PHYSICAL MODELING OF SLAG POOL HYDRODYNAMICS IN SLAB CURRENT-CARRYING MOULD
Part 1. Ingot melting

K.A. TSYKULENKO
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Investigations of hydrodynamics of slag pool in slab current-carrying mould were carried out. Assessment of effect of different schemes of connection of electrodes of a current-carrying section on nature of hydrodynamic flows was made by changing current value in the electrode–bottom plate circuit, distance from the bottom plate to the current-carrying section and depth of immersion of the electrodes. Qualitative pattern of distribution of hydrodynamic flows in the slag pool of the slab current-carrying mould was obtained. Results of the investigations will be used in designing of these moulds and determination of dimensions of the intermediate section and current-carrying areas.

Keywords: slab current-carrying mould, schemes of power supply source connection, modeling of hydrodynamic flows

Hydrodynamic flows in slag and metal pools in canonical process of electroslag remelting (ESR) are investigated sufficiently well. Balance of hydrodynamic forces and main directions of slag and metal flows were determined both for single-electrode and multi-electrode schemes of remelting at different circuit designs of the power supply source connection [1–5]. The ESR process was investigated in a slag mould [6, 7] and with application of magnetic fields [8, 9].

Perfection of the ESR technology caused development of a new equipment — a current-carrying mould, which ensures additional rotation of the slag pool in horizontal plane [10]. However, hydrodynamics of a slag pool in such mould is not completely clear. Modeling of the ESR process in the current-carrying mould did not give answer to the question if directions of the flows change in vertical plane (and if they change, then how), described for the canonical scheme [11]. Presented in this work scheme of the experiment corresponds more to the ingot melting process than to the process of electroslag cladding. It also remains unclear how pattern of hydrodynamic flows changes in case of transition from moulds of round section to moulds of rectangular section.

The purpose of this work is determination of optimal scheme of the current-carrying mould connection for melting of slabs from the viewpoint of the melt mixing and uniform distribution of flows.

For investigation of the slag pool hydrodynamics in a slab current-carrying mould a model from organic glass was made, which simulated such mould with 150×55 mm section (Figure 1). The current-carrying section represented copper plates-electrodes, installed flush with internal surfaces of the model. Between adjacent electrodes a 5 mm clearance was left, which simulated insulating elements of a real current-carrying mould. If necessary, adjacent electrodes were connected by copper jumpers for ensuring different schemes of connection. Middle separation section represented a belt of electrically interconnected copper

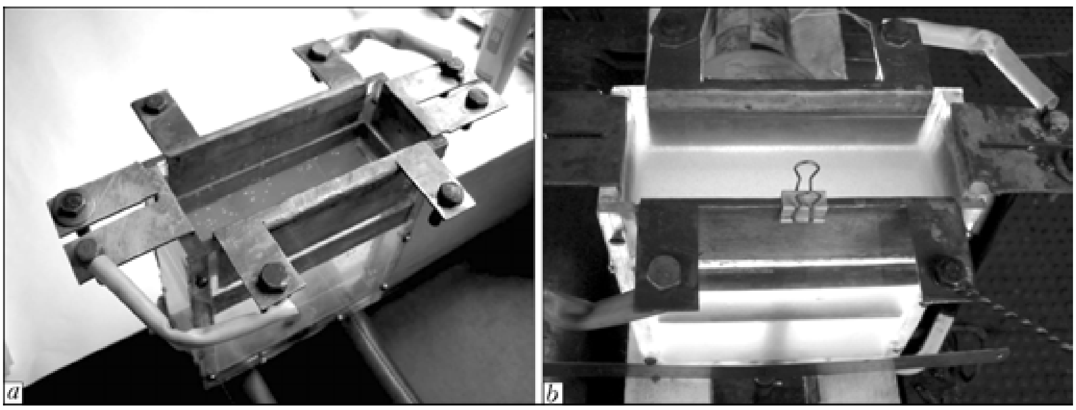


Figure 1. General view of model before (*a*) and in course (*b*) of experiment

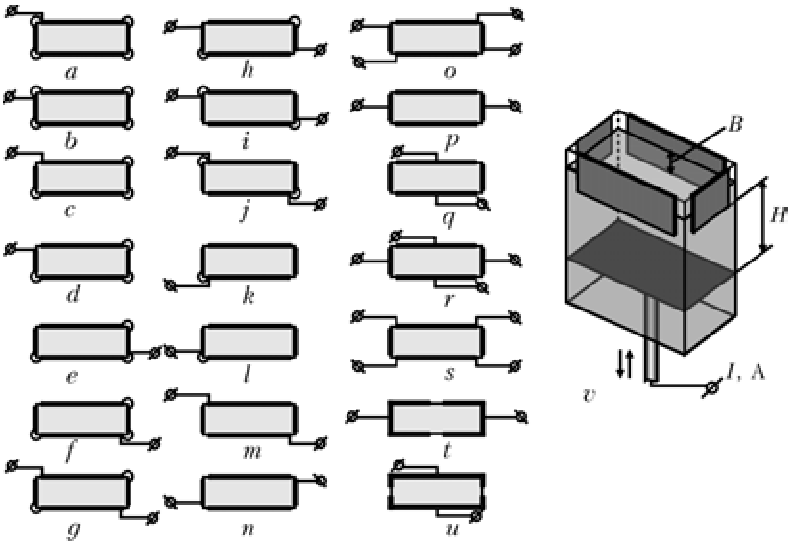


Figure 2. Investigated schemes of connection of current-carrying section electrodes (*a*–*u*) and model with parameters *H*, *B* and *I* changeable in course experiments (*v*): *a*–*u* — see explanations in the text

plates, installed with the same clearance below the current-carrying section. The lower copper plate, which simulated the bottom plate (the ingot), could move from the level of the separation section to the model bottom at the distance up to 110 mm (see Figure 1). Taking into account the fact that it was planned to investigate only distribution of current and directions of hydrodynamic flows, concentrated solution of calcium chloride, which was used in some models for canonical scheme of ESR and in modeling of this process in a current-carrying mould of round section, was selected as a medium for simulation of the slag melt [11]. Electrodes of the current-carrying section were connected to one pole of the power source, and bottom plate — to the other. Alternating current welding transformer with 60 V open-circuit voltage was used as a power source. Value of current in the experiments was regulated by means of a ballast rheostat within I = 20–110 A. In process of the experiments influence of different schemes of connection of electrodes of the current-carrying section on character of distribution of hydrodynamic flows was investigated, whereby not just value of current I in the electrodes–bottom plate circuit, but also distance H from the bottom plate to the current-carrying section and depth B of immersion of the electrodes were changed (Figure 2).

The whole big volume of the obtained actual material can not be, unfortunately, presented within the framework of this article, that's why here only main characteristic peculiarities of distribution of current and hydrodynamic flows are presented.

The experiments have confirmed evident assumption about spreading of current along the current-carrying section, consisting of several electrodes: the greater is the distance from the current lead area, the lower is current in the circuit of the current-carrying electrodes (Figure 3, *a*, *b*). Increase of the number of breaks in this circuit causes proportional reduction of value of current in each area of the current lead (Figure 3, *b*, *c*), whereby to the electrode of a bigger width corresponds current of a higher value (Figure 3, *d*). Such distribution of current will, undoubtedly, affect character of flows in the slag pool.

Main hydrodynamic flows in a slab current-carrying mould in majority of investigated cases represent flows, directed from the electrodes downwards along walls of the mould to the bottom plate and ascending in its central part. Similar character of flow movement was registered in ESR in a conventional mould with small depth of a slag pool between two bifilar connected electrodes [3] and in a slab mould with a current-conducting wall [7] (Figure 4). Such flows are also characteristic of free convection, occurring in the canonical ESR scheme in case of temperature differential [5]. But while in the canonical ESR scheme forces of free convection counteract electromagnetic

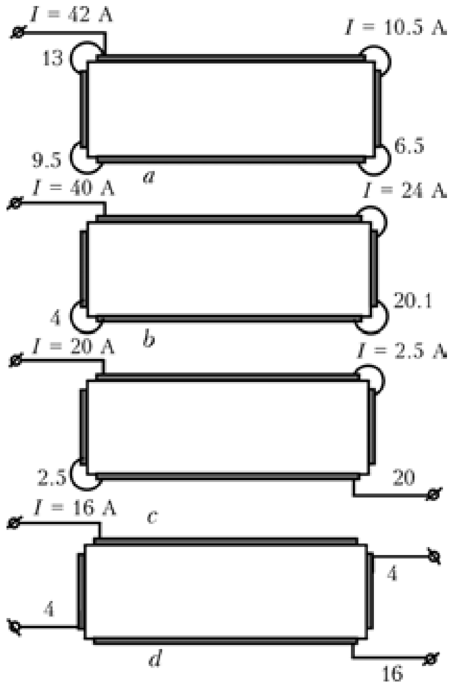


Figure 3. Distribution of current in circuit of current-carrying section of electrodes without breaks (*a*) and with one (*b*), two (*c*) and four (*d*) breaks

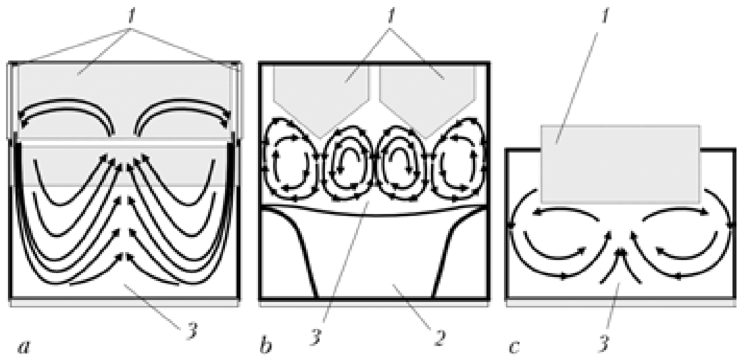


Figure 4. Main hydrodynamic flows in slab current-carrying mould (*a*), conventional mould with bifilar scheme of connection and small depth of slag pool (*b*) [3] and slab mould with current-carrying wall (*c*) [7]: *1* — electrodes; *2* — metal pool; *3* — slag pool

forces, in ESR in the current-carrying mould they, in all evidence, coincide. In order to give answer to the question if the observed flows are consequence of manifestation of the electromagnetic forces, a number of experiments were carried out, in which the model was positioned horizontally, like for example in study [1]. In horizontal position of the model character of the flows does not change, just small reduction of their speed is observed. In addition to the flows observed in the direction electrodes–bottom plate, it was also necessary to register flows caused by flowing of current along the current-carrying section over circuit of the electrodes. That's why all subsequent experiments with different schemes of connection, presented in Figure 2, were carried out in vertical position of the model.

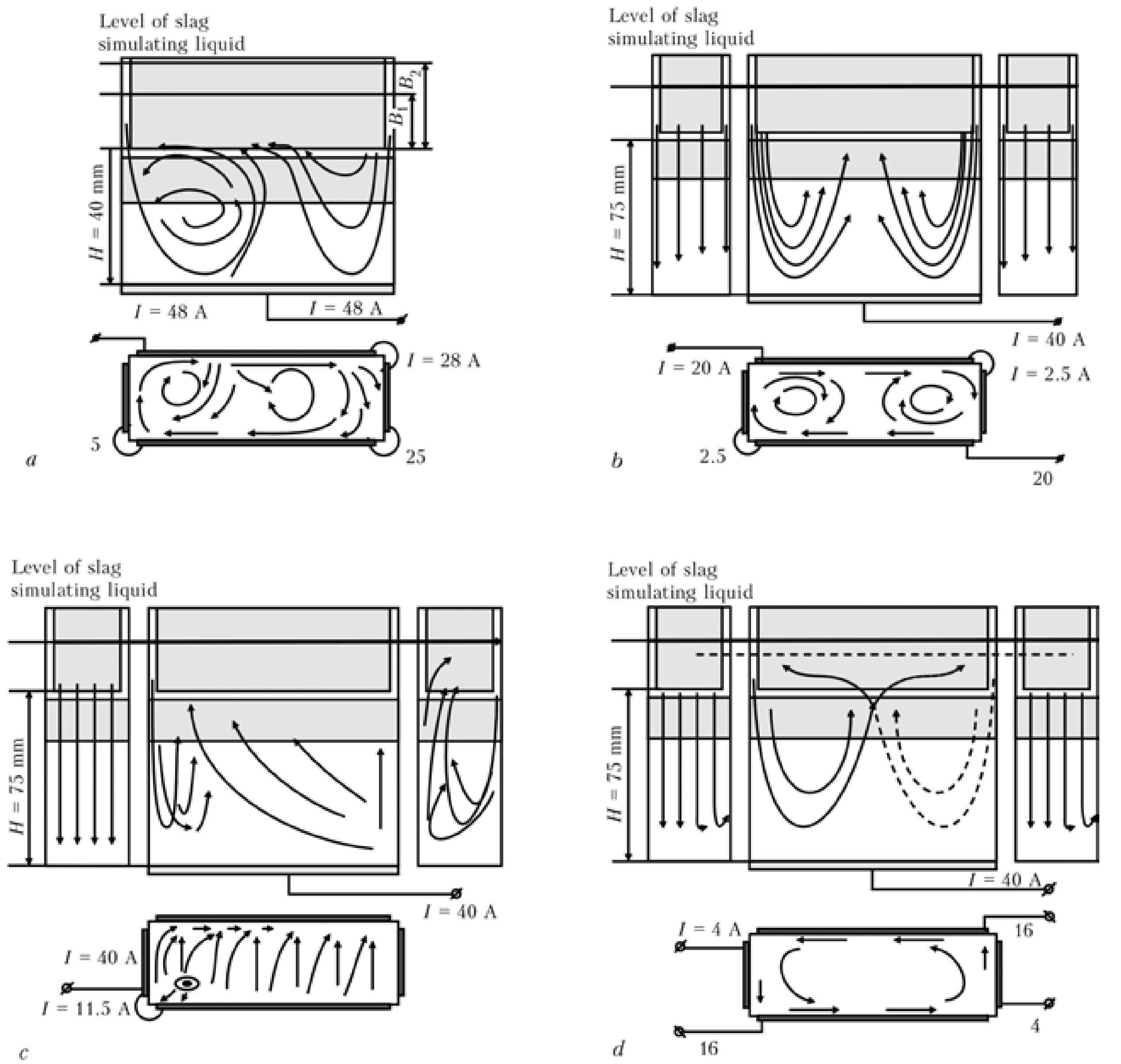
If the current-carrying section has no breaks in circuit of the electrodes (see Figure 2, *a*, *b*), main influence of character of the flows will be exerted by the place of the current-carrying cable connection, whereby ascending flows somewhat shift from the mould center in the direction opposite to the place of connection. Growth of current value causes increase of the shift and speed of the flows. The same effect is achieved by reduction of distance H from the bottom plate to the current-carrying section. Connection of a cable to one of narrow electrodes of a current-leading section of the slab mould enables formation along surface of the model, on which this electrode is located, of more intensive flows than at its opposite surface. When value H is determined, it may happen that flows at the opposite surface of the model will not achieve the bottom plate, and in this place will be a quite area. In addition, a small eddying in horizontal plane of the mould model, shifted from the center to the connected electrode, is observed. Speed of rotation of this flow is small, but it may increase as depth B of immersion of the electrodes reduces.

Presence of a break in circuit of electrodes of the slab mould current-carrying section causes formation of horizontal flows, directed from the place of the cable connection along circuit of the electrodes over perimeter of the section to the break. In case of connection of a current-carrying cable to a wide electrode, shift of the ascending flow from center of the mould significantly exceeds that for a close current-carrying section, other conditions being the same. In addition, this flow is also shifted in direction of the connected wide electrode. Near a narrow, located adjacent to the break electrode, a flow is formed, which rotates in horizontal plane. Its intensity increases by means of value H reduction or increase of current in the electrode–bottom plate circuit, whereby current itself shifts in the direction opposite to the place of the cable connection.

It should be noted that formation of flows and their highest intensity in all investigated cases took place not near surface of the solution, which simulated slag, but in the area of transition from the current-carrying section to the middle separation section located near lower boundary of the electrodes. In this area flows, ascending from the bottom plate, collide with horizontal flows and shift in the direction corresponding to the scheme of the current-carrying section connection. In case of big deepening of the electrodes (Figure 5, *a*), it may happen that the ascending flows will not reach surface of the slag pool or their manifestation will be less pronounced.

As a whole, if the current-carrying section has one break (see Figure 2, *c*), character of distribution of hydrodynamic flows in a slab mould is asymmetrical. In case of connection of a cable to a narrow electrode, located adjacent to a break in the circuit of the current-carrying mould section (Figure 2, *d*), more uniform distribution of flows occurs, while in case of connection of the cable to the middle of the current-carrying section (Figure 2, *e*, *f*) descending flows are observed in central part of the mould.

Two breaks, located diagonally in the circuit of the current-carrying section electrodes (see Figure 2, *g*–*j*), make hydrodynamic flows symmetrical. In case of connection of the cables to the wide electrodes (Figure 5, *b*), flows ascend strictly in center of the mould, and two circular horizontal flows, located near narrow electrodes, are also available. In case of connection of the cables to the narrow electrodes, intensity of rotation of these flows reduces, which is, evidently, connected with changes of values of the current, which flows in the circuit of the current-carrying section electrodes. Along the mould walls in direction from places of connection of the cables to the breaks horizontal flows are also formed. It should be noted that increase of the number of breaks in the current-carrying section reduces their speed. If one uses a



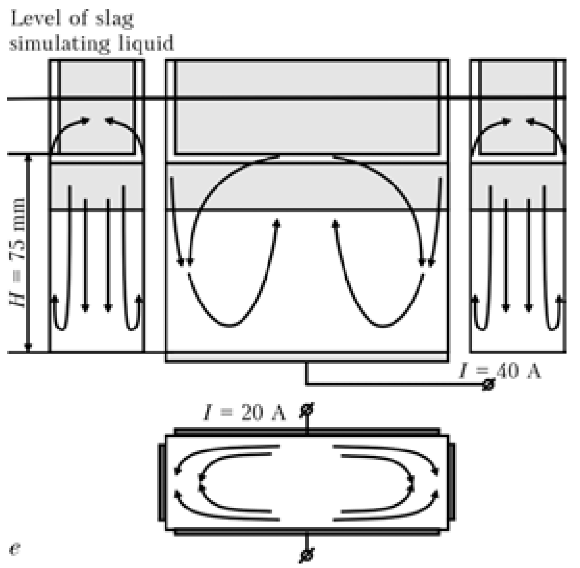


Figure 5. Schemes of flows of liquid, which simulates slag, at different versions of connection of current-carrying section of mould: *a*–*e* — see explanations in the text

scheme with counter-connection (see Figure 2, *i*, *j*), such flows will counteract each other, while circular horizontal flows will form only when distance from the bottom plate to the current-carrying section is small (in the investigated cases 40–50 mm).

Presence of three breaks in the circuit of the current-carrying section electrodes (see Figure 2, *k*, *l*) causes significant distortion of the ascending flows (Figure 5, *c*). Change of the place of the electric cable connection from a narrow to a wide electrode enables certain shift of the ascending flows rightwards. Between opposite, not connected to the power source electrodes, current flow was registered. Depending upon position of the bottom plate and place of the current-carrying cable connection, values of current in this circuit constituted 1.1–3.0 A.

Four electrodes of the slab mould current-carrying section, connected individually to the power source (see Figure 2, *o*, *r*), may, depending upon area of connection, ensure a symmetrical, but rather variable picture of formation of the flows in the slag pool. So, electrodes, connected in such way that areas of connection of each of them are located immediately adjacent to the breaks of the current-carrying section and do not border with each other, ensure presence of four flows ascending in central part of the mould. They shift in the form of a circular horizontal flow in lower part of the current-carrying section and may reach (depending upon values H and B) surface of the slag pool nearer to narrow sides of the mould, leaving undisturbed central part of its surface (Figure 5, *d*). If areas of connection of electric cables are located in center of the electrodes, shift of vertical flows does not occur. Hear flows, directed from the electrodes downwards along the mould walls to the bottom plate, become practically at once ascending ones and their intensity reduces by means of their approach to the mould center, where even a small descending flow is formed.

Having left a portion of the electrodes unconnected to the power source (see Figure 2, *m*, *n*, *p*, *q*, *s*) and used not three, like in Figure 2, *k*, *l*, but four breaks, an attempt was made to compensate distortion of the flows by means of a respective scheme of connection of the current-carrying cables. In case of connection of just two wide electrodes from opposite sides, a pattern of relatively uniform distribution of flows was obtained. Here, like in cases with one and two breaks, horizontal flows of low intensity, directed from the place of connection of the cables along the electrodes over perimeter of the section to the break, were observed. From the connected wide electrodes along the mould wall, vertical flows were formed, which converged in its central part. From narrow non-connected to the power source electrodes, weak descending flows formed. They, evidently, formed due to flow through the narrow electrodes of low current, registered earlier in the circuit of non-connected electrodes. At lower value of current, in comparison with current in the wide electrodes, velocity of such flows is also noticeably lower. In case of the current increase near the current lead areas, formation of intensive eddy flows in horizontal plane occurred. Change of the current lead from the wide electrodes to the narrow ones caused disappearance of the rotating along perimeter of the mould flow and formation of descending flows, directed from central part of the wide electrodes and ascending ones at a certain distance from the narrow electrodes. Into the same area also ascend more intensive flows, formed by the narrow electrodes.

If areas of connection of electric cables are located in center of the wide electrodes, a certain central area of the slag pool remains relatively quite (Figure 5, *e*). Flows of liquid, moving from the wide electrodes to the bottom plate, segregate from their central part and meet near the narrow electrodes. Here these descending flows superimpose on flows from the narrow non-connected electrodes and being repelled from the bottom plate transit into the ascending flows, located at a certain distance from the mould center. One may try to explain such character of distribution of the flows, in contrast to the scheme with individual connection of each electrode in central part, by presence of the horizontal component of current along the wide electrodes and its high value, while connection in center of just narrow electrodes does not create such pattern, which is, evidently, connected with small length of these electrodes. As it was shown earlier, velocity of horizontal flows reduces by means of increase of the number of cuts and reduction of the current-carrying circuit length. That's why horizontal flows in such scheme of connection, evidently, do not reach necessary intensity. Here flows from the narrow current-carrying electrodes to the bottom plate, ascending in central part of the mould, and descending flows of small intensity from the wide electrodes along the mould walls are observed.

It is remarkable that in all schemes with passive non-connected to the power source electrodes, flows are formed, which go from lower edge of the connected electrodes upwards in direction of ends of the non-connected electrodes. In scheme of connection, presented in Figure 2, *m*, such flows move in surface layers of the slag pool, thickness of which is approximately equal to deepening of the current-carrying section, opposite main flows.

Wish to form opposing horizontal flows stipulated testing of the connection schemes, presented in Figure 2, *s*–*u*. In all these cases distribution of flows was symmetrical. In case of connection of wide electrodes on two opposite sides near each of these walls of the model two vertical ascending flows formed. Ascending flows of lower intensity, which did not reach the bottom plate, also occurred near the narrow not connected to the power source electrodes. In the same place also formed small eddies in horizontal plane. Along the wide electrodes appeared insignificant opposite flows directed from area of connection of the cables. In the connection schemes with E-like pair of electrodes (see Figure 2, *t*, *u*) horizontal flows were insignificant and distributed according to direction of current from areas of connection of the cables. From areas of connection of the cables two vertical flows formed, descending along the walls and ascending in their center, whereby upper area of the pool, corresponding by its width, approximately, to clearance between the electrodes (in the investigated case 10 mm) and by its depth to deepening of the electrodes, remained relatively quite.

So, carried out preliminary investigations allowed obtaining qualitative pattern of distribution of hydrodynamic flows in a slag pool of the slab current-carrying mould. The most favorable, from the viewpoint of symmetry of hydrodynamic flows in a slag pool, should be considered scheme with two symmetrical breaks in circuit of the current-carrying section electrodes.

The data obtained will be used in designing of the current-carrying moulds and determination of dimensions of the intermediate section and areas of the current lead.

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