Application of Lorentz Force Velocimetry to Open Channel Flow

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**Abstract:** Lorentz Force Velocimetry (LFV) is a noncontact method for flow measurement in electrically conducting fluid, especially in high temperature, opaque and aggressive molten metal. The principle is based on exposing the flow to a magnetic system and measuring the drag force acting upon it [1]. The aim of present paper is to study the application of LFV for open channel liquid metal flows, to numerically obtain the relationship between the measured Lorentz force and the flow rate. This provides the calibrating criterion of LFV. To this end, we firstly investigate a metal bar with different cross-section shapes passing through the magnetic system; Secondly, we study the relationship by a multiphysics numerical model fully coupling Navier-Stokes equations and Maxwell equations.

**Introduction**

In metallurgy industry, there are a number of valuable interests to quantitatively measure or control flow rates in open channel flows, i.e. the process of ladle pouring, melt transport, and die casting. The hot, aggressive melt with a free surface makes the measurement more difficult.

LFV is a noncontact velocity measurement technique. When an electrically conducting fluid moves across magnetic field lines, which are either produced by a current-carrying coil or by a permanent magnet, the induced eddy currents lead to a Lorentz force which brakes the flow. The Lorentz force density is roughly:

\[ f \sim \sigma v B \]  

where \( \sigma \) is the electrical conductivity of the fluid, \( v \) its velocity and \( B \) the magnitude of the magnetic field. By virtue of Newton's law, an opposite force acts upon the magnet-field-generating system and drags it along the flow direction [1,2]. A LFV is a technique which determines the flow rate from a measurement of this force. In this regard, the work has been reported on the study of dry calibration [3,4], laboratory and plant tests [5,6]. An open channel flow yields to a complex velocity distribution due to its free surface where there is no wall stress constraint. The present paper is devoted to characterize this flow measurement via the LFV technique.

**Problem at hand and numerical model**

In practice, the flow can be distinguished to pipe flow and open channel flow. Fig. 1 illustrates the velocity distribution of a pipe flow and an open-channel flow (resp. in Fig. 1(a) and Fig. 1(b)). Note that here we show the flow that are not fully developed. The former has bounded, non-slip walls, the latter has one free surface exploiting to the air besides other non-slip walls. Further, it has a complex velocity distribution in the core flow.
Fig. 1 Sketch of velocity distribution of (a) duct flow and (b) open-channel flow with constant initial velocity. 1. inlet velocity; 2. no-slip walls; 3. free surface; 4. core flow.

Fig. 2 shows an exemplary configuration using LFV to measure flow rate for open channel flow. The velocimeter is installed underneath the channel where the molten aluminum passes by. The system mainly consists of two permanent magnets, a soft-iron yoke using to concentrate the magnetic lines path, a refractory channel, molten aluminum, and a force sensor mounted on the back of the magnet-field-generating system (not shown in Fig. 2).

A multiphysics numerical model is built to compute the Lorentz force acting upon the magnet-field-generating system. The numerical model is based on the Reynolds-Averaged Navier-Stokes (RANS) method. The problem is solved by fully coupling Navier-Stokes equations and magnetic induce equations,

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u = -\nabla p + \nu \nabla^2 u + \frac{1}{\mu_0 \rho} (\nabla \times B) \times B, \quad \nabla \cdot u = 0,$$

$$\frac{\partial B}{\partial t} + (u \cdot \nabla)B = (B \cdot \nabla)u + \frac{1}{\mu_0 \sigma} \nabla^2 B \quad (2)$$

where $u$ is velocity field, $t$ time, $p$ its pressure, $\nu$ kinematic viscosity, $\mu_0$ magnetic permeability, $\rho$ density, $B$ magnetic field strength, $\sigma$ electric conductivity. The $k$-$\varepsilon$ turbulent model is used and the logarithmic wall function is applied to the no-slip walls. The free surface is set as the open boundary condition and its deformation is neglected.

We focus on the introduction of the calibrating criterion of LFV applying to the open channel flows with this numerical method. Alternatively, the distribution of the eddy current, the force density induced by the interaction of the flow and the magnetic field, and the velocity field influenced by the magnetic obstacle are not presented in this paper.

**Results**

In order to investigate the main features of LFV technique and neglect the detail of flow, we firstly report the results of an electrically conducting solid metal bar passing through a permanent magnetic field with a certain velocity, the so-called dry calibration [3,4].

The measured force depends on both the velocity distribution and the spatial distribution of the magnetic field [1]. Here we only study the influence of the velocity distribution on the open channel flow. The channel shapes vary case to case in different metallurgical performances or processes. In
order to detect the influence of channel shapes, three kinds of cross-section shapes: rectangular, trapezoid and round are selected. Note that the volume flux in dry calibration and the flow rate in open channel flow are broadly called flow rate throughout this paper for simplification. Fig. 3 shows that the Lorentz force acting upon the magnetic system vs. the flow rate for three different cross-section shapes of aluminium bars. These aluminium bars have the same baseline. The maximum cross-section areas were set to be always the same (100 cm²), independently of the geometry. As the heights increase for these three shapes, the flow rates increase correspondingly, but the increasing ratios are evidently not the same. That is, for a given flow rate, different heights correspond to different cross-section shapes. Fig. 3 shows that the curves of the measured Lorentz force vs. the flow rate for three different cross-section shapes are quite different. This can be relative to the inhomogeneity of the magnetic field. The curve representing rectangular cross-section is particularly different from the other two. It reveals that even with the same magnetic system, one need to calibrate LFV for the channels with different cross-section shapes before application.

Let us focus on the situation of a metal bar with the rectangular cross-section. It shows that the measured Lorentz force linearly increases with the moving speed, and non-linearly increases with the height of metal bar [3]. In order to combine the contribution of these two parameters, a scaling law is obtained,

\[ F \propto Q \cdot \left( \frac{h}{W} \right)^2 \]  

(3)

where \( Q \) is the flow rate, \( h \) the height of solid metal conductor, and \( W \) the width that we fix to 10 cm. This formula is well fitted for both experimental and numerical results in the present conditions as seen in Fig. 4. However, this scaling law still remains without a clear physical meaning, and needs to be further addressed. Hence in the following a numerical model accounting for velocity distribution of open channel flow is clearly necessary.

With this numerical model, we compute the cases of solid metal conductor, duct flow and open channel flow respectively with the same cross-section shape \( H \times W = 8 \text{ cm} \times 10 \text{ cm} \). We can draw a number of useful conclusions from Fig. 5. First, in case of solid metal bar, the numerical result (triangle symbols) is well in agreement with the experiment results (round symbols). It indicates...
that this numerical model is a reliable tool for LFV studies. This result shows that the Lorentz force linearly varies with the flow rate in case of the solid metal bar; Second, the relationship between the Lorentz force and the flow rate for the duct flow case (diamond symbols) yields the similar linear relationship as that of the solid case, but the Lorentz force becomes slightly small. It results from both the influence of turbulent fluctuation and the interaction of magnetic field and velocity field (depending on the interaction number: $N = \frac{\partial B}{\partial \rho_i} L$ which represents the ratio of magnetic force and inertial force, here $L$ is the typical length, $\mu_0$ is typical velocity of flow); Third, in the open channel flow case, a dash line is drawn to be parallel with the lines mentioned in the first and second points, with the help of this line, one can find that the relationship between the Lorentz force and the flow rate (rectangular symbols) does not keep linearly. Comparing with that of duct flow, the measured Lorentz force significantly decreases probably resulting from the presence of the free surface.

![Graph showing Lorentz force vs. flow rate for different cases](image)

Fig. 5 Comparison of Lorentz force vs. flow rate for a liquid aluminium open channel flow, duct flow and dry calibration of solid aluminium bar using LFV technique. $H \times W = 8 \text{cm} \times 10 \text{cm}$.

**Summary**

We present some main features of the application of LFV to the flow rate measurement for open channel flows by a multiphysics numerical model. This numerical model has the ability to compute the calibrating factors (or curves) for arbitrary cross-section shapes of open channel flows. Further work may involve the transient simulation relative to free surface deformation, magnetic field optimization and characteristics of the realistic flow in an open channel.

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**References**