Inertial wave observations in liquid metal by means of ultrasound Doppler velocimetry

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This experimental study considers the transient flow inside a liquid metal column exposed to a pulsed rotating magnetic field. To measure two-dimensional velocity fields of the secondary flow in the radial-meridional plane a novel ultrasound Doppler system was used. A linear ultrasound transducer array equipped with 25 transducer elements is used to measure the flow field in a square plane of 67 x 67 mm². The application of advanced processing techniques like a simultaneous excitation of multiple transducer elements and a segmented array technique enable high data acquisition rates as well as a high spatial resolution. The measurements revealed transient flow regimes showing distinct inertial oscillations and coherent vortex structures.

Keywords: Ultrasound Doppler method, flow field measurements, electromagnetic stirring, rotating magnetic field, inertial waves, flow control

1 INTRODUCTION

Electromagnetic stirring during solidification has been proved to be a striking method for achieving a purposeful alteration of the microstructure of casting ingots, such as grain refinement or the promotion of a transition from a columnar to an equiaxed dendritic growth (CET). However, the imposition of a rotating (RMF) or a travelling magnetic field (TMF) also causes problems like the occurrence of typical segregation pattern or a deflection of the upper free surface. A permanent radial inward (RMF and downward TMF) or outward (upward TMF) flow along the solidification front is responsible for the transport of solute to the axis or the wall of the ingot resulting in typical freckle segregation pattern filled with alloy of eutectic composition [1, 2]. Several studies have been devoted to overcoming the handicaps of rotary stirring with the specific goal to generate a vigorous stirring in the bulk without considerable deformations of the free surface [3-5]. It was shown recently, that the application of modulated AC magnetic fields offers considerable potential for optimizing the melt stirring [6, 7]. It became apparent that a careful adjustment of the modulation parameters is required in order to create intense secondary flows with periodic reversals of the flow direction. Especially, the secondary flow can be organized in such a way that periodic reversals of the flow direction occur adjacent to the solidification front, which has been experimentally verified as an important method to prevent flow-induced macrosegregation [8].

Within this paper we especially consider the effect of a modulated RMF on the isothermal liquid metal flow inside a circular cylinder, whereas the RMF is applied in form of successive rectangular pulses. Previous investigations revealed the existence of an optimal pulse length T_P, where a maximum intensity of a periodic meridional flow can be observed [7]. In that case the corresponding pulse frequency f_P relates to the eigenperiod of inertial waves in a developed regime, as given by Greenspan [9].

2 EXPERIMENTAL SET-UP

A schematic view of the experimental setup is shown in figure 1. A cylindrical vessel made of Plexiglas was used with an aspect ratio $A = H_0/2{\bullet}R_0 = 1$. The size of the inner diameter of $D = 2{\bullet}R_0$ and the height H_0 was chosen to be 67.5 mm. The cylinder is closed by rigid lids and filled with the eutectic alloy GaInSn. The experiments were performed in the magnetic induction system PERM at HZDR with a bore diameter of 200 mm, wherein the fluid vessel was placed concentrically. In order to preclude flow artifacts arising from symmetry deviations of the experimental setup (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 a radius of 35 mm, which approximately corresponds to the radial dimension of the container, the variance of the magnetic field strength was found to be smaller than 3%.

The ultrasound Doppler velocimetry (UDV) was used to perform measurements of the fluid flow inside the cylinder. Details with respect to the measuring principle can be found in [10]. The DOP2000 velocimeter (model 2125, Signal Processing SA, Lausanne) equipped with an 4 MHz transducer (TR0405LS, acoustic active diameter 5 mm) was applied to measure the primary azimuthal flow at two vertical positions. By attaching the ultrasonic transducer to the wall of the fluid container, the acoustic coupling between sensor and fluid was realized through the curved cylindrical surface. Moreover, a flow mapping of the meridional flow was realised by using a new measuring system. Details of the measuring system are given in [11]. The system operates with a linear array of 25 single transducers attached to the plane-parallel bottom wall of the flow container (see figure 1) and work with a frequency of 8 MHz. Each single transducer element has an active area of 2.5 x 5 mm. The segmental array is actuated in groups of two elements to achieve a low beam divergence. This square transducer can be traversed by half of its edge length that corresponds to one element pitch to achieve a small distance of the measuring line of 2.5 mm. A high temporal resolution can be realized by a parallel operation of four transducer pairs. To minimize the crosstalk between the active elements to a tolerable level four inactive array elements between are required. The spatial resolution in lateral direction varies from 5 mm at the sensor to approximately 7.5 mm at the lid 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 0.5 and 6 Hz. The accuracy of the velocity data can be assessed to be better than 0.15 mm/s.

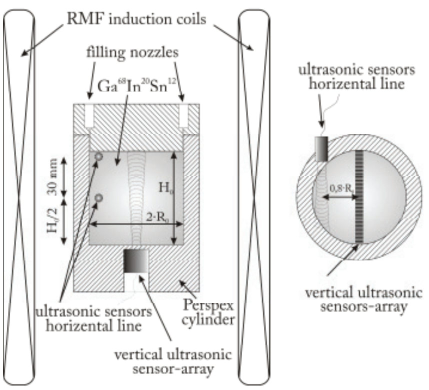

Figure 1: Schematic view of the experimental setup

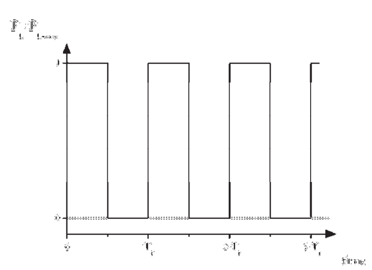

Figure 2: Modulation scheme of the Lorentz force F_L.

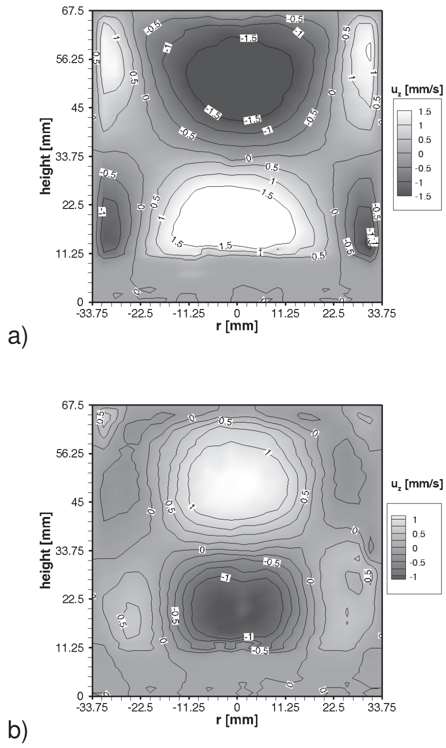

Figure 3: Snapshots of the vertical velocity across the vertical mid-plane of the cylinder recorded by the US sensor array for T_P = 20 s at B_{RMF} = 0.46 mT: (a) typical double vortex of the secondary flow; (b) "inverse" double vortex

3 RESULTS

The modulation scheme of the pulsed RMF as considered within this study is displayed in figure 2. As a consequence the fluid flow experiences a sequence of spin-up and spin-down processes. The duration of the particular pulse cycles T_P turns out to be a crucial control parameter. Measurements of the secondary flow have been carried out for different values of T_P. Figure 3 shows two snapshots of the flow pattern obtained for B_0 = 0.46 mT and a pulse cycle of T_P = 20 s. The typical structure of the toroidal double vortex can be detected in figure 3(a).

The secondary flow in the central region is directed upwards in the bottom part and downwards in the upper part of the cylinder, respectively. In figure 3(b), an inversion of the flow direction can be observed. A so-called "inverse" double vortex is formed at lower intensity. The mean values of the vertical velocity u_z averaged over both the total measuring time and the vertical cylinder cross section, which can be calculated at follows:

$$\overline{U_z} = \frac{1}{T \cdot H_0 R_0^2} \int_0^T \int_{H_0/2}^{H_0} \int_{-R_0}^{R_0} r\sqrt{u_z^2}\, dr\, dz\, dt \qquad (1)$$

Respective results are drawn in figure 4 vs. the pulse duration cycle T_P for magnetic fields of 0.46 mT and 2.25mT.

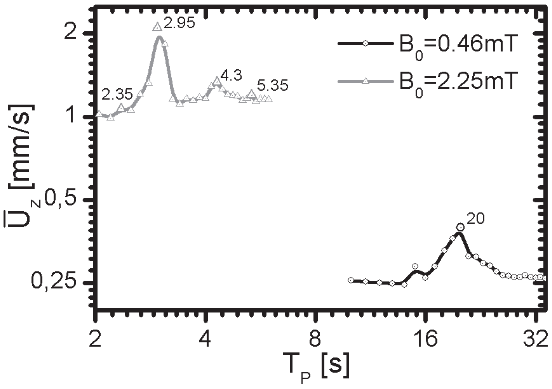

Figure 4: Dependence of the intensity of the secondary flow on the duration of the pulse cycle

It becomes obvious that the intensity of the secondary flow for $B_{RMF} = 0.46$ mT exhibits a pronounced maximum around $T_P = 20$ s, where distinct periodic reversals of the secondary flow have been observed. This resonance peak is shifted to lower T_P with increasing magnetic field strength, in particular the maximum is found at $T_P = 2.95$ s for $B_{RMF} = 2.25$ mT. Moreover, further maxima of the magnitude of the averaged secondary flow appear at larger pulse durations. Figure 5 show snapshots of the vertical flow obtained for pulse durations which correspond to the four marked points in figure 4. It is interesting to note that the new flow pattern is characterized by an increment of vortex cells in radial or axial direction.

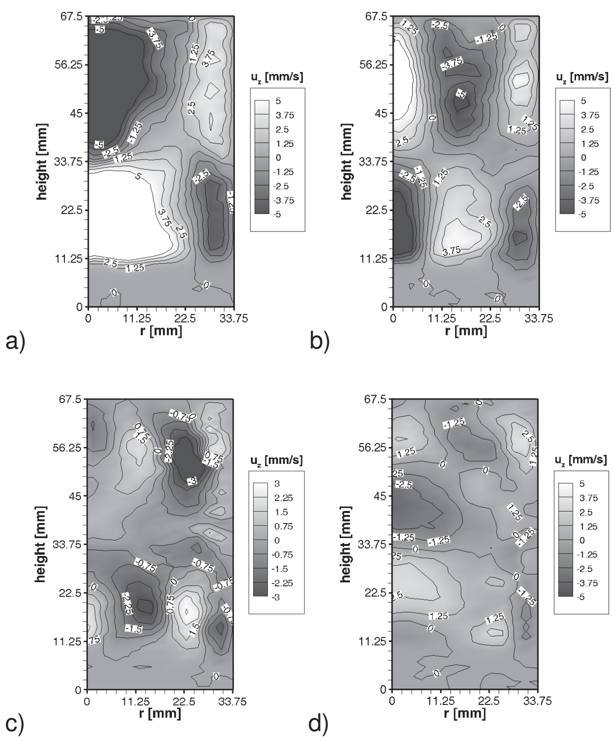

Figure 5: Snapshots of the vertical velocity across the vertical mid-plane of the cylinder recorded by the US sensor array at $B_{RMF} = 2.25$ mT: (a) $T_P = 2.95$ s, (b) $T_P = 4.3$ s; (c) $T_P = 5.3$ s and (d) $T_P = 2.35$ s

Figure 5(a) show the well-known double vortex flow structure for the maxima in the flow intensity for $T_P = 2.95$ s. For higher pulse durations we find two (figure 5(b)) and three (figure 5(c)) vortices in radial direction, respectively, which corresponds to the minor maxima in figure 4 at pulse duration times of $T_P = 4.3$ s and $T_P = 5.35$ s, respectively. Figure 5(d) shows the flow structure for a lower pulse duration time. In this case four vortices in axial direction are visible. This flow structure corresponds to the small peak at $T_P = 2.35$ s in figure 4.

All these differences in the flow intensity and structure must be reflected by the azimuthal velocity component. Figure 6 shows the time series of the azimuthal velocity for two positions and three pulse durations. The vertical position is in the midplane and in the near of the upper horizontal boundary layer (see figure 1). The pulse duration matches with the main maximum in the flow intensity, the second maximum at $T_P = 4.3$ s and a pulse duration between these distinguished points. By the switch-on and switch-off of the electromagnetic force a pulsation of the azimuthal velocity in the midplane is generated and can observed for all three pulse durations. In the vicinity of the horizontal boundary the pulsation is also visible but with a remarkable phase shift in comparison to the midplane. For the two maxima a reversal of the vertical gradient in the azimuthal flow is observable which does not exist for the pulse duration of $T_P = 3.7$ s. These strong periodic changes in the vertical gradient of the azimuthal velocity generate an oscillation of the meridional flow and vice versa the oscillation of the meridional flow influences the transport of angular momentum.

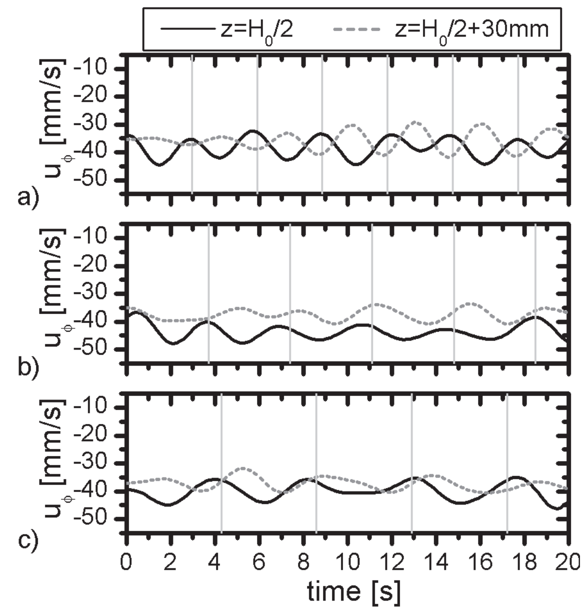

Figure 6: Time series of the azimuthal velocity in the midplane and in the near of the horizontal boundary at $B_{RMF} = 2.25$ mT: (a) $T_P = 2.95$ s, (b) $T_P = 3.7$ s and (c) $T_P = 4.3$ s

4 DISCUSSION

The present study concerns a liquid metal flow being exposed to a pulsed RMF. The alternating power-on and power-off of the magnetic field generates successive spin-ups and spin-downs of the rotating fluid flow. Abrupt changes in the energy injection rates promote the propagation of inertial waves through the interior of the fluid [12, 13]. Such waves were derived for the case of small perturbations in a fluid which rotates as solid body [9]. The Coriolis force balances the pressure gradients and generates the restoring force for the inertial waves. Theoretical eigenvalues of the inertial waves are given in the book of Greenspan (page 82) [9]. Considering the axisymmetric inertial mode k = 0, n = 2, m = 1 we obtain eigenperiods of 20.6 s and 3.1 s for magnetic field intensities of 0.46 mT and 2.25 mT, respectively. These results agree very well with the experimentally identified T_P values for the respective main resonance peaks. The parameter region around these resonance frequencies of the driving force appears as an optimal operating range for an efficient electromagnetic stirring, because the intensity of the secondary flow reaches a distinct maximum here. Moreover, the permanent reversals of the flow direction make this flow regime promising for applications in directional solidification processes.

A prolongation of the pulse duration T_P at 2.25 mT produces minor maxima of the magnitude of the secondary flow. Using the equation from Greenspans book we yield eigenperiods of 4.6 s and 6.4 s for higher radial modes and 2.3 s for higher axial mode, which corresponds fairly good to the minor peaks in figure 4. These higher modes manifest themselves in new secondary flow pattern showing an incremented number of vortex cells in radial or axial direction (see figure 5).

5 CONCLUSION

In this present study, we have discussed the impact of a discontinuous applied rotating magnetic field with subsequent equidistant pulses. A new ultrasound Doppler array measurement technique was used and a two-dimensional-one-component flow mapping of transient flows with a high time resolution was realized. Other groups measured 2D flow structures before [14,15] but only the time-averaged pattern. For the case of time modulated magnetic fields and the resultant discontinuous fluid flow the possibility of highly time-resolved flow measurements is indispensable to understand the flow structure.

The electromagnetic stirring method that uses a modulated RMF offers a considerable potential to enhance the stirring efficiency and to optimize the properties of castings by a well-aimed flow control during solidification. Further investigations are necessary to improve the understanding of the development of various flow regimes under the influence of a time-modulated driving force.

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