The sensitivity of the flow driven by a travelling magnetic field to axial alignment

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The present experimental study is concerned with the sensitivity of the flow driven by a travelling magnetic field (TMF) to axial alignment. Referring to the center axis of the TMF generating coil system the fluid volume was stepwise dealigned. Because the flow induced in a TMF is, basically, of a torus type, vertical velocity components are representative for the motion in the meridional plane. To acquire velocity profiles the Ultrasound Doppler velocimetry (UDV) was used which allows gathering the whole profile along the ultrasonic beam. Several transducers were mounted at the bottom of the fluid covering vessel and connected to the multiplexer channels of the UDV device. Eutectic GaInSn was used as working fluid. Analysing mean velocity profiles and the spatiotemporal properties of the flow, the study shows, that already for small deviations from coaxial conditions the flow topology changes.

Keywords: Ultrasound Doppler Velocimetry, Fluid flow, Travelling magnetic field, Stirring

1 INTRODUCTION

In crystal growth, the transport and distribution of the melt components, such as oxygen, as well as particles emitted from the covering crucible is influenced by the flow. In its native form, without any external influence, the flow is a buoyant convection intrinsic to the specific crystal growth method. Externally applied magnetic fields provide a useful contactless method to influence the flow in particular when material transport inside the melt in a definite way is required.

Studies on travelling magnetic fields in crystal growth started first at the mid/end of the 1990s [1-2] and still are matter of investigation [3-7]. Usually, and to our best knowledge common to scientific investigations hitherto, numerical flow simulations are based on coaxial conditions between the axis of the coil system and that of the fluid containing vessel. Such ideal assumptions are in experimental setups and in particular on industrial scale hardly accomplishable, if ever feasible. Comparisons between theory and experiment have, therefore, to be done in a careful and critical manner.

The aim of the present work is to study experimentally the sensitivity of the fluid flow driven by a TMF displacing the covering vessel stepwise away from the coaxial position. Prior to the experimental setup, measuring technique and results the principle of the action of a TMF on electrically conducting melts will be briefly recalled.

2 THE MAGNETICALLY DRIVEN FLOW

Applying any AC magnetic field with strength $\boldsymbol{B}$ to a volume 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 $\boldsymbol{f}_L=\boldsymbol{j}\times\boldsymbol{B}$. Consequently, the fluid will be set in movement towards the direction of the acting force. Under axisymmetric conditions, Grants and Gerbeth [5] derived a simple analytical expression for $\boldsymbol{f}_L$ acting by a TMF on a melt with height H and radius R as

$$\boldsymbol{f}_L = \tfrac{1}{2} F r^2 \boldsymbol{e}_z, F = \frac{\sigma\omega B^2 k R^5}{4\rho\nu^2}, \qquad (1)$$

with the forcing parameter F and k the wave number being a measure for the axial extension of the coil system. σ, ρ and ν are the electrical conductivity, density and kinematical viscosity of the melt, and ω is the frequency of the TMF. Besides low-frequency and low-induction approximations a long wavelength TMF with $2\pi/k$ » R was assumed in Eq. (1).

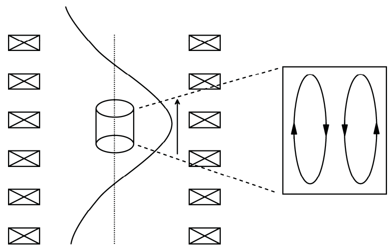

Figure 1: Sketch of the flow in an upward travelling magnetic field. The fluid follows the travelling direction at the perimeter of the container and closes in the centre opposing the Lorentz force, which is weaker there.

The force is of pure axial character and increases radially from the centre of the melt toward the surrounding coils. Thus, it drives a flow in the meridional plane, which is sketched in Figure 1 for an upward travelling magnetic field. Detailed information on the fluid flow may be found in [6-8].

3 SETUP AND MEASUREMENT TECHNIQUE

For the present study eutectic GaInSn was chosen which is liquid at room temperature and has the properties ρ = 6361 kg/m^3, ν = 3.4·10^{-7} m^2/s, and σ = 3.3·10^6 S/m. In order to investigate the driving action of the applied TMF on the fluid, the covering container was positioned inside the home-made MULTIMAG (MULTIpurpose MAGnetic field) facility in which the TMF is generated by six circular solenoids in an axial linear arrangement. Supplying the coils with a 60°-phase-shifted current results, depending on the phase sequence, in a downward or upward travelling field. For further technical details on MULTIMAG [9] is referred to.

The Ultrasound Doppler Velocimetry technique was applied to acquire velocity profiles u_z in the vertical direction at several radial positions. The measuring principle is well known and described in the literature [10]; merely a short description will be recalled here. An ultrasonic transducer acting as emitter sends short ultrasonic pulses with a certain repetition frequency into the fluid. After a pulse sequence, the transducer switches into the receiver mode and collects the scattered echoes, which come back from small tracer particles inside the fluid. The measured time of flight of the ultrasonic pulse relates to the position of the tracers whereas small differences in the time of flight between consecutive pulses are determined by a correlation technique. This phase shift is a measure for the velocity of the particles in the particular measuring volume. Two main features make this technique attractive for our purposes. Firstly, in contrast to optical measurement methods, such as PIV, the applicability in opaque fluids and secondly the possibility to acquire a whole velocity profile along the ultrasonic beam line. To acquire the velocity profiles the commercial DOP2000 velocimeter (Model 2032, Signal-Processing, Lausanne, Switzerland) with an integrated multiplexer module was equipped with seven 8 MHz transducers. All sensors were mounted at the bottom of the fluid covering vessel with the inner dimension of 60 mm in diameter and height. Six of them were azimuthally allocated every 60° near to the vessel rim at the radial position 24 mm, the seventh in the centre. The mean time between consecutive sensors or multiplexer channels was about 150 ms, to acquire one complete set of profiles the time amounts to slightly over 1 second. 6000 profiles per channel were acquired for each measurement, which results in a total recording time of almost two hours.

For an accurate and well-defined displacement between the vessel and the TMF axis, the vessel was mounted on a non-magnetic XY-stage with a positioning sensitivity of 0.01 mm.

4 MEASUREMENTS AND RESULTS

Naturally, the first measurement has to cover the axisymmetric case. Thus, the aligned "zero"-position was deduced in a multistep procedure by recording the ultrasonic profiles and repositioning the vessel. Figure 2 shows the recorded velocity profiles in this case.

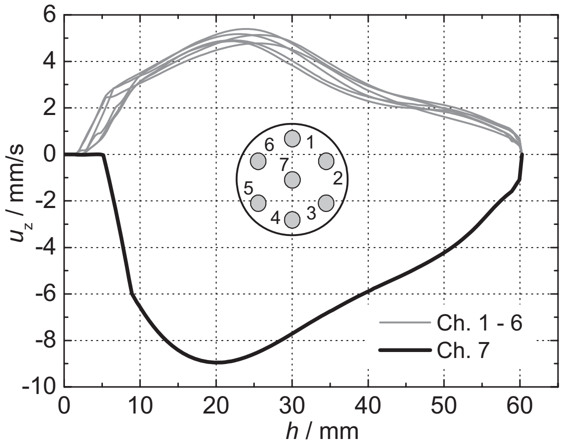

Figure 2: Mean velocity profiles recorded for F=1.0·10^6 under axisymmetric conditions. Positive values indicate a flow away from the sensor, which means here an upward oriented flow. Negative values mean a flow towards the sensor, here downward oriented. The inset shows the allocation of the sensors.

Displacement steps, afterwards, each 0.125 mm were applied between the centered zero-position and 1 mm. The displacement was always along one of the axis of the XY-stage, which accords with the diameter between the sensors no. 2 and 5. Displacing the filled vessel in this manner the fluid volume gathered by sensor no. 2, called outer sensor henceforth, gets closer to the surrounding coils. By contrast, the region gathered by sensor no. 5 (called inner sensor) will get closer to the center axis of the TMF.

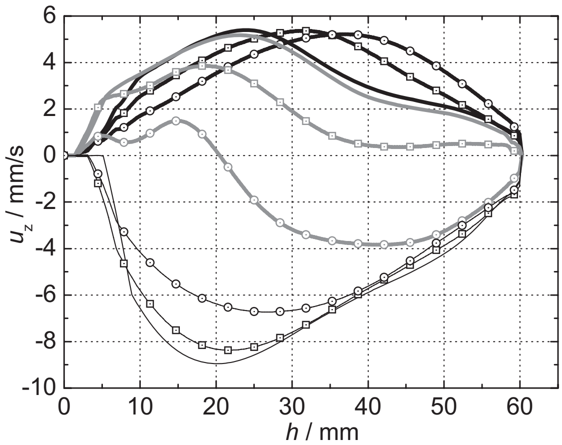

Figure 3: Mean velocity profiles at selected positions along the shifting diameter. Thick black lines indicate the outer, thick grey lines the inner and the thin black lines the centre sensor. Lines without symbol refer to the axisymmetric case, squares and circles to the shifted steps of 0.5 and 1.0 mm, respectively.

As can be seen in the figure, a displacement of up to 1 mm shows no qualitative influence on the flow in the volume part gathered by the outer and centre sensors. This becomes also obvious from the spatiotemporal structure shown in Figure 4 and extracted time series in Figure 5. A dealignment of up to 1.0 mm, cf. Figure 5, causes rather a certain stabilizing effect on the flow regarding the amplitude of velocity fluctuations.

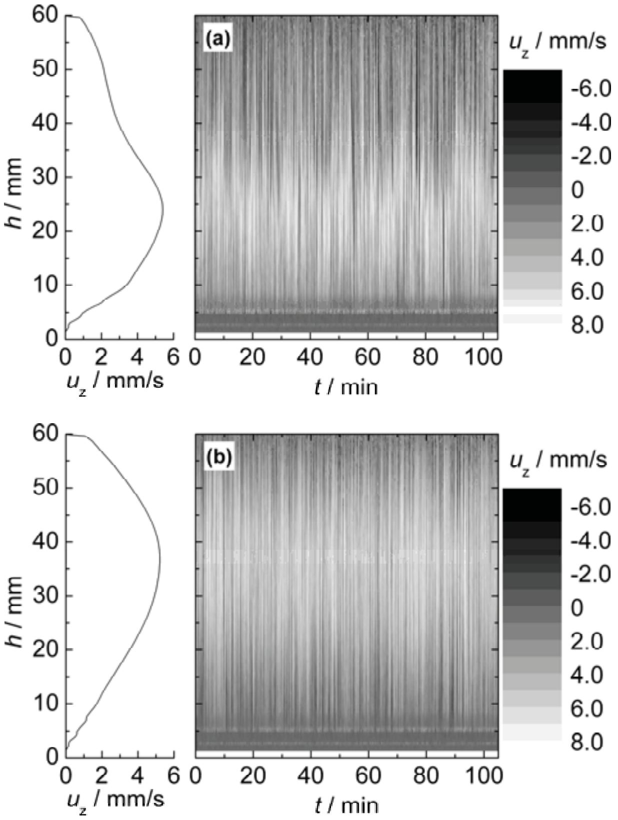

Figure 4: Spatiotemporal flow structure recorded with the outer sensor; (a) illustrates the coaxial zero position and (b) the 1.0 mm dealigned case. The calculated mean velocity profiles are shown on the left side.

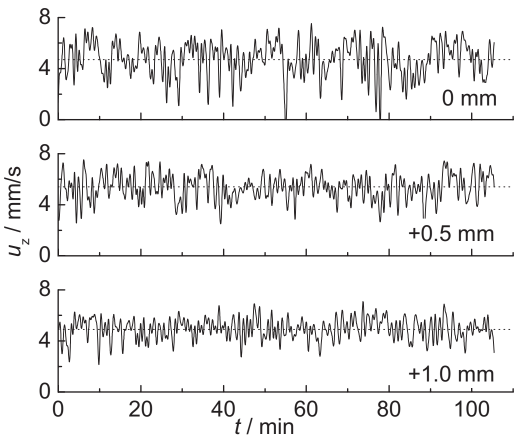

Figure 5: Extracted time series at the half height of the fluid volume from data recorded with the outer sensor. The dealignment steps are indicated in the figures just as with dotted lines the calculated mean velocities.

On the other hand, through dealignment of the vessel, the part of the fluid measured by the inner sensor gets more and more toward the axis of the TMF where the driving action of the Lorentz force is weaker. Depending from the dealignment distance, the Lorentz force cannot balance the recirculating flow coming from the outer side and the flow at the inner side becomes therefore less stable and even reverses its flow direction. Figure 6 illustrates this behaviour by means of time series extracted from the ultrasonic data stemming from the inner sensor.

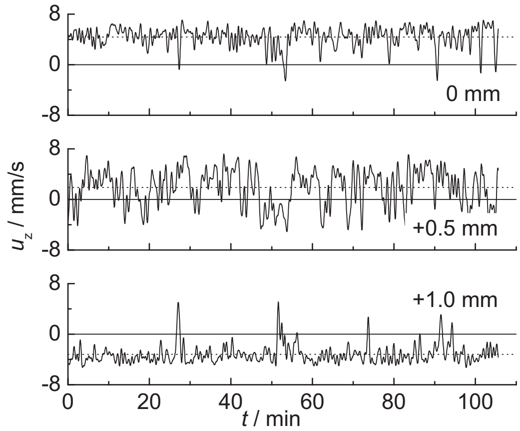

Figure 6: Extracted time series at the half height of the fluid volume from data recorded with the inner sensor. The dealignment steps are indicated in the respective figure, dotted lines are calculated mean velocities.

Regarding the calculated mean profiles, Figure 7 illustrates in detail the sensitivity of the flow to the dealignment of the vessel by steps of 0.125 mm. Starting from the aligned position, for a displacement of about 0.5 mm the vertical flow velocity decrements to almost zero in the upper half of the container. With further displacement the flow changes its structure from a single vortex to rather a double vortex in which the upper vortex becomes more and more distinct.

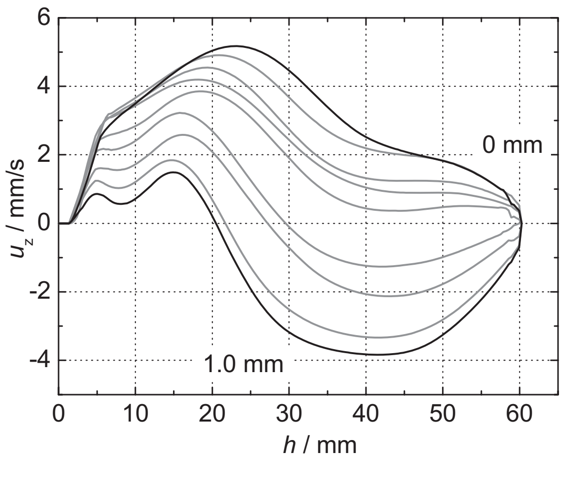

Figure 7: Mean vertical velocity profiles recorded with the inner sensor for displacement steps of 0.125 mm between the coaxial zero-position and the 1.0 mm shifted one.

In comparison to Figure 4, Figure 8 shows the spatiotemporal structure for the inner sensor.

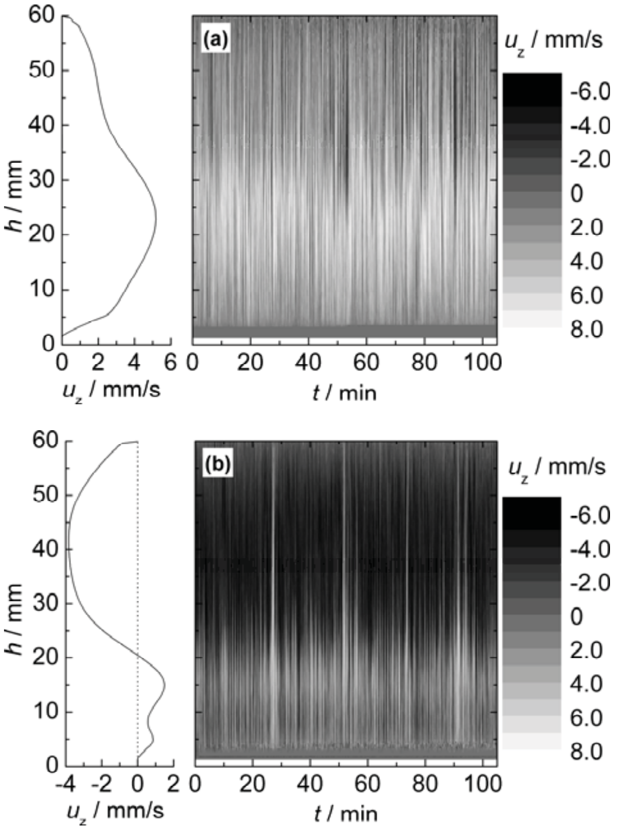

Figure 8: Spatiotemporal flow structure recorded with the inner sensor. Legends for (a) and (b) are the same as in Figure 4.

5 SUMMARY

The present study gives insight into the flow driven by a TMF. In contrast to the usual coaxial arrangement between the fluid and the axis of the magnetic field, in the present work the corresponding axis were stepwise displaced. Performed ultrasonic measurements evince clearly the sensitive behaviour of the TMF driven flow to the axial alignment with the coil system producing the TMF.

6 ACKNOWLEDGEMENTS

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