LORENTZ FORCE FLOWMETER IN INDUSTRIAL APPLICATION

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Lorentz force velocimetry is an innovative technique for non-contact measurement of the flow rate and accumulated mass of moving conductive fluids like high-temperature liquid metal alloys. In this work we present the results of industrial tests of the Lorentz force flowmeter (LFF) at a secondary aluminum production plant. The measurements were carried out in an open channel, within which the primary melt is transported from the rotary furnace to the holding furnace. The uncertainty of measurement is obtained by comparing the measured accumulated mass with the results of preliminary weighting of the alloy components.

1. Introduction. In this paper, we consider a new technique of the flow measurement in high-temperature electrically conductive fluids like high-temperature liquid metal alloys during the open channel transportation. When a liquid, characterized by its electric conductivity σ, flows with a velocity $\mathbf{v}$ through an externally applied stationary magnetic field $\mathbf{B}$, eddy currents $\mathbf{j}$ are induced within the liquid. As the result of the interaction of these currents and the applied magnetic field, Lorentz forces are generated. The Lorentz forces tend to brake the flow. This well-known electromagnetic braking effect is described by the equations of magnetohydrodynamics (Ohm's law and Lorentz force equation):

$$\mathbf{j} = \sigma\left(\mathbf{E} + \mathbf{v}\times\mathbf{B}\right), \qquad \mathbf{f}_{\mathrm{L}} = \mathbf{j}\times\mathbf{B}, \tag{1}$$

where $\mathbf{E}$ is the electric field and $\mathbf{f}_{\mathrm{L}}$ is the Lorentz force density. The resulting Lorentz force can be obtained by integrating over the volume:

$$\mathbf{F}_{\mathrm{L}} = \int_V \mathbf{f}_{\mathrm{L}}\,\mathrm{d}V. \tag{2}$$

Combining equations (1) and (2), it is easy to show that the Lorentz force scales as

$$F_{\mathrm{L}} \sim \sigma B^2 \dot{V} L. \tag{3}$$

Here, B is a characteristic amplitude of the applied magnetic field, $\dot{V}$ is the volumetric flowrate subject to measurement, and L is a characteristic length scale, over which the magnetic field interacts with the fluid. The flowrate can be written as $\dot{V}=uS$, where u is the mean velocity and S is the cross-section. In turn, by the Newtons third law, the moving liquid exerts a counterforce of equal strength on the system that generates the magnetic field [1]. The method of the Lorentz force velocimetry is based on the measurement of this counterforce as, by equations, it is proportional to the flowrate of the liquid [2, 3]. During previous investigations [4] it has been proved that the magnetic field has a complicated spatial distribution within the volume of the electromagnetic interaction and calibration characteristic of LFF (for instance, the relationship between the measured Lorentz force and the

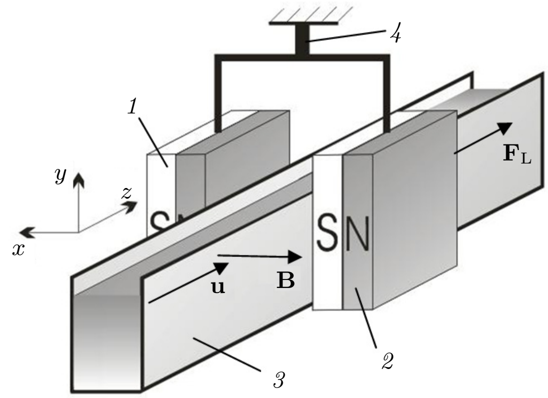

Fig. 1. Lorentz force flowmeter design. *1*, *2* – magnetic system; *3* – liquid metal flow (an open channel case is shown); *4* – force sensor.

mean flow velocity should be significantly non-linear). The goal of the current paper is a practical validation of the statements given in the previous works of the authors dedicated to this measurement technology. The results of the industrial application of the Lorentz force velocimetry in the secondary aluminum industry will be presented in this work.

2. Measurement technique and data processing. The design principle of the Lorentz force flowmeter is shown in Fig. 1. The external static magnetic field is generated by two sets of permanent magnets (pos. *1*, *2* in Fig. 1). The liquid metal flows within a channel (pos. 3) and interacts with the applied magnetic field. The channel with the liquid melt is situated within the magnetic system. The Lorentz force, acting on the magnetic system, is measured using a digital force sensor (pos. *4*). In our case, the magnetic Reynolds number is relatively small ($\mathrm{Rm} = 0,05\ldots0,5$). Physically, this implies that the primary magnetic field is not distorted by the flow, i.e., the secondary magnetic field generated by the eddy currents is small if compared to the primary magnetic field. Hence, the force sensor signal is proportional to the component of the mean velocity in the direction of the liquid melt flow [1]. The signal of the Lorentz force sensor represents the primary measurement data array. Further data processing implies the following steps.

2.1. Filtering of the data array. The filtering is done in several steps using the combined method of moving average. The procedure can be described by the equation

$$y_i = \frac{W_{i_0-n}x_{i_0-n} + W_{i_0-n+1}x_{i_0-n+1} + ... + W_{i_0+n-1}x_{i_0+n-1} + W_{i_0+n}x_{i_0+n}}{\sum\limits_{j=i_0-n}^{i_0+n} W_i},$$

where y_i is the i-th element of the filtered array; x_i is the i-th element of the initial array (the Lorentz force signal level); W_i denotes weight coefficients. The relationship is applied multiple times with subsequent reduction of the data array. The filtering effect on the data is shown in Fig. 2.

2.2. Evaluation of the Lorentz force data array $\{F_n\}$. The Lorentz force is evaluated using the following calibration equation

$$F_i = K_1 \cdot (U_i + U_0),$$

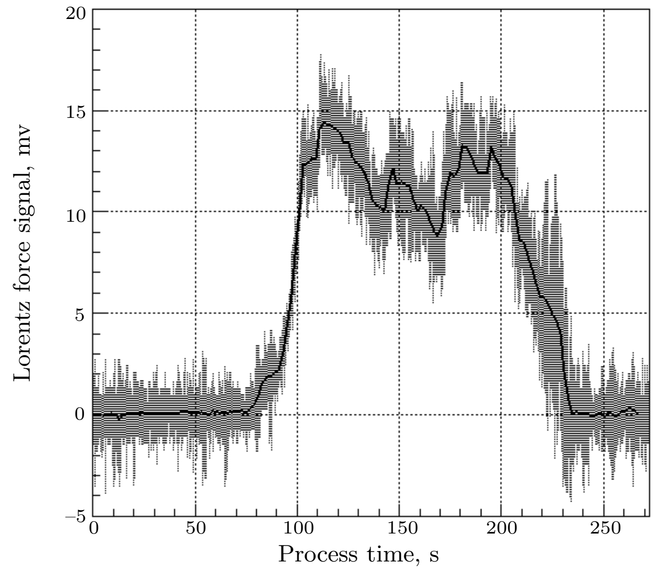

Fig. 2. Example of filtering results for the Lorentz force sensor signal.

where K_1 is the LFF force calibration constant, U_i is an instant level of the sensor signal, U_0 denotes offset of the sensor signal corresponding to zero flowrate.

2.3. Evaluation of the flow velocity $\{v_n\}$. The velocity of the flow is given as follows:

$$v_i = \frac{K_2 F_i}{\sigma B^2} = \frac{K_v F_i}{\sigma}, \tag{4}$$

where K_2 is the velocity coefficient, σ is the electric conductivity of the fluid metal, B is the mean induction of the magnetic field, K_v is the effective velocity coefficient incorporating non-separable variables K_2 and B, which correlates nonlinearly with the Lorentz force.

2.4. Correction of the electric conductivity value at a given temperature. Electric conductivity influences the measured value as a divider in equation (4). As given in [5], the electric conductivity of liquid metals decreases linearly with the increasing temperature, i.e.,

$$\sigma = \frac{1}{\alpha T + \beta},$$

where α and β are the temperature coefficients of the electric resistivity for a liquid metal, T is the temperature of the liquid metal. For instance, nominal values for α and β for liquid aluminium [5] are

$$\alpha = 0,0145\,\mu\Omega \cdot \text{cm} \cdot \text{K}^{-1}; \quad \beta = 10,7\,\mu\Omega \cdot \text{cm}.$$

2.5. Evaluation of the magnetic field reduction due to the evaluated temperature of the magnets. The magnetic field change ΔB due to the magnet temperature change ΔT is

$$\Delta B = \gamma \Delta T.$$

where γ is the temperature coefficient, a typical value in our experiments was −0.16 mT/K. ΔB can be used for correction of the results of LFF measurement if an increased temperature of the magnets is registered.

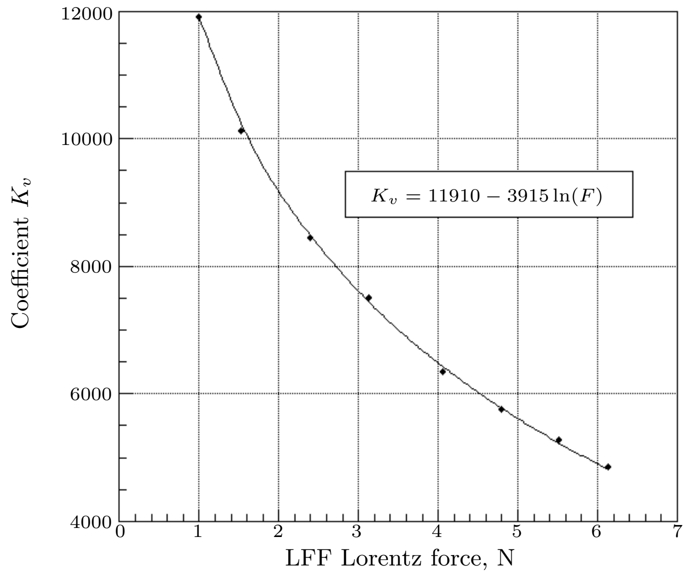

Fig. 3. Calibration characteristic of the LFF obtained during the procedure of liquid calibration of LFF in a reference channel.

2.6. Evaluation of the velocity coefficient K_v. We have found that a non-linear correlation exists between the velocity coefficient K_v from equation (4) and the measured Lorentz force. This finding can be expressed as

$$K_v = X_1 + X_2 \ln(F_i). \tag{5}$$

The calibration characteristic of the LFF used in the experiments is shown in Fig. 3. The parameters of the correlation function are evaluated during the LFF calibration procedure. The dry calibration technique for LFF is discussed in detail in [4]. The liquid calibration of LFF will be discussed elsewhere.

The non-linear character of relationship (5) can be explained as follows. Equation (3) is valid as it is for the case of homogeneous velocity field at a given cross-section of the flow. This situation is realizable in case of the motion of a solid metal bar with a given constant cross-section with different velocities through the magnetic system [4].

On the other hand, in the open channel for each mean velocity of the liquid metal flow we have a different flow cross-section and, therefore, a different volume of the electromagnetic interaction. Moreover, for each mean velocity of the flow we have a different velocity profile as the Reynolds numbers change. This means that in the open channel the velocity coefficient K_v in equation (3) is not a constant any more. Particularly for low Lorentz forces, the velocity coefficient K_v should be much higher for expression (3) to yield a real velocity of the flow. As a secondary effect, the sensitivity threshold at very low flow velocities is expectable when no Lorentz force signal is registered by a given LFF system. The volume of the electromagnetic interaction as well as the mean velocity would be too small in this case.

Having the value of the velocity coefficient K_v, it is possible to evaluate the mean flow velocity from equation (4) as well as the volume flowrate and the integrated mass of the liquid metal.

3. Experimental results. Industrial tests of LFF equipment presented in this paper were carried out at a secondary aluminum plant, where the primary

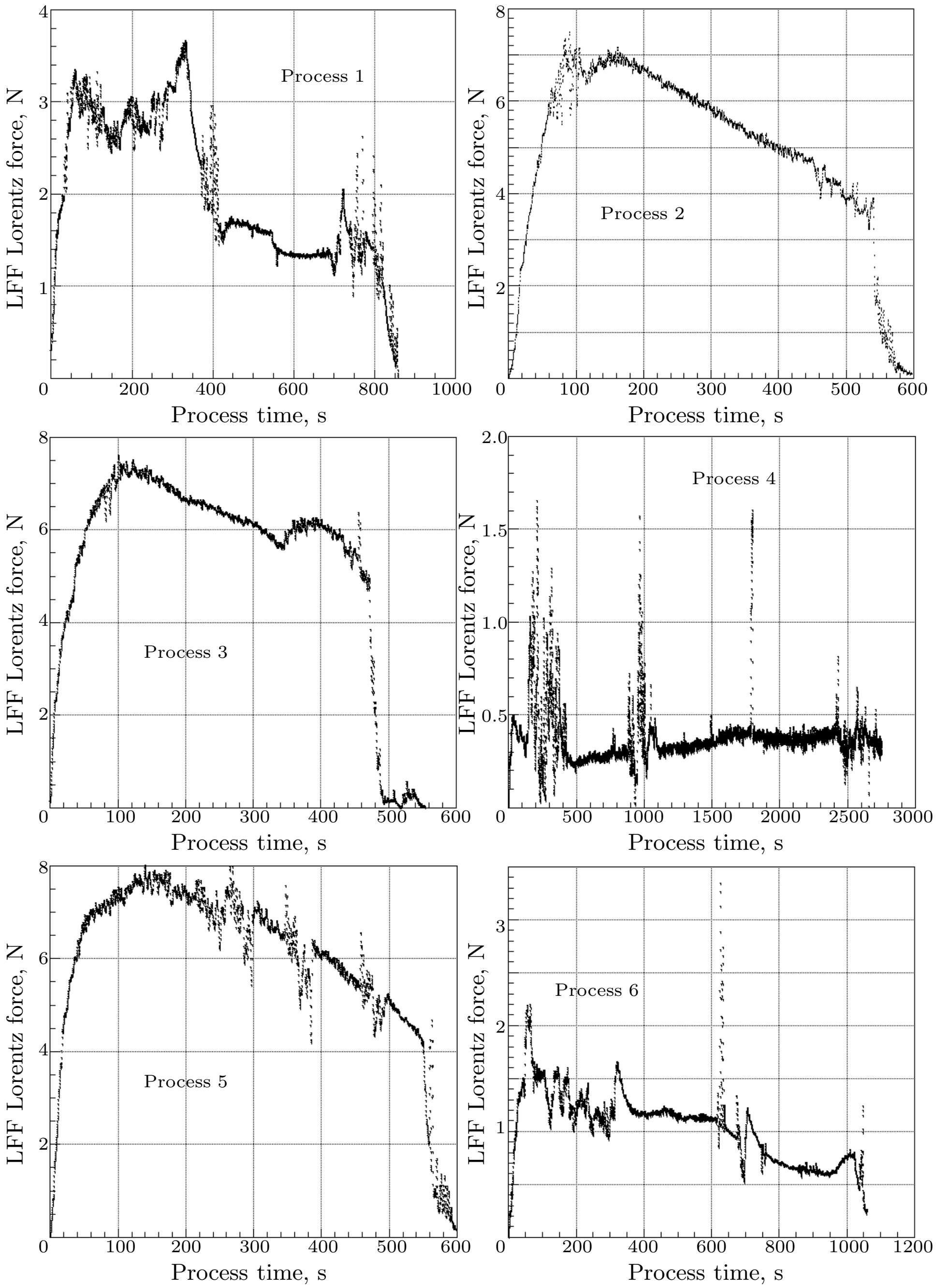

Fig. 4. Time diagrams of processes No. 1–6 of the open channel transportation of liquid aluminum alloys. The form of the curves illustrates complicated appearances in the open channel, like channel waves (especially, process 4), or time irregularity of the furnace discharge (for instance, in process 1 two significantly different flowrates appeared in consecutive order).

aluminum melt flows in an open channel from the rotary furnace into a holding furnace. The LFF measurement data were registered during the channel transportation of the liquid aluminum alloy. The time diagrams of the selected processes

Table 1. Key parameters of the selected processes.

Process No.	Duration, s	Estimated mass, kg	Si, %	Cu, %
1	873	12725	10,17	2,31
2	600	13122	8,25	2,67
3	559	12640	8,69	3,14
4	2756	12593	8,56	2,87
5	600	13317	7,86	0,28
6	1064	10449	8,19	2,22

Table 2. Results of measurement of the accumulated mass.

Process No.	Estimated mass, kg	Estimation uncertainty, %	LFF measured mass, kg	Deviation, %
1	12725	0,4	12643	-0,6
2	13122	1,8	13155	0,3
3	12640	2,6	12504	-1,1
4	12593	2,6	12745	1,2
5	13317	2,5	13838	3,9
6	10449	3,8	10238	-2,0

are presented in Fig. 4. The key parameters of the processes are given in Table 1. The estimated mass of the transported alloy was evaluated using the method of preliminary weighting of the alloy components.

The results of measurement of the accumulated mass are presented in Table 2. It can be seen that the difference between the accumulated mass measured using the LFF and the estimated mass is almost always less than the uncertainty of the estimation itself. This result positively characterizes the method of measurement.

4. Conclusions. The non-linear correlation (5) between the velocity coefficient K_v and the measured Lorentz force can be successfully used as a basis for the method of calibration and interpretation of the measurement data obtained using the LFF in the open channel flow. Any calibration characteristic is valid for the particular case of LFF installation in a given channel only.

Industrial application has shown that the Lorentz force flowmeter can provide valuable measurement data despite the severe industrial conditions.

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