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Investigations of electrically driven liquid metal flows using an ultrasound Doppler flow mapping system

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ABSTRACT

This paper presents a combined experimental and numerical study of the properties of a liquid metal flow inside a cylinder driven by the application of a strong electrical current. The interaction between the electric current running through the melt and the corresponding induced magnetic field produces so-called electro-vortex flows. We consider here a configuration of two parallel pencil electrodes immersed at the free surface. Velocity measurements were performed by means of the Ultrasound Doppler method. A linear array of 25 singular transducers was used to determine the two-dimensional pattern of the vertical flow component. Numerical simulations of the magnetohydrodynamic (MHD) problem were conducted to calculate the Lorentz force, the Joule heating and the induced melt flow. Experimental and numerical results reveal a complex three-dimensional flow structure of the liquid metal flow. In particular, two pronounced downward jets are formed below both electrodes. The flow structure appears to be symmetrical with respect to two vertical cross sections being perpendicular to each other and one of the two planes contains the electrodes. The comparison between the experimental data and the numerical results shows a very good agreement.

1. Introduction

Liquid metal technologies gain in importance for the metal industry, for example, the production of cast parts, the continuous casting of steel and the crystal growth at the semiconductor industry. As well the role of liquid metal technologies grows steadily for the branch of energy industry. Present and future examples may be found at the nuclear power industry, more precisely at fast breeder power plants and fusion reactors. However, also renewable energies may benefit from liquid metal technologies, for example with respect to the application of liquid metal coolants at concentrated solar power plants. Applications in the energy sector typically utilize liquid metals as coolant, however, future prospects consider liquid metals also for energy storage systems.

Safe and reliable operation of such liquid metal systems, optimization of industrial processes and the guarantee for best product quality require a comprehensive knowledge of fluid flow phenomena and related transport processes. Numerical simulations could provide a better understanding of complex flow behavior, but, experimental data are indispensable with respect to a validation of the respective CFD codes. The determination of flow quantities in liquid metals is considerably impeded by the special material properties. Powerful optical methods as used for measurements in transparent liquids are obviously not applicable in molten metals.

For the last two decades the ultrasound Doppler method became a very powerful tool to investigate the velocity structure in liquid metal flows as reported for various metallic fluids [1–3]. Originating from the medical branch the pulse-wave ultrasound Doppler method has been established for fluid flow measurements in physics and engineering by the pioneering work of Takeda [4].

The measuring principle is based on the pulsed echo technique. Ultrasonic pulses of a few cycles emitted from an acoustic transducer propagate into the fluid along a measuring line which is identical to the continuation of the transducer axis. A part of the ultrasonic pulse energy is scattered by microparticles suspended in the liquid. Their echo signal is received by the same transducer within the time period between two emissions. A short sequence of such echo signals contains the entire information of the velocity profile along the ultrasonic beam. Knowing the sound velocity of the liquid, the axial position of the scattering particles along the measuring line is determined from the measured time span between the burst emission and the reception of the respective echo signals. The movement of the scattering particles inside the measuring volume between two consecutive bursts will result in a small time shift of the echo signal. A correlation analysis between the echo signals of consecutive bursts reveals the flow velocity

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profile for all positions along the measuring line. Owing to the Nyquist theorem, the product of measurable maximum velocity and penetration depth is limited by the sound velocity and the ultrasonic frequency. Ultrasonic methods are non-invasive, but not contactless since a continuous acoustic path from the ultrasonic transducer to the fluid under investigation is required. For a more detailed description of the basics of the measuring principle the reader is referred to Takeda [5].

The standard ultrasound Doppler systems measure linear velocity profiles, however, the enhancement of the capabilities towards a multidimensional flow mapping with high frame acquisition rates and spatial resolutions would be exceedingly desirable for examinations of highly turbulent, three-dimensional flows such as occurring during electromagnetic stirring of metals. Detailed investigations of such kind of complex flows and a validation of respective numerical simulations require a multidimensional acquisition of the flow field with a reasonable temporal and spatial resolution. Imaging techniques becomes more and more important for detailed explorations of three-dimensional turbulent flows, in particular with respect to the generation of a suitable experimental data base for an efficient validation of respective numerical simulations. First approaches of a flow mapping with a multiline ultrasound Doppler system were performed by Takeda [6] who measured the mercury flow in a liquid metal target of a spallation neutron source. Mapping rates about 2 Hz were realized while applying up to 12 measuring lines. More recently, measurements of a submerged liquid metal jet have been reported by Timmel et al [7]. A horizontal adjustment of 10 transducers provided a two-dimensional visualization of the horizontal velocity component utilizing a 10-channel commercial ultrasonic Doppler device. However, the use of a finite number of singular sensors by sequential sampling restricts the spatial and temporal resolution of the measurements. New measuring systems are under development using specific combinations of linear sensor arrays and have recently been demonstrated in liquid metal flows driven by a rotating magnetic field [8].

In the present paper we demonstrate the capabilities of an array measuring system using the example of a liquid metal flow driven by a strong electric current. The application of electric currents during the solidification of metal alloys was found to be beneficial for achieving superior mechanical properties of the solidified material. The improvement of the product quality is obtained by a distinct grain refinement [9,10]. However, the physical mechanism of the grain refinement has not been understood so far. Various effects are under discussion, such as the fragmentation of dendrites induced by the electric current [11], the reduction of the nucleation activation energy [12], or the break out and the transport of little grains from the boundary by the periodic Lorentz force [13]. Most of the previous studies did not consider the possibility that significant melt flows can be created by an intense Lorentz forces which results from the interaction between the strong electrical current and the self-induced magnetic field. The effect of such kind of electro-vortex flows on the solidification of Al–Si alloys was investigated by a recent study [14].

This paper presents an extension of this experimental and numerical study focusing on the characteristics of the forced melt flow induced by the strong electric currents in an isothermal melt without solidification. A set of experiments was conducted using the eutectic alloy GaInSn at room temperature to obtain quantitative information about the isothermal flow field. The mean flow structure as well as the time-varying flow field are measured and compared to predictions obtained by corresponding numerical simulations.

The paper is structured as follows: The flow problem under consideration and respective numerical simulations are briefly described in the following section. A description of the experimental setup and the measuring system is given in Section 3. Section 4 contains the presentation and discussion of the measuring results. Some experimental findings are compared with corresponding numerical predictions. The concluding remarks can be found in Section 5.

2. Formulation of the problem and numerical scheme

We consider a finite cylinder with radius R_0 and height H_0 filled with a liquid metal. Two parallel pencil electrodes with electrically insulated lateral surfaces are immersed into the melt through the free surface and arranged symmetrically with respect to the cylinder axis. The application of an electric potential between the electrodes produces an electric current which closes through the liquid metal between the electrodes. Any electric current through an incompressible, viscous and electrically conducting liquid is accompanied by corresponding magnetic field. In general, the interaction between the applied electric current and the induced magnetic field creates a Lorentz force $\boldsymbol{J} \times \boldsymbol{B}$ which may drive a fluid motion. The simplest configuration of a homogeneous current distribution through a cylindrical column becomes unstable when the axial current exceeds a critical value being specific for a given fluid and geometry. Recently, this phenomenon known as Tayler instability [15] was experimentally observed and numerically analyzed [16,17]. The experimental assembly of two pencil electrodes as considered within this study implies a non-homogeneous distribution of the electric current (see Fig. 1(a)). Such a configuration shows a significant rotational component of the Lorentz force and does not feature a threshold value of applied current which has to be exceeded before a flow sets in. Convection starts as early as a weak electric current is flowing through the liquid metal.

Numerical computations have been performed to calculate the actual distributions of electric current and magnetic field as well as the resulting Lorentz force. Furthermore, these simulations provide predictions of the flow field in the liquid metal column.

The finite element code *OPERA* (*Cobham plc.*) was used to compute the electric current $\boldsymbol{J}$ and the magnetic induction $\boldsymbol{B}$ distributions in the melt and all electrically conducting parts of the facility including the immersed electrodes. In case of a direct current imposed on the electrodes we solve the Laplace equation for the electric potential $\nabla^2\varphi = 0$ taking into account the charge conservation $\nabla\cdot\boldsymbol{J} = 0$ and the continuity of the current density $\boldsymbol{J}$ at the interface between two regions with different electric conductivities: $J_n = -\sigma_1 \boldsymbol{n}\cdot\nabla\varphi_1 = -\sigma_2 \boldsymbol{n}\cdot\nabla\varphi_2$. The magnetic induction $\boldsymbol{B}$ was calculated from the current density $\boldsymbol{J} = \sigma(-\nabla\varphi)$ using the Biot–Savart law:

$$\boldsymbol{B}(\boldsymbol{r}) = \frac{\mu_0}{4\pi}\int d^3\boldsymbol{r}' \frac{\boldsymbol{J}(\boldsymbol{r}') \times (\boldsymbol{r} - \boldsymbol{r}')}{|\boldsymbol{r} - \boldsymbol{r}'|^3} \tag{1}$$

The boundary conditions for the electric potential are defined using the amplitude of the imposed electric current at the end of the electrodes: $I = \int_A d\boldsymbol{s}\cdot\boldsymbol{J}$, where A is the area of the electrode's cross section.

The flow in the volume containing the melt was simulated numerically by means of the open source library *OpenFOAM* [18] solving the Navier–Stokes equation together with the incompressibility condition $\nabla\cdot\boldsymbol{u} = 0$ and including an electromagnetic force density term:

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u}\right) = -\nabla p + \eta\nabla^2\boldsymbol{u} + \boldsymbol{J}\times\boldsymbol{B} \tag{2}$$

The boundary conditions for the flow field are the no-slip condition $\boldsymbol{u} = 0$ at the solid container walls. For the melt surface

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