Time dependent 2D flow structure measurements arising from melt stirring by means of various AC magnetic fields

Sven Franke[a,b], Dirk Räbiger[b], Jürgen Czarske[a], Gunter Gerbeth[b] and Sven Eckert[b]

[a] Laboratory of Measurement and Testing Techniques, Faculty of Electrical Engineering and Information Technology, Technische Universität Dresden, 01062 Dresden, Germany

[b] Department Magnetohydrodynamics, Institute of Fluid Dynamics, Helmholtz-Zentrum Dresden-Rossendorf, P.O. Box 510119, 01314 Dresden, Germany

We present an experimental study concerning the flow inside an isothermal liquid metal column exposed to various magnetic field configurations. This paper is aimed at highly resolved, quantitative velocity measurements in the eutectic alloy GaInSn by means of the pulsed-wave ultrasound Doppler method. A novel ultrasound system was used to measure two-dimensional velocity fields of the secondary flow in the radial-meridional plane. The imaging system employs two arrays each of 25 transducer elements allowing for a fast electronic traversing with concurrently high spatial and temporal resolution. The study considers time-modulated fields or combinations of traveling magnetic fields (TMF) and rotating magnetic fields (RMF) revealing different flow structures and flow intensities. The results demonstrate different variants of electromagnetic melt stirring, some of them showing the potential to enhance the stirring efficiency and to optimize casting properties during solidification.

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

1 INTRODUCTION

AC magnetic fields unlock an enormous potential to realize a variety of flow structures in molten metals, which makes the electromagnetic stirring attractive for controlling the melt flow during solidification [1]. However, electromagnetically-driven melt convection may also produce segregation freckles on the macroscale [2]. The achievement of superior casting structures needs a well-aimed control of melt convection during solidification, which in turn requires a detailed knowledge of the flow structures.

Previous investigations considered the use of time-modulated rotating magnetic fields to control the heat and mass transfer at the solidification front [3]. It has been shown recently under laboratory conditions [4], that an accurate tuning of the magnetic field parameters can avoid segregation effects, however, a mismatch of the relevant modulation parameter deteriorate the results. Another idea concerns a superposition of RMF and TMF. However, a simultaneous application of RMF and TMF with comparable field frequencies generates a stationary three-dimensional force which breaks the axial symmetry of the flow [5]. Instead operating both fields at the same frequency we studied the case of a small frequency shift in the present study.

Our activities aim at an efficient strategy for adjusting the microstructure of castings by optimizing the melt convection during solidification. We propose the application of modulated or superimposed AC magnetic fields as a new approach of electromagnetic melt agitation, which should overcome the segregation effects known from the conventional electromagnetic stirring.

2 FLOW MAPPING SYSTEM

The pulsed ultrasound Doppler method has proved as a reliable and attractive flow measuring technique for non-transparent fluids as liquid metals [6]. However, a multidimensional flow mapping with a sufficient spatial and temporal resolution, as required for a detailed study of time-dependent flow structures, is distinctly limited with current ultrasound Doppler devices [7]. Hence, we developed a two-dimensional ultrasound Doppler velocimeter utilizing two linear transducer arrays [8, 9]. Each array is segmented into 25 plane transducer elements of 2.4×5 mm² with an element pitch of 2.7 mm (fig. 1).

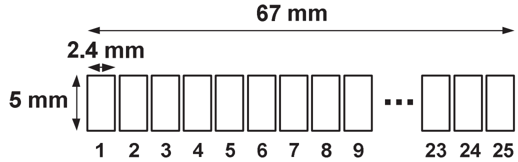

Figure 1: Design of a linear transducer array

A single array allows the flow field measurement of the velocity component perpendicular to the transducer surface. In an orthogonal arrangement of the arrays both components of the velocity field in the spanned measuring plane of 67×67 mm² can be acquired [10]. Other array configurations are possible as well.

An electronic traversing by means of a specific time-division multiplex scheme provides a high spatial as well as a high temporal resolution. A suitable spatial resolution is achieved by the operation principle of segmental arrays: In operation two adjacent transducer elements are interconnected to act as one transducer of approx. 5 × 5 mm² resulting in a low beam divergence over the measuring depth. However, this active transducer pair, equivalent to the measuring line of the velocity profile, can be shifted by only one element pitch. In summary the lateral resolution of approx. 3 mm in the focal point is in the same magnitude as the measuring line pitch of the velocity profiles of 2.7 mm [8].

Two novel approaches are implemented to extend the temporal resolution [9, 10]. The first method concerns a multi-beam operation which is aimed at to scan as many profile measuring lines (respectively transducer pairs) in parallel as possible. There, a sufficient distance between the simultaneously excited transducer pairs is selected to reduce the crosstalk (due to the divergence of the ultrasonic beam) between the active measuring lines below a tolerable level of -40 dB [8]. The second method is related to the pulsing strategy: For the evaluation of a single velocity profile a multitude of typically 30 to 100 echo signals is needed. Conventional multiline systems acquire the echo signals of the separate profile lines successively resulting in a distinct time difference between the acquisition of the first and of the last measuring line meanwhile the flow structure may change distinctly. The experimental conditions of most of our small scale model experiments reveal an echo acquisition time much shorter than the pulse repetition time. Our second approach utilize this idle time to acquire the echo signals of further measuring lines. This interlaced echo signal acquisition in combination with the multi-beam operation allows to measure the entire flow field in the same time as a conventional device acquires a single velocity profile. Frame rates of flow mapping up to 30 fps are achieved typically.

The multiplex scheme involving all introduced approaches is shown in figure 2. The technical implementation of the measuring system is described in [9] and [10] in detail.

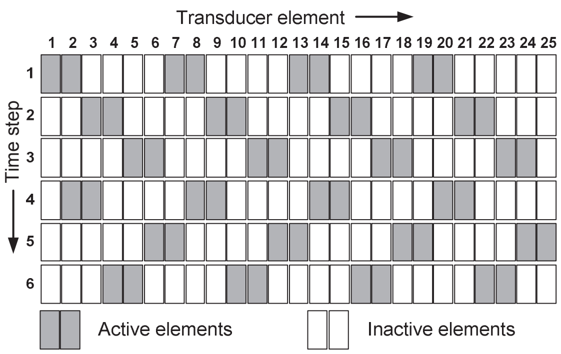

Figure 2: Multiplex scheme for single array

3 EXPERIMENTAL SETUP

A schematic view of the experimental setup is shown in figure 3. A cylindrical vessel made of perspex was used with an aspect ratio $A = H_0/2 \cdot R_0 = 1$. The size of the inner diameter of $D = 2 \cdot R_0$ 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. The magnetic system consists of a circular arrangement of six induction coils and six induction coils arranged one above the other for generating a RMF or TMF, respectively. A magnetic field frequency f_{RMF} of around 50 Hz was selected being small enough to neglect any influence arising from the skin effect. 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.

A flow mapping of the radial-meridional flow was carried out with one transducer array at the lower lid measuring the vertical velocity u_z across the meridional cross section. Due to constructive limitations the second array was not applied. For the flow investigations in this setup the second component of the measuring plane is not mandatory because of the axial symmetry of the vessel. The spatial resolution in lateral direction varies from 5 mm at the sensor over 3 mm at the focal point 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 13 Hz.

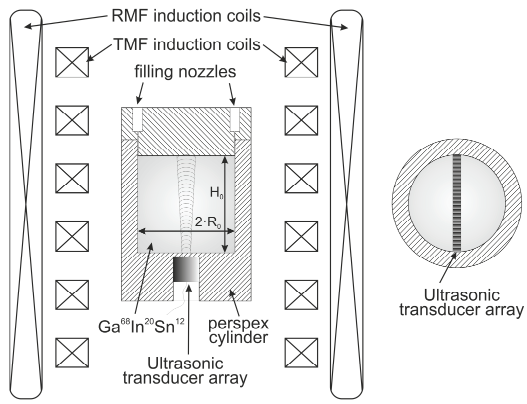

Figure 3: Schematic drawing of the experimental setup

4 RESULTS

In the first study a continuous RMF was applied generating a swirling flow in the primary azimuthal plane. Figure 4a displays a schematic drawing and figure 4b a representative snapshot of the flow structure of the secondary meridional plane occurring at a magnetic field strength of B_0 =0.46 mT. It becomes apparent that the main secondary flow structure in the form of two toroidal vortices is represented by the upward and downward flow components, whereas Taylor-Görtler vortices can be observed additionally in the midplane on the left sidewall. In this case the magnetic field strength generates a flow structure slightly above the threshold of instability, which manifests itself in form of such vortices.

Figure 5 illustrates the transient behavior of the flow on power up the RMF ("spin-up") for $B_0 = 0.46$ mT. For evaluating the different variants of electromagnetic stirring the vertical velocity of the radial-meridional plane is averaged across the volume of the cylinder (assuming an axisymmetric flow) as a

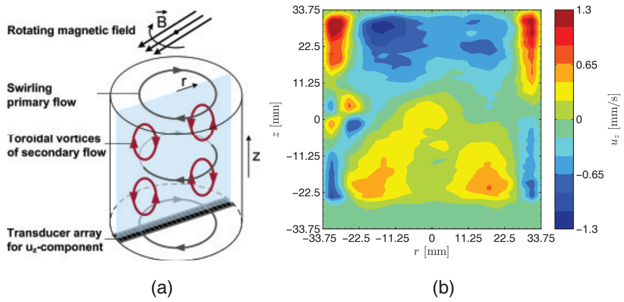

Figure 4: Schematic drawing (a) and snapshot (b) of double vortex of meridional plane at cont. RMF ($B_0 = 0.46$ mT)

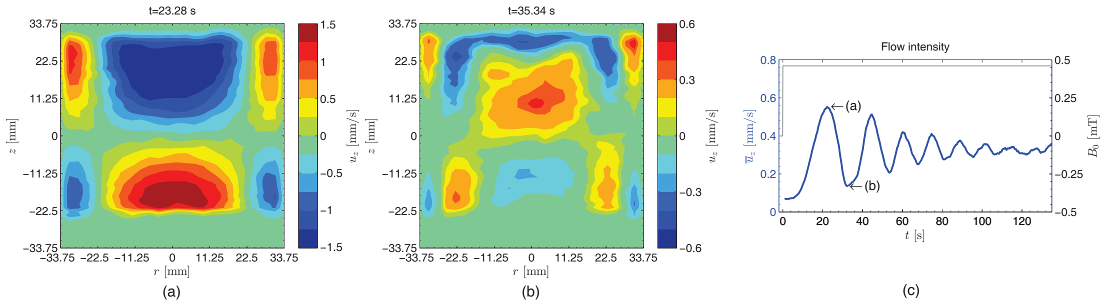

Figure 5: Flow pattern of a RMF spin-up process ($B_0 = 0.46$ mT)

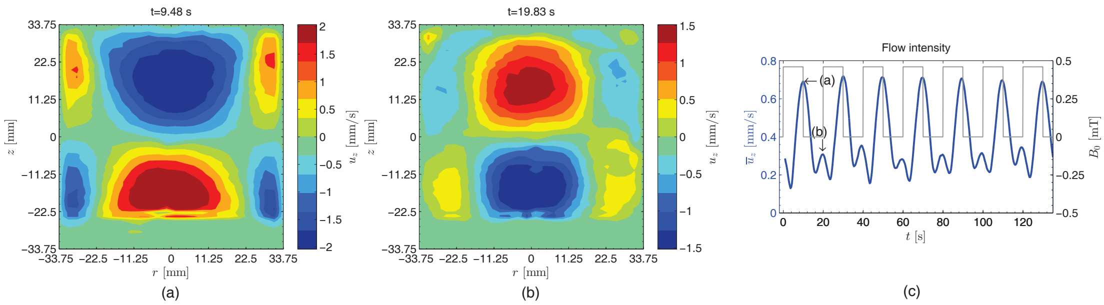

Figure 6: Flow pattern of a pulsed RMF at resonant pulse cycle duration ($T_P = 20$ s, $B_0 = 0.46$ mT)

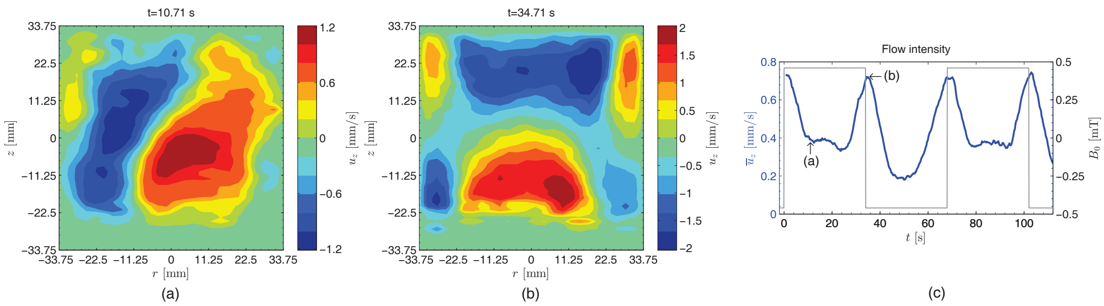

Figure 7: Flow pattern of an alternating RMF at resonant pulse cycle duration ($T_P = 68$ s, $B_0 = 0.46$ mT)

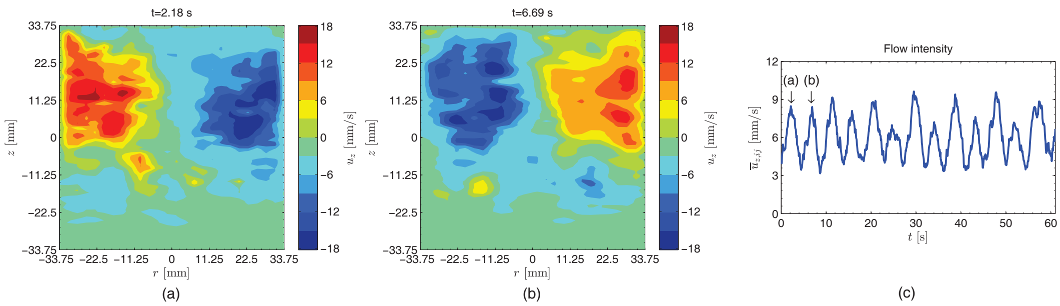

Figure 8: Flow pattern of a combined RMF and TMF ($B_{0,RMF} = 1.1$ mT, $B_{0,TMF} = 1.3$ mT, $\Delta f = 0.1$ Hz)

measure of the flow intensity:

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

The time course $\overline{u}_z(t)$ of the spin-up (blue curve in figure 5c) reveals a transient oscillation with a distinct overshoot. The grey curve illustrates the course of the magnetic field. Figure 5a represents the double vortex structure occurring at the first maximum of flow intensity. At the first intensity minima a higher mode of vortex structure arises as shown in figure 5b.

The application of a pulsed RMF initiates the fluid flow to experience a sequence of spin-up and spin-down processes at particular pulse cycle durations revealing a flow pattern as shown in figure 6. The secondary flow is characterized by permanent reversals of the flow direction of the basic double vortex. Figure 6a shows the typical vortex structure where the secondary flow in the central region is directed upwards in the bottom part and downwards in the upper part of the cylinder. In contrast the snapshot in figure 6b reveals the “inverse” toroidal double vortex not arising at a continuous stirring. Figure 6c illustrates the oscillating behavior of the flow intensity showing up global and local maxima. The flow structure of figure 6a coincides to the global maxima whereas the flow pattern of figure 6b is found at the local maxima. In comparison to the continuously applied RMF a significant increase in the flow intensity especially in the central region can be noticed.

Another example for a modulated RMF is displayed in figure 7. The application of pulse sequences of alternating direction induces the formation of a big circulation role (fig. 7a) between the rising and falling edge of each pulse. At the edges the flow intensifies to its maximum resulting in a frequency doubling of the flow oscillation toward the frequency of the pulse sequence (fig. 7c). The flow structure at the edges reveals the normal toroidal double vortex (fig. 7b). At the alternating RMF, too, an intensification of the secondary flow in comparison to the permanent stirring with the same magnetic field strength is achieved.

A completely other approach is the superposition of RMF and TMF with a small difference of the respective field frequencies. It is known that a combination at the same frequency generate a strong circulation role in the meridional plane which is stable in space [5]. In case of a small difference in the frequency, this circulation role begins to rotate and generates therewith a flow with alternating flow direction, but, keeping their symmetry in the long-term average. Two snapshots of such a fluid pattern with a phase shift of 180° to each other are shown in figure 8a and 8b. The averaged midplane velocity $\overline{u}_{z,ij}(t)$ in figure 8c illustrates the rotation of the circulation role.

5 SUMMARY AND CONCLUSIONS

In this study we investigated the impact of electromagnetic stirring by means of various AC magnetic fields on the flow structure in a metal melt. Thereto a liquid metal column of the eutectic alloy GaInSn was exposed to continuous as well as pulsed rotating magnetic fields. In addition a combination of RMF and TMF was considered. The temporal-spatial flow pattern in the column was measured with a new two-dimensional ultrasound system providing a spatial and temporal resolution previously not attained.

It was shown that a powered on RMF induce a distinct transient oscillation of flow. The enforcement of a sequence of such spin-up and spin-down processes at pulsating and alternating RMFs results in a considerable intensification of the meridional flow in comparison to a continuous RMF. A combined RMF and TMF also increases the flow intensity. Furthermore, beside the flow intensification, the continuous transitions among the flow structures (e.g among double vortex and inverse double vortex) avoid segregations and provide prospects for tailoring the microstructure of the solidifying alloy [4].

REFERENCES

[1] Willers B et al: The columnar-to-equiaxed transition in Pb–Sn alloys affected by electromagnetically driven convection, Mat. Sci. Eng. A 402 (2005), 55-65.
[2] Nikrityuk PA et al: A numerical study of unidirectional solidification of a binary metal alloy under influence of a rotating magnetic field, Int. J. Heat Mass Transfer 46 (2006), 1501-1511.
[3] Eckert S et al: Efficient Melt Stirring Using Pulse Sequences of a Rotating Magnetic Field: Part I. Flow Field in a Liquid Metal Column, Metall. Mater. Trans. B 38B (2007), 977-988.
[4] Willers B et al: Efficient Melt Stirring Using Pulse Sequences of a Rotating Magnetic Field: Part II. Application to Solidification of Al-Si Alloys, Metall. Mater. Trans. B 39B (2008), 304-316.
[5] Cramer A et al: Experimental investigation of a flow driven by a combination of a rotating and a traveling magnetic field, Phys. Fluids 19 (2007), 118109
[6] Takeda Y: Development of an ultrasound velocity profile monitor, Nucl. Eng. Design, 1991, 126: 277-284.
[7] Takeda Y, Kikura H: Flow mapping of mercury flow, Exp. Fluids 32 (2002), 161-169.
[8] Franke S et al: Ultrasound Doppler system for two-dimensional flow mapping in liquid metals, Flow Meas. Instrum. 21 (2010), 402-409.
[9] Franke S et al: 2d-2c Ultrasound Doppler Array Velocimeter for Flow Investigations in Liquid Metals, 7th ISUD, Göteborg (2010), 89-92.
[10] Franke S et al: Two-dimensional Ultrasound Doppler Velocimeter for Investigations of Liquid Metal Flows, 15th Int. Conference on Sensors and Measurement Technology, Nuremberg (2011), 165-170.