

# Local flow structures in liquid metals measured by ultrasonic Doppler velocimetry

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## Abstract

Ultrasound Doppler velocimetry (UDV) has been successfully applied to measure local velocities in mercury and the eutectic alloy InGaSn. Two different kinds of magnetic fields established the fluid motion in a cylindrical vessel. For both, the rotating and the travelling field, agreement with expectations from theory and local measurements employing different techniques was achieved.

The deliverance of a profile by UDV instead of one value at one fixed co-ordinate, typical for almost any other method, allowed for the determination of the topology in a plane covered by the ultrasonic beam while the sensor was traversed. These area-wide results are, by nature, time averaged, respectively, mean velocities.

The range of flow regimes regarding the magnitude of velocity which is detectable by means of the Doppler procedure begins already in the turbulent region. For the case of the rotating magnetic field, spectral distributions of time series of velocity signals measured at different positions in the fluid volume will be presented.

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*Keywords:* Ultrasonic Doppler velocimetry; Magnetohydrodynamics; Liquid metal; Electromagnetically driven flows

## 1. Introduction

The use of ultrasonic techniques for flow measurements is well established for the goal of determining the integral flow rate in a pipe [1]. Many tasks concerned with process or product optimization in branches like metallurgy, crystal growth or electrochemistry require the knowledge of the local flow structure. Here important phenomena like mixing, separation of inclusions, transport of dopants or the energetic balance in electrolyses cells are essentially determined by local flow properties. The possibility to measure small time of flight differences between reflected pulses provides the basis to measure local velocity fields by means of ultrasonics. This method is known as ultrasonic Doppler velocimetry (UDV).

During the last decade, UDV became a powerful tool as can be seen from the commercial availability of complete systems. Its capability to deliver data from

liquid metal flows was first demonstrated by Takeda [17] for mercury. Brito et al. [2] showed that UDV works for gallium too. This may not be simply taken for granted because mercury and gallium differ strongly with respect to their physical and chemical properties which are important for the availability of scattering particles as well as the wetting behaviour at walls. Gallium heavily suffers from oxidation whereas the noble metal mercury does not to such an extent. As we shall see such differences have an influence on the applicableness of UDV to the various melts.

Obviously, ultrasonic measurements are very attractive for flows of opaque liquids for which the usual optical techniques like LDA or PIV are not suitable. For a recent review on measuring techniques for opaque liquid metal flows, we refer to [8]. A second feature of ultrasonics is even more attractive for the application to hot or aggressive fluids: it can operate through walls enclosing the melt.

Today several tendencies can be observed which are concentrated on an appraisal of aptitude or further improvement of the pulsed Doppler method. One branch

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arises from the attempts in the areas of metallurgy and crystal growth to obtain a better understanding of the fluid flow involved within their high temperature processes. Commercially available transducers are limited to a maximum between 150 (permanent operation) and 200 °C (short term load). Transducers for higher temperatures exist, e.g. GaPO<sub>4</sub>, LiNbO<sub>3</sub>, but their sensitivity is usually not sufficient for Doppler measurements. Eckert and Gerbeth [5] report on successful UDV measurements in liquid sodium employing a standard sensor. The problem they had to solve was the acoustic coupling through a stainless steel wall containing the chemical aggressive sodium rather than the temperature of about 170 °C. For an application to metallurgically interesting melts at higher temperatures, Eckert et al. [6] report on the development of an acoustic wave-guide. On this basis, successful measurements exist for melts like Pb–Bi in the range of 200–400 °C, Cu–Sn at about 620 °C and liquid aluminum at about 750 °C [6,8].

A second line of UDV development consists of increasing the spatial and temporal resolution of complex flow structures. On the one hand, this encompasses the application of several transducers to overcome the limitation of one-dimensional information delivered by one of them alone. First attempts employing an array of transducers have been reported by Takeda and Kikura [18]. On the other hand, this development aims at the investigation of turbulent properties of the flow. Turbulence analysis by means of UDV is presently at its very beginning. As a recent paper devoted to technical measurement aspects, we refer to Sato et al. [15] who reported on an increase of the profile scan rate by one order of magnitude using an advanced auto-correlation procedure.

The present paper contributes to the investigation of complex flow structures in liquid metal flows. For this purpose, we have chosen the flows driven by two types of alternating magnetic fields, the rotating magnetic field (RMF) and the travelling magnetic field (TMF). In a cylindrical container, the RMF primarily drives a flow in the azimuthal direction, but due to the viscous friction at the bottom and top walls a secondary, radial–meridional flow occurs. In many applications like mixing or the heat and mass transport in crystal growth technologies, this secondary motion plays a determining role. In the second case of a TMF, there is no azimuthal rotation of the melt but a radial–meridional flow, only. Main goals of our work are to measure these mean flow structures and to obtain first 2D-results on the turbulent properties of the flow. That required to find a good compromise between the spatial resolution to map the complex flow structure, the sensitivity to distinguish the velocity fluctuations from the mean flow, and the sampling rate. The paper concentrates on the details and problems encountered by

the application of UDV rather than the fluiddynamic aspects.

## 2. The magnetically driven flows

The RMF/TMF driven flows in a cylindrical container are often considered to be well known. This is true insofar the basic laminar flow is considered. The steady RMF driven flow consists of an almost rigidly rotating core separated from the bottom and top walls by pronounced horizontal boundary layers. In those layers, the centrifugal force is only partially balanced by the wall shear, resulting in an inward directed pressure gradient which drives a secondary flow. This secondary flow consists of a double vortex structure with the flow radially inwards at the bottom and top walls, but radially outwards at mid-height of the container. Compared to the primary rotation of the fluid, the maximum velocity of the secondary motion is believed to be smaller by a factor in the range of 5–10. It should be emphasized that to the best of our knowledge, this secondary flow structure has never been validated in experiments, mainly due to the missing measuring techniques for its resolution. For a review of the RMF driven flow, we refer to Davidson [4]. The stability of this rotating flow has only recently been resolved [10], showing an interesting non-linear non-normal transition to turbulence leading to highly intermittent flows considerably below the threshold of linear stability [11]. This parameter range, however, is not of interest here as our present experiments are in the turbulent regime. Estimates about the flow field in the turbulent range were made by Davidson [3].

The flow field driven by a TMF is straightforwardly determined by the driving force components in the radial and vertical directions resulting in a single vortex flow structure. The flow direction depends on the phase relation between the TMF coils and can be easily adjusted upwards or downwards at the sidewall of the container. For a numerical simulation of the TMF driven flow, we refer to Mazuruk [13].

Let us introduce some basic parameters describing these flows. The magnetic fields are characterized by a frequency  $\omega$  and an amplitude  $B$ , the fluid volume by a radius  $R$  and a height  $H$ . The metallic melt has a density  $\rho$ , a kinematic viscosity  $\nu$ , and an electrical conductivity  $\sigma$ . We restrict our studies to the case of low frequency fields with a small shielding parameter  $S = \mu\sigma\omega R^2 \ll 1$  where  $\mu$  is the magnetic permeability. It means that the alternating magnetic fields penetrate through the melt without distortion. For the RMF, it then turns out [4] that the resulting flow field is basically determined by a single parameter, the Taylor

number

$$Ta = \frac{\sigma \omega B^2 R^4}{2\rho v^2}. \quad (1)$$

More exactly, the Taylor number remains as single characteristic parameter, besides the aspect ratio  $R/H$ , if the low-induction approximation  $Ha \ll Ta^{1/6}$  is fulfilled, implying that the flow does not influence the driving volume force.  $Ha$  is the Hartmann number  $Ha = BR\sqrt{\sigma/\rho\nu}$ .

Though the action of the TMF depends, besides  $\omega$  and  $B$ , also on the ratio between the vertical coil spacing and their radius, we describe it for simplicity by the same Taylor number (Eq. (1)) following Mazuruk [13].

### 3. UDV in liquid metals

The measuring principle of UDV is well described in the literature [17]. With a certain pulse repetition frequency (PRF) short ultrasonic pulses are sent into the fluid. The method is based on the existence of scattering particles in the fluid which reflect the ultrasonic waves. The measured time of flight  $\delta t$  of the ultrasonic pulse determines the location of the particle, whereas the small differences in  $\delta t$  between consecutive pulses relates to the local velocity. Both informations together deliver a full profile of the local velocity distribution along the ultrasonic beam. More exactly, the projection of the unknown three-dimensional velocity field onto the ultrasonic beam is measured. Which specific problems arise if UDV shall be applied to liquid metal flows? The essential problems for that case are:

- Thermal restrictions of the ultrasonic transducer at high temperatures.
- Acoustic coupling between material boundaries.
- Resonance effects regarding the transmission through container walls.
- Allocation of suitable tracer particles in the fluid to scatter the ultrasonic wave.

A solution of the temperature problem consists in the use of acoustic wave-guides as already mentioned above [6]. If we restrict our considerations to low temperatures, the problems with respect to the beam transmission, the wetting or the reflecting particles remain.

A good wetting contact between the liquid metal and the active acoustic surface guarantees the reception of Doppler signals. Non-wetted interfaces can cause a sudden change of the acoustic impedance if gas layers or impurities are present. This leads to reflections being detrimental with respect to the beam transmission. The large surface tension of the liquid metals and the occurrence of oxide layers complicate significantly the wettability. In many experiments, the liquid metal flow

to be measured is enclosed by stainless steel walls. Here, the oxide layers on the steel surface have to be carefully removed by a thermal [9] or a chemical treatment [5], respectively. Our experiments presented within this paper show that also a good acoustic coupling can be achieved to a metallic melt through a wall made from Perspex. In this case, one does not expect a wetting between the melt and the wall. However, we observed a spreading of a InGaSn drop on a Perspex plate if a high concentration of oxides at the surface of the liquid metal occurs. The oxides seem to work as a kind of glue covering the Perspex surface as thin film. In the case of mercury, an acoustic contact was received if the fluid container was carefully filled to avoid any gas layer at the inner walls.

The reception of a Doppler signal requires the existence of reflecting particles inside the liquid. We are not aware of any detailed, quantitative studies in liquid metals focusing on the dependence of signal properties on parameters like the concentration, the morphology (e.g. size, shape) and the acoustic properties of the suspended scatterers. Difficulties arise if reflecting particles should be added in a well controlled way to liquid metal flows: such particles have nearly to match the fluid density to prevent a slip between the motion of the fluid and the particles and to guarantee a homogeneous distribution in the entire fluid volume. The particles have to be wetted by the liquid avoiding agglomeration effects. Moreover, an efficient method must be available to separate the particles from the fluid after the measurements to minimize a contamination of the fluid. Having this in mind, it is obvious to try to work solely with the natural impurities such as oxides or microbubbles being always present in metallic melts with a technical purity standard. Our experiences regarding the tracer problem will be discussed in Section 5.3.

### 4. Experimental aspects and the set-up

The velocity measurements have been carried out in a combined RMF/TMF magnet with 90 mm bore diameter and a height of 220 mm. The set-up for the six RMF coils is that of the windings of an asynchronous motor, with the liquid metal being the rotor. For the TMF, six solenoids have been used in the usual manner of supplying them with a 60° phase shifted current between adjacent coils. The principle arrangement of the combined field magnetic system is depicted in Fig. 1. To gain induction ferromagnetic yokes were employed as magnetic return paths. Special care was taken to control the magnetic field strength because it enters the Taylor number quadratically. New developed current controlled three-phase AC-supplies (EAAT Ltd., Chemnitz, Germany) were used allowing to balance

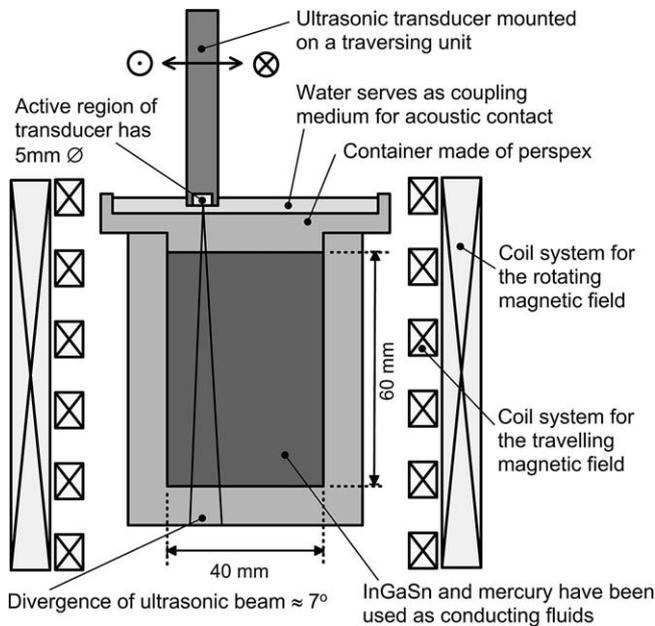


Fig. 1. Principle of the experimental set-up used for UDV measurements of electromagnetically driven convection in a cylindrical column of liquid metal. The figure is not drawn to true scale except the container and the UDV related measures. Real dimensions of the magnetic system are 90 mm in free inner diameter and 220 mm in height.

the coils heat up and thereby the change of their electrical resistance during the experiment.

The homogeneity of both fields was checked by a 3-axis Gauss meter (Lakeshore model 560, sensor type MMZ2560-UH). The variation of the induction was determined to be smaller than 3% within a radius of 20 mm, which was selected as the radial dimension of the cylindrical container. The aspect ratio of the container was chosen as 1.5.

Measurements were made in the RMF using the eutectic alloy InGaSn, while the experiments in the TMF were carried out with mercury. For the radius  $R = 20$  mm maximum Taylor numbers of  $Ta_{\max} = 4.9 \times 10^7$  for the RMF with InGaSn, and  $Ta_{\max} = 1.3 \times 10^8$  for the TMF with mercury, respectively, can be achieved according to Eq. (1). The corresponding Hartmann numbers are given as  $Ha_{\max} \approx 20$  for both field types. Calculating the shielding parameters for maximum attainable field strengths gives  $S_{\max} = 0.26$  for the combination InGaSn/RMF, respectively  $S_{\max} = 0.08$  for mercury and the TMF for the powerline frequency of 50 Hz used in the experiments. According to Davidson [3], the low frequency approximation gives accurate results in the limit of 1% up to  $S = 1.4$ .

A lid has been mounted on top of the container. This choice was guided by several requirements: first the protection of the liquid surface from heavy oxidation. Next, the experimental data should later be compared to numerical simulations which become

much more problematic in case of a free surface. The ringing effect of the ultrasonic transducers following immediately after the pulse emission prevents velocity measurements directly at the sensor surface. A 15 mm thick lid helps to skip this dead region in order to make the region directly below the metal surface, which is of high interest from a fluidmechanical point of view, accessible. The upper part of the lid was machined as an annular rim. During the experiments, it was filled with water acting as acoustic coupling medium between the transducer and the surface of the lid. Installation of the ultrasonic transducer at the top of the lid, with the axis aligned to that of the container, determines that the vertical component of the velocity can be measured. A cross-beam (Isel dual track feed unit 1) allows for a radial positioning of the sensor with an absolute precision of 0.0125 mm at a repeatability of 0.01 mm. For data acquisition and processing, we used the DOP 2000 (model 2150, Signal-Processing, Lausanne, Switzerland) with the 8 MHz transducer (TR0805LS) for mercury and the 10 MHz variant (TR1003LS) for the InGaSn, respectively. The choice of these high emission frequencies was guided by the higher resolution which was indeed needed as we shall see in Section 5. On the other hand, the attenuation increases with the frequency too. As a consequence, the signal quality for the mercury became unacceptable with the 10 MHz transducer. The lateral size of the measuring volume just behind the lid can be estimated to be 5 mm for the 8 MHz transducer and 3 mm for the 10 MHz transducer, respectively. Taking into account the divergence of the ultrasonic beam inside the different fluids [6], we obtain lateral sizes of about 7.5 mm for the 8 MHz sensor, and 9 mm for the 10 MHz transducer at the bottom of the cylinder. To get a pictorial impression about the spatial resolution the ultrasonic beam is sketched, together with the container, in Fig. 1.

An as high as possible PRF appears desirable to increase the profile scan rate which limits the power spectra of the velocities by Nyquist's theorem. It is well known, e.g. described in the DOP 2000 users manual, that the product of maximum measuring depth with the maximum measurable velocity is a linear function of the PRF. For our specific geometry, we did not discover any problems with the depth, but the sensitivity was decreasing rapidly with increasing PRF due to the increasing measurement range. According to the algorithm implemented in the DOP2000 a couple of emissions is required to construct a profile, which was the most severe restriction regarding bandwidth. It was somehow an optimization task which could be satisfactorily solved with approximately 6 kHz PRF and 128 emissions for the RMF, respectively, 2 kHz and 50 emissions for the TMF. By that we reached a profile scan rate of 37 Hz for the RMF and 30.4 Hz for the

TMF from which we can expect to cover essential information about the turbulent characteristics of the flows under investigation.

## 5. Results and discussion

### 5.1. Mean flow

We restricted both measurements using the TMF as well as the RMF to the 50 Hz powerline frequency. As always the same container was used, the only determining parameter for the strength of the driving force, besides the physical properties due to the different liquids, was the magnetic induction  $B$ . The experiments have been carried out at  $Ta_{\text{TMF}} = 3.2 \times 10^7$  and  $Ta_{\text{RMF}} = 9.5 \times 10^6$ . The corresponding Hartmann numbers are 7.6 and 7.2, respectively. Thus the low-induction limit is almost fulfilled. There was no reason to keep both Taylor numbers identical, so we chose them from the aspect of receiving reasonable velocity profiles with typical values being roughly comparable. For the investigated values of  $Ta$ , the flow is already turbulent. Consequently, a flow map for the mean velocity has to be an average over at least several periods of the lowest frequency of velocity fluctuations. For each of the 41 radial positions, we sampled 512 profiles. The results are shown in Figs. 2 and 3. To the first impression the maps look rather asymmetric. During preparatory tests where we did not specially focus on the very precise adjustment of the container and the magnet, this asymmetry was much more pronounced. For the TMF, even

the torus structure was not recognizable. For the maps depicted here, we had to align all axes very properly by means of a spirit level. As expected, the flows under consideration are very sensitive against tilting between the axis of the magnet and the container, and the measurements even more depend on the precise adjustment of the ultrasonic transducer.

It can be clearly seen that the details of the flow structure are smeared out in the lower part of the container, the reason of which is a loss of spatial resolution described in Section 4. It becomes significant already for the small depth of 60 mm used here. Nevertheless, the structures of a single vortex for the TMF driven flow and the double vortex of the secondary flow induced by a RMF could be clearly resolved by means of UDV. For a qualitative comparison to more recent numerical results, we refer to Grants and Gerbeth [10] for the RMF and to Mazuruk [13] for the TMF.

Unfortunately we had no access to the azimuthal velocity component by UDV due to geometric restrictions of the magnet. A well established technique to measure local velocities in conducting fluids is the potential difference probe (PDP) described, e.g. by Ricou and Vives [14]. We employ this method in the usual modification of replacing the permanent magnet at the tip of the probe by a weak DC magnetic field applied to the whole fluid volume [8]. For the weakly turbulent regime, we found an excellent agreement with the scaling law provided by Davidson [3] up to a Taylor number of  $Ta \approx 1.7 \times 10^6$ . Thus, the regime where the UDV experiments have been performed fall

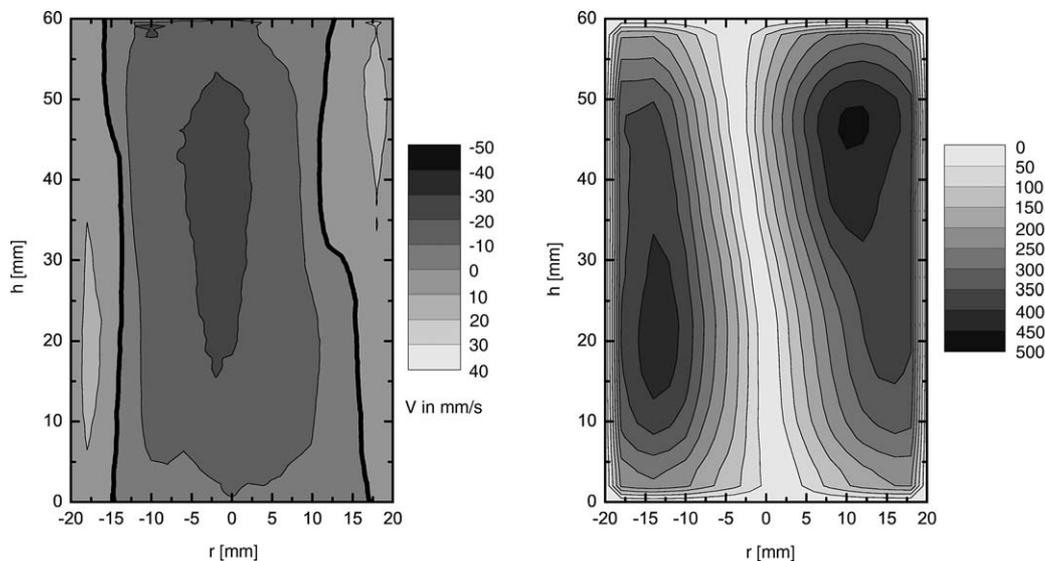


Fig. 2. Flow mapping of the axi-symmetric mean flow driven by a travelling magnetic field. Left: iso contours of the vertical velocity component  $v_z$  in a plane through the centre of the container; right: streamfunction  $\Psi$  numerically calculated from the measured velocities. In the contour plot, the boundary between up- and downstream regions is depicted by a thick line, for the upwards travelling field the downstream return flow is located in the middle of the vessel. To clearly demonstrate the flow structure, we choose the absolute value in the presentation of  $\Psi$ . The *left vortex* rotates clockwise whereas the *right one* spins counter-clockwise.

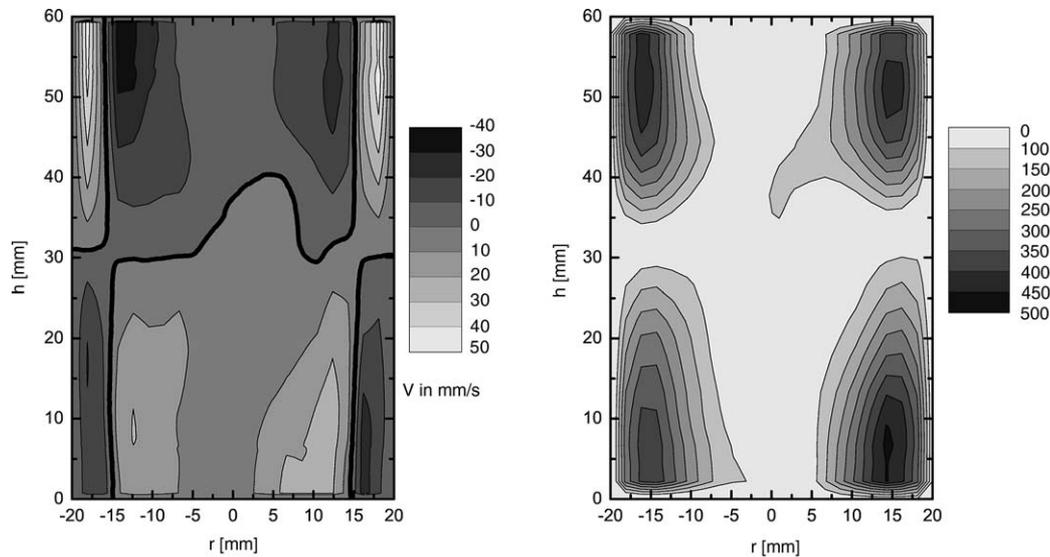


Fig. 3. Double vortex structure of the axi-symmetric mean flow driven by a rotating magnetic field. Left: iso contours of the vertical velocity component; right: streamfunction numerically calculated from the measured velocities. For a more detailed description, see caption of Fig. 2.

already in the highly turbulent region. Here, the PDP result was  $v_{\text{phi}} = 19.2$  cm/s measured at a radial position of 75% of the container radius. From the known radial dependence of  $v_z$  the maximum velocity for the swirl is estimated as 20.5 cm/s. In Figs. 2 and 3, the range of velocity values span from  $-20$  to 30 mm/s for the primary type flow of the TMF whereas it covers a difference of 90 mm/s for the RMF's secondary recirculation. The ratio between the respective maximum velocities of primary to secondary RMF driven flow calculates as 4.6, which we can state as a good agreement to the theoretical expectations. Care must be taken in an attempt to compare the mean flow results between RMF and TMF on the basis of the Taylor number alone.  $Ta$  determines the strength of the driving forces. To estimate velocities the underlying scaling laws have to be known. Recalculating the dimensional velocities from the theoretical expectations based on the Taylor number we found reasonable agreement with the experimental result.

## 5.2. Velocity fluctuations

One of the most important questions in materials processing, particularly for transport and mixing of liquid metals, is that about magnitude and distribution of turbulence. The formula to calculate the turbulence intensity resembles that for the standard deviation across a time series. It is straightforward to create a map for the velocity fluctuations from the same data as used already for the mean values. It should be noted that such a fluctuation map is that of one velocity component. Since the different radial positions are not

acquired instantaneously there is no means to calculate the perpendicular direction as has been implicitly done in Figs. 2 and 3 when computing the streamfunction for the mean flow. The results for both field types are depicted in Fig. 4. Compared with Figs. 2 and 3, it seems that the regions of highest velocity fluctuations are related to the gradient of the mean flow field rather than to the absolute values.

We found only one publication where a mapping of turbulent intensity is given together with its mean flow field. In their numerical work, El-Kaddah and Natarajan [7] define this intensity as the turbulent kinetic energy  $k$  normalized with respect to the mean velocity  $v_m$ . Despite the facts that  $k$  may be interpreted as the square of our fluctuation map, and that the driving force in [7] is mainly located in the bulk whereas in our case at the container walls, agreement can be stated at least to qualitative level with regard to the correlation of fluctuations to the gradient of the velocity field.

Comparing the mean as well as the maximum values from the fluctuation maps to that of the mean velocity, it is striking that this ratio is much higher for the TMF. Care should be taken with the interpretation, in order to judge that an RMF driven flow is less turbulent deserves further investigation of the other velocity components.

The maximum achievable profile repetition frequencies were 37.2 Hz for the RMF, and 30.4 Hz for the TMF, respectively. These values allow, at least for a limited bandwidth, the calculation of a spectral distribution by means of Fourier transformation. The application of the standard FFT leads to problems, because null samples occurred at different positions in the particular velocity profiles caused by an insufficient

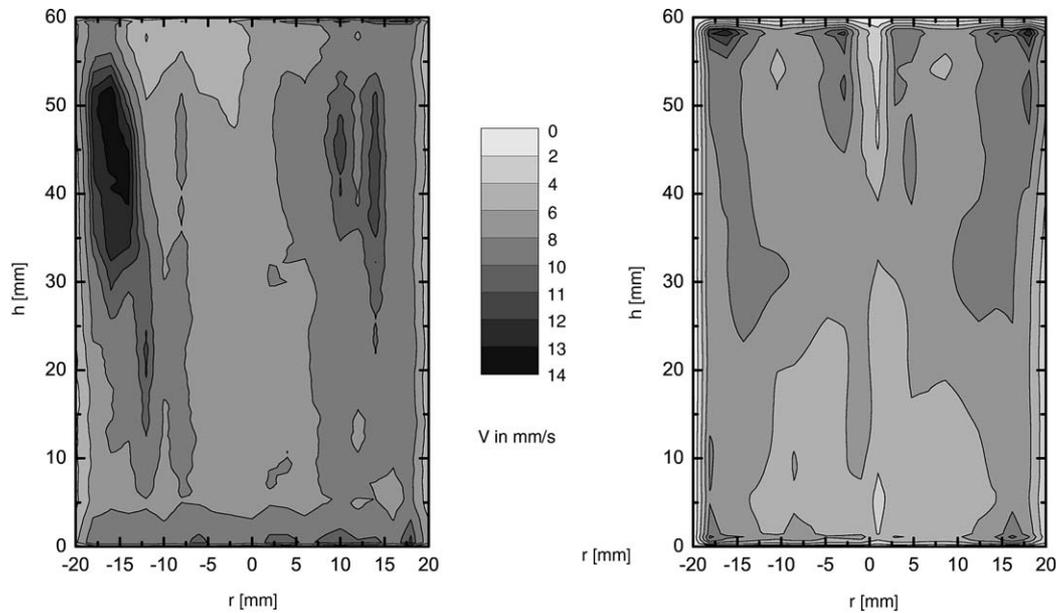


Fig. 4. Iso contours of the standard deviations of the vertical velocity component  $v_z$ ; left: flow driven by a travelling magnetic field; right: for the rotating field. These fluctuations belong to the mean velocities from Figs. 2 and 3.

correlation of the echo signals at the corresponding measuring gates. One reason for this phenomena could be a lack of tracers in the measuring volume. Having a fairly high spatial resolution of 250, respectively 370 gates in the vertical direction compared to the 41 radial positions, we decided to calculate the missing values within each profile. Here the same holds as for the time dependence, the simple filters solely average and smear out the spatial information. Good experience was made with filtering coefficients according to Savitzky and Golay [16] and Bezier splines. Time series at one coordinate were transformed by the moving overlapping window method which delivers superior results at a small loss in spectral resolution. Conveniently Hamming windowing was applied to take account of the end effects.

Fig. 5 contains the results for the RMF. The four graphs show different regions regarding the radial position which are described in the caption. Most interesting are the spectra for the outer 3 mm at the rim and the centre 5 mm. The power density at the rim is higher in average and nearly constant whereas large structures are found in the centre. One explanation is the centrifugal force scaling linear with the radial position which damps large scale structures. The other point of view is that large vortices created in the inviscid bulk are swept through the viscous boundary layer by the recirculation where they decay. We tried to calculate spectra for the TMF driven flow too. We do not fully provide these results here because they are not as reliable as that for the RMF flow due to the numerous null samples.

### 5.3. Discussion of the UDV applicability

It seems appropriate for the scope of this paper not to present the results only, but to report also on the measuring problems arising during the course of the experiments. Originally we intended to do all experiments with the eutectic melt InGaSn which is liquid at room temperature. In the case of the experiment with an applied TMF, no velocity profiles could be detected. The reasons for this failure could not be completely clarified until now, but it became obvious that the procedure to prepare the metallic melt and to fill the fluid container has a significant influence on the quality of the Doppler signals.

Replacement of the InGaSn by mercury allowed for the acquirement of velocity profiles. Mercury has a lower sound velocity (1450 m/s) compared to that of InGaSn (2740 m/s), resulting in a better spatial resolution. On the other hand, mercury belongs to the group of precious metals characterized by a small oxidation rate. The lack of impurities may give rise to a problem for the UDV measurements because inhomogeneities inside the liquid are necessary to generate the Doppler echoes.

Kikura et al. [12] introduced gas bubbles into mercury to generate reflecting particles. The motion of gas bubbles in heavy fluids is strongly governed by the buoyancy force. For larger bubble diameters, this leads to a discrepancy between the liquid and the bubble velocities with respect to the amplitude as well as the direction. Furthermore, a large gas fraction can generate a bubble driven motion. Accurate measurements of

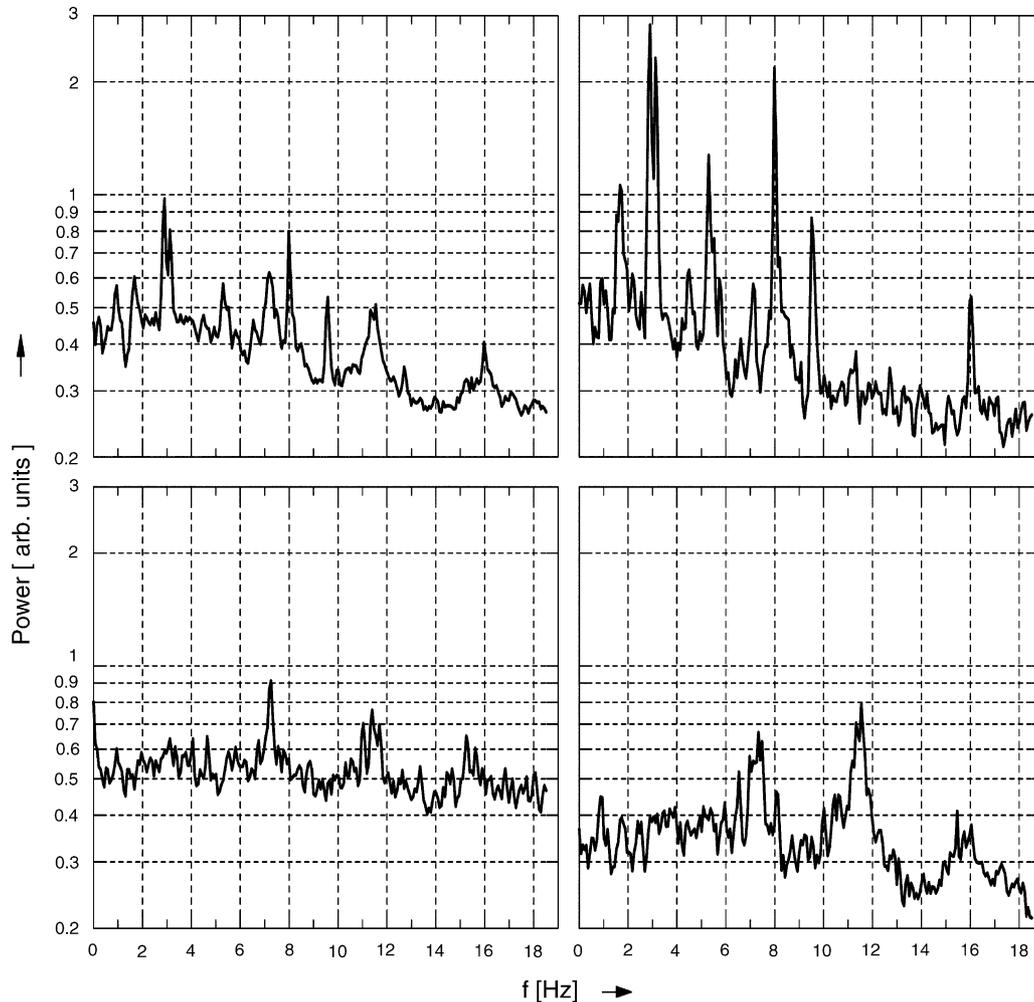


Fig. 5. Spectral distribution of velocity fluctuations of the flow driven by the RMF for four different radial regions. Top left: average in whole container; top right: in the centre; bottom left: at the rim; bottom right: midway between centre and the rim. In each of the four graphs averaging across the full height of the container is performed.

the actual flow velocity become very complicated. To minimize such effects, the formation of solely microbubbles is desired. However, in the case of metallic melts, it is very difficult to control the size of the generated bubbles.

For our experiments, in a closed container, the possibility of gas injection was explicitly excluded. At the launching of the measurements velocity profiles were acquired, however, the quality of the signals was not optimal in the sense that exceeding 50% of all data were null samples in the case of TMF with mercury. The data rate was not sufficient to calculate spectral distributions for these measurements as presented for the RMF experiments with InGaSn in the previous section. With increasing experimental time, the measuring signal deteriorated. This observation indicates that microbubbles generated by the filling of the container may act as tracers. These bubbles will separate from the fluid in the lapse of time.

From own experience, we know that InGaSn is usually not problematic with respect to the availability of a satisfactory amount of tracers. The alloy shows a high oxidation rate on air. We have found that the formation of gallium oxides is preferred leading to a decrease of the gallium content in the melt. At temperatures close to the eutectic temperature already small deviation from the eutectic composition causes the formation of a two-phase region with a distinct amount of solid fraction. Here, the situation could arise that the UDV measurements will be complicated by too many tracers increasing significantly the attenuation. Further phenomena like the agglomeration behaviour of the oxides or the adhesion on the container walls should also have a distinct influence on the ultrasonic measurements.

The current knowledge about these effects is still fragmentary. Therefore, we will intensify our investigations concerning these problems in the future. Several

techniques are currently under investigation with respect to the refinement of the metallic melt to provide fluids with a controlled purity. Special care has also to be taken to guarantee the cleanliness of the inner container walls before filling it with the melt under controlled atmosphere.

## 6. Conclusion

In the present study, we have shown that UDV possesses the ability to measure and visualize flow fields in liquid metals at room temperature. These flow maps, previously available only numerically, attain a high degree of topological resolution. Details, like the vortex's eye location in the comparable weak secondary recirculation of an electromagnetically driven swirling flow, compare well between our case study and theory. This is true for the mean velocities, and continues to be the case for integral values like the turbulence degree.

Fully time resolved analysis in the sense of spectral decomposition of the velocity fluctuations was only partly successful. In the case of an RMF driven flow in InGaSn, pronounced maxima in the power spectrum are apparent in the low frequency range, indicating large scale convective oscillations. A similar evaluation of data acquired from mercury under the impact of a TMF was hindered by numerous null samples. The hence less trustworthy result is one maximum at a very low frequency which may be interpreted as an oscillation of the whole torus.

The measurements revealed that the preparation of the liquid as well as the filling technique of the fluid container could become very important to receive ultrasonic echo signals with a good quality. Further investigations are necessary to achieve a better understanding of the dependence of the ultrasonic Doppler signal on the concentration and the properties of reflecting tracers in liquid metal flows.

We can state that UDV, already in its commercially available variant, has proven to be a valuable and powerful tool for flow mapping in low temperature liquid metals.

## Acknowledgements

Financial support from “Deutsche Forschungsgemeinschaft” in frame of the Collaborative Research Center SFB 609 is gratefully acknowledged. We are grateful to J. Hüller for his valuable technical support

in preparing the experiments, and to G. Gerbeth for critical reading of the manuscript.

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