A RANS NUMERICAL MODEL FOR CALIBRATION OF LORENTZ FORECE FLOWMETER APPLYING TO METALLUGY INDUSTRY

Xiaodong Wang[*a)], Yurii Kolesnikov[**], Rico Klein[**], Christian Karcher[**] & Andre Thess[**]
[*]*College of Materials Science and Opto-Electronic Technology, Graduate University of Chinese Academy of Sciences, Beijing,100049, China*
[**]*Institute of Thermodynamics and Fluid Mechanics, Ilmenau University of Technology, P.O. Box 100565, Ilmenau, 98684, Germany*

In metallurgy industry, there exist a number of valuable interests to quantitatively measure or control flowrates of melt, i.e. the process of ladle pouring, melt transport, and die casting. Particularly, exist of free surface and feathers of hot, aggressive melt often make measurement more difficult. In view of the harsh working conditions it is desirable that the flowmeters developed for these applications be contactless, robust and reliable. Lorentz force flowmeter - LFF (also termed as Lorentz force velocimetry - LFV) can meet these requirements.

As the elaboration in the ref. [1, 2] and as seen in Fig.1, when an electorally conducting fluid moves across magnetic field lines with velocity $\boldsymbol{u}$, a magnet-field-generating system here denoted by a magnetic dipole (magnetic moment $\boldsymbol{m}$) which can be either a current-carrying coil or a permanent magnet, the induced eddy currents ($\boldsymbol{J}$) lead to a Lorentz force ($\boldsymbol{F_L}=\boldsymbol{J}\times\boldsymbol{B}$) which break the flow. By virtue of Newton's law, an opposite force (($\boldsymbol{F_M}= -\boldsymbol{F_L}$) acts upon the magnet system and drags it along the streamwise, a Lorentz force flowmeter is a device which determines the flowrate from a measurement of this force. Clearly, LFF is a noncontact velocity measurement device.

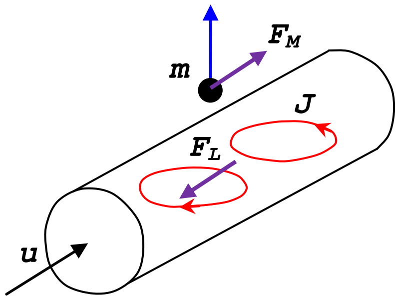

Fig.1 Principle schematic of Lorentz force flowmeter.

A RANS MULTIPHYSICS MODEL

As the other type of flowmeters, a key to successful application of LFF is calibration – the accurate determination of the relation between the measured force acting upon the magnet system and the desired mass flow rate. The relationship between measured force F_m and the unknown mass flow rate $\dot{m}$ can be expressed in a scaling law as:

$$F_M = cd\Sigma B_0^2\dot{m} \tag{1}$$

where $\Sigma=\sigma/\rho$ [$\mathrm{S\cdot m^2/kg}$] is the specific electrical conductivity, σ [S/m] the electrical conductivity, ρ [$\mathrm{kg/m^3}$] the density of liquid metal; d [m] the typical length scale of the flow, B_0 [T] a characteristic value of the magnetic field strength, and $c(Re, Ha)$ a dimensionless calibration function whose determination is the central focus of the present paper, Re is Reynolds number, Ha is Hartmann number. For that purpose, a multiphysics numerical model is built to compute the Lorentz force acting upon the magnet 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,

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

where $\boldsymbol{u}$ is velocity field, t time, p its pressure, ν kinematic viscosity, μ_0 magnetic permeability, $\boldsymbol{B}$ magnetic field strength. The k-ε turbulent model is used and the logarithmic wall function is applied to the no-slip walls.

In practice, duct flow and open-channel flow are the two most common flow types of applying LFF to measure liquid metal flowratey. For duct flow, one can solve full MHD Eqs.(2) directly to obtain the calibrating function. For open-channel flow, accounting for free-surface effect, phase field of multiphase model is adopted, the air above the surface is set as the first phase, and the liquid metal is considered as the second one, $\boldsymbol{u}$ in Eqs.(2) is taken as the average fluid velocity, the equations governing the interface dynamics of a two-phase flow can be described by the Cahn-Hilliard equation:

$$\frac{\partial\boldsymbol{\phi}}{\partial t} + \boldsymbol{u}\cdot\boldsymbol{\nabla\phi} = \boldsymbol{\nabla}\cdot\frac{\gamma\lambda}{\varepsilon_i^2}\boldsymbol{\nabla\phi} \tag{3}$$

where ϕ is the dimensionless phase field variable; λ the mixing energy density, ε_i is a capilary width, λ and ε_i are related to the surface tension coefficient via $2\sqrt{2}\lambda/3\varepsilon_i$. The k-ε closure model is used for simulate the turbulence flow.

APPLYING TO DUCT FLOW AND OPEN-CHANNEL FLOW

Being as an example of application of duct flow, we study a jet molten metal flow of GaInSn eutectic alloy passing through a nozzle with a conical shape. The flowmeter consists of a Halbach array which is assembled using eight

a) Corresponding author. Email: xiaodong.wang@gucas.ac.cn.

segments of NdFeB permanent magnets with special orientation of magnetization as shown in the inset of Fig.2. Such combination of the magnetizations provides inside the pipe the distributions of magnetic field homogeneous in the horizontal plane and non-homogeneous along vertical coordinate. B_0 = 0.26T, $d = 5$mm, $Ha = 46.9$, Re range around the order of 10^4, the other parameters can be seen in the ref. [3]. Our simulations involve both magnetostatic computations of a complex-shaped magnet system and magnetohydro-dynamic computations of the flow of a liquid metal in a nozzle under the influence of a predominantly transverse magnetic field.
The magnetic field, eddy current, and force density are computed but shown here [3]. Fig.2 shows that both the experimental and numerical data of Lorentz force are linear in dependence on flowrate. A notable result is that they coincide with an accuracy of 3.4%, which indicates a possibility of numerical turbulent model application as a tool for preliminarily calibration of a LFF manufactured for industry.
We study molten aluminum transport in an open-channel whoes flowrate being measured by a LFF as shown in Fig.3. The flowmeter is installed underneath the channel where the molten aluminum passes by. The magnetic field is exerted by a pair of face-to-face cubic permanent magnets. Note that the present numerical model can be adapted to any random cross-section shape of the channel, thus the change of flowrate as well as the variation of hight and surface area of the open-channel can be computed by this model. In the present exmaple, $B_0 = 0.0062$T, typical length = 35mm, Ha = 8.8, the order of Re is around 10^4.
The model has ability of computing not only the magnetic field, the eddy current, the force density, but also the velocity profile and the evolution of free surface deformation. We do not introduce here for the limit of the scope. Fig.3 shows the force varying with the flowrate which appear non-linear relationship. The reason of this non-linearity comes from two aspects: the declining walls of the channel reveals that the flowrate increase faster than the incrase rate of the hight; the magnetic field is highly non-homogenous due to the relative long distance between the two magnets. The former one comes from the measured flow and the later one comes from the configuration of LFF itself, these can be referrenced to the LFF design.
Once we determine the relationship of the Lorentz force and the flowrate for duct flow or for open-channel flow as seen in Fig.2 and 3, the calibration function can be immidiately determined according to Eq.(1), application of LFF to measure liquid metal flowrate becomes explicit, reliable and robust.

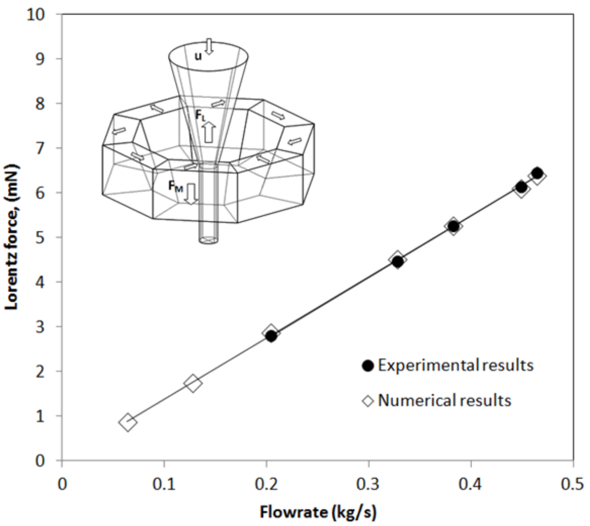

Fig.2 Numerical calibration for a duct flow, inset shows a LFF sketch of an octagonal Halbach-array magnet system in which magnetization directions are different as indicated by arrows. The inner surface of magnet segments is inclined under the same angle as the angle of conic part of the nozzle.

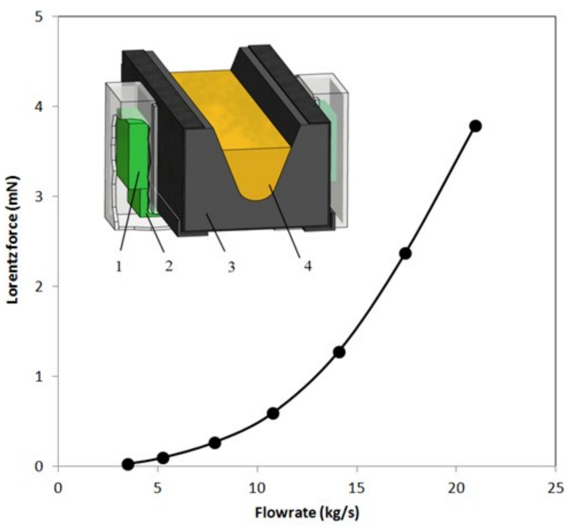

Fig.3 Numerical calibration for an open-channel flow. Inset shows an exemplary configuration of LFF to measure flowrate. The system mainly consists of 1-two permanent magnets, 2-soft-iron yoke, 3-refractory channel, 4-molten aluminum, and a force sensor mounted on the back of the magnet system.

SUMMARY

We present a RANS numerical model for calibrating LFF. Two common metallurgy industry flow types: duct flow and open-channel flow have been studied with this model. For duct flow, the computing calibration constant demonstrates coincide with accuracy of 3.4% with an experimental model. For open-channel flow, a multiphase model is built to take free surface into account. The free surface deformation, magnetic field optimization and characteristics of the realistic flow in an open channel can be simulated by this numerical model.

References

[1] Thess A., Votyakov E., Kolesnikov Y.: Lorentz force velocimetry. *Phys. Rev. Lett.* **96**, 164501, 2006.
[2] Thess A., Votyakov E., Knaepen B., Zikanov O.: Theory of the Lorentz force flowmeter. *New J. Phys.* **299**, 1-27, 2007.
[3] Wang X.D., Kolesnikov Y., Thess A.: Numerical calibration of Lorentz force flowmeter. *Meas. Sci. Tech.* (accepted).