The Lorentz force flowmeter (LFF) is a measuring device utilizing localized static magnetic fields for the non-contact measurement of the flow rate in electrically conducting fluids. In case of highly aggressive or high-temperature conductive fluids, it is difficult to reproduce in a laboratory the conditions typically met in application. Hence, calibration becomes a difficult task. For the LFF used for open channel flow measurement in liquid aluminum, we adapt a robust calibration method. This method utilizes reference device calibration data to calibrate other devices. In a first step, liquid calibration involving the fluid flow is performed in a reference open channel with a given reference LFF device. In a second step, the liquid calibration characteristic is transferred from the reference LFF device to the test LFF device during a dry calibration procedure, in which liquid metal flow is replaced by the motion of solid metal bars through the magnet systems of both reference and test devices. Hence, the liquid calibration is needed once for the reference device only. This combined calibration strategy may also be applied to similar measurement devices.

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1. Introduction

The Lorentz force flowmeter (LFF) is a measuring device utilizing localized static magnetic fields for non-contact measurement of the flow rate in electrically conducting fluids. The device bases its operation on the principles of magnetohydrodynamics (MHD). When a liquid, characterized by the velocity field \( \mathbf{u} \) and electrical conductivity \( \sigma \), flows into an externally applied static magnetic field \( \mathbf{B} \), eddy currents \( \mathbf{j} \) are induced within the liquid. As the result of the interaction of the eddy currents with the applied magnetic field, Lorentz forces are generated within the liquid. The Lorentz forces tend to decelerate the flow. This is a well known electromagnetic braking effect [1]. In turn, by Newton’s 3rd law, a counterforce of equal strength acts on the magnet system that generates the magnetic field. The Lorentz force, \( F_L \), scales as

\[
F_L \sim \sigma \cdot B^2 \cdot \dot{V} \cdot L,
\]

where \( B \) is the characteristic amplitude of the applied magnetic field, \( \dot{V} \) is the volumetric flow rate (which is to be measured by the LFF) and \( L \) is a characteristic length scale over which the magnetic field interacts with the fluid [2]. This scale is given by the length of the magnet system in the flow direction. The flow rate can be represented by \( \dot{V} = u \cdot S \), where \( u \) is the mean longitudinal velocity and \( S \) is the flow cross section. \( S = b \cdot h \) for a rectangular cross section, where \( b \) is the width and \( h \) is the height. The scaling relation (1) holds strictly for the cases of laminar pipe flow [1] or for the motion of a solid body with constant cross section.

For further consideration of the basic physics of LFF and the cases of successful application of Eq. (1) in particular we refer to [2–4] as well as to a similar work on the rotating flowmeter, which was independently performed and reported on in [5]. In these articles, two different types of LFF for pipe flow were considered, namely flowmeters with a rotating and with a stationary magnet system. The analytical model of the LFF device based on a magnetic dipole model of the LFF magnet system has been presented along with the experimental results of the circular channel flow measurement with mentioned LFF devices at a low temperature. It is found both analytically and experimentally that for pipe flow the LFF device has a linear calibration curve (volumetric flow rate as a function of the Lorentz force). This is not the case for the open channel flow, as further investigations have shown [6]. In application, i.e. the production of secondary aluminum, characterized by open channel flow, the relation (1) does not hold explicitly while the electromagnetic interaction volume changes with flow velocity (due to the flow level variation).

If the primary magnetic field created by the LFF magnet system is significantly distorted by the magnetic field generated by the induced eddy currents in the fluid volume, then any change of the electrical conductivity of the moving medium causes changes in the primary magnetic field \( B \), which introduces additional nonlinearity in Eq. (1). The magnetic Reynolds number \( \text{Re}_M \) is a dimensionless parameter, which shows if such nonlinearity should be taken into account [7]. In our system, the magnetic Reynolds number is defined assuming the respective length scale \( L \) to be equal the flow level, and \( \text{Re}_M \) is found to be lower than unity.
Hence, changing the electrical conductivity of the moving medium, each point of the LFF calibration curve can be easily corrected by multiplying it with a ratio between the actual and the reference value of the electrical conductivity.

In the present paper we consider a method of calibration of the Lorentz force flowmeters. Hereby, we shall make use of the scaling law according to Eq. (1). The paper is organized as follows. In the next paragraph we present a detailed description of the LFF device and discuss in detail the consequences of the scaling equation (1). Moreover, we shall address some specific aspects of LFF calibration. In Section 3 we show results of the dry calibration procedure and combine these results with the liquid calibration data (liquid calibration involves liquid metal flow in a reference open channel). The key step of the LFF device calibration, a derivation of the liquid calibration curve for the test LFF device without an actual liquid calibration of it, is presented in Section 4. Finally, Section 5 provides the main conclusions, followed by acknowledgments and references.

2. Design of the Lorentz force flowmeter and the dry calibration equipment

The mechanical design of LFF for open channel flows in the secondary aluminum industry and the photograph of the device in application are shown in Fig. 1. The external static magnetic field is generated by two sets of the permanent magnets (pos. 1, 2), which are mounted on a steel yoke. The yoke is connected to a force sensor (pos. 4). This sensor is a beam-type load cell, which allows us to measure the integral load applied on the magnet system solely in the flow direction. The channel (pos. 3) carrying the melt flow is placed between the LFF magnets.

The magnet system consists of NeFeB magnet blocks with dimensions 100 mm × 20 mm × 20 mm, which are arranged to form a total pole area of 140 mm × 200 mm. The magnetic field is directed transversally as shown by vector \( \mathbf{B} \) in Fig. 1. The magnets are mounted on a steel yoke showing a \( \Pi \)-form that closes the outer magnetic circuit. The distance between the poles is 250 mm. The order of magnitude of the magnetic induction in the middle is \( B = 0.1 \) T.

The data processing system of LFF implies a force sensor conditioning circuit with an analog-to-digital converter and a USB 2.0 interface. The force data is transferred with prescribed sample rate to a standard PC. The data processing, including filtering, logging and measurement results calculation, is based on a LabView\textsuperscript{®} visual instrument. Additionally, the temperature at the magnet surface is measured with a Pt100-type sensor.

2.1. Specific problems of LFF calibration

The LFF devices discussed in this paper are intended to measure a flow rate in transport channels carrying liquid aluminum alloys. At the typical working temperature of 750–850 °C, aluminum melts are highly aggressive and it is impossible to use the conventional measurement techniques implying direct contact of the sensors with the liquid. Consequently, the range of possible techniques which could provide traceability during LFF calibration
reduces to the reference device–test device scheme. Moreover, in application there is no common standard for the design of the liquid metal transport channels. Hence, the particular channel geometry must be a part of the calibration scheme. On the other hand, calibration of the LFF device on an industrial channel may disturb the production process. It is also prohibitively expensive to construct and operate a calibration device for liquid aluminum at original scale in a laboratory. That is why the method of dry calibration can be beneficial. The idea of dry calibration of the electromagnetic flowmeter implies metrological investigation of the device without an actual liquid flow. Such techniques are known to be used for ultrasonic flowmeter implementation. The idea of dry calibration of the Lorentz force flowmeter implies metrological investigation of the device without an actual liquid flow during the calibration and the flow cross section is fixed. The reference bars are made of AlCuMgPb alloy (Material Nr. 3,1645). They are uncoated and have a surface roughness Ra about 2.5. The electrical conductivity of the bars (measured using Forster Signatrol® device at environmental temperature 18.5 ± 0.1 °C in a thermostatic room) is given in Table 1.

The LFF signal has shown no significant fluctuations which could point to internal inclusions or defects in the reference bar structure. Mechanical vibrations of the step motor are reduced to a very low value by mechanical uncoupling of LFF from the step motor mounting frame. Applying the signal filtering (the method of weighted moving average, which minimizes the information loss) allows us to make the parasitic vibrations’ influence negligible.

The location of the reference bar within the LFF magnet system is strictly defined because the calibration results are unique for every location (due to inhomogeneous spatial distribution of the magnetic field). In our experiments we fix the width of the reference bars at b = 0.1 m and vary the height.

The Lorentz force sensor generates a primary measurement signal (DC voltage) registered by the data acquisition system. Calibration of this sensor is carried out by applying the set of definite loads to the magnet system in the flow direction. The calibration characteristic of the sensor is linear. Consequently, the measured Lorentz force \( F \) can be represented by the linear function of the electrical output of the sensor:

\[
F = K_F \cdot E,
\]

where \( E \) is the instant level of the sensor signal and \( K_F \) is the calibration constant of the force sensor.

To investigate the method, we have carried out a series of experiments in which reference bars with various cross sections were moved through the magnet system with different velocities. Resulting LFF dry calibration characteristics are shown in Fig. 3. It can be seen from Fig. 3 that for a constant cross section of the reference bar the Lorentz force depends linearly on the reference bar velocity and volumetric flow rate. Eq. (1) is valid in this case. On the other hand, Lorentz force depends nonlinearly on the height of reference bars at a constant velocity. This behavior can be attributed to the variable electromagnetic interaction volume as well as to the inhomogeneity of the spatial distribution of the magnetic field in the magnet system of LFF.

The volumetric flow rate of the reference bar for a given cross section can be represented as a function of the measured Lorentz force on the basis of Eq. (1):

\[
\dot{V} = \frac{F}{\sigma \cdot B^2 \cdot L} = K_v \cdot F,
\]

Table 1

<table>
<thead>
<tr>
<th>Reference bar cross section width × height (mm)</th>
<th>Electrical conductivity of the alloy σ (Ω·m)</th>
<th>Electrical conductivity of the alloy ( B ) (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 × 100</td>
<td>21.43 ± 0.25</td>
<td>21.32 ± 0.25</td>
</tr>
<tr>
<td>100 × 50</td>
<td>22.25 ± 0.25</td>
<td>20.73 ± 0.25</td>
</tr>
<tr>
<td>100 × 25</td>
<td>20.73 ± 0.25</td>
<td>20.73 ± 0.25</td>
</tr>
</tbody>
</table>

2.2. Calibration equipment and LFF dry calibration diagram

The scheme of the dry calibration equipment for the Lorentz force flowmeter is shown in Fig. 2(a). The installation consists of the Lorentz force flowmeter in test (pos. 1) and a reference bar (pos. 2). The reference bar is moved through the magnet system of the LFF along the flow direction by a linear step motor (pos. 3). In comparison with the open channel conditions the velocity field of the flow is stationary and homogeneous; there are no velocity fluctuations due to turbulent fluid motion, and the flow cross section is fixed. The reference bars are made of AlCuMgPb alloy (Material Nr. 3,1645). They are uncoated and have a surface roughness Ra about 2.5. The electrical conductivity of the bars (measured using Forster Signatrol® device at environmental temperature 18.5 ± 0.1 °C in a thermostatic room) is given in Table 1.

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The volumetric flow rate of the reference bar for a given cross section can be represented as a function of the measured Lorentz force on the basis of Eq. (1):

\[
\dot{V} = \frac{F}{\sigma \cdot B^2 \cdot L} = K_v \cdot F,
\]
where $K_V$ is a calibration factor that incorporates the characteristic electromagnetic interaction length $L$, the effective magnetic induction $B$ and the electrical conductivity of the liquid alloy. In our dry calibration experiments the volumetric flow rate (m$^3$/s) varies from $10^{-4}$ to $6 \cdot 10^{-3}$.

Introduction of the calibration factor $K_V$ is necessary because variables $B^2$ and $L$ cannot be separated. According to Eq. (3), $K_V$ is defined by

$$K_V = \frac{\dot{V}}{F}.$$  
(4)

The main goal of this paper is to extend the analysis of the calibration factor to obtain a robust mathematical model of the LFF calibration.

3. Discussion of the calibration procedure

In this paragraph the transfer of the liquid calibration curve from the reference LFF device to the test LFF device using dry calibration data will be discussed in detail.

3.1. Liquid calibration curve of the reference LFF device

The LFF measurements in an open channel flow of aluminum alloy were discussed in [6]. In our current study the calibration curve of the LFF for open channel flow is based on Eq. (4). In [6] the relationship between the calibration factor $K_V$ and measured Lorentz force has been introduced and the liquid calibration curve of LFF was obtained (this curve is shown in Fig. 4). The analytical representation of this curve was obtained in the form

$$K_V(F) = A_1 - A_2 \ln(F),$$  
(5)

where $A_1$ and $A_2$ are model coefficients. In the open channel flow, the level $h$ correlates with the mean flow velocity $u$ and with the volumetric flow rate $\dot{V}$ [11]. Consequently, a direct relationship $K_V = K_V(\dot{V})$ exists, which can be well approximated using the following regression model:

$$K_V(\dot{V}) = B_1 \cdot \dot{V}^2 - B_2 \cdot \dot{V} + B_3,$$  
(6)

Here, $B_1$, $B_2$, and $B_3$ are regression coefficients. By this we extend the analysis given in [6]. In our case, Eq. (6) for the reference LFF device has the form $K_V(\dot{V}) = 18.154 \cdot \dot{V}^2 - 0.6552 \cdot \dot{V} + 0.0064$. By combining (5) and (6) we readily obtain:

$$\dot{V}(F) = \frac{B_2 - \sqrt{4 \cdot A_1 \cdot B_1 + B_2^2 - 4 \cdot B_1 \cdot B_3 - 4 \cdot A_2 \cdot B_1 \ln(F)}}{2 \cdot B_1}.$$  
(7)

Eq. (7) is a new suitable analytical form of the LFF calibration curve (see Fig. 5). It directly links the flow rate $\dot{V}$ with the measured Lorentz force in the open channel flow.

3.2. Adapting the liquid calibration data to the dry calibration data

To make the liquid calibration data comparable and combinable with the dry calibration data, we should account for the difference in electrical conductivities of the liquid and solid aluminum alloys $\sigma_L$ and $\sigma_S$. For that we introduce a reduced volumetric flow rate of liquid metal $\dot{V}_{L_k}$ defined as follows:

$$\dot{V}_{L_k} = \frac{\dot{V}_L}{\sigma_L}.$$  
(8)

The reduced liquid volumetric flow rate of liquid metal is adapted to the volumetric flow rate in the dry calibration experiments. As shown in Fig. 6, these parameters become comparable after this step.
It can be seen in Fig. 6 that each point of the LFF liquid calibration curve can only be crossed by one and only one dry calibration line. Consequently, each Lorentz force measured at a given volumetric flow rate in an open channel can be reproduced by one and only one combination of the solid bar height and velocity (if the width of the reference bars is fixed as in our case).

The main concept of the liquid calibration curve transfer is based on the following statements:

1. For a given volumetric flow rate the Lorentz force measured in an open channel flow can be obtained in a dry calibration experiment using one and only one combination of equivalent reference bar height \( h_{\text{REF}} \) and equivalent reference bar velocity \( V_{\text{REF}} \) (if the width of the reference bar as well as its material properties are fixed).

2. Two LFF devices of the same type register different Lorentz force values for the same reference bar heights and velocities due to differences in magnetic field distribution within their magnet systems. These differences can be evaluated using solely the dry calibration experiment. If the liquid calibration curve for one of the mentioned LFF devices (a reference LFF device) is known, then the results of this evaluation can be used to reconstruct the liquid calibration curve of the other LFF device (a test LFF device) without actual liquid calibration of it.

In the next paragraph we consider a practical implementation of these concepts on the basis of an exemplary calibration of two LFF devices.

### 4. Liquid calibration curve derivation for the test LFF device

The set of the dry calibration lines (Fig. 6) can be analytically represented by the slope as a function of the reference bar height. We propose following mathematical representation characterized by high regression accuracy:

\[
\tan \alpha = C_1 \cdot e^{-C_2 \cdot h},
\]

where \( \alpha \) is the slope angle and \( C_1, C_2 \) are model parameters. Considering the dry calibration data of the reference and the test LFF devices in our case, we obtain the following forms of Eq. (9):

\[
\tan_{\text{REF}} \alpha = 0.0041 \cdot e^{-24.359 \cdot h}; \quad \tan_{\text{TEST}} \alpha = 0.003998 \cdot e^{-25.01 \cdot h}.
\]

The graph of the relationship (9) for the reference LFF device is given in Fig. 7.

Note that the Eq. (9) is a complete dry calibration data for the LFF device. This data is known for both the reference and the test LFF devices. The relation (9) is unique for each exemplar of the device despite the identity of the reference bars and the dry calibration experiment conditions. This uniqueness can be used to reconstruct the liquid calibration curve of the test LFF device. Let us rearrange the Eq. (9) as follows:

\[
h_{\text{EQ}} = - \ln \left( \frac{\tan_{\text{REF}} \alpha}{C_1} \right) / C_2 = - \ln \left( \frac{F/\dot{V}}{C_1} \right) / C_2.
\]

Here the values \( F \) and \( \dot{V} \) are the coordinates of known data points of the liquid calibration curve of the reference LFF device (see Fig. 6). We define the equivalent height of the reference bar \( h_{\text{EQ}} \) which is needed in a dry calibration experiment to achieve the same Lorentz force as in an open channel flow. It is not necessary that we have the reference bar of this particular height as long as we work with analytical forms of the calibration data (like the calibration curve in Fig. 7). That is why the heights considered here are considered equivalent. Introducing the obtained equivalent heights into Eq. (9) for the test device yields the respective \( \tan_{\text{TEST}} \alpha \) calibration function for the test device. The Lorentz forces which are measured by the test LFF device with the equivalent reference bar heights are readily obtained using the following equation:

\[
F_{\text{TEST}} = \frac{\dot{V}}{\tan_{\text{TEST}} \alpha},
\]

which is valid by definition if one considers a slope of a dry calibration line going from the origin of the coordinate system through a single point with coordinates \( (F; \dot{V}) \), see Fig. 6 for clarity. Eq. (11) predicts measured Lorentz force in an open channel with liquid metal flow for the test LFF device. After this step a full set of the liquid calibration points \( (F_{\text{TEST}}; \dot{V}) \) for the test LFF device is derived. Hence, all the liquid calibration curves (like those shown in Figs. 4 and 5 for the reference LFF device) can be reconstructed also for the test LFF device using Eqs. (4)–(7). The resulting liquid calibration curve of the test LFF device is shown in Fig. 8. The initial liquid calibration curve of the reference LFF device is also plotted for comparison.

The estimation of the measurement uncertainty during calibration is based on document [12]. The partial uncertainties are calculated using the mean values and standard deviations of the respective input parameters. The sensitivity coefficients are calculated based on the equations presented in this paper. Extended...
measurement uncertainty is taken as a calculated resulting uncertainty times 2. Currently, in our experiments the accuracy of the LFF measurement equipment is between 3% and 10%, depending on the harshness of the industrial environment. The maximum realizable accuracy of this type of LFF measurement technique could be expected in the range between 0.5% and 2.5%. The accuracy of the dry calibration experiment can be increased by using the reference bars made of pure aluminum with the same electrical conductivity instead of aluminum alloy with increased probability of variation of this parameter like in our case. The accuracy can also be increased by introducing the real time electrical conductivity measurement technique. The electrical conductivity in liquid aluminum can be measured using the eddy current method. We are currently testing a working prototype of the device based on this principle. The flow level in an open channel can be measured using the optical distance sensor based on the triangulation technique. The real problem is a density measurement in liquid metals. This parameter is important for high accuracy measurements of the integral mass of the transported alloy.

5. Conclusions

Our primary task in this work was to generally introduce the method of the LFF device calibration. The procedure discussed above makes it possible to predict the open channel liquid calibration curve of the test LFF device using the dry calibration results and the calibration data of the reference LFF device. This demonstrates that the dry calibration technique is of great importance to the Lorentz force velocimetry.

The LFF device considered is also applicable besides to other liquid metals like cast iron or liquid steel, besides aluminum alloys. It is important to estimate the measurability of the Lorentz forces in advance, especially if the flowing medium has a relatively low electrical conductivity. The method yields higher uncertainties at lower volumetric flow rates as the electromagnetic interaction weakens. As for practical application, some problems could be met when choosing the installation site for the device. There are channels with liquid steel which are mounted directly in a floor. The channel materials should not be ferromagnetic. The cooling effort must be estimated when applying the device within an industrial process, because permanent magnets change the magnetization with temperature. Here, introducing a temperature correction can improve the measurement accuracy.

Measuring the density of liquid metal in-situ is an actual problem. Having it solved we could measure the integral mass of liquid metal with higher accuracy. This point should be considered in future works together with the electrical conductivity measurement and the temperature correction.

There are no other special limitations regarding the use of this type of LFF and this calibration technique which we could name for today.

Acknowledgements

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