Application of the Ultrasound Doppler method for velocity measurements in an electromagnetically-stirred liquid metal

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This experimental study considers the transient liquid metal flow which is generated inside a cylindrical container by discontinuously applying a rotating magnetic field (RMF). The focus is on the fluid motion arising from the impulsive spin-up from the resting state, a single pulse or a sequence of RMF pulses. The ultrasonic Doppler velocimetry (UDV) 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 primary, swirling flow and the secondary flow in the radial-meridional plane. The experimental results show an excellent agreement with recently published numerical results. The investigations reveal that the recirculating flow in the radial- meridional plane undergoes characteristic oscillations. Periodic reversals of the meridional flow direction can be observed for a specific length of the RMF pulses.

Keywords: Liquid metal, electromagnetic stirring, rotating magnetic field, velocity profile, Ultrasound Doppler method

1 INTRODUCTION

Alternating current (AC) magnetic fields are commonly used in industrial practice for melt stirring. The requirements arising from the particular metallurgical or casting operation can be manifold. 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.

We consider here the standard case of electromagnetic stirring by means of a rotating magnetic field (RMF). For a liquid metal inside a cylindrical vessel, the imposition of an RMF creates a primary motion in form of a swirl. A secondary recirculating flow in the r-z plane, which consists of a double vortex structure for the laminar case, results from the Ekman pumping at the horizontal walls [1]. Although the amplitude of the primary motion is several times higher than the secondary flow, its contribution to an efficient bulk mixing is marginal, because it consists mainly of an almost rigidly rotating core. The convective transport in vertical and radial direction is mainly achieved by the secondary flow. An amplification of the secondary flow causes an intensification of the mixing rate, which can be realized in the simplest way by increasing the magnetic field. At sufficiently high field intensities so-called Taylor-Görtler vortices occur, moving along the sidewalls of the cylinder and dissipate inside the Bödewadt layers. Such vortex structures are very efficient with respect to melt mixing [2]. On the other hand, an increase of the magnetic field also accelerates the primary, swirling flow, which results in an increasing deflection of the free surface. Instabilities at the meniscus region should be strictly avoided in many applications, because they can lead to surface defects or the entrainment of gas. In addition, specific problems arise if the rotary stirring is applied during directional solidification. The double-vortex structure of the secondary flow results in a radial inward flow along the solidification front, which transports the solute towards the axis of the ingot and is therefore responsible for typical segregation pattern [3, 4]. A mitigation of the problem could probably be achieved if the flow in the mushy zone can be oriented by turns in different directions.

A possible approach to overcome the handicaps of rotary stirring is the use of a time-modulated RMF. The goal is to amplify the secondary, recirculating flow, but to limit the amplitude of the swirling flow at the same time. A purposeful practice of melt stirring requires suitable flow measurements which deliver a detailed knowledge of the magnetic field impact on the flow. Therefore, this study is concerned with the experimental investigation of specific flow pattern arising from an impulsive change in the magnetic field strength, known as the spin-up or spin-down, respectively. In detail, we present velocity measurements arising from an RMF spin-up, a single pulse and a pulse sequence, respectively.

2 EXPERIMENTAL SET-UP

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^2s^{-1}. A schematic view of the experimental set-up is depicted in figure 1. The fluid vessel is a closed cylinder made from Perspex with a radius R_0 of

30 mm. The height of the liquid metal column H_0 was chosen to be 60 mm ensuring an aspect ratio $2R_0/H_0$ of unity. The experiments were performed in the magnetic induction system KOMMA at FZD. Six coils are arranged in one pole-pair connection to create the rotating magnetic field. The fluid vessel was placed concentrically inside the bore diameter of the magnetic system. In order to preclude flow artifacts arising from symmetry deviations of the experimental configuration (vertical alignment, conformity of both the cylinder and 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 container diameter of 60 mm the variance of the magnetic field strength was found to be smaller than 3%.

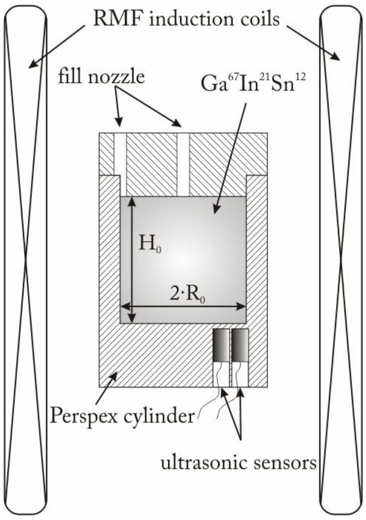

Figure 1: Schematic view of the experimental set-up

In the last twenty years the UDV technique became an accepted method for flow investigations in various liquid metals [5-8]. In the present study we used an 8 MHz transducer, which was attached to the plane-parallel bottom wall of the fluid container having a thickness of 2.5 mm. The vertical alignment of the transducer allowed for recording axial profiles of the vertical velocity between the bottom and the lid of the fluid cylinder. All velocity measurements presented in this paper have been obtained at radial positions of $r/R_0 = 0.6$ and 0.9, respectively. 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 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 ranging from 2 to 25 Hz. The accuracy of the velocity data can be assessed to be better than 0.15 mm/s. The geometrical restrictions of the experimental configuration, namely the small bore diameter of the coil system, did not permit for the determination of the azimuthal velocity component.

3 RESULTS

3.1 RMF spin-up

The spin-up of a fluid in a rotating axisymmetric container is a classical problem in fluiddynamics which has been reviewed by Benton and Clark [9]. The problem concerns a fluid being at rest or in the state of steady rotation, which experiences an increase of the angular velocity. Analytical and numerical studies concerning the spin-up of an RMF-driven flow have been published recently [10, 11]. In case of an RMF spin-up from the rest the azimuthal Lorentz force initiates a rotating motion of an electrically conducting liquid. The resulting imbalance between the centrifugal forces and the radial pressure gradient in the horizontal Ekman layers drives the fluid radially inwards. Required by continuity, a secondary circulation occurs in the meridional plane. Unlike the rotational direction, the sense of secondary circulation in the steady state is such that the interior fluid near the cylinder mid-plane is moving towards the side walls. In contrast to the case of a rotating container the secondary flow is an inherent feature of the steady state RMF flow. Nikrityuk et al. [11] divided the RMF-driven spin-up into two phases: a so-called initial adjustment time in which the secondary flow is firstly established in form of two toroidal vortices and a subsequent inertial phase showing distinct inertial oscillations until the flow reaches a steady state after the spin-up time.

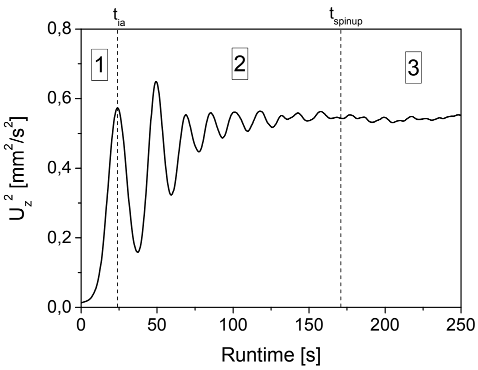

Figure 2: U_z^2 averaged over the vertical velocity profile, obtained at a radial position of r/R_0 = 0.9 and a magnetic field strength of B_0 = 0.42 mT (1 – initial adjustment phase, 2 – inertial phase, 3 – steady state).

Figure 2 displays the evolution of the square value of the vertical velocity U_z averaged along the vertical measuring line at

$$U_z^2 = \frac{1}{H_0}\int_0^{H_0} u_z^2 dz \qquad (1)$$

This quantity can be considered as a qualitative measure describing the intensity and kinetic energy of the secondary circulation in the meridional plane. The curve in figure 2, which has been obtained from an ensemble average of five miscellaneous reruns, reveals an oscillatory raise of the vertical velocity before a steady state is reached. Following the suggestions given by Nikrityuk et al. [11] we can identify the so-called initial adjustment phase and the inertial phase, respectively. We determined the duration of the initial adjustment phase, t_{ia}, as a function of the applied magnetic field strength B_0 from our experimental data (see figure 2). Figure 3 shows a satisfying agreement between experiment and numerical calculations [11] in the subcritical Ta number range although in the case of the numerical analysis the initial adjustment time was derived from the time history of the volume-averaged meridional velocity U_{rz}. A further increase of the magnetic field intensity reveals that t_{ia} follows a *1/B*-dependency in the turbulent range.

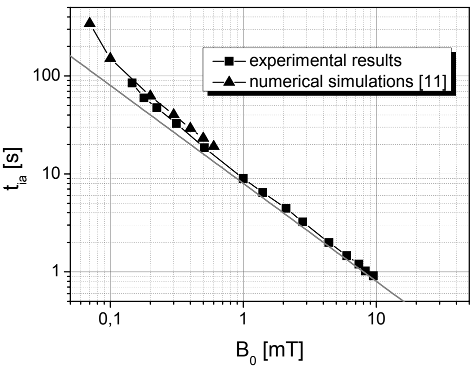

Figure 3: Influence of the magnetic field B_0 on the initial adjustment time t_{ia}

3.2 RMF single pulse

The flow arising from the application of a single RMF pulse is governed by an impulsive spin-up from the rest state followed by a spin-down phase due to the inertia of the fluid. Nikrityuk et al. [12] found that the recirculating flow in the meridional plane becomes especially pronounced if the pulse length t_P of the electromagnetic forcing is consistent with the initial adjustment time. Figure 4 shows a transient flow pattern using an RMF pulse with the amplitude B_0 of 2.8 mT and the pulse length t_P of 3.6 s, which corresponds to the duration of the initial adjustment phase t_{ia} for the case considered here. At the beginning an ascending flow appears in the upper part of the container and a descending motion in the lower part, which indicates the formation of two toroidal vortices usually appearing during the initial adjustment phase. The shutdown of the RMF does not extinguish the secondary flow immediately. The double vortex structure undergoes oscillations, the double vortex decays temporarily and will be displaced by another vortex pair emerging at the horizontal endwalls and spreading towards the mid-plane. It is important to note that the velocity shows a reversal of its direction. At the mid-plane a short-time erasement of the flow structure seems to occur before the vortices expand over the other half of the container.

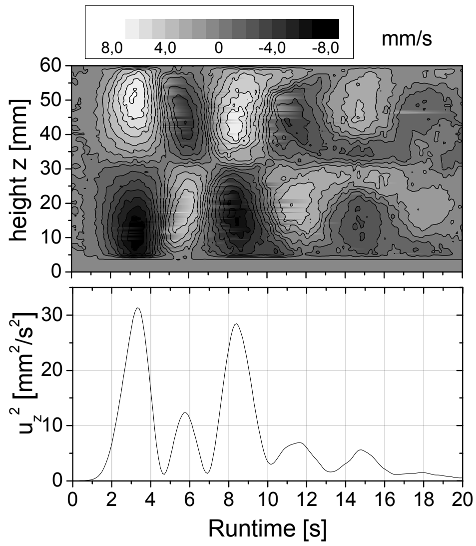

Figure 4: Spatiotemporal plot of the vertical velocity and corresponding temporal development of U_z^2 (RMF pulse with B_0 = 2.8 mT and t_P = 3.6 s, r/R_0 = 0.9)

3.3 RMF pulse sequence

As a next step we consider a succession of RMF pulses. As shown in figure 5 additional parameters emerge, namely, the pulse length t_P and the time between two subsequent pulses t_D, also called as dormant period. If equal periods of driving and inactive phases are chosen, the respective pulse frequency $f_P = 1/(2{\cdot}t_P)$ appears as new important control parameter. Recent results demonstrated the occurrence of a distinctive double-vortex structure with high velocity values and periodic inversions of the vorticity only in a very narrow range of pulse frequencies [13].

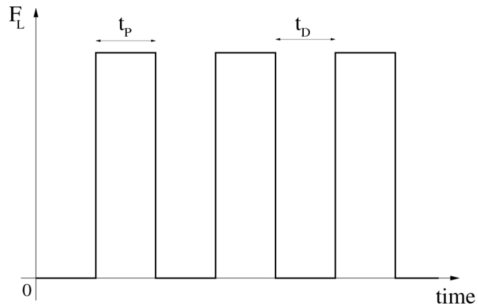

Figure 5: Temporal scheme for the modulation of the electromagnetic force F_L

An explanation of this phenomenon requires an understanding of the interaction between the primary and the secondary flow. The energy transfer between the rotary motion and the meridional flow is governed by inertial waves [11, 14]. Preliminary results [13] reveal that a characteristic flow pattern will be achieved if the pulse frequency f_p corresponds to the eigenperiod of inertial waves in a developed regime as given by Greenspan [15]. This is confirmed by figure 6 in which the square values of the vertical velocity averaged over both the measuring line and the total measuring time are drawn vs. the frequency f_P. It becomes obvious that pronounced maxima occur at selective frequencies, varying for different values of the magnetic field B_0. These maxima correspond to values of the frequency where distinct periodic reversals of the secondary flow have been observed [13]. As expected, the excitation of different modes becomes more pronounced with increasing B_0.

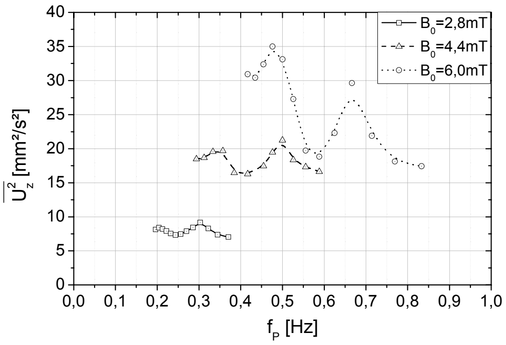

Figure 6: Intensity of the secondary flow vs. frequency f_P, ($\overline{U}_z^2$ - average over velocity profile and measuring time)

4 DISCUSSION AND CONCLUDING REMARKS

We presented velocity measurements in a cylindrical liquid metal column with a flow which is driven by an application of an intermittently applied RMF. Thereby, the focus was especially directed on generic situations such as the spin-up, a single pulse or a sequence of equidistant pulses. By delivering both the instantaneous velocity profiles and the resulting spatiotemporal flow structure the ultrasound Doppler method provides a valuable insight into the vortex dynamics of such nontransparent, oscillating flows. Our experimental results show a very good agreement with previous numerical predictions [11-13].

The flow measurements show the capability of intermittently applied RMF to overcome the limited mixing character of conventional rotary stirring. A suitable choice of parameters provides high mixing intensities by a distinct intensification of the secondary flow, which can reduce the mixing time for industrial applications. Moreover, it becomes possible to control the direction of the secondary circulation. The outcome of the present study demonstrates that a preferential intensification of the secondary flow requires the careful adjustment of the respective frequencies f_p for pulsing the rotational direction of the RMF. The respective optimum for f_p depends on the magnetic field strength B_0, the material properties of the liquid and the geometry under consideration. A mismatch of the relevant parameters may prevent an improvement of the mixing intensity, actually, the results may become worse compared to the situation of a continuously applied RMF.

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