UDV study of a liquid metal vortex flow

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Abstract. The characteristics of an oscillating vortex flow of liquid metal were studied experimentally using an ultrasound Doppler velocimeter (UDV). The flow was generated by a local alternating magnetic field induced in a rectangular thin cell filled with gallium eutectic. The influence of medium temperature change and stirring on the UDV measurements was considered. The best set of parameters providing the reliability of long-term measurements were determined. The non-monotonic behavior of dependence of the local kinetic energy on the external alternating magnetic field intensity was found.

1. Introduction
The studied flow is initiated by an external alternating magnetic field generating a vortex electric current in the metal. An electromagnetic force is consequently generated by the interaction of the current with the magnetic field. This force gives rise to appearance vortex flows. In most cases the area of magnetic field generation is localized, which is associated with restriction to inductor size. Generation of a vortex flow with a few largescale eddies was described in [1]. Such a flow is able to keep its pattern only at small force values. When the intensity of force action increases and exceeds some critical value, the flow becomes unstable [2]. In this case the eddies are moving in the layer plane. In our previous work [2], we used the potential probe (PP) for velocity measurements. This type of the probe can determine only the local characteristics of the flow [3, 4]. It is also interesting to measure the spatial characteristics of the flow and the flow patterns. However, the existing optical methods (e.g. PIV) cannot be used for this purpose because of the optical opacity of liquid metals. For this reason, application of an ultrasound doppler velocimeter (UDV) is justified. This device has been widely used in similar research studies (e.g. [5, 6, 7]).

The study focuses on the study of a liquid metal flow in a plane rectangular layer (figure 1). The layer thickness is much less than its planar sizes. The region under the influence of an alternating magnetic field is located in the center of the plane. The value of the vector component transversal to the layer magnetic induction exceeds the value of the plane component. The influence of an alternating magnetic field generates the vortex electric current. The electromagnetic force is directed from the periphery of the region to its center. At the initial time, four-eddies flow of liquid metal are initiated.

The main purpose of this work is to investigate the velocity of the examined liquid metal (gallium eutectic). To this end, it is necessary to determine the dependence of the mean kinetic
Figure 1. Sketch of layer and flow initial pattern: 1 – area of magnetic field localization, 2 – flow of liquid metal, 3 – streamlines of initial flow. Dimensional parameters $L_X = 200$ mm, $L_Y = 100$ mm, $d_X = 67$ mm, $d_Y = 56$ mm.

energy and oscillation frequency on the strength and frequency of an vortex current in the inductor coil. To describe the flow properties, four parameters were used. The first is the mean local kinetic energy of the flow $W_y$ defined as the time average value of the velocity squared. The subscript $y$ shows the projection of the velocity component onto the coordinate axis. The second is the dominant frequency of velocity profile oscillations $f_d$ defined as the frequency which corresponds to the Fourier transform energy maximum of the local velocity. The third is the spectrum filling coefficient $k_S$ defined as the frequency averaged over the spectral energy density normalized to unity. The maximum value of 1024 matches the so called white noise, and the minimum value of 1 matches harmonic oscillations. The latter is the relative number of lost velocity profile points $N_l$. The lost points are defined as the points whose value does not exceed 5% of the mean velocity value.

Ultrasound doppler velocimetry includes emitting ultrasound wave packages by an ultrasound doppler sensor, their consequent adoption, and calculation of the Doppler frequency shift between the emitted and received wave packages. The ultrasonic silicon gel has to be used to provide sound contact between the probe and the wall. However, the presence of sound-reflecting particles moved by the flow in the medium is necessary. The gallium oxide particles reflect ultrasound waves in gallium eutectic. These particles are formed by oxidation of gallium in the atmosphere [8]. This means that the UDV measures not exactly the velocity of the medium, but the velocity of solid particles. Thus, the possible lack of repeatability of energy dependencies can be explained not only by the random behavior of eddies or the changes in the properties of media subjected to heating caused by Joule losses, but also by the changes in the number of sound-reflecting particles. The stirring of dispersion medium by the intensive flow leads in this case to sedimentation of sound-reflecting particles or, on the contrary, to washing the particles away from the walls of the cell. This affects the qualitative and quantitative characteristics of a reflecting ultrasound signal (e.g. [9]). Furthermore, the variation of medium temperature as well the drying of an ultrasound gel can influence the results of velocity measurements. Therefore, one more purpose of this work is to develop a measurement method that would allow getting high-accuracy and repeatable results.

The existing method of electromagnetic force generation has found the use in industrial applications. Travelling and rotating magnetic fields are generally used for contactless transport of the molten metal through technological channels (e.g. [10]), as well as for mixing flows generated in enclosed volumes (e.g. [11]). Contactless generation of the molten metal flow is useful for continuous casting. Besides, the application of stirrers for manufacturing cylindrical ingots in aluminium semicontinuous casting machines is being extensively investigated (e.g. [12]). The supporting rollers of a steel continuous casting machine can, after small update, generate an alternating magnetic field. This makes it possible to generate a stirring flow (e.g. [13]). There is no traveling magnetic field, this machine design assures proper mixing of a hardened ingot core.

A liquid metal flow passing through the channel can also be obtained in the absence of a
traveling magnetic field method. Bearing this in mind, a channel of specific configuration was developed [14]. An electromagnet in this channel creates a local electromagnetic force and generates thus a large-scale vortex flow. The resulting centrifugal force causes the pressure drop in the pump channel. The use of one or several inductors allows one to create a stirring flow in an enclosed rectangular channel filled with molten metal [2]. In the production of solid ingots the stirring has a strong impact on the crystallization process [15]. The simple device described in this paper may find application in different research laboratories to produce metals and alloys in comparatively small quantities. Stirring provides homogenisation of inclusions and temperature distribution, grain refining and smoothing of the crystallization front (e.g. [16, 17, 18]).

As can be seen from above, the liquid metal flow generated in plane layers by an external alternating magnetic field is important problem. The instability of eddies is desirable for stirring the liquid metal [2] and undesirable for pumping the flow through the channel [14]. This provokes the interest in a detailed study of such flows.

2. Methods

The experimental setup (fig. 2) consists of the plexiglass cell 1 filled with liquid gallium eutectic (density 6256 kg/m$^3$, kinematic viscosity $3.1 \cdot 10^{-7}$ m$^2$/s, conductivity $3.56 \cdot 10^6$ Sm, sound speed 2828 m/s). Dimensions of the cell are $200 \times 100 \times 15$ mm$^3$. The cell is placed in the gap between the poles of the C-core inductor 2. The AC power source is used as the power supply 3 (Pacific Smart Source). The non-contact ampere-meter FLUKE i2000 Flex AC Current probe controls amperage with accuracy to second decimal places of ampere. The cover of the cell is equipped with two PP 4 with diameters of 10 and 18 mm and the chromel-aluminum thermocouple 5. The data acquisition card 6 Nation Instruments c-DAQ receives the signals from PP and a thermocouple. The UDV probe 7 allows measuring velocity component in any cross section of cell.

![Figure 2. Experimental setup: 1 – plexiglass cell filled with gallium eutectic, 2 – C-core inductor, 3 – AC power supply, 4 – potential probes, 5 – chromel-aluminum thermocouple, 6 – data acquisition card, 7 – UDV probe.](image)

The amperage measurement is much easier than the magnetic induction measurement. Therefore the dependence of induction in the gap on the current in coils can be found. Such measurements were made by Lake Shore 421 Gaussmeter. This dependence governed by the linear law allows one to present results in terms of current, but not magnetic field induction.

The velocity profiles were measured for different values of the external magnetic field by UDV in the cell section chosen for the study. To check the quality of the obtained data, it is more convenient to make a Fourier analysis of velocity in a single point of the profile instead
of the full-profile analysis. Moreover, comparison of energy parameters in a single point of the velocity profile with the available data is more adequate than the spatial average of the velocity profile. Since the velocity profile oscillations are quite similar to harmonic oscillations, the single dominant frequency $f_d$ exists in the velocity spectrum. This frequency influences the eddy shape and oscillating movement. The time interval between velocity profile records was 124.9 ms. This imposed limitations of 4 Hz on the maximum resolvable frequency of a spectrum. The specific filter was used to determine $f_d$. If $k_S$ had a value more than 240, the velocity signal was considered as chaotic. Hence it can be concluded that the dominant frequency does not exist, and $f_d$ can be defined as zero.

3. Results
The first step toward eliminating factors that affect negatively velocity measurements included study of $W_y$ varying with time under constant ambient conditions. The velocity profile evolution is recorded for 66 minutes with UDV (about $2^{15}$ profiles). In addition, the velocity profile and the PP and thermocouple readings were recorded simultaneously. This provided the opportunity to compare the nature of energy dependencies obtained by different methods. When the recording was completed, every record was divided into 30 separate parts. The mean values were found by time averaging of these parts.

The analysis of UDV measurements indicates that $W_y$ declines significantly after approximately 30 minutes of the experiment (figure 3). To investigate this feature, the dependence of $N_l$ on time has been found (figure 4). It is evident that the valid signal of the UDV velocity is being absorbed by the background noise. Thereby we have arrived at the conclusion that the long-duration velocity measurements carried out with UDV (more than 2000 s) do not provide high-quality results.

**Figure 3.** Evolution of mean local kinetic energy.

**Figure 4.** Evolution of the number of lost point on the velocity profile.

Mixing and heating of the liquid metal, as well as the drying of ultrasound gel, can influence velocity measurements. During the next step, an attempt was made to eliminate the influence of these factors. The velocity measurements of low-intensity flow (coil current was 4.0 A, current frequency was 50.0 Hz) were made using the UDV. Each experiment consisted of 12 records of velocity profiles. The time interval of a single record was 256 s (2048 velocity profiles), whereas the stirring time in the presence of a strong magnetic field (coil current was 8.0 A, current frequency was 50.0 Hz) was 180 s. In the first experiment, measurements were made without renovation of the drying ultrasound gel within the time intervals between velocity profile recordings (exp. 1). The second experiment included renovation of the gel after every record (exp. 2). In the third experiment (exp. 3), the liquid metal in the cell was preheated to 50 degrees using a water temperature regulator before measurements started. Figure 5 demonstrates how $W_y$ varies with time. It is obvious that in all the experiments the process of stirring improves the stability of mean energy. At the same time, the time dependence of $f_d$ demonstrates similarity and stability. However, the $f_d$ tends to decrease slightly in experiments 1 and 2. The pulsations
of local kinetic energy increase. The PP indicates the constancy of kinetic energy. This fact suggests that the change in the gallium eutectic temperature has a negative influence on the UDV velocity measurement accuracy, and the stirring affects positively.

The time dependence of $N_l$ is even a more important characteristic than $W_y$. Figure 6 illustrates the improvement in stability measurements for metal preheating. The $N_l$ do not exceed 7% of the mean velocity. When the liquid metal was stirred at varying temperature, $N_l$ was about 60%. Therefore, the preheating of liquid metal and the constancy of the medium temperature during measurements improve the stability of velocity and energy characteristics of the flow measured by UDV.

The most appropriate system relaxation time was found at the following stage. It is the shortest time at which the system can recover. To determine it, we performed a number of additional experiments. The indicated values of PP and thermocouple allow one to control the state of the system and UDV measurements as well. The current in the inductor coils had a value of 8.0 A. The high flow intensity provided good stirring during the experiment. The measurement time was 1956 s (16384 velocity profiles). Each of the signals was divided into 20 parts. The data obtained was averaged and provided the dependencies similar to described above. After each measurement the power supply was shut down and the system was returned to relaxation condition during the set time of 15, 30, 45 and 60 minutes between each of the following two measurements.

Using the described method the time dependencies of $W_y$ and $N_l$ were established for five measurements (figure 7). It is obvious that the initial condition and 60 minutes after the relaxation period are most similar. At the same time it is seen that the dependencies of 30 and 45 minutes relaxation periods also show almost similar results. It is necessary to note that the PP data suggest a 7 fold increase in kinetic energy. Furthermore, the time dependence of $N_l$ increases slightly (less than 5% in all measurements). The best result was obtained for the 15 minute relaxation time. In this case, the growth of $N_l$ is less than half percent.

The results allowed us to develop the measuring procedure for getting high-quality and repeatable velocity and energy dependencies using UDV. Figure 9 demonstrates the velocity evolution in two ways. The first implies application of the proposed method, and the second includes direct UDV measurements without any specific procedures.

The determined difference between velocity evolutions makes it possible to distinguish between the evolutions of kinetic energies. In the case of direct velocity profile measurements,
Figure 7. Evolution of mean kinetic energy for different relaxation standstill periods: 1 – initial condition, 2 – 15 minute relaxation, 3 – 30 minute relaxation, 4 – 45 minute relaxation, 5 – 60 minute relaxation.

Figure 8. Changes in the number of lost velocity profile points for different relaxation standstill periods: 1 – initial condition, 2 – 15 minute relaxation, 3 – 30 minute relaxation, 4 – 45 minute relaxation, 5 – 60 minute relaxation.

it was impossible to obtain repeatable results for the mean energy $W_y$. On the other hand, our measurement method gives the repeatable dependencies of $W_y$ on the current intensity and frequency of the coil. In addition, the time dependencies of mean energy calculated using UDV and PP are close (figure 10).

Figure 9. Evolution of the velocity at a fixed point: 1 – measured using the developed method, 2 – directly measured.

Figure 10. Mean kinetic energy evolution: 1 – calculated from UDV measurements, 2 – calculated from PP measurement.

The dependencies of $W_y$ (figure 11) and $f_d$ (figure 12) on the current frequency of the coil were determined. The mean kinetic energy demonstrates a non-monotonic dependence on the alternating magnetic field frequency.

Figure 11. Mean local kinetic energy vs. magnetic field frequency.

Figure 12. Vortexes oscillation frequency vs. magnetic field frequency.

Figure 11 shows a well-marked oscillation together with a background increase of $W_y$ in the
frequency range 25 to 105 Hz. Thereafter the energy gradually decreases when the magnetic field frequency exceeds 110 Hz. This provides insights into qualitative changes in flow patterns. The frequency of eddy oscillations increases linearly with the frequency of the magnetic field. Therefore the intensity of the stirring can be improved with growing coil current frequency under the same amperage.

4. Conclusions
It was found that application of UDV for long-duration measurements essentially differs from short-duration measurements. The preliminary recording of the velocity of gallium eutectic showed the lack of repeatability of mean kinetic energy dependencies on the external force intensity. It was found that the UDV recordings are becoming unreliable during long-time profile recordings. The investigation of parameters which influence liquid metal flow velocity measurements (stability of medium temperature, sound-reflecting particles of gallium oxide distribution, acoustic properties of ultrasound gel) showed that temperature variations have a strong negative effect on the velocity signal quality. In some cases this can leads to a complete loss of the profile. The stability of energy characteristics of the flow measured by UDV under temperature regulation was found. The high intensity stirring of eutectic also affects positively the quality of recordings. It causes a decrease in the number of profile lost points. In addition the relaxation standstill between the experiments improves the data quality. The data recorded with relaxation time periods more than 15 minutes are in good agreement with the results of several tests. As can be seen from above, we have found the experimental parameters best suited for getting accurate data.

The use of the described method in the flow parameters investigation allows us to determine the non-monotonic dependence of local kinetic energy on the external alternating magnetic field value and frequency. This proves the qualitative changes of the flow structure. The frequency of the velocity profile oscillation increases almost linearly with increasing magnetic field frequency. Therefore the vortex flow in a rectangular cell generated by the local alternating magnetic field is unsteady, and its behavior significantly depends in the magnetic field frequency.

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