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FLOW OF LIQUID METAL IN A CYLINDRICAL CRYSTALLIZER GENERATING TWO-DIRECTIONAL MHD-STIRRING

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Motions of liquid gallium alloy generated in a two-directional cylindrical MHD-stirrer are examined. Results of experimental investigations of the flow and magnetic field topologies are presented. Measurements were taken using a dual-axis potential probe and induction coils. Experimental results for time-averaged flows are compared to theoretical results. Aalysis of turbulent fluctuations of the flow shows that the flow turbulence is three-dimensional and plays an essential role in the stirring processes.

1. Introduction. It is well recognized that melt stirring used in continuous or semi-continuous casting of aluminum and aluminum alloy ingots improves the ingot surface. An ingot must have a fine crystalline structure with additives distributed uniformly over its cross-section and the ingot surface must be smooth. It is clear that both the topology and the intensity of stirring in a crystallizer affect the melt crystallization process. Azimuthal stirring of a melting metal provides a more homogeneous distribution of additives due to breaking of the dendrites at the crystallization front of the melt.

Stirring is traditionally carried out by MHD-stirrers, which generate a rotating magnetic field in the bulk of liquid metal [1]. However, an improved model of the device has been recently proposed for simultaneous generation of the azimuthal (toroidal) and meridional (poloidal) flows [2, 3], which can be controlled independently. The device can be used in continuous casting machines for the in-line control of the crystallization front at the liquid-solid interface for different kinds of alloys. The use of these stirrers can essentially improve the crystalline structure of the cast ingot owing to breaking of the dendrites and grinding of the grains formed during crystallization. They provide a homogeneous distribution of alloy components along the horizontal section of the ingot. A flat front of crystallization has actually a twofold effect. It leads to a more homogeneous cross-section structure of the ingot (from the edge to the center) and eliminates the stress concentrations such as coarse grains or dendrite crystals, which eventually improve the quality of the ingots and billets intended for cold plastic working. The metal flow carried downward along the crystallizer walls by "poloidal" stirring washes out the crystalline crust formed at the walls and carries the colder metal away from the edge to the center of the ingot, where a funnel is formed due to delayed cooling.

In the production of silumin ingots by a traditional method without a stirrer, the manufacturers often run into the problem of the non-uniform additive distribution. At the external surface of the ingots (near-surface layer 1–3 mm deep) the content of silicon is considerably higher than in the bulk. Such a distribution leads to a lot of technological defects, for example, in the manufacture of light alloy wheel disks. In contrast to the traditional method, the two-directional stirring technique yields a more qualitative final product, which has the form of a cylindrical ingot with the external surface of high quality. The produced billets can be subjected to subsequent machining without additional mechanical treatment of their surfaces.

The use of two-directional stirring in the manufacture of composite materials (e.g., aluminum alloys) allows one to obtain a final product, which is by no means a mechanical mixture of the initial components in the form of solidified metal. The obtained material is an aluminum alloy with a fine crystalline structure, including homogeneously distributed filling agents and intermetalloids formed of the introduced metallic components and chemically bound elements from the basic metal and nonmetallic fillers [4]. These materials demonstrate the enhanced physical properties, which result, for example, in increase of the high-temperature strength [4].

As it has been already mentioned, the MHD stirrers, producing two-directional stirring with separately regulated intensities of poloidal and toroidal components, have a much stronger effect on the crystallizing ingot than the stirrers generating only the rotating metal flow.

A key to its effective application is a comprehensive topological analysis of the flows driven in such a stirrer. Therefore, the objective of this paper is a detailed study of the flow pattern in the bulk of liquid metal. The experimental setup is described in Section 2. The magnetic field and velocity field measurements and the topologies are described and discussed in Section 3. Discussion and conclusions are presented in Section 4.

2. Experimental setup. The experimental setup is schematically shown in Fig. 1. It consists of a cylindrical vessel with a liquid gallium alloy placed in a two-directionnal MHD stirrer. The stirrer is a cylindrical inductor driving both a travelling magnetic field (along the axial direction in cylindrical coordinates) and a rotating magnetic field (along the radial direction in cylindrical coordinates). The coils inducing the travelling and rotating fields are independently fed from two

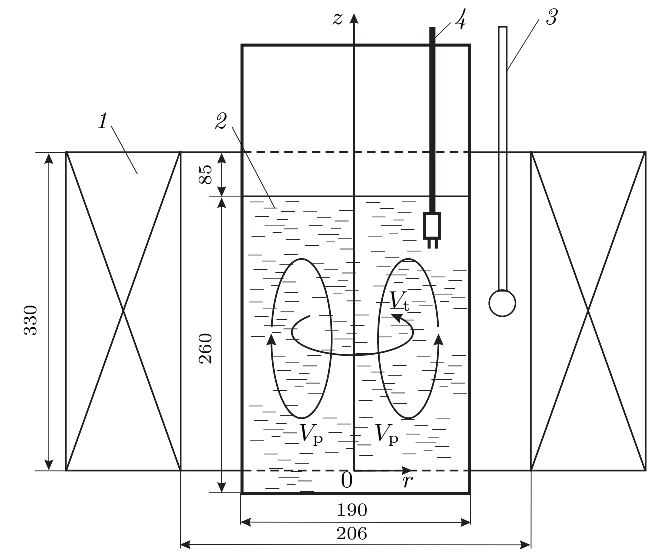


Fig. 1. Schematics of the experiment: *1* – MHD stirrer, *2* – gallium alloy in the cylindrical vessel inside the stirrer, *3* – magnetic field sensor, *4* – electromagnetic transducers of the radial and azimuthal velocity.

Table 1. Experimental parameters, setup and MHD stirrers.

Position	**Notation**	**Inductor**
Radius of the cylinder with liquid metal [m]	R	0.095
Cylinder length [m]	L	0.300
Bore radius of inductor [m]	R_c	0.103
Bore length of inductor [m]	L_c	0.300
Amplitude value of travelling field electric current [A]	I^{trv}	1–15
Amplitude value of rotating field electric current [A]	I^{rot}	1–20
Number of turns per phase of the rotating field	$N^{rot,w}$	192
Number of turns per phase of the travelling field	$N^{trv,w}$	190
Sliding	S	1
Pole pitch for the travelling field [m]	b_z	0.048

three-phase autotransfomers (220/380 V, 50 Hz) providing up to 20 A, i.e., 10 kVA. The geometrical and electrical characteristics of the stirrer are listed in Table 1. A stainless steel cylindrical vessel with its walls of 1 mm thick and inner diameter of 190 mm placed in the stirrer simulates a crystallizer with the heated head generally used in continuous casting machines. The vessel is filled with a gallium alloy (87.5% Ga; 10.5% Zn; 2% Sn), which remains liquid at room temperature. Since the upper boundary condition for the flow is the free surface, the vessel is filled up to 260 mm from the bottom to avoid the gallium overflow when the liquid is set to rotation. As it will be seen further, the typical measured flow velocities U lie in the range 0.1–1 m/s. The resulting flow is thus fully turbulent because the integral Reynolds number estimated as $UD/2\nu$ reaches a value of 10^5, where D is the vessel diameter and ν is the viscosity of gallium.

The flow features and the magnetic field topology have been investigated using two different sensors: a magnetic field transducer and a velocity transducer. Measurements by these transducers are taken at different time moments.

The magnetic field transducer consisting of a 50-turn flat coil 10 mm in diameter is shown in Fig. 2*a*. This transducer gives access to the 50 Hz magnetic field component that drives the flow. The coil axis can be vertically or radially aligned, thus providing the spatial distribution of the radial and axial components

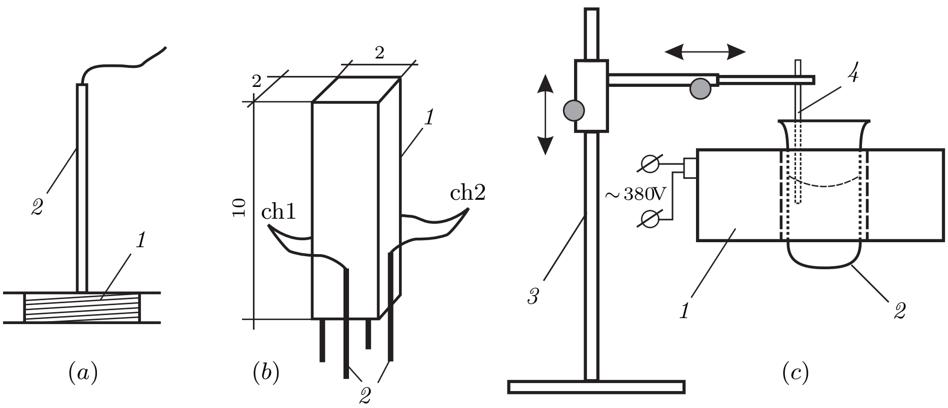


Fig. 2. Schemes of the measurements: (*a*) magnetic field transducer: coil *1* with holder *2*; (*b*) conduction velocity transducer: magnetized bar *1*, tungsten contacts *2*; (*c*) setup for measurement of flow velocity in the cylindrical vessel: inductor *1* (stirrer), cylindrical vessel with gallium alloy *2*, two-coordinate stand *3*, two-component velocity probe *4*.

of the travelling and rotating magnetic fields in the axial direction. The magnetic field inhomogeneities, which are caused by the discreteness of the magnetic coils generating the field by the 3-phase current, are smoothed by a large number of ferromagnetic coils incorporated into the device (all in all 84 coils). In the following, the axial symmetry is assumed for the flow and magnetic field topologies. Measurements are taken along two stirrer directions: along the axis of the device ($r = 0$) and along the inner cylinder of the stirrer ($r = 103\,\mathrm{mm}$); the position of the transducer and the coordinate axis are shown in Fig. 1.

The velocity was measured by potential probes. The method implies correlation of the potential difference measured between two electrodes with the local characteristics of the velocity field. Previous investigations have shown that this correlation can be realized when the electrodes are set in the vicinity of a localized strong permanent magnet B_0 [5–8]. For our setup, the recorded potential difference between two points is

$$\Phi_{AB} = \int_A^B \nabla\phi \cdot \mathrm{d}\mathbf{l}$$

with

$$\nabla\phi = \mathbf{u} \times \mathbf{B} - \mathbf{j}/\sigma - \partial_t \mathbf{A},$$

where $\mathbf{j}$ is the current density, σ is the electric conductivity of the liquid, and $\mathbf{A}$ is the vector potential. Under the condition of strong imposed field localized around the electrodes [8] and under the assumption that the motions are slow enough and the current density is vanishingly small, the potential difference yields

$$\Phi_{AB} = \int_A^B (\mathbf{u} \times \mathbf{B}) \cdot \mathrm{d}\mathbf{l}.$$

The experimental setup is shown in Fig. 2*b*: the potential difference is measured between the tungsten electrodes placed 2 mm apart (distance d) around a 0.2 T neodyme-iron-bore permanent magnet magnetized along its length. Under conditions like those described in this work, a similar probe was shown to provide a dynamic measure of the fluid velocity, with temporal resolution being from continuous to a few hundreds Hertz (about 300 Hz for our conditions).

In order to take measurements, a velocity probe is attached to a movable coordinate device, whose position can be adjusted to any prescribed point inside the liquid metal. The probe assembly allows for simultaneous measurements of the azimuthal and radial velocities of the liquid metal flow. The velocity transducer is calibrated in a cylindrical vessel 366 mm in diameter, filled with the gallium alloy to a depth of 20 mm. The vessel is mounted on a speed-controlled rotating table. The transducer is then immersed into the alloy to a depth of 10 mm (158 mm away from the rotation axis) and the velocity is obtained from the rigid-body rotation of the fluid.

The primary (direct) output voltage $\delta \approx UB_0 d$ is low (of order of 200 μVs/m). It is immediately supplied to a differential amplifier "AD8221" with a gain of 100 located inside the probe. The transducer output signals are digitized using the "34970A" data acquisition system (Agilent Technologies, USA) with a built-in $6\frac{1}{2}$ Digit Digital Multimeter and a 20-Channel Relay Multiplexer. For measurement of the azimuthal and radial velocity components, two channels of the Multiplexer are used. Since the stirrer operates at a feed current of 50 Hz, the transducer data are integrated over an integer number of power-cycles. The scanning procedure is set in such a manner that for each position the data are repeatedly (50 samples) integrated over 20 power-cycles. The velocities are then evaluated by averaging the values over these 50 samples. A systematic error can be estimated from the sample standard deviation for a typical data acquisition as 0.06 ms^{-1} – a better resolution could be obtained by providing careful shielding of the 50 Hz component from the feeding coils. Velocity fluctuations are found separately based on high speed data acquisition from a 24-bit data card "LAi-24USB" sampling at 800 Hz. Finally, the current supplied to the stirrer is monitored by an "ACTACOM ATC 2012" induction ammeter.

3. Magnetic and velocity field measurements. Measurements are taken for three possible operations: poloidal stirring, toroidal stirring and combination of poloidal and toroidal stirring at the same driving current in two sets of coils.

The magnetic field profiles are obtained for the travelling and rotating magnetic field components (B_r, B_z) along the longitudinal z-axis (Fig. 1). Measurements are taken at the surface and at the center of the bored hole of the inductor and illustrated in Figs. 3 and 4.

The velocity components (V_r,V_φ) are measured by a 2-axis velocity probe at different points of the cylindrical cavity filled with the gallium alloy. The axial evolution of the azimuthal velocity component for different radii is shown in Fig. 5*a* for the motion imparted to the fluid by the rotating magnetic field only. Profiles at the radial position $r = R/2$ are found to be similar for currents driving the rotating field in the range of 0 to 15 A. Except for the region near the bottom boundary layer, the azimuthal velocity profile is roughly constant along the axis of the vessel. In the bulk of the flow, the azimuthal velocity increases for radii below 3 cm and then becomes roughly constant, so it corresponds to the gradient of angular velocity along the radius.

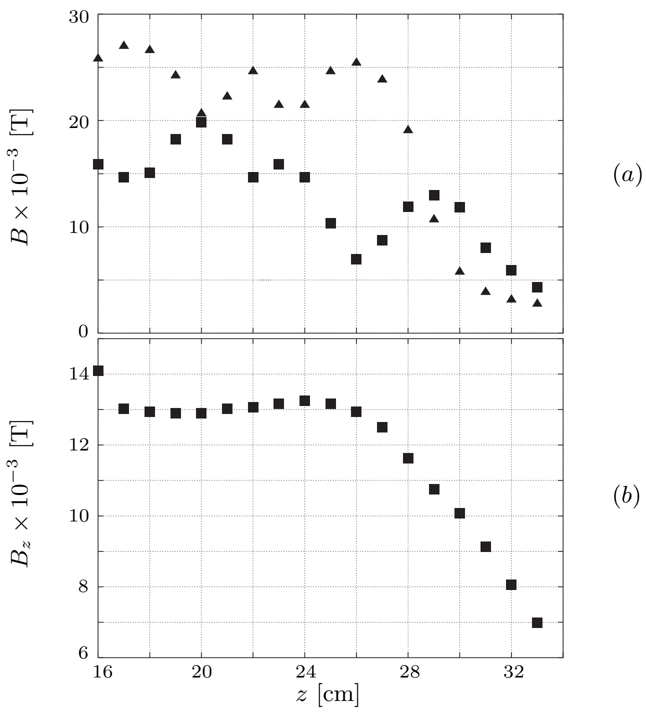


Fig. 3. Travelling magnetic field as a function of coordinate z: (*a*) at the surface of the inductor bore ($r = 103$ mm); (*b*) at the center of the bore ($r = 0$); experiment ($f = 50$ Hz, $I^{\text{trv}} = 10$ A).

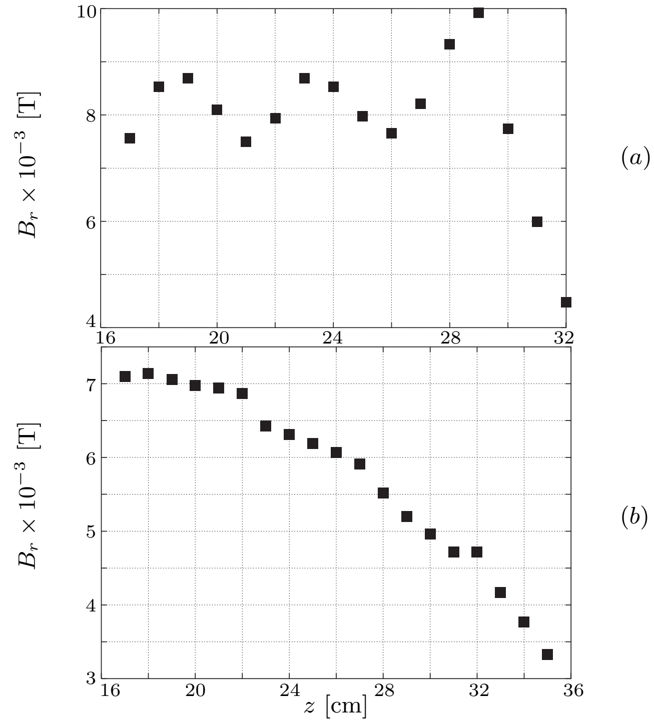


Fig. 4. Rotating magnetic field as a function of the coordinate z: (a) at the surface of the inductor bore; (b) at the center of the bore; experiment ($f = 50\,\mathrm{Hz}$, $I^{\mathrm{rot}} = 10\,\mathrm{A}$).

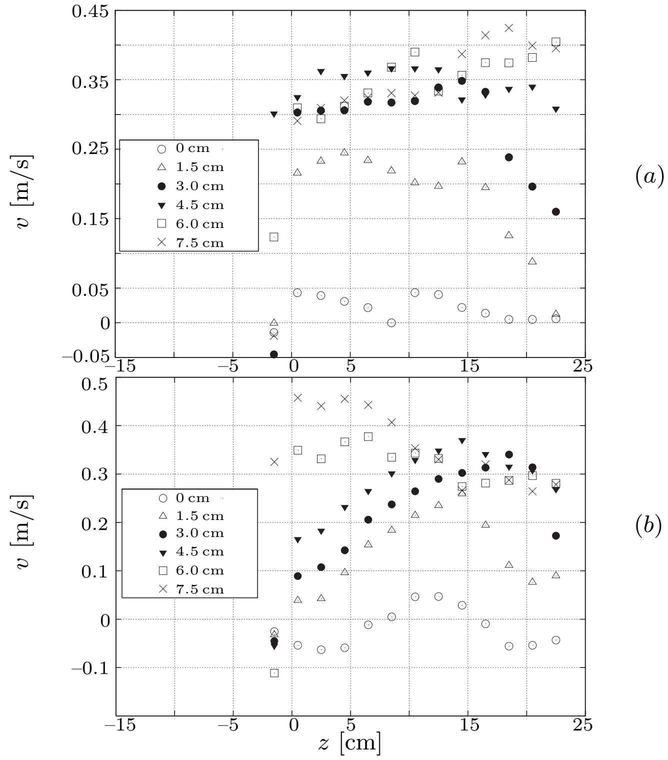


Fig. 5. Profile of the azimuthal velocity along the axis for various radial distances: (a) rotating magnetic field only; (b) travelling and rotating magnetic fields in the stirrer; electric current in the winding is 5 A.

Fig. 5*b* displays the corresponding results for the case when the flow is driven by the combined action of the travelling and rotating magnetic fields in the MHD stirrer. It is clear that the entire flow topology has modified. The velocity field in the cylindrical cavity can now be represented as a superposition of the toroidal and poloidal components, and the measured fields can be used to derive a more complete topology by projecting them onto the allowed modes.

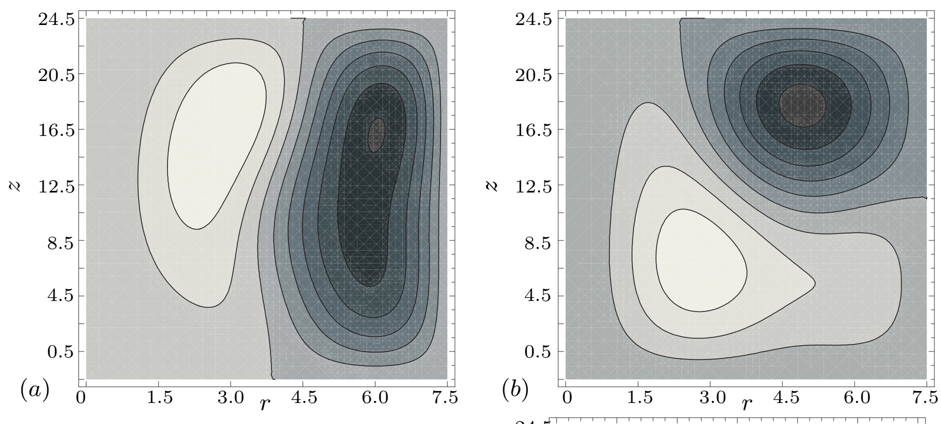
To this end, we first assume that the flow is axially symmetric and z-independent. The stream function can be related to the poloidal velocity as

$$V_r = \frac{1}{r}\frac{\partial \psi}{\partial z}; \qquad V_z = -\frac{1}{r}\frac{\partial \psi}{\partial r}.$$

Then the continuity equation is trivially satisfied. We then express the stream function as a series expansion in basis functions, each of them satisfying the condition of wall impermeability [3, 4]

$$\psi = \sum_{nm}^{NM} A_{nm} \frac{r}{R_0} \sin\left(\frac{n\pi r}{R_0}\right) \cos\left(\frac{m\pi z}{h} - \frac{\pi}{2}\right),$$

for which the coefficients are adjusted using the experimental measurements. The resolution of the flow sampling restricts our choice to $N = 3$ and $M = 3$. Fig. 6 displays the profiles of the flows generated in liquid metal under the action of either rotating or travelling magnetic field, or under the combined action of both. It is seen that the rotating magnetic field generates both a toroidal flow by spinning



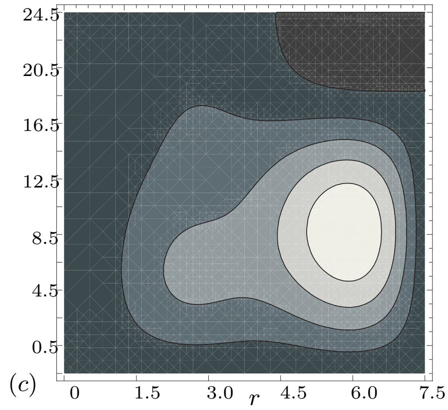


Fig. 6. Poloidal flow pattern obtained by projection onto modes: (*a*) poloidal flow induced by the toroidal flow excited by a single rotating magnetic field; (*b*) poloidal flow induced by a field travelling downward the cavity walls; (*c*) poloidal flow induced by both rotating and travelling fields.

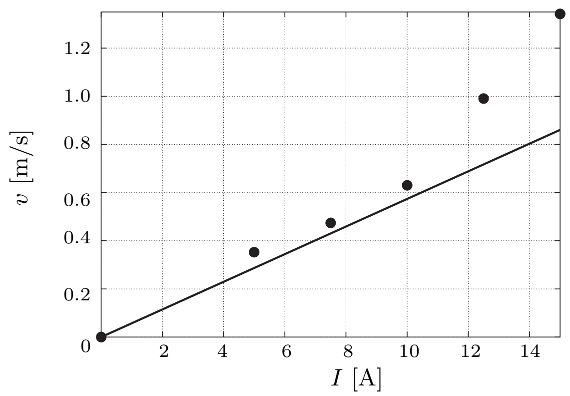


Fig. 7. Maximum velocity of the azimuthal flow generated by a rotating magnetic field as a function of the current in the windings; dots – experimental values, solid line – model (see the text).

the liquid metal in the cylindrical cavity and a poloidal flow. The magnetic field, travelling downward the walls of the cavity, excites the poloidal flow. In both cases, this is a two-vortex flow. Under the combined action of the rotating and travelling magnetic fields, the toroidal and poloidal flow components are generated in the melt. In this case, the poloidal flow has a predominantly single-vortex pattern. As it follows from Fig. 6, a tailored flow topology can be generated by tuning the combined action of the rotating and travelling magnetic fields.

The variation of the azimuthal velocity with the electric current intensity in the windings of the rotating field inductor can be evaluated from the flow model described in [3, 4]. It is seen that our data are in good agreement with the reported results for current values up to 10 A (Fig. 7). In practice, these regimes of stirring are in most common use. Model simulation at the values of winding current

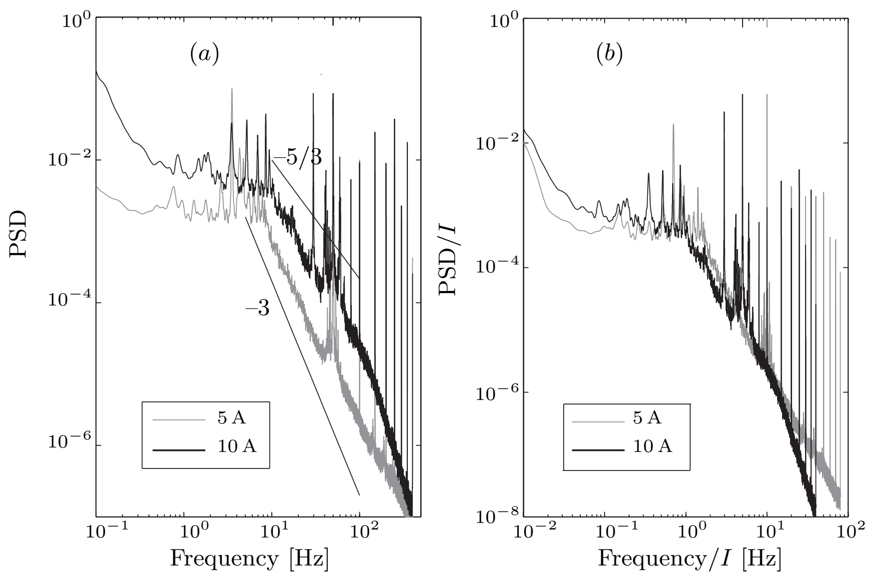


Fig. 8. Spectra of the azimuthal velocity showing fluctuations. (*a*) Spectra for two different currents driving the rotating field; (*b*) spectra normalized by the driving current.

exceeding 10 A gives underestimated results. This can be attributed to the fact that for current values higher than 10 A the liquid metal in the cavity rotates with such a rate that the funnel at its surface occupies increasingly more space, and the level of the metal near the walls rises significantly. These flow conditions are not taken into account in the model simulations of the electromagnetic forces, which drive flow motions. However, the model proposed in [3, 4] can be readily applied to approximate engineering calculations, especially in the range of ordinary current values.

The previous discussion of the velocity topology was used in the time-averaged velocity measurements. Note, however, that the flow is strongly turbulent and the velocity fluctuations should not be ignored. As it follows from the earlier study [2], even in such complicated motions driven by the the combined action of toroidal and poloidal flows, the particles will follow practically the same (though a very intricate) trajectory, and, therefore, the only condition, under which the particle can go all way through the liquid, is to create turbulence in the bulk.

Typical temporal spectra of the azimutal velocity component are shown in Fig. 8 for two values of the current driving a single rotating magnetic field. The spectra clearly demonstrate the importance of the 50 Hz component, which dominates the typical turbulent spectrum exceeding it by two orders of magnitude. Fluctuations display a typical inertial behaviour in the range [10–100 Hz]. Although ascribing a power-law exponent to the inertial range is a difficult task since the probe cut-off frequency is relatively low if compared to the injection frequency, we observe that the slopes are lower for a lower driving current. Increasing the current strength from 5 to 10 A increases the exponent approximately from –3 to –5/3. This tendency could be a signature of the transition from the spectrum of quasi-2D turbulence to that of quasi-3D one [10]. Thus, for purely rotating (high) currents, three-dimensional turbulence enhances the mixing and breaks the initial bi-dimensionality of the flow. Note, however, that a decrease in spectral exponent could also be due to perturbations induced by the probe holder or neglecting the assumption of negligible current in the potential probe operation.

4. Conclusions. Thus, as the experiments showed, the travelling and rotating magnetic fields generated by the stirrer inductor can initiate intensive stirring flows in a cylindrical vessel with liquid metal. The flows initiated under the mutual action of these fields have a rather complicated topology. Such flows prove to be essentially turbulent that leads to intensification of the transfer processes in metal and improves the stirring effect.

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REFERENCES

[1] Yu. Gelfgat, J. Priede. MHD-flow in a rotating magnetic field (review). *Magnetohydrodynamics*, vol. 31 (1995), no. 2, pp. 188–200.

[2] Yu. Gelfgat, J. Krumins, M. Abricka. Motion of an electrically conducting fluid in a cylindrical volume exposed to the influence of superimposed rotating and travelling magnetic fields. *Magnetohydrodynamics*, vol. 35 (1999), no. 1, pp. 1–12.

[3] S. Denisov, M. Mann, S. Khripchenko. MHD-stirring of liquid metal in cylindrical mould with free surface. *Magnetohydrodynamics*, vol. 33 (1997), no. 3, pp. 306–314.

[4] S. Denisov, S. Khripchenko, I. Kolesnichenko, A. Yudakov. MHD-stirrer for cylindrical moulds of continuous casting machines fabricated aluminum alloy ingots. *Proc. the 4-th International Conference "Electromagnetic Processing of Materials"* (Lyon, France, 2003), pp. 178–183.

[5] R. Ricou and C. Vives. Local velocity and temperature measurements in molten metals using an incorporated probe. *Int. J. Heat Mass Transfer*, vol. 25 (1982), pp. 1579–1588.

[6] A. Tsinober, E. Kit, and M. Teitel. On the relevance of the potential-difference method for turbulence measurements. *J. Fluid Mech.*, vol. 175 (1987), pp. 447–461.

[7] T. von Weissenfluh. Probes for local velocity and temperature measurements in liquid metal flow. *Int. J. Heat Mass Transfer*, vol. 28 (1985), pp. 1563–1574.

[8] A. Cramer *et al.* Experimental study on the sensitivity and accuracy of electric potential local flow measurements. *Flow Measurement Instrumentation*, vol. 17 (2006), pp. 1–11.

[9] V. Noskov, R. Stepanov, S. Denisov, P. Frick, G. Verhille, N. Plihon, and J.-F. Pinton. Dynamics of a turbulent spin-down flow inside a torus. *Phys. Fluids*, vol. 21, 045108 (2009), 7 p.

[10] U. Frisch. *Turbulence: The Legacy of A.N. Kolmogorov* (Cambridge University Press, 1995).

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