the flow rate changes little and finally drops to zero. In run B, a similar amount of aluminium was discharged over a longer period of time.
Figure 4 Flow measurement in liquid aluminium: Normalised force measured by the Lorentz force flowmeter as a function of time. The Inset shows the geometry of the channel for which the measurement was performed. During the measurement, the velocimeter was mounted under the channel so that the magnetic field lines crossed the flow in horizontal direction.

The results demonstrate that Lorentz force velocimetry is not only principally feasible but also works in harsh industrial environments characterised by heat, dust, and occasional strong vibrations.

Summary and conclusions
We have demonstrated that Lorentz force velocimetry is a contactless method that can accurately and reliably determine the flow rate of liquid metals. Our tests show that Lorentz force velocimetry performs particularly well under harsh industrial conditions such as encountered in metallurgy. Further developments will include capabilities for directional sensitivity and commercialization according to demand.

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