Parameters of electrical discharges with liquid metal electrode

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Abstract. The paper describes investigations of formation of high current electrical discharges emerging under free surface of liquid metal in tasks of melting and mixing intensification with use of electrovortex flow control. Discharge electrical characteristics, parameters of its ignition, visualization pictures of free surface deformation are presented here. Mechanisms of formation of the discharge over the liquid metal are discussed.

1. Introduction
Systems with electric arc under the liquid metal surface are taking place in many electrometallurgical processes: electro-arc welding, re-melting, casting, getting of liquid metal heat transfer agent, melt purification, waste recycling. Intensification of mixing and heat transfer in a bath of melt are provided by electrovortex flows induced as a result of interaction of passing through the liquid metal electric current with its own magnetic field. Electrovortex structures are specified by electric current density distribution that is set in vicinity of the contact of the arc with the liquid metal. In that case study of features of electrical discharge formation is important especially for the systems with pulse mode of power supply.

2. Experimental setup
Experiments are carried out with a test section, shown in figure 1, that is a cylindrical container 2 of 10 cm diameter and 5 cm height (or semispherical container of 18.8 cm diameter) filled with molten metal playing the role of a cathode [1]. A steel rode electrode 1 with semispherical edge of 2 cm diameter (or a copper rode electrode of 0.5 cm diameter) is dipped initially into the molten metal on a depth of semispherical edge radius. Molten plumbum and eutectic alloy of gallium-indium-tin (weight content is Ga – 67%, In – 20.55%, Sn – 12.5%, melting temperature is 10.5°C) are used as a working liquid in the experiments. Plumbum and its eutectic alloy with lithium are potential heat transfer agents for advanced fast neutron reactors. Gallium-indium-tin is suitable for physical modeling of the systems since it has low melting point and relatively low toxicity. Electric current in the circuit is organized by an accumulator power source and by a three-phase power supply 3 with open circuit voltage up to 13 V and 20 V correspondingly.

Electrical parameters, circuit current $I$ and voltage $U$ measured between the electrode and the free surface of the liquid metal, are registered with a four-channel digital recording oscillograph 4 Tektronix TDS 2014. Electric current is defined through the voltage drop on a current shunt 5 (0.2 MΩ and 0.05 MΩ). Processes visualization is performed with a high speed digital photo
camera 6 Citius Imaging C10 of following specification: maximum matrix resolution – 652 × 496, pixel size – 10 µm, maximum registration rate – 10000 frames per second, time of exposure – from 6 µs, synchronization accuracy – 1 µs. Synchronization scheme gives required time sequence and time intervals between switching on of electric current and triggering of recording equipment. Electric current runs the oscillograph generating a pulse signal to trigger the video camera. The oscillograph and the camera record processes before and after electric current switching on. The experiments were carried out in air and argon at $P = 1$ atm.

3. Results and discussion
Phenomena under consideration are complex and include the processes of free surface deformation, arc ignition and formation of a single wave at the interface of the liquid metal. Task of this work is to reveal causes and conditions for electrical discharge ignition, which will be the first step in the study of arc influence on hydrodynamics and heat transfer that in its turn specify the electrovortex structures. The melt in the experiments is exposed to a number of forces causing the motion of fluid under the rod electrode. Electromotive body force and gasdynamic force take the main part among them. The gasdynamic force is caused by the electric arc when overpressure is generated by plasma flow as a result of pinch effect and of nonuniformity of the cross section of an arc column.

Results of the experiments with the molten plumbum are presented in figure 2 demonstrating the phenomenon in the system through the voltage $U$ measured between the rod electrode and the liquid metal. Obtained data show the following processes development during experimental runs. There is no any discharge in the system on the first stage after switching on of the power supply and the voltage drop on the contact is $U \sim 2$ V, the current in the circuit is $I \sim 500$ A. Then the free surface deforms under the action of the electromotive body force that is a result of the interaction of passing through the liquid metal electric current with its own magnetic field, the voltage drop on the contact $U$ and the current in the circuit $I$ start to rise and fall correspondingly. Further rapid increase of the voltage drop on the contact $U$ corresponds to reduction of the contact area between the rode electrode and the liquid metal. The electrical discharge is ignited after the contact area gets its critical size and the voltage drop on the contact $U$ gets its maximum value in the experimental run. Corresponding oscillogram ranges of figure 2 demonstrate evolution of the electric arc of following parameters: $U_{\text{arc}} \sim 10$ V, $I_{\text{arc}} \sim 100–200$ A.

Mechanism of electrical discharge ignition in the experiments is similar to the method of arc initiation by initial contact and further separation of electrodes [2]. The energy corresponding
Figure 2. Voltage $U$ measured between the electrode and cylindrical container versus time.

Figure 3. Contact surface deformation and electrical discharge ignition.

to the work function of cathode material is required for electron emission from the surface in that case. We can use the value of ionization potential for plumbum oxide 9.7 eV to estimate breakdown voltage. The value is lower then the open circuit voltage in the experiments that approve the ignition of the electrical discharge due to free surface deformation caused by the action of the electromotive body force. Fast heat release at discharge ignition leads to gasdynamic explosion within a narrow area under the melt surface, to increase of pressure in the electrode gap, to further free surface deformation and as a result, to further growth of discharge length. Stationary state of the system is defined by equality of the electromotive and gasdynamic forces acting on the molten metal and of hydrostatic pressure forces of the melt. Cathode voltage drop for plumbum is 7.5–10 V. So the power source is not enough to sustain the arc with increasing length under the experimental conditions and electric current breaks. The condition of equilibrium of forces is not achieved in the experiments and the processes have non-stationary character in the system.

Free surface deformation and discharge ignition repeat during the run of experiment with following parameters: frequency of discharge ignition due to deformation of free surface $\sim 30$ Hz, time of discharge evolution $\sim 7$ ms, frequency of discharge pulsations $\sim 0.5$ ms. As the rode electrode is an anode the pulsations of the discharge reflects movement of a discharge
attachment point to the electrode along it [3, 4]. High-speed videos confirm the picture of processes development described above. Results of the experiments with plumbum and gallium-indium-tin are the same qualitatively [5]. Video frames of figure 3 obtained by high-speed imaging represents contact surface deformation, its detachment from the rode electrode and ignition of the electric discharge under the eutectic alloy. Electrical discharge parameters for the case are: $U_{arc} \sim 0.24$ V, $I_{arc} \sim 520$ A.

4. Conclusion
Experimental studies of formation of the electrical discharges over the surface of the liquid metal were carried out. Discharge characteristics and parameters of its ignition were determined. Wave form, free surface deformation and discharge evolution were visualized. It was confirmed that the cause of discharge ignition is deformation of the free surface due to action of the electromotive body force. The results will be used at investigations and estimations of influence of electrical discharge formation on vortex structures and velocity field in the bath of the liquid metal in study of magnetohydrodynamic method for intensification of mixing and heat transfer in technical devices.

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