Investigations of the bulk flow inside a cylindrical liquid metal column generated by diverse AC magnetic fields

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This presentation considers various situations where the flow inside a liquid metal column is driven by different configurations of AC magnetic fields. The Ultrasound Doppler Method has been used to determine profiles of the fluid velocity in the ternary alloy GaInSn. The azimuthal and vertical velocity components have been measured allowing for an analysis of both the swirling flow in the horizontal planes and the flow pattern in the radial-meridional plane. In the first part we study the combination of a traveling and a rotating magnetic field which may generate a specific flow phenomenon in form of a concentrated vortex with properties similar to a tornado. The second part is concerned with the transient liquid metal flow which is generated by the discontinuous application of a rotating magnetic field (RMF). Such new approaches have been recently suggested for melt stirring during solidification of metal alloys. Finally, we consider an RMF-driven flow which is influenced by an oxide layer at the free surface of the metallic melt. Our measurements demonstrate that the occurrence of the oxide layer may lead to an unexpected oscillating behaviour of the bulk flow.

Keywords: Ultrasound Doppler Method, liquid metal, electromagnetic stirring, mixing

1 INTRODUCTION

Alternating (AC) magnetic fields are widely used in casting, metallurgy and crystal growth for melt stirring. For instance, the electromagnetic stirring is applied to provide an efficient mixing of metallic melts, to control the flow at the mold region in the continuous casting process or to achieve a purposeful alteration of the microstructure of casting ingots. In general, the principle of electromagnetic melt stirring can provide a diversity of flow pattern according to the requirements of the application under consideration. Besides simple variations of magnetic field strength and frequency, combinations of various kinds of magnetic fields and/or temporal modulations of the magnet field parameters are possible to produce different structures of the flow-driving Lorentz force. A detailed knowledge about the transient flow structures arising from the field modifications is necessary for a well-defined flow control. A mismatch of the relevant modulation parameters may lead to worse results.

2 EXPERIMENTAL SETUP

We consider an axisymmetric configuration of a finite, closed cylinder filled with liquid metal which is affected by diverse AC magnetic fields. The flow measurements have been carried out using the ternary eutectic alloy Ga68In20Sn12, which has a melting point of about 10°C and shows the following properties at room temperature: electrical conductivity $\sigma = 3.2\times10^{6}$ Sm^{-1}, density $\rho = 6.36\times10^{3}$ kgm^{-3} and viscosity $\nu = 3.4\times10^{-7}$ m^{2}s^{-1}.

A schematic view of the experimental setup is depicted in Fig. 1. Fluid vessels were made from Perspex with a radius *R* of 30 mm and 45 mm, respectively. The height of the liquid metal column *H* was chosen to be 60 mm or 90 mm ensuring an aspect ratio *2R/H* of unity. The experiments were performed in the magnetic induction system COMMA at FZD. Six coils are arranged in a pole-pair connection to create the rotating magnetic field with an effective magnetic induction up to a maximum value of 25 mT. The fluid vessel was placed concentrically in the bore diameter of the magnetic system. In order to preclude flow artifacts arising from symmetry deviations of the experimental set-up (vertical alignment, conformity of both the cylinder and the magnetic field axis), special care was necessary to ensure a precise positioning of the cylinder inside the magnetic system. The homogeneity of the magnetic field was checked using a 3-axis Gauss meter (Lakeshore model 560, sensor type MMZ2560-UH). Within the radial dimension of the fluid container, the variance of the magnetic field strength was found to be smaller than 3%.

The flow velocities were measured by a DOP2000 velocimeter (model 2125, Signal Processing SA) equipped with 8 MHz (TR0805LS) transducers. Two pairs of ultrasound transducers were arranged horizontally at the cylinder side wall to measure the azimuthal velocities. Sensor 1 and 2 were positioned 15mm above the cylinder bottom, while sensor 3 and 4 were situated 15mm below the free surface. The radial distance between the two pairing sensors is 2*d* = 16 mm. Each transducer acquired directly the velocity component projected on the ultrasound beam line. The distribution of the fluid azimuthal velocity along the cylinder radius can be reconstructed based on the method described in [1]. In the experiment, we also measured the vertical velocity profiles by arranging an array of transducers vertically along the diameter at the cylinder bottom. Fig. 1 shows an example with a single transducer at the center of the cylinder bottom. Because of the divergence of the ultrasonic beam the lateral size of the measuring volume increases with the distance from the transducer. Hence, the spatial resolution in lateral direction varies from 5 mm at the sensor to approximately 7.5 mm at the opposite wall of the fluid vessel. In axial direction a spatial resolution of about 1.4 mm was achieved. The velocity data were acquired with sampling frequencies between 3.5 and 25 Hz. The accuracy of the velocity data can be assessed to be better than 0.15 mm/s.

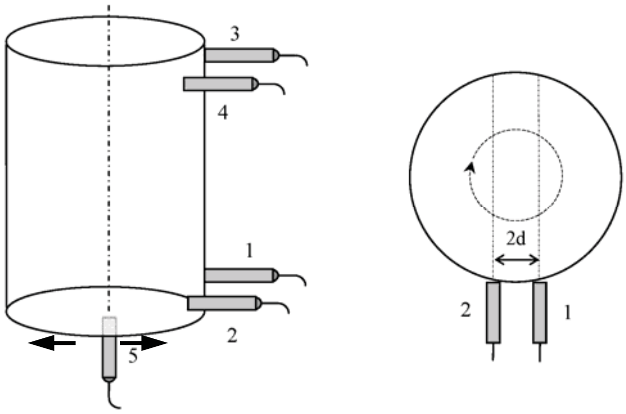

Figure 1: Sketch of the experimental setup showing the arrangement of the ultrasonic transducers to measure the swirling flow (sensors 1-4) and the vertical velocity (sensor 5).

3 RESULTS

3.1 Superposition of different AC magnetic fields

When rotation is added to a converging flow, an intense vortex appears which may become manifest in many spectacular flows ranging from bathtub vortex tropical cyclones. Both, the converging flow and the rotation can be induced by magnetic forces in a volume of liquid metal. We consider here a GaInSn melt in a cylindrical container. The poloidal flow is driven by an axial upwards traveling magnetic field, and the azimuthal flow is produced by a rotating magnetic field. Both resulting forces are schematically drawn in Fig. 2(a). A separate application of a TMF causes a converging flow at the top of the cylinder as shown in Fig. 2(b).

Acting alone the TMF drives a downward mean flow in the central portion of the cylinder (Fig. 3(a)). The negative velocities correspond to a descending flow. The superposition of an additional RMF suppresses the downward motion along the axis until a reversal of the flow direction can be observed. The condition of this flow reversal was found to occur at a constant ratio of axial and azimuthal forces [1]. This axial velocity reversal is associated with the formation of a two-cell structure as shown in Fig. 3(b). Similar flow patterns have been observed in tropical cyclones and tornados as well as in respective laboratory models [2, 3] or numerical simulations [4]. Such structures are generated when the radial inflow is stopped and turned back at some equilibrium radius by inward increasing centrifugal forces.

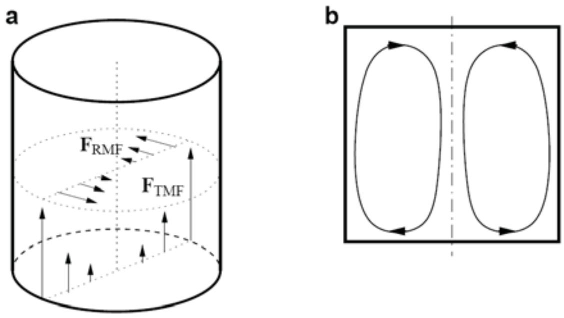

Figure 2: (a) Schematic representation of the body forces induced by TMF and RMF, respectively; (b) the meridional flow pattern in an upwards TMF-driven flow.

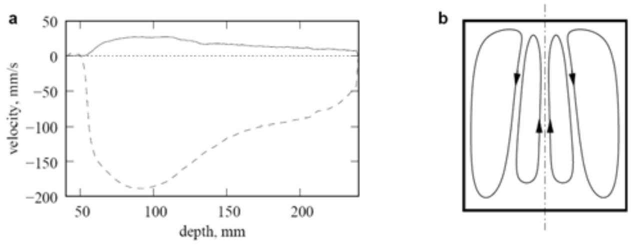

Figure 3: (a) Axial velocity along the cylinder axis for the application of a TMF (dashed line) and combined TMF and RMF (solid line); (b) schematic representation of the two-cell regime.

3.2 Electromagnetic stirring using a time-modulated RMF

Recently, it has been demonstrated that a melt stirring using a modulated RMF can enforce higher mixing rates, but at lower energy consumption as compared with a continuously applied RMF [5]. We investigated the case if an RMF acts upon a cylindrical column of liquid metal, while the field strength is modulated in two different ways. First, we used a succession of RMF pulses that always have the same rotational direction. Second, we applied an RMF pulse sequence of alternating direction.

The problem of macrosegregation has to be considered as a key problem concerning magnetic field application for melt stirring during the solidification of metal alloys [6]. This phenomenon is attributed to the secondary flow driven by the Ekman-pumping specifically arising in a rotating fluid in form of a double vortex. The radial component of the secondary flow, which passes along the solidification front, conveys solute-rich melt towards the axis of rotation. Consequently, the radial convection along the solid-liquid interface causes an accumulation of solute in the central region of the sample, whereas a corresponding depletion of solute has to be registered in regions near the lateral walls. Thus, the segregation problem could likely be avoided by melt stirring with a permanent change of flow direction at the solidification front.

A pronounced double vortex structure with a periodic inversion of the sign of vorticity can be obtained by melt stirring using a pulsed RMF [5]. However, such a flow pattern can only be obtained for a very narrow range of pulse frequencies. This is illustrated by the time series of the local velocity presented in Fig. 4. A frequency of 0.475 Hz provides regular oscillations of the vertical velocity. The realization of lower or higher frequencies implies a weakening of the secondary flow and a loss of the periodicity of the flow.

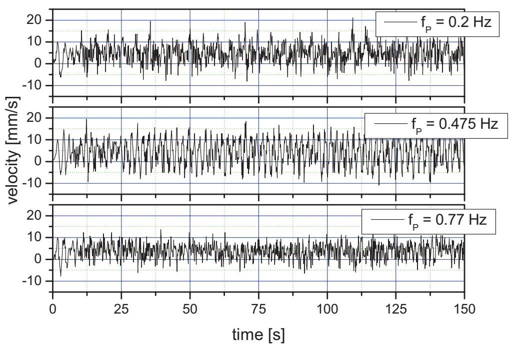

Figure 4: Time series of the vertical velocity in case of RMF pulses with unidirectional sense of rotation showing the effect of variations of the pulse frequency f_p.

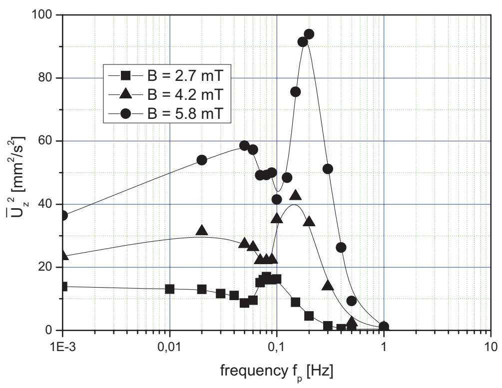

Figure 5: Dependence of the intensity of the secondary flow on the frequency of reversals of rotational direction f_p.

The parameter f_p plays an important role also in the case of an RMF pulse sequence of alternating direction. The square value of the vertical velocity U_z represents an indication with respect to the intensity of the secondary meridional flow. Fig. 5 displays this quantity as function of the frequency f_p. It becomes obvious that pronounced maxima of the energy of the secondary flow occur at selective frequencies, varying for different values of the magnetic field strength. Recent investigations have demonstrated that the optimal values of these modulation frequencies correspond to characteristic time scales of the RMF spin-up process [5, 7].

3.3 Influence of oxide layers on an RMF-driven flow

Liquid metal flows driven by an RMF inside a cylindrical container have been frequently investigated by numerical simulations for both situations of a free surface of the melt or a solid boundary at the top of the fluid vessel. The solid end walls are responsible for the existence of an axial gradient of the angular velocity which drives the secondary motion in the radial-meridional plane in form of a double vortex structure. Albeit the ideal assumptions taken as boundary conditions for the numerical calculations almost all technical applications of melt stirring occur with a free surface of the melt which is covered by an oxide layer.

We conducted measurements of the bulk flow inside a liquid metal column at which the fluid surface was covered by a layer of oxides. Figure 6 reveals a peculiar phenomenon which was observed within a particular parameter range. In case of a complete coverage of the free surface with oxide particles the secondary flow may become unstable and exhibits distinct periodic oscillations.

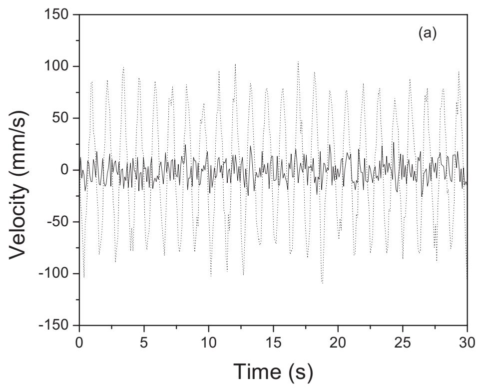

Figure 6: Time series of the vertical velocity on the cylinder centerline in the case of a regular RMF-driven flow (solid line) and in case of appearing flow oscillations (dotted line)

This effect can be explained by the nonlinear interaction between the primary swirling flow and the secondary flow [8]. This interaction manifests itself in a variation of the poloidal vortex lines, the best known example of which is the inertial wave in case of an RMF spin-up [9]. The secondary flow, which is induced by an axial gradient in the swirl, tends to eliminate the non-uniformity in the angular velocity by a redistribution of angular momentum. The inertial oscillations during the RMF-driven spin-up are forced by the rapid increase in the rotation rate. Because of viscous damping, these oscillations decay and can be observed therefore only over a finite period of time. The permanently occurring oscillations in the present case are triggered by the oxide layer at the surface. This covering layer is affected by a torque induced due to the swirling fluid below and a friction force from the side walls. At the beginning of the process, if the rotation rate is low, the layer is coupled with the wall and not moving therefore. This situation is similar to the case of an enclosed cylinder.

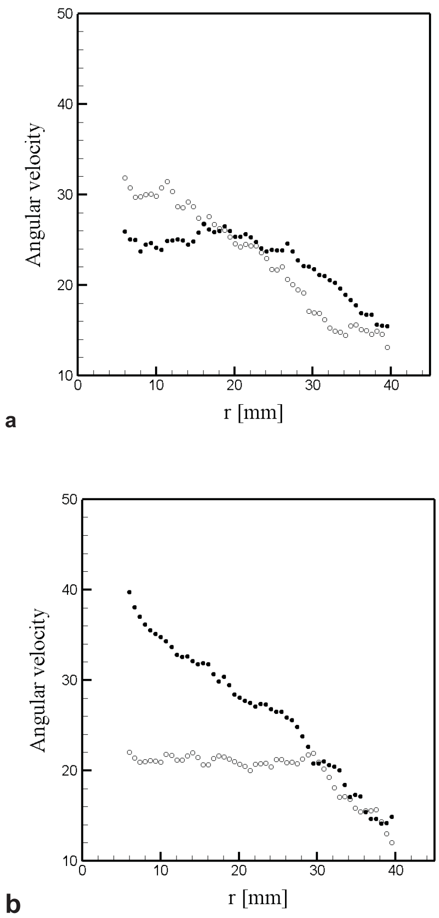

Figure 7: Two snapshots showing the differential rotation in the cylinder. Solid dots represent the angular velocity profile 15 mm above cylinder bottom (transducer 1); open circles represent the angular velocity profile 15 mm below the free surface (transducer 3). (a) the core of the fluid column rotates faster at the surface; (b) the core rotates faster at the bottom of the cylinder.

An acceleration of the liquid provokes a separation of the oxide layer from the side walls. Owing to the uneven boundary conditions the fluid rotates faster now at the surface. A poloidal flow comes up which redistributes the angular momentum leading to an acceleration of the liquid above the bottom of the vessel accompanied by a deceleration of the swirl near the surface. The oxide layers may reattach to the side wall and finally an inversion of the swirl distribution occurs. As a result, the azimuthal velocities in the upper and the lower part of the cylinder are always in anti-phase, i.e. the rotation beneath the surface reaches a maximum if the rotation rate is lowest near the bottom. The existence of the differential rotation is demonstrated in Fig. 7, which contains two typical snapshots from our measurements of the azimuthal flow showing the different angular velocities below the surface and above the bottom of the fluid vessel at two selected moments.

4 SUMMARY

Miscellaneous examples have been presented within this paper illustrating the variety of flow phenomena arising from the application of different kinds of magnetic fields on a liquid metal column. The Ultrasound Doppler Method appears as an effective tool for exploring the diverse structures of the bulk flow. Especially, this technique provides a valuable insight into the vortex dynamics of such non-transparent, unsteady flows.

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