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Abstract
Ultrasound velocity measurements were performed in a liquid metal flow (GaInSn) inside a cubic vessel. The flow was driven by the combined action of a rotating (RMF) and a travelling magnetic field (TMF) leading to an inherent three-dimensional electromagnetic force distribution in the fluid. As a result flow structures develop which are essentially determined by the frequency difference and the strength relation of both fields. The driving force is stationary for identical frequencies whereas it undergoes a slow temporal modulation in case of slightly varying frequencies. Beside the magnetic field parameter the alignment of the TMF's to the fluid volume's axis plays a crucial role. A novel ultrasound array system was used in the present study to measure two velocity components in two perpendicular planes (2d-2c) simultaneously. This contribution reports on the influence of axial alignment on the flow, and on the flow dynamics resulting from slightly different field frequencies of the RMF and the TMF.

Key words: Ultrasound Sensor Array, Flow Field Measurements, Magnetohydrodynamics, Electromagnetic Stirring

Introduction
Electromagnetic processing of materials is well established in industrial applications such as steel casting or crystal growth. Both static and alternating magnetic fields may be employed in order to optimize the stirring process by means of Lorentz forces. The trend for the last years has been to combine and tailor the action of different magnetic field types. A prerequisite for such studies are suitable bulk flow measurement instruments. In opaque fluids the UDV (ultrasound Doppler velocimetry) technique provides a great potential [1, 2]. In a previous work [3] ultrasound velocity measurements in a liquid metal flow were performed in order to study the combined action of an RMF and a TMF. Only one traversable transducer was used in this study. In [4] the flow driven by a TMF was the object of investigation. Few transducers were used to study the sensitivity of the flow with respect to a shift between the axes of the liquid metal column and of the TMF. The present work is devoted to the combination of the previous studies using a novel ultrasound array system. As we shall see, this system allows to measure simultaneously both velocity components in an entire plane. Furthermore, it is demonstrated that the use of ultrasound arrays extends the capabilities for flow mapping significantly.

The measurement system and the experimental setup
For a detailed description of the entire system including the electronics we refer to [5, 6], thus, only some relevant information will be reviewed in this section. The measuring principle is based on the well-known pulsed-wave Doppler technique [2]. A short ultrasound pulse is thereby emitted by an ultrasound transducer into the fluid under investigation. The wave propagates through the fluid and is scattered on small particles such as oxides inherently present inside the medium. Assumed the particles follow the fluid without slip, the scattered wave contains information about the position and the velocity of these particles. Thus, a 1d-1c (1 dimension and 1 component) velocity profile can be obtained along the sound propagation direction. Instead of single transducers, the system used in the present work utilizes ultrasound line arrays to gain a 1c velocity measurement in the spanned plane. Each array consists of 25 piezo-transducer elements with a size of 2.5×5 mm^2 and a gap of 0.2 mm between them. Hence, a measurement field of 67 mm width is covered by such an array. During operation, two adjacent elements are always driven together acting as a single square transducer of 5 mm edge length. In order to scan the entire field covered by one array in a high temporal resolution without cross-talk between the transducer, their operation is parallelized by a special time division multiplex scheme [6]. A frame rate of up to 30 Hz is possible per array. To determine two or more velocity components multiple arrays have to be utilized in a suitable arrangement. Hence, the arrangement as shown in the picture in Fig. 1 is able to deliver the required information to reconstruct the 2d-2c velocity field in an entire plane. Due to technological reasons given by the ultrasound array, a cubic vessel was chosen as the object of the present investigation. The inner dimensions of 67×67×67 mm^3 match the field size of the transducer array. Four arrays were used in a crossed-plane configuration as

shown in Fig. 2. The arrays spanning the horizontal half-height plane capture the primary swirling flow, whereas the arrays of the vertical plane measure the secondary meridional flow inside the vessel. The cube was filled with the eutectic alloy GaInSn. For the purpose to drive the electromagnetically-induced flow in the melt, the vessel was installed inside the MULTIMAG (MULTIpurpose MAGnetic) research facility [7]. MULTIMAG offers a variety of magnetic field types and linear superpositions thereof since it was built without any ferromagnetic yokes. The RMF used here was produced with six rectangular solenoids arranged hexagonally and the TMF with six linearly arranged solenoids in the vertical direction. To allow a precise positioning with respect to the axis of the TMF coil system, the vessel with the assembled transducer arrays was placed on a non-magnetic two-axes crossbar.

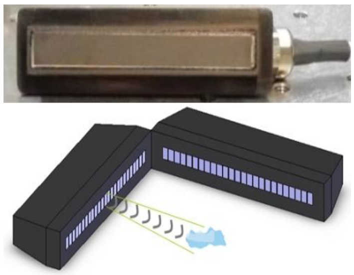

Fig. 1: A picture of the the ultrasound linear array and below it a schema illustrating a crossed arrangement for the reconstruction of a 2d-2c velocity field.

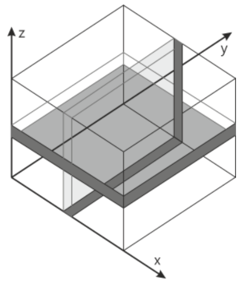

Fig. 2: The measurement configuration used here. Each of the planes is at the half height to the vessels edge, respectively.

The electromagnetically driven flow

Applying an AC magnetic field with strength $\boldsymbol{B}$ to a cylindrical volume with height H and radius R of liquid metal induces an eddy current $\boldsymbol{j}$ within the fluid and the interaction of the current with the magnetic field that produced it leads to an electromagnetic Lorentz force $\boldsymbol{f}_L=\boldsymbol{j}\times\boldsymbol{B}$ acting on the fluid as a volume force. The here used RMF and TMF cause, operating separately, an axisymmetric base flow. Although we use a cubic vessel, the fundamental concept in a cylinder is broadcasted for the present work. Without going into details, we refer to [3, 4] and references therein for this purpose, the forces may be expressed as

$$\boldsymbol{f}_R = Ta\, r\, s(r,z)\,\vec{e}_\varphi\,, Ta = \frac{\sigma\omega_R B_R^2 R^4}{2\rho\nu^2} \qquad (1)$$

$$\boldsymbol{f}_T = \frac{\rho\nu^2}{R^3}\frac{F}{2}\left(f_z,\, f_r,\, f_\varphi\right), F = \frac{\sigma\omega_T B_T^2 k R^5}{4\rho\nu^2} \qquad (2)$$

Apart from material and geometry characteristics the above Taylor number Ta and forcing parameter F are determined by the strength and frequency of the applied magnetic field and represent a dimensionless measure for the driving action of the respective magnetic field. Assumed that axisymmetric condition prevails between the axes of the liquid metal column and that of the magnetic field, the Lorentz force in Eq. (2) has a sole axial component. However, this force exhibits non-vanishing components f_r and f_φ if a certain displacement between the axis is present. Beside the respective body forces an additional interaction term occurs in the Lorentz force in the case of a combined RMF/TMF [3]:

$$\boldsymbol{f}_L = \boldsymbol{f}_R + \boldsymbol{f}_T + \boldsymbol{f}_I = \boldsymbol{f}_R + \boldsymbol{f}_T + \left(\boldsymbol{j}_R\times\boldsymbol{B}_T + \boldsymbol{f}_T\times\boldsymbol{B}_R\right),\ \boldsymbol{f}_I = -\frac{\sigma B_R B_T}{4}\, r\sin(\Delta\omega t+\varphi-kz)\,(\omega_R k r\boldsymbol{e}_\varphi + \omega_T\boldsymbol{e}_z) \qquad (3)$$

If the frequency difference $\Delta\omega = \omega_R - \omega_T$ exceeds a certain value determined by inertia, the impact of the interaction term on the flow vanishes and one is concerned with the linear superposition of the respective forces. Thus, for equal frequencies, $\Delta\omega=0$, the interaction force has only components in the φ- and z-directions and depends on these components. It becomes static but helical and therewith 3d. As soon as the frequencies differ slightly, up to $\Delta\omega \sim u/R$, the force is slowly modulated in time and its influence on the fluid flow decreases accordingly. All measurements presented in the next section were done for $Ta=2\times10^6$ and $F=2\times10^6$ at the technical relevant power line frequency of $\omega=2\pi 50$ Hz, or in the case of the combined fields in its vicinity.

Results

The first step covers the axisymmetric case of the TMF. Thus, the unshifted "zero"-position in the TMF was deduced in a recursive procedure by recording the flow and repositioning the vessel until the best possible axisymmetry was reached. The meridional and horizontal flow maps in the Fig.'s 3 and 4 illustrate this axisymmetric case.

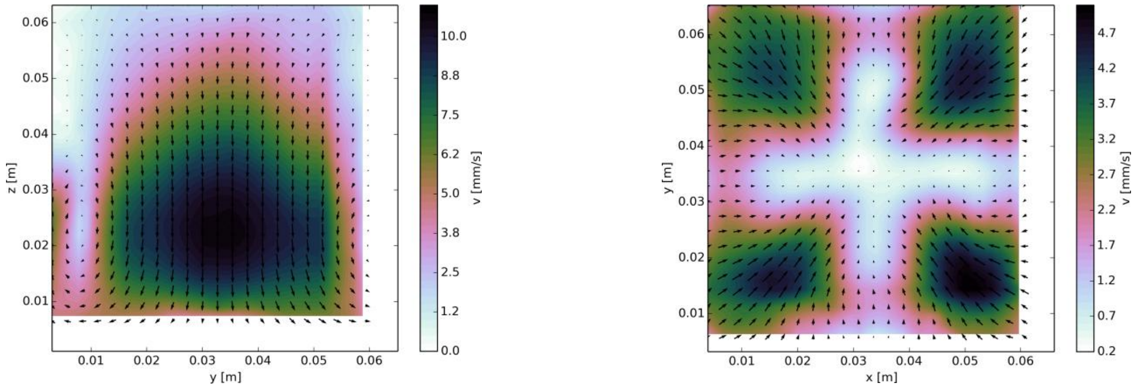

Fig. 3: TMF flow maps under axisymmetric conditions. On the left side the meridional and to the right the horizontal plane, respectively. The arrows indicate the flow direction and the length correlates with the calculated velocity magnitude shown in the color bar.

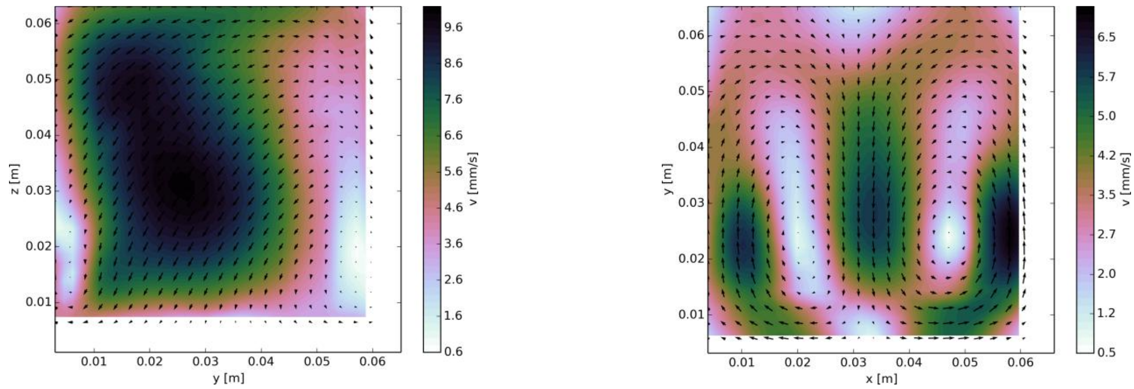

Fig. 4: The same as in Fig. 3 for a shift of 2 mm between the TMF's and vessel's axes.

As can be seen from the vector fields, a measurement in the direct vicinity of the transducers of both velocity components was not possible. This is due to stationary echoes which were caused by multiple reflections inside the vessel wall. These stationary echoes impede the measurements because they interfere with the echoes from the flow. Since a cubic vessel was used, the inward oriented radial flow shown on the right side of Fig. 3 is not so evenly distributed as it would be expected in a cylindrical vessel. Nevertheless, the axisymmetric orientation becomes obvious. Displacing the vessel 2 mm away from the center axis of the TMF, the original toroidal structure in the meridional plane is completely destroyed (see Fig. 4 left). Furthermore, in accordance with Eq. (2), a non-vanishing horizontal component f_φ occurs in the Lorentz force, thus, leading as well to a completely changed flow in the horizontal plane (see Fig. 4 right).

Applying a combined RMF/TMF with identical frequencies the meridional flow consists of a 3D single large-scale cell [3]. A particular meaning becomes in this context the seemingly arbitrary azimuthal angle φ in Eq. (3), which is well defined by the phase relation of the currents in both coil systems. Both vertical and horizontal flow maps were recorded, therefore, in steps of 45°. The Fig.'s 5 and 6 show some examples.

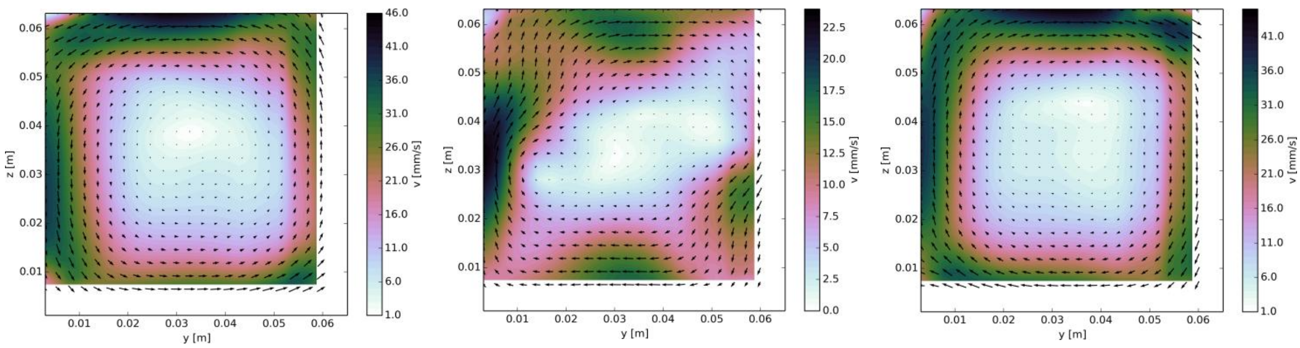

Fig. 5: Vertical flow maps measured with a phase difference of 0°, 90°, and 180° between the RMF and the TMF.

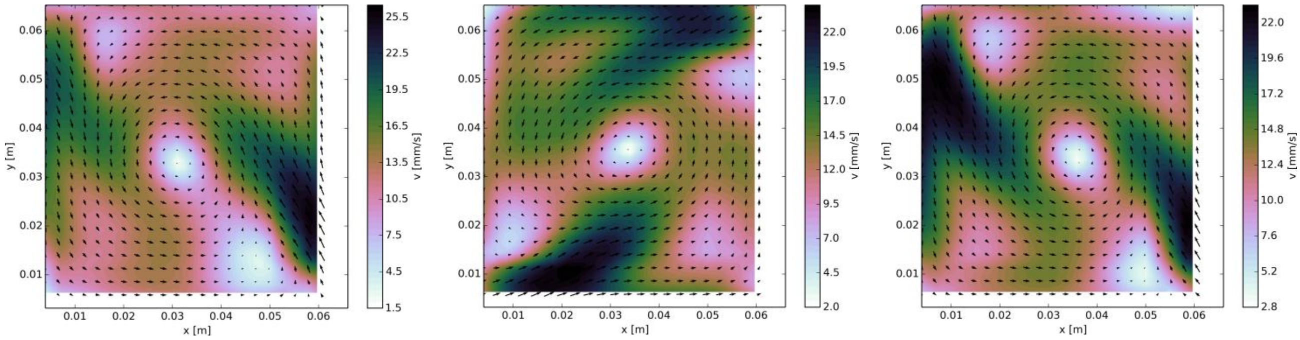

Fig. 6: The same as in Fig. 5 but in the horizontal measurement plane.

Whereas for φ=0° in the meridional plane the rotation sense of the flow is seemingly counter clockwise it changed completely to a clockwise one for φ=180°. It is emphasized that not the flow itself is changed but rather the prevailing static structure was rotated inside the fixed laboratory measurement frame. Thus, varying φ between 0° and 360° allows a precise positioning of the whole structure. The flow maps in Fig. 6 show that the azimuthal rotation sense is not affected by φ. The large-scale flow cell begins to rotate by non-vanishing frequency difference $\Delta\omega$, which becomes obvious by analyzing the local flow velocity at one fixed position. The diagrams in Fig. 7 show the vertical velocity component near to the rim of the vessel as function of the time and the frequency difference. The change in the flow direction is clearly observed for not too large $\Delta\omega$ (on the left in Fig. 7) as it was already argued in context with Eq. (3).

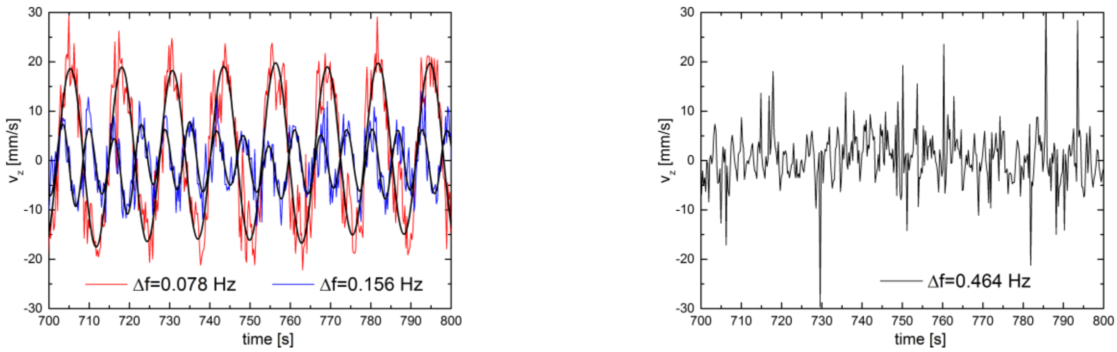

Fig. 7: The vertical velocity component near to the vessels rim for slightly different frequencies (left diagram) between the TMF and the RMF. For a higher difference (right diagram) the velocity large scale oscillations disappear.

Conclusions

The flow driven by a TMF and a combined RMF/TMF was studied experimentally. A new ultrasound array system was used, thus allowing to measure simultaneously both the complex flow map in different planes and also the transient flow. In contrast to previous works, the results demonstrate that a more complex study of the spatio-temporal behavior of the flow is now possible without the restrictions of using either one traversed single sensor or few of them at different positions. The present UDV array system offers great potential for the field of MHD and of the interaction between electromagnetic fields and conductive fluids.

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