Application of UDV for Studying the Flow and Crystallization of Liquid Metal in the Process of Electromagnetic Stirring

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We study the operation of the MHD stirrer in a cylindrical channel with a liquid metal based on the results of experiments and 3D numerical simulations. The investigations described in this paper are focused on hydrodynamic and crystallizing processes. Experimental investigations of the velocity field and its oscillations in a cylindrical crucible filled with a gallium alloy were performed using ultrasonic Doppler velocimeter measurements. The results of testing experiment in the plane layer showed that the UDV device has the advantage of determining the solid-liquid interface without direct contact of the UDV probe with the melted metal. The results of measurements allowed us to trace the evolution of the flow velocity and solid-liquid interface.

Keywords: travelling and rotating magnetic fields, continuous casting, mixing of melting metal

1 INTRODUCTION

Many technological processes (continuous ingot casting, preparation of special alloys) are accompanied by crystallization of metal in a liquid phase. The efficiency of these processes can be essentially improved by stirring molten metals. Under real operating conditions testing of the currently used stirring regimes for adequacy is a very complicated problem. With the advent of modern, high precision devices, the analysis of these processes can be readily accomplished under the laboratory conditions. The investigations made by the author provide the basis for finding the most optimal process parameters and configuration. Experiments with metals in industrial environment requires greater effort and special equipment. Modeling of metallurgical processes in the laboratory conditions using special metal alloys with low melting point allows us to bypass the obstruction [1].

In this paper, the flow and crystallization process are studied using the gallium alloy (87.5% Ga; 10.5% Zn; 2% Sn), which is in a liquid state at room temperature. The objective of this study is to explore the process of crystallization in a liquid metal in the presence of a vortex flow and to determine the optimal conditions for effective metal stirring.

The volume of liquid metal is under the action of the alternating magnetic filed. In the liquid metal the alternating magnetic field induces a vortex electric current. The interaction of the electric current with the magnetic field generates an electromagnetic force, which initiates a vortex stirring flow. Due to the non-uniform action of the electromagnetic (em-) force the initiated flow is unstable and has a complicated vortex structure. The investigations are focused on the electromagnetic and hydrodynamic processes. The stirrer consists of ferromagnetic cores *I* (fig. 1) and a set of copper coils, which generate an alternating magnetic field inside a cylindrical volume. One part of the coils generates the rotating magnetic field (RMF) and the other generates travelling magnetic field (TMF) along the axis of the cylinder. The stirrer is also provided with an internal water cooling system *II* to avoid overheating. The entire construction is protected by a case *III* made of material, which allows a short-term contact with a melted metal. A cylindrical crucible *IV* filled with liquid metal (magnesium, aluminum, lead, tin, etc) is placed inside the cylinder.

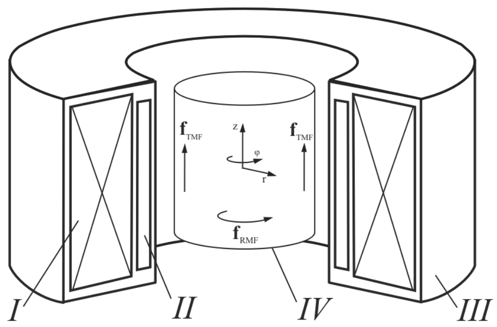

Figure 1: Sectional scheme and photo of MHD-stirrer.

2 EM-FORCE AND FLOW

We studied the forces acting on the cylinders of different height placed inside the stirrer and calculated the intensity of electromagnetic forces as a function of the value and the frequency of feeding current. The cylinders are placed inside the stirrer and have a single rotation degree of freedom coincident with the MHD-stirrer axis. Torque is defined indirectly by processing angular acceleration measurements. It has been found that with increasing current the value of the moment grows quadratically (fig. 2). As the frequency of the electric current decreases, the moment increases (fig. 3) due to the increased penetration of the magnetic field inside the conductor – the depth of the skin layer.

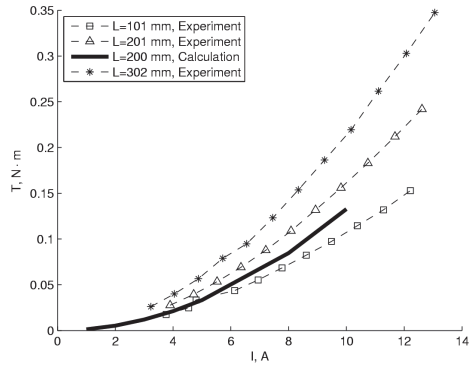

Figure 2: Torque of em-force vs coil current of RMF.

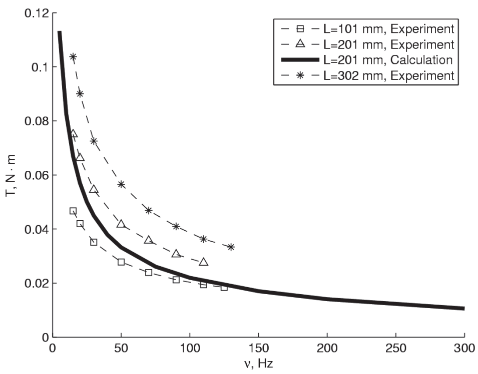

Figure 3: Torque of em-force vs frequency of RMF.

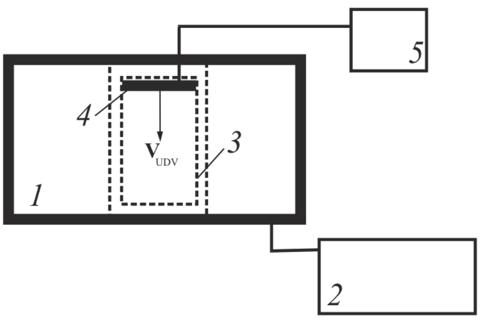

Figure 4: Scheme of the experimental setup for studying velocity.

Investigation of the velocity field was carried out in the experimental setup shown in fig. 4. The setup consists of the following part: MHD stirrer 1, power supply source for RMF and TMF coils 2, stainless steel cylindrical channel filled with liquid metal 3, UVD sensors inserted into the holder 4, and UDV 5. The vessel is filled with a gallium. To measure the velocity field we employed the UDV (DOP 2000, Model 2125, Signal Processing, Lausanne, Switzerland). In the holder the UDV sensors 4 are arranged in row along the diameter at an equal step. This allows us to restore the flow picture in the plane [2] and to evaluate the degree of the flow symmetry. The experiment showed (fig. 5, 6) that the intensity of velocity oscillation increases with the growth of the feeding current for RMF and TMF. The errorbars are equal to rms of the velocity in fixed point. The eddies are oscillating near the equilibrium position.

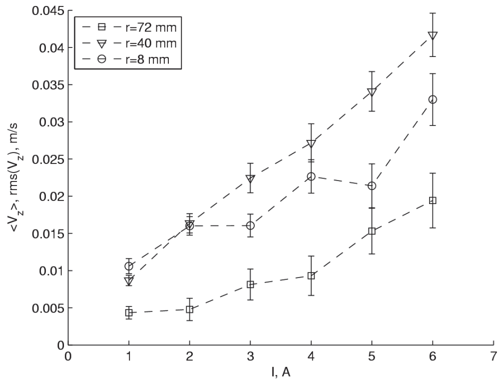

Figure 5: Mean velocity and rms vs feeding current of RMF obtained by UVD.

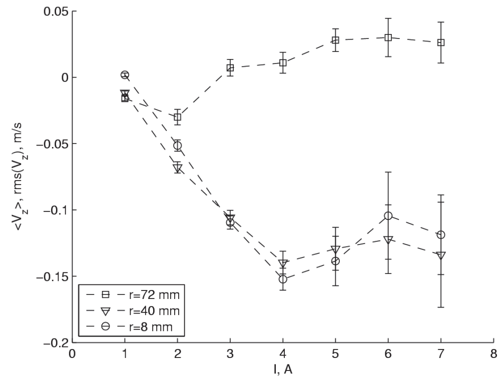

Figure 6: Mean velocity and rms vs feeding current of TMF obtained by UVD.

In calculation (fig. 7, 8) several secondary toroidal eddies are generated in the RMF case and one poloidal eddy is generated in the TMF case. The profiles have obtained for cylindrical channel of L=0.16m and for z=0.053m. Origin point is placed on the bottom center of the cylinder. The eddies have almost the same intensity for small values of feeding current frequency. The frequency increasing leads to the growth of the eddies located close to the vertical boundary and to fading of the central eddies. The near-wall velocity increases due to the change of the em-force topology because of skin-effect. However, the flow intensity does not essentially change for the frequency values larger than 50 Hz.

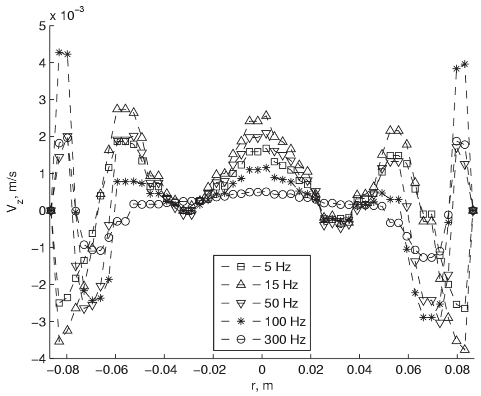

Figure 7: Numerically calculated velocity profiles for several values of RMF frequency.

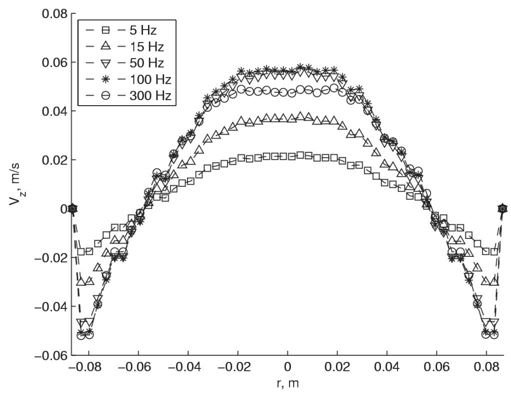

Figure 8: Numerically calculated velocity profiles for several values of TMF frequency.

3 TEST OF UDV IN THE STUDY OF PROCESS IN THE PLANE LAYER

We performed test experiment in a plane layer with free surface. The position of the interfaces obtained with UDV was compared with the interface position determined from the analysis of the obtained photographs. We investigate the flow and solidification in a thin layer of the liquid metal (fig. 9) with dimensions of 200 x 100 x 10 mm. Two opposite walls of the cell are copper heat exchangers. Two other walls, as well as the bottom of the cell are thermally insulated. The metal layer is placed into the gap of C-shaped ferromagnetic core (C-core). The bias coils place on the C-core and connect to AC power source. This leads to the generation of planar unstable vortex flow [3]. The five UDV probes were located in the hot wall. The probes emit an ultrasonic wave of a certain frequency, which falls on the solid-liquid interface. After this the wave is reflected back from the solid phase. This is clearly seen on the profile of echo signal. Using this effect it is possible to determine the solid-liquid interface in experiment.

We have tested the accuracy of the solid-liquid interface position using this technique. We studied the liquid metal layer with the free surface without MHD-stirring. The position of the interface was defined by UDV and photo camera. The testing results show (fig. 10) that the error in the identification of the solid-liquid interface is no more than 5mm with the cell length of 200 mm. This result indicates the ability of the UDV to determine the interface without direct contact of the probe with the melted metal.

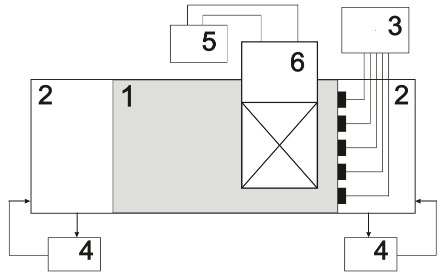

Figure 9: Scheme of the setup: 1-cell, 2- heat exchangers, 3-UDV, 4- thermostat, 5-tranformer, 6-inductor.

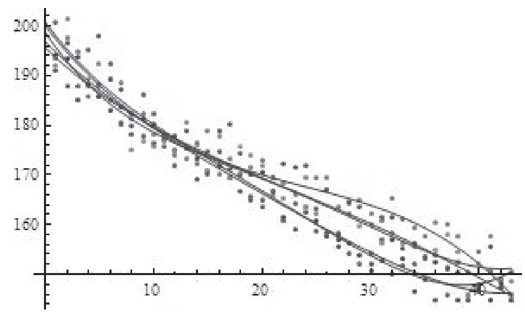

Figure 10: Evolution of the solid-liquid interface without stirring (dots – UDV data, lines – data obtained form the photo).

The investigations show, that the flow influences on the behavior and shape of the solid-liquid interface. It was found, that the crystallization rate increases with increasing intensity of stirring (fig. 11). In this case, the solid-liquid interface quickly goes to a steady state.

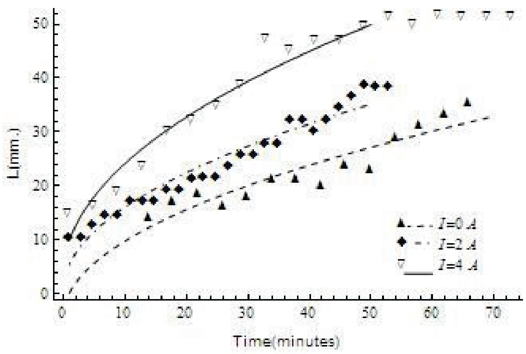

Figure 11: Evolution of the solid-liquid interface for different feeding current I of the inductor generating the flow.

4 FLOW AND CRYSTALLIZATION IN CYLINDRICAL VOLUME

To study the velocity and crystallization we have assembled the experimental setup (fig. 12). The setup consists of the following part: MHD stirrer 1, power supply source for RMF and TMF coils 2, stainless steel cylindrical channel 3 filled with gallium or gallium alloy, UVD sensors inserted into the holder 4, and UDV 5 (DOP-2000). The cold heat exchanger 6 is placed in the bottom of the cylindrical channel 3 and connected to the “cold” thermostat 7. The hot heat exchanger 8 is placed in the top of the channel and connected to the “hot” thermostat 9. When we set the temperature of the heat exchanger 6 smaller than solidification temperature the liquid metal starts to solidify. The solid-liquid interface starts to move from the bottom of the channel towards to the top. We will measure the movement of the interface as well as the evolution of the velocity profiles during solidification process. Additionally the setup includes the thermocouples, conductive velocimeters, and hall and current sensors 10 connected to multichannel data acquisition system 11. The described kit of the probes will allows us to obtain detailed information about crystallization process, evolution of the velocity, temperature, and turbulent properties of the flow. Now we are performing the experiments and calculations of the processes.

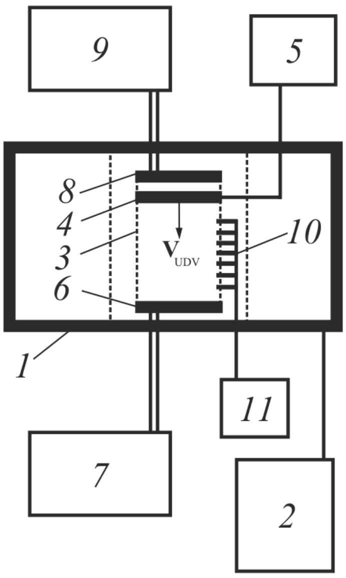

Figure 12: Scheme of the experimental setup for studying velocity and crystallization.

5 SUMMARY

We have studied the em-force, and the flow structure in liquid metal using UDV and calculations. We have measured the forces acting on the aluminum cylinders of different height placed inside the stirrer and calculated the intensity of em-forces as a function of the value and frequency of RMF and TMF. The investigation of the velocity field showed that the flow was unstable already at moderate stirring. This can be seen from the low-frequency perturbations of the velocity profiles. The perturbations were caused by a drift of large-scale vortex structures through the layer of liquid metal. With the growth of the feeding current for RMF and TMF, the intensity of velocity oscillations increases. In the case of RMF, the secondary poloidal flow consists of dissimilar eddies, whereas in the case of TMF – of a single eddy. The interaction of these flows gives rise to the flow with high velocity gradients, which is an indication of intensive molten metal stirring. The obtained results allow us to proceed with studying the essentially non-stationary crystallization processes taking place in the MHD-stirrer of our design.

The results of testing experiment in the plane layer showed that the UDV device has the advantage of determining the solid-liquid interface without direct contact of the UDV probe with the melted metal. The results of measurements allowed us to trace the evolution of the flow velocity and solid-liquid interface.

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