Measurement of electrical conductivity of liquid metals using Lorentz force sigmometry

S. Alkhalil, Y. Kolesnikov, Ch. Karcher

Institute of Thermodynamics and Fluid Mechanics, Technische Universitaet Ilmenau
P.O. Box 100565, D-98684 Ilmenau, Germany

Corresponding author: christian.karcher@tu-ilmenau.de

Abstract
Lorentz force velocimetry (LFV) is a non-contact electromagnetic technique that can be applied to measure flow rate and/or local velocities in electrically conducting liquids like metal melts. The technique is based on the principles of magnetohydrodynamics: when the moving conductor interacts with an externally applied magnetic field, Lorentz forces are generated within the melt. During LFV, the counterforce to the Lorentz force is measured. Acting on the system that produces the external magnet field, this counterforce is proportional to the flow rate or the local velocity and the electrical conductivity of the melt. Hence, in application the knowledge of electrical conductivity is demanded. To this end we develop an electromagnetic technique for non-contact measurement of electrical conductivity of metal melts, termed Lorentz force sigmometry (LOFOS). During LOFOS, Lorentz forces are measured that are generated by a well-defined pipe flow for which mass flow rate is determined via a weighing procedure. The present paper describes the physical laws controlling LOFOS operation, shows the mathematical procedure of the evaluation of electrical conductivity and addresses the problem of calibration of a respective Lorentz force sigmometer. In detail, we present laboratory measurements at room temperature using solid metal bars and the liquid metal alloy GaInSn in eutectic composition as test melts. Here, uncertainty of measurement less than 0.5% and about 3% for solid and liquid tests, respectively. Currently, high-temperature applications of LOFOS in tin and copper melts are on the way.

Key words: Lorentz force, electrical conductivity, liquid metal

Introduction

In metallurgic high-temperature applications like continuous casting of steel [1] or production of secondary aluminum [2], measurement of flow rate or local velocities is still a challenging task. Here, due to chemical aggressiveness of metals melts at high temperatures and mostly unknown wetting characteristics between melt and probe, non-contact measurement techniques are of interest. However, as liquid metals are non-transparent, optical methods cannot be applied. On the other hand, liquid metals are excellent electrical conductors so that electromagnetic measurement techniques are promising candidates to meet the challenge. Among these candidates, flow meters based on the measurement of (i) flow-induced Lorentz forces [3], [4] that are acting as a braking force on the flow but in turn as a counteracting pulling force on an externally arranged magnet system and of (ii) flow-induced phase shifts [5] of electrical fields between a submitting coil and two receiving coils have been developed and already successfully applied under industrial conditions.

A drawback of both methods is that for the evaluation of melt velocity from the measured data, the electrical conductivity of the melt (or likewise magnetic Reynolds number) has to be known. However, this thermophysical quantity is often unknown as it strongly depends on both temperature and composition of the melt. To overcome this drawback, among others [6], two non-contact electromagnetic flow measurement techniques have been developed of which the measured quantity is independent of conductivity. The first one is called time-of-flight Lorentz force velocimetry [7], [8] which is based on the measurement of the transit time of any vortices advected by the flow when passing two externally applied localized magnetic fields that are separated by a certain distance. As a sensing signal the Lorentz lift force induced by the vortices is used. The time of flight is obtained by cross-correlating the two force signals. The second one is the pivoted permanent magnet [9], which is put into rotation when arranged in the vicinity of a channel within which a liquid melt is flowing. In the ideal case of a frictionless bearing, the rotation speed of the magnet solely depends on melt velocity and a geometric parameter. However, also these two methods have some limitations. In application the first method suffers from a weak signal-to-noise ratio while the second method shows limited temporal and spatial resolutions.

In the present paper we address the problem of non-contact measurement of electrical conductivity of liquid metals in order to support the flow measurement techniques described above which need this melt property as an input quantity. The method is called Lorentz force sigmometry (LOFOS), as electrical conductivity is usually denoted by the Greek letter sigma. The paper is organized as follows. First we give a brief introduction into the fundamentals of LOFOS. Next we describe our model test stand and shall present results of our model experiments. Finally, we give a short summary and an outlook on future activities in this field.

Fundamentals

Like LFV, LOFOS is based on the measurement of Lorentz forces that are generated by the electromagnetic interactions of a moving conductor and an externally applied magnetic field. These interactions are described by Ohm's law and the equation defining the induced Lorentz force density. These equations write as [10], [11]

$$\mathbf{j} = \sigma[\mathbf{E} + (\mathbf{u} \times \mathbf{B})], \quad \mathbf{f}_L = \mathbf{j} \times \mathbf{B}. \tag{1), (2}$$

Here, $\mathbf{j}$ denotes the eddy current density, $\mathbf{E}$ is the electrical field, $\mathbf{B}$ is the magnetic flux density, $\mathbf{u}$ is the velocity vector, and $\mathbf{f}_L$ is the Lorentz force density. Finally, σ denotes the electrical conductivity. Upon inserting Eq. (1) into Eq. (2), using the scales $u \sim U$, $B \sim B_0$, and $E \sim UB_0$, and integrating over the volume $V \sim L^3$ we obtain the relations

$$F_L \sim \sigma B_0^2 L^3 U \text{ or } F_L \sim \sigma B_0^2 L Q, \tag{3), (4}$$

where F_L is the measured Lorentz force, $Q \sim UL^2$ is the volumetric flow rate that is controlled in experiment and L is a characteristic length scale. Next, we introduce the total mass $M = \int_{t_0}^{t_0+\Delta t} (Q/\rho) dt$ that is accumulated during the operation time interval Δt and the respective total time-integrated Lorentz force $F_L^* = \int_{t_0}^{t_0+\Delta t} F_L(t) dt$. The quantity M is likewise measured in experiment by using a weighing device while F_L^* can easily be calculated numerically from the raw signal of the force sensor. Solving for the target quality σ we eventually obtain the equation

$$\sigma = \rho K F_L^* / M, \tag{5}$$

where ρ is mass density, $K = (cLB_0^2)^{-1}$ is the calibration factor and c denotes a dimensionless geometry coefficient. Hence, after calibration and with the measured data F_L^* and M at hand, the electrical conductivity shall be determined.

Experimental set-ups and results

Our procedure during model experiments, sketched in Figs. 1 and 3, consist of two steps. In a first step we use solid bars, see position (1) in Fig. 1, of copper and aluminum of known conductivity, geometry and mass that are moved with a controlled (5), (6) linear speed of U = 10 cm/s through a localized magnet field generated by a cylindrical Halbach array of permanent magnets (2). During these experiments we record the time-dependent Lorentz force, see Fig. 2, that pulls on the magnet system using a respective sensor based strain gauge technique (3). The arrangement is completed by a support (4) for the magnet system. With the quantity M know by simple weighing, we can determine the calibration factor to be $K = 35546\ (\mathrm{mT}^2)^{-1}$. In a next step we repeat this procedure by using a bar made of brass and of the same geometry as before. Evaluating again the measured data for F_L (see Fig. 2) and M and using the now known value of the calibration factor K, we can determine the electrical conductivity of brass to be $\sigma = 13.963$ MS/m. This value is only 0.47% lower than the exact value given on the data sheet. Hence, this model experiment demonstrates that LOFOS can be used to measure electrical conductivities of solid metals with high accuracy.

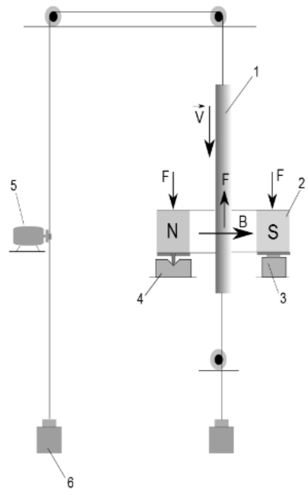


Fig. 1: LOFOS using solid metal bars.

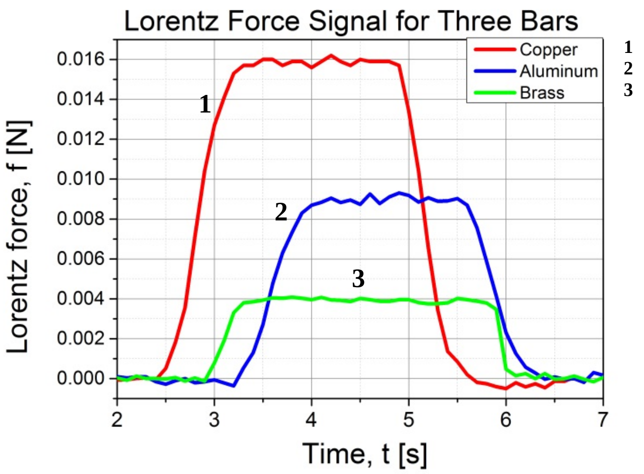
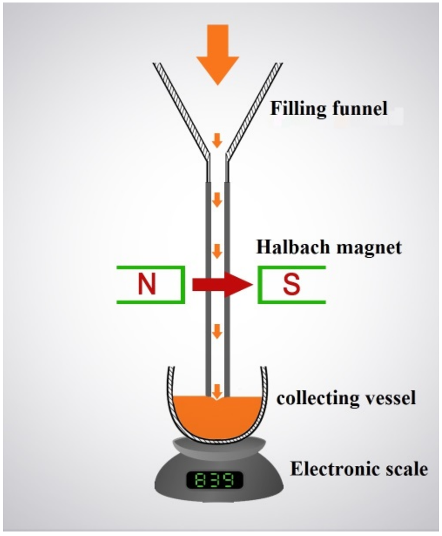


Fig. 2: Measured Lorentz for copper, aluminum, and brass bars.

In a second series of model experiments we apply LOFOS to the measurement of electrical conductivity of liquid metals. In order to find the calibration factor for this case we use the metal alloy GaInSn in eutectic composition. The benefits of this choice are that this alloy is in liquid phase at room temperature and its thermophysical properties are well documented in literature [12]. Fig. 3 shows the modified experimental set-up. A volume of V = 600 ml of the alloy is poured into a filling funnel made of fused silica and is delivered in a pipe with inner diameter of 8 mm. After having passed the Halbach magnet system where the Lorentz force measurement is conducted, the melt is collected in a vessel that is placed on an electronic weighing device. Hence, both mass flow rate and accumulated mass are likewise registered during the experimental runs.



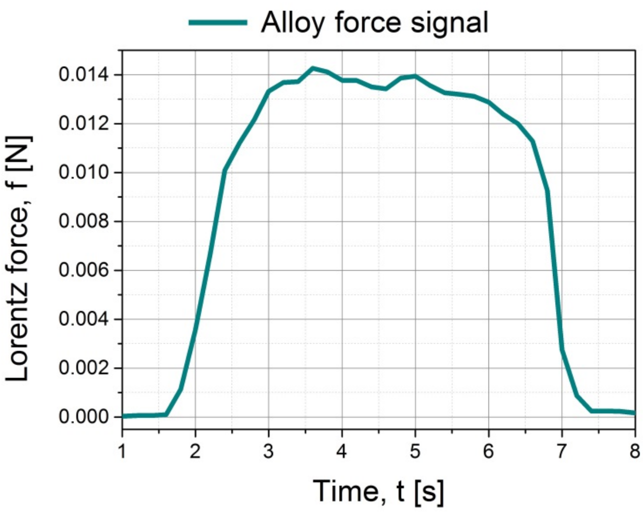


Fig. 3: LOFOS using liquid metals .

Fig. 4: Measured Lorentz for test melt GaInSn.

Fig. 4 shows the measured Lorentz force during a typical run. After a transient period at the beginning, we find an almost constant Lorentz force within a typical time of operation about 4 s. At the end of the experiment another transient regime is observed due to the ceasing of the melt flow. Upon repeating this test experiment for several times we are able to determine the respective mean calibration factor to be $K = 31103\ (mT^2)^{-1}$. The standard deviation of the measurements is about 3%.

After having found the calibration factor for liquid metals, we turn now to the measurement of electrical conductivity for hot melts. Test experiments using tin melts operating at a temperature of 550°C are currently one the way. Such high temperatures are necessary to avoid solidification within the needle-type pipe. Again, major modifications of the test stand have been performed in order to meet the new challenges of temperature measurement and control, vessel material, and the evaluation of both melt density and characteristic magnetic flux density B_0, cf. Eq. (5), both of which decreasing with increasing temperatures. First results show promising as test runs indicate that also in this case LOFOS can be used to measure electrical conductivity.

Summary and outlook

Lorentz force sigmometry is a non-contact electromagnetic method to measure electrical conductivities of liquid metals. It is based on the physical fact that the Lorentz force, induced by melt flow through an externally applied magnet field, depends linearly on the melt conductivity. The method has been tested first by modelling melt flow by the linear movement of solid metal bars of known conductivity. By that the calibration factor of the experimental set-up has been determined in order to apply the method to solid materials with unknown conductivity. Our experimental findings have clearly demonstrated that Lorentz force sigmometry can be successfully in this case. Uncertainty of measurement is less than 0.5%. In the case of liquid metals, things are physically more complicated. Using the model melt GaInSn, the determination of the calibration factor shows a standard deviation of about 3%. However, first runs using liquid tin at 550°C show that the proposed method may operate fine under such conditions. As a future step it is planned to use molten copper as a further test melt at about 1250°C.

Acknowledgment
The authors gratefully acknowledge support by the Deutsche Forschungsgemeinschaft DFG within the Research Training Group (RTG) on Lorentz force velocimetry and Lorentz force eddy current testing under grant GRK 1567. The authors are also thankful for helpful discussions with Professors Andre Thess (Institute of Engineering Thermodynamics of German Aerospace Center, Stuttgart) and Thomas Froehlich (Institute of Process Measurement and Sensor Technology of Technische Universitaet Ilmenau).

References
[1] M. Blair, T. L. Stevens (1995), Steel Castings Handbook, ASM International, Materials Park
[2] C. Schmitz (2006), Handbook of aluminium recycling, Vulkan-Verlag GmbH, Essen
[3] A. Thess, E. V. Votyakov, Y. Kolesnikov (2006), Phys. Rev. Let. 96, 164501
[4] Y. Kolesnikov, Ch. Karcher, A. Thess (2011), Metall. Trans. B 42, 441-450
[5] J. Priede, D. Buchenau, G. Gerbeth (2011), Meas. Sci. Technol. 22, 055402
[6] S. Eckert, D. Buchenau, G. Gerbeth, F. Stefani, F. P. Weiss (2011), J. Nuc. Sci. Technol. 48, 490-498
[7] D. Jian, Ch. Karcher (2012), Meas. Sci. Technol. 23, 074021
[8] N. Dubovikova, Ch. Karcher, Y. Kolesnikov (2014), PAMM 14, DOI 10.1002/pamm.201410343
[9] J. Priede, D. Buchenau, G. Gerbeth (2011), J. Appl. Phys. 110, 034512
[10] P. A. Davidson (2001), An Introduction to Magnetohydrodynamics, Cambridge University Press
[11] R. Moreau (2013), Magnetohydrodynamics, Springer, Berlin
[12] T. Iida and R. I. L. Guthrie (1988, The Physical Properties of Liquid Metals. Oxford Science Publications