Application of the video correlation method to measure the velocity on the surface of a liquid metal

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Abstract. In this work, the applicability of the video correlation method proposed by the authors for measuring the velocity on the surface of a liquid metal in an electrovortex flow in a hemisphere is investigated. The method is based on calculating the cross-correlation of the brightness signals of two closely spaced points in the video. It is shown that the method allows quite simply determining the velocity of the liquid metal.

1. Introduction
To measure the velocity of liquid metal in laboratory conditions, various methods are used, both probe and non-contact. All probe methods (fiber-optic [1], thermocorrelation [2], thermoelectric, etc.) have a disadvantage, which consists in some distortion of the flow when the probe is placed in it, at the same time, non-contact methods, for example, ultrasonic, also have their own limitations - a significant limitation on the types of working fluids and the need for complex processing of results.

Observing the surface and, accordingly, determining the velocity on the free surface of the liquid metal (in the corresponding installations, in particular, laboratory installations simulating electric arc furnaces have such a surface) can provide useful data on the flow structure. The use of fiber optic or ultrasonic techniques is redundant for such purposes. To measure the velocity on the surface, you can use optical methods associated with tracing the trajectories of marker objects. However, firstly, with good spatial and temporal resolution, these methods impose significant requirements on the quality of the image used, and secondly, the automation of trajectory tracking requires the use of rather complicated algorithms.

This paper investigates the possibility of using the video correlation method to measure the surface velocity of a liquid metal in an electric vortex flow as a simple alternative to the tracking method.

2. Experimental technique
The experiments were carried out on the experimental setup shown in Fig. 1. A copper hemispherical container with a diameter of 188 mm was filled with an indium-gallium-tin eutectic alloy (weight concentrations: Ga-67%, In-20.55%, Sn-12.5%, and physical properties: melting point +10.5°C, \( \rho = 6482 \, \text{kg/m}^3 \), \( \nu = 4.3\times10^{-7} \, \text{m}^2/\text{s} \), \( \sigma = 3.3\times10^6 \, \text{S}\) [3]). A cylindrical copper electrode with a hemispherical tip and a diameter of 5 mm was placed at the center of the liquid metal surface. The power supply system of the facility consisted of a three-phase rectifier, assembled according to the Larionov scheme with a maximum electric current of \( I \sim 1500\,\text{A} \). To create an external axial magnetic field (MF), we used a solenoid consisting of 228 turns of wire, having a diameter of 2.77 mm, and capable to generate MF of up to 0.1 T.

When an electric current passes from the central electrode through the liquid metal to the container wall, as a result of the interaction of the current \( \mathbf{J} \) with its own magnetic field \( \mathbf{B} \), an electromagnetic...
force \( \mathbf{F} = \mathbf{J} \times \mathbf{B} \) arises, leading to the formation of the so-called electrovortex flow (EVF) [4]. EVF take place in all electrometallurgical units, for example, electric arc and electroslag direct current furnaces, where they have a significant effect on the processes of heat and mass transfer [5].

In a hemispherical axisymmetric geometry without external magnetic fields, the EVF has the form of a single toroidal vortex directed vertically downward in the subelectrode region. The applied external axial MF \( (B_z) \) creates an azimuthal force \( F_\phi = -J_r B_z \) causing the flow to swirl in the azimuthal plane. The distribution of the azimuthal velocity on the surface along the radius can be measured by the methods associated with flow visualization.

To visualize the flow, before the start of the experiment, an acid solution was poured onto the open surface of a liquid metal covered in air with an oxide film; and the chemical reaction between the acid and oxides led to the appearance of hydrogen bubbles (markers) on the surface (Fig. 2). Azimuthal rotation under the action of an external magnetic field was recorded by a video camera with a frame rate of 240 fps. Along the selected radius, pairs of points were set at a fixed distance \( (D_L \sim 4\text{mm}) \) from each other (Fig. 3). Oscillograms of pixel brightness at these points, obtained for 30 s, were saved, and then, for each pair of points, the cross-correlation function was calculated using (1).

\[
R(t) = \frac{1}{N} \sum_{i=1}^{N} I_1(i\Delta\tau)I_2(i\Delta\tau + t)
\]

here: \( I_1, I_2 \) is the brightness of pixels, \( i \) is the frame number, \( 1/Dt \) is the frequency of the frames, \( t \) is the shift time, and \( N \) is the number frames. An example of oscillograms of the brightness of two pixels is shown in Fig. 3. The maximum of the correlation function corresponds to the shift time \( Dl_{\text{max}} \) between the brightness functions, i.e., the flow rate between the points may be found as \( U = Dl_{\text{max}} / t_{\text{max}} \).

The main time spent for obtaining the velocity on the surface in the experiment consists of the following components: 1) video recording time, 2) video decoding and video splitting into separate frames, and 3) calculation of cross-correlation for intensity functions. In our case, with a video recording time of 30 s, the processing of 7200 frames for 20 pairs of points took \( \sim 260 \) s.
A study to determine the type of acid and its concentration for the quality of visualization was also carried out (Fig. 4). The use of a 3% HCL solution apparently leads to the formation of a salt film on the liquid surface; therefore, it is not possible to fix the rotation on the surface. When using a 20% HCL solution, a salt film is also formed, but in smaller quantities, in this case rotation is observed, but the value of the azimuthal velocity is greatly underestimated in comparison with other experiments. Using 40% HCL gives satisfactory azimuth velocity data. When using solutions of phosphoric acid of various concentrations (5, 42 and 85%), satisfactory results are obtained. Hydrochloric acid has a high volatility; therefore, it is advisable to use phosphoric acid of any concentration for experiments.

3. Numerical technique
For comparison, the numerical calculation of the electrovortex flow velocity was carried out. To solve the equation of motion, the finite volume method was used on an unstructured 2D axisymmetric grid in cylindrical coordinates ($\partial \ldots / \partial \varphi = 0, U_\varphi \neq 0$) [6].
The computational domain had the form of a quarter of a circle with an inner radius $R_1 = 2.5$ mm and an outer radius $R_2 = 94$ mm, and consisted of 2700 cells, the symmetry axis coincided with the $z$ axis, and the free surface coincided with the $r$ axis (Fig. 5). The equations of motion (Navier-Stokes and continuity equations) are as follows (1–2):

$$\begin{align*}
\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \nabla) \mathbf{U} &= -\frac{1}{\rho} \nabla p + \nu \Delta \mathbf{U} + \frac{1}{\rho} \mathbf{F}, \\
\nabla \cdot \mathbf{U} &= 0.
\end{align*}$$

where $\mathbf{U}$ is the fluid velocity, $\rho$ is the fluid density, $\nu$ is the kinematic viscosity, $p$ is the pressure and $\mathbf{F}$ is the electromagnetic force, we assume the fluid is incompressible and isothermal.

The calculations were carried out in the non-inductive approximation, where the electromagnetic one has the form (3):

$$\mathbf{F} = (\mathbf{J} + \sigma \mathbf{U} \times (\mathbf{B} + \mathbf{B}_{\text{ext}})) \times (\mathbf{B} + \mathbf{B}_{\text{ext}}),$$

where $\mathbf{B}$ is the self-magnetic field, $\mathbf{B}_{\text{ext}}$ is the external axial magnetic field, and $\sigma$ is the electrical conductivity.

We need a stationary solution, but in problems with an external magnetic field, we have to solve a non-stationary problem until a stationary state is reached. Initial value of the velocity in a whole container: $\mathbf{U}|_{t=0} = 0$.

The boundary conditions on the electrodes are the wall: $\mathbf{U} = 0$, on the open surface – slip: $U_z|_{z=0} = 0$, $\frac{\partial U_r}{\partial z}|_{z=0} = 0$.

4. Results

For the study, three modes were chosen: $I=100$ A, $B_z = 4\times10^{-5}$ T; $I=100$ A, $B_z = 10^{-5}$ T and $I=100$ A, $B_z = 2\times10^{-5}$ T. The results are shown in Fig. 6 and the comparison of the experimental and calculational results is presented in Fig. 7.

The difference between the calculated and experimental results is quite large, and this can be explained by several factors.

First of all, the behavior of bubbles on the surface strongly depends on the hard-to-control oxidation state of the surface and the acid concentration, thus it is difficult to unambiguously determine the boundary condition for the calculation. Also, with an excessive number of bubbles, they interlock with each other and equalize the velocity along the radius. Finally, the behavior of the marker bubble on the surface is related to the velocity of the liquid in a complex way [7]. Nevertheless, this method (measuring the velocity using hydrogen bubble markers) can show rather good results [8], and this videocorrelative method can be applied to any moving objects with a predetermined direction of motion.

We also compared the video correlation method for determining the velocity and the traditional method of tracking markers. During tracking, the time taken for the bubble to travel along an arc (quarter circle) was measured, the result is shown in Fig. 7 (line and dots $1a$). The results are in good agreement, given the different temporal resolution of the methods.
Figure 6. Dependence of the azimuthal velocity on the surface on the radius at $I=50A$, $B_z=4e^{-3}$ T. 
1 – calculation; 2 – experiment HCl 36%, $H_3PO_4$ 85%.

Figure 7. Dependence of the azimuthal velocity on the surface on the radius at $I=100A$, and different $B_z$: 1 – 4e-5 T; 1a – 4e-5 T (tracking); 2 – 1e-3; 3 – 2e-3.

Conclusions

This article shows the effectiveness of the proposed video correlation method. The method was applied to determine the velocity of motion of hydrogen bubbles on the open surface of the In-Ga-Sn eutectic alloy on an experimental setup for the study of electric vortex flows.

The method turned out to be quite effective in terms of the processing time of the experimental data; if necessary, the method can be accelerated by using parallel computations and continuous processing of incoming data.

The results of measuring the velocity obtained using this method are in satisfactory agreement with the numerical calculation and are in good agreement with another method for determining the velocity from the video image - the method of object tracking. The accuracy of the method depends on the temporal and spatial resolution of the video filming.

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