# INFLUENCE OF MHD PROCESSES ON OPERATING CHARACTERISTICS IN WORKING AREAS OF MAGNETODYNAMIC INSTALLATIONS FOR ALUMINIUM ALLOYS

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Factors are determined which reduce the operation efficiency of casting magnetodynamic installations for aluminium alloys. It is shown that the basic way to enhance technical parameters of magnetodynamic installations is the reduction of dispersion and the increase of magnetic field concentration in the T-shaped working area of magnetodynamic installations and also the decrease of the negative influence of vortex structures at the working area boundaries. A 3D measuring method of magnetic fields distribution has been developed. Ways for the optimization of systems generating electromagnetic fields and their superposition in the working area of magnetodynamic installations are defined.

**Introduction.** The magnetodynamic installations (MDI) for aluminium alloys have been successfully used for a long time in casting technologies for alloys treatment and casting.

Presently, the energy-saving requirements (not more than 0.08 kW·h/kg) for the melting-dosing devices used in casting technologies have became more demanding. This is determined by the development of technologies and by the expansion of alloy brands, enlargement of the casting size, weight and geometry, e.g., in the processes of casting under pressure, semi-continuous and continuous pouring. In particular, it is necessary to provide wider possibilities of magnetodynamic devices at the expense of created pressure (from 30 kPa to 50 kPa), realization of modes for intensive heating (from 3 °C/min to 10 °C/min) and stirring of melts (with rates from 1 to 10 m/sec), and also expansion of the range of mass flowrates realized at pouring toward both their increase (from 3 kg/sec to 10 kg/sec) and reduction (from 0.3 to 0.05 kg/sec).

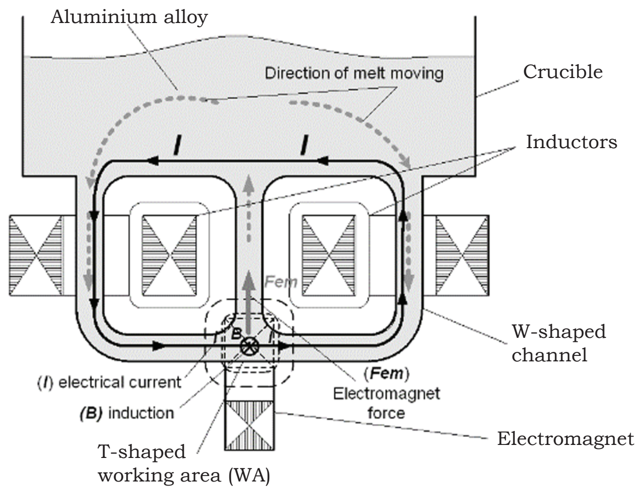
Analysis of the results of previous studies of MHD processes at the MDI boundaries and in its working area (WA) and estimation of the factors which decrease the operation efficiency of the MDI for aluminium alloys [1–4] showed that the basic way to increase the pressure and flowrate is in reduction of dispersion and in increase of the concentration of magnetic field lines created by an electromagnet, as well as in eliminating the negative effect of vortical structures appearing at the WA boundaries as a result of slump of the magnetic field [5, 6], and as well as in neutralization of the effect of liquid metal intaking in the WA due to the interaction of the magnetic field of AC current in a liquid metal conductor (a coil of liquid Al alloy) with the magnetic field in the electromagnet core [7, 8].

**1. Problem formulation.** To solve these problems, it is necessary to study the processes of distribution of magnetic fields in the WA of the MDI along with the distribution of induced current density, to investigate the MHD interaction in the WA, leading to the generation of volumetric electromagnetic forces and appearance of liquid metal flow, to define conceptual approaches to improve the geometry of the channels and MDI working area, as well as to modify its electromagnetic systems in order to enhance and stabilize the pressure, supply and MDI operational characteristics.

In order to better understand the reasons of MHD phenomena appearing in the MDI channels and WA, which negatively affect the hydraulic and operating characteristics of such installation, electromagnetic processes in the T-shaped WA were investigated under different operation modes.

At the first stage of our investigation, we studied the influence of design elements (the metallic casing of the channel) of the MDI (Fig. 1) on the distribution (distortion, dispersion, absorption) of the magnetic field induced by an external electromagnet. At the second stage, the features of magnetic field distribution in the T-shaped WA were studied by imitating the presence of metal by placing an aluminium plate in the horizontal cavity of the W-shaped channel (Fig. 1), which repeats the rounding of the T-shaped WA environs, with the passing AC currents induced by electromagnetic systems (inductors).

To systematize the experimental data on magnetic induction distribution and topology, a vertical coordinate matrix for point measuring of the magnetic field induction in the MDI T-shaped WA was used (Fig. 1).



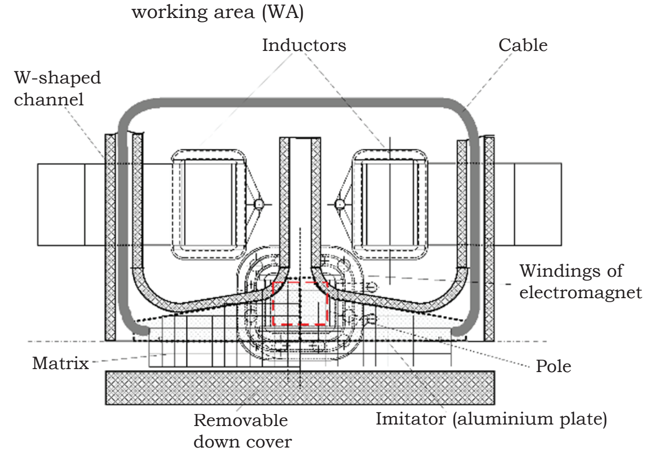




*Fig. 1.* Schematic views of the MDI ($a$) and W-shaped channel ($b$) and the research scheme of magnetic induction distribution in the imitation mode.

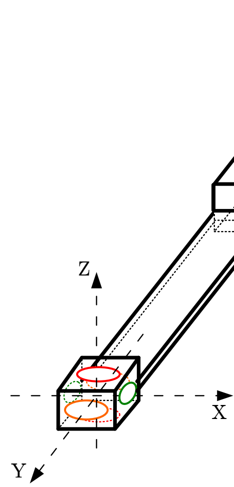



*Fig. 2.* Schematic of the three-vector induction sensor: $X$ – horizontal (tangential component); $Y$ – vertical (tangential component); $Z$ – normal (normal component); $N$ – total output (ground).

The matrix consists of cells of 20 mm in width and height in accordance with the geometry of the induction measuring sensor tip. To study the magnetic induction distribution of the coordinate matrix, in accordance with the geometry of the envelope of the horizontal part of the W-shaped channel in the vicinity of the WA, a model was produced, which was placed in the cavity of the MDI channel. In the experiments, in order to place sensors in the cavity of the WA, the bottom removable cover of the MDI channel was removed.

With the purpose to study in detail the spatial distribution of the magnetic field (to 1.0 T) in the MDI T-shaped WA and to record instantaneous values of the vector components of magnetic induction, a 3D-sensor has been developed [9]. The 3D sensor made it possible to realize continuous measuring of the normal ($Z$) and two tangential ($X$, $Y$) components of magnetic induction (Fig. 2).

Dispersion of the magnetic field (distribution of normal and tangential components of the magnetic field) not far from the T-shaped WA was measured by an device, which provided simultaneous three-vector measuring of the magnetic field parameters at the given point in the WA. The 3D induction sensor consists of six Hall probes, mounted as a cube (cap) with a 6 mm rib, providing three output signals ($U_x$, $U_y$, $U_z$), the variable voltage of which was proportional to the intensity of the magnetic field in three mutually perpendicular directions at the point of sensor location.

Signals from the parallel-arranged pairs of transducers were summed, and the average measured value of the induction inside a pair of sensors and, in general, the output signals ($U_x$, $U_y$, $U_z$) were characterized by a spatial measurement point located at the geometric center of symmetry of the cube formed by the Hall probes.

The distribution of magnetic induction, the dispersion, and the influence of the design elements of the channel in the WA and in systems, producing electric currents and their interactions, were studied in three regimes: ($a$) with the switched on electromagnet of the MDI (without liquid metal conductor-imitator); ($b$) with the switched on electromagnet and the aluminium plate placed in the channel (imitator); ($c$) with the switched on electromagnet and with the aluminium plate placed in the channel, with the passing electric current induced by the inductors.

(a)

(b)

(c)

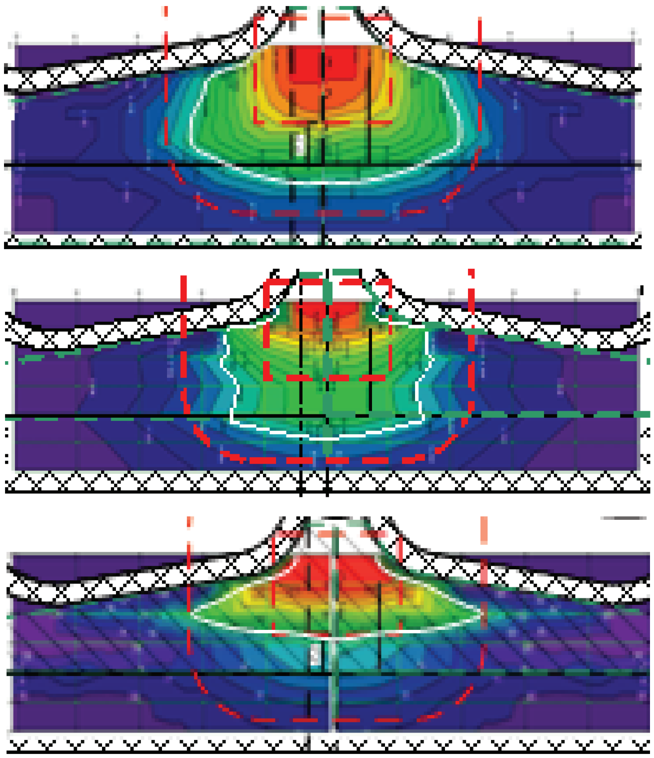


*Fig. 3.* Distribution of the normal components of induction in the MDI T-shaped WA in the imitation mode: (*a*) with the electromagnet switched on ($B \neq 0$; $I = 0$); (*b*) with the "imitator" ($B \neq 0$; $I = 0$); (*c*) with the "imitator" placed on the horizontal plane of the T-shaped WA, with the current ($B \neq 0$; $I \neq 0$) (white line corresponds to 20% of the basic value of magnetic induction).

The experimental investigation showed (Fig. 3*a*) that in areas 1 and 2 of the plane about the electromagnet pole there was a distortion of the distribution of the magnetic field lines as a result of the interaction with the material of the channel casing. The area of maximum normal values of the magnetic induction was found neighboring to the projection of the electromagnet pole, and about the T-shaped WA plane of the MDI the closeness of induction (by the value not below 0.05 T) was distributed over $35 \div 40\%$ of its area, where the electromagnetic pressure was created. The maximum value of magnetic induction corresponded to the center of the electromagnet pole.

The analysis of the magnetic induction topologies in the presence of the imitator (Fig. 3*b*) (the imitator is an 8 mm thick aluminium plate made of aluminium alloy) showed a characteristic for the imitation mode "deflection of the normal component of magnetic induction for vertical lines and narrowing on the horizontal line (the white line corresponds to 20% of the basic value of magnetic induction). This follows from the interaction of the external magnetic field with the eddy electric currents, appearing in the flowing conducting Al alloy, and its contours, which enhances the reactive resistance of the magnetic field.

To imitate a MDI working mode (pumping), the aluminum plate was placed on the horizontal section of the W-shaped channel (see Fig. 1*b*), and its left and right sides were connected to a copper cable of 150 mm$^2$ cross-section, passing through the cavity of the lateral branches of the W-shaped channel. In this case, the W-shaped channel of the MDI created a closed electric circuit corresponding to the currents (1–5 kA) induced by the inductors at co-phased switching on (the pumping mode).

In the experiments, the MDI was switched to the mode of pumping. Each of the windings (30 coils in each winding) of the inductors was supplied with the same voltage magnitude of 42, 53 and 57.5 V, and the windings of the electromagnet, respectively, with 45, 53 and 60 V.

When investigating the influence of MHD processes in the MDI working area on the operating characteristics in the imitation mode, with the inducted electric current passing through the aluminium plate and the with superimposed external magnetic field, it was shown that the concentration of the normal component of magnetic induction in the zone of the outlet pipe of the WA increased by 25% and by 15% at the bottom of the WA (Fig. 3*c*). Thus, the effective area of the WA, where the electromagnetic forces are created, makes no more than 60% of its actual value.

A graphic image of the algebraic difference of the redistribution of the magnetic induction normal component determined by the action of the magnetic field of the electric current passing in the metallic conductor in the WA is shown in Fig. 4.

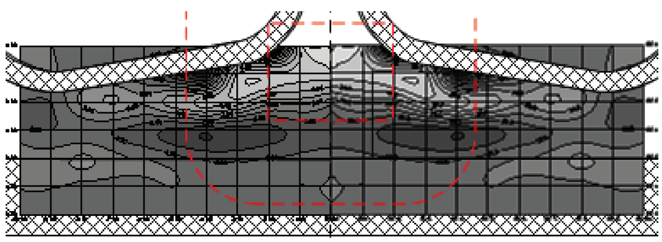


*Fig. 4.* Topology of the redistribution of the normal component of the magnetic field induction in the MDI T-shaped WA in the imitation mode.

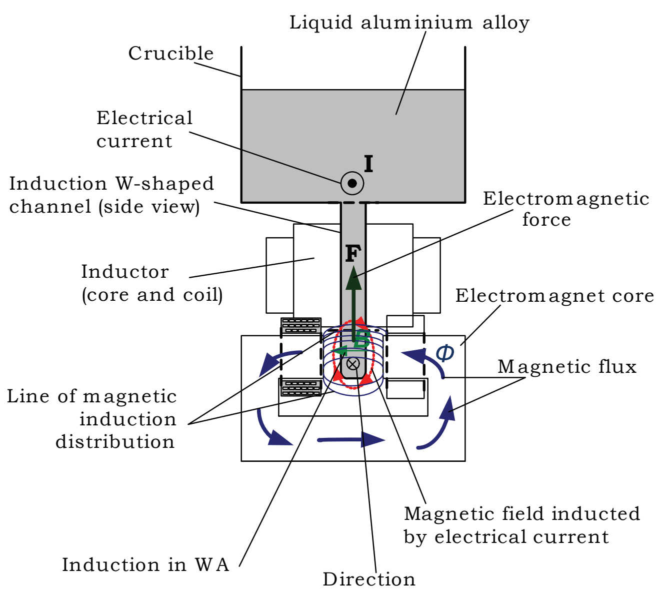



*Fig. 5.* Mechanism for the occurrence of the "anchor" in the MDI WA.

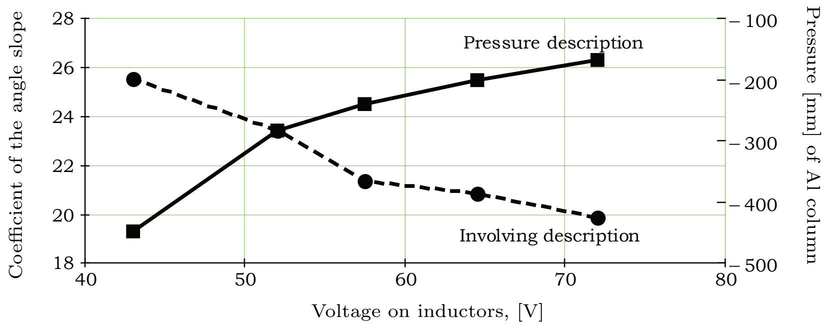



*Fig. 6.* Dependence of the pressure and negative component of the electromagnetic force on the inductors voltage.

The determining MHD effect (Fig. 3*c* and Fig. 4) is defined as a reaction of the "anchor" in the MDI WA [10], as a result of the interaction between an external alternating magnetic field generated by an electromagnet and an alternating magnetic field induced in the liquid-metal conductor in the horizontal area of the W-shaped channel, which meets the direction of the external magnetic field in the bottom part of the WA and corresponding direction in the top part.

Fig. 5 explains the interaction mechanism of the external alternating magnetic field produced by an electromagnet with the magnetic field induced by the liquid metal conductor (the "anchor").

The influence of the "anchor" increases with the increase of the electric current density $j$ in the WA and stipulates the unevenness of the induction distribution that results in decrease of the electromagnetic interaction efficiency and in appearing of areas of differentiated distribution, both by the electromagnetic forces $F_{\mathrm{em}}$ and by the electromagnetic pressure $P_{\mathrm{em}}$.

Analysis of the pressure descriptions in the MDI in dependence on the parameters of inductors and electromagnets operation [4, 11] (Fig. 6) has shown that with the increase of the voltage in the inductors, the angle of slope of the pressure characteristics decreases (Eq. (1)) and the dependence of the pressure coefficient loses linearity:

$$H_{\mathrm{Al}} = kU_{\mathrm{ind}} + h_{\mathrm{int}}\ [m], \tag{1}$$

where $H_{\mathrm{Al}}$ is the pressure by the height of the aluminium alloy column $(0 \div 1.25\,\mathrm{m})$; $k$ is the coefficient of pressure $(19.3 \div 26.3)$; $U_{\mathrm{ind}}$ is the voltage in inductors in the "co-phase pumping mode" $(43 \div 72\,\mathrm{V})$; $h_{\mathrm{int}}$ is an involved pressure as a function of $U_{\mathrm{ind}}$, $h_{\mathrm{int}} = f(U_{\mathrm{ind}})$ $(-0.198 \div -0.426\,\mathrm{m}$ of the aluminium alloy column).

Another important aspect, which determines the influence of MHD processes on the operation of the MDI, there is the influence of electromagnetic processes from the interaction of the magnetic fields of electric currents in the liquid metal conductor in the channel with the core (yoke) of the electromagnet. This influence is characterized by the appearance of "intaking" effect as a result of the negative vector of electromagnetic pressure in the WA, the value of which makes $20 \div 25\%$ of the pressure in the MDI (Fig. 6). Thus, the maximum value of the electromagnetic pressure created in the MDI corresponds to $30 \div 35\,\mathrm{kPa}$, and the loss of pressure due to the induction in the disconnected coils of the electromagnet makes from 6.0 to 8.75 kPa.

Along with the above, the tangential component of induction was studied in this case, too (Fig. 1), on the $Y$-axis corresponding to the component of the magnetic field induced in the T-shaped WA by an alternating current, which, when

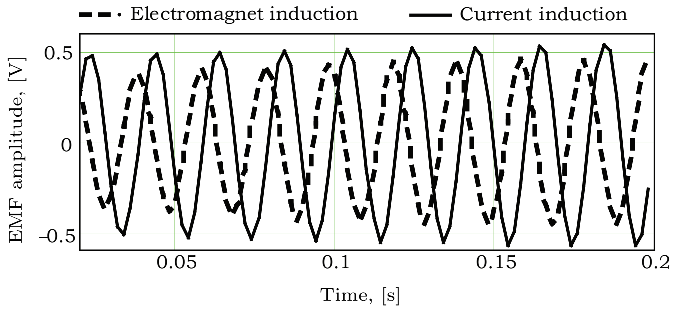



*Fig. 7.* Phase angle between alternating magnetic fields of the electromagnet and induction of the electric current $23^\circ \div 43^\circ$ $(0.18\pi \div 0.28\pi)$ in the MDI WA center.

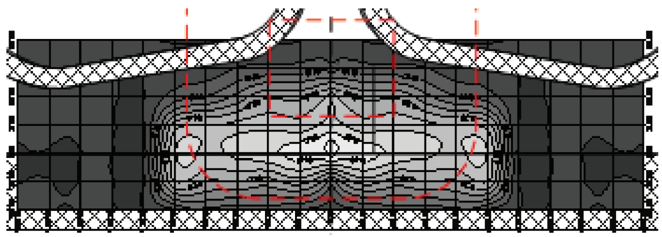


*Fig. 8.* Frontal topology and distribution graph of the tangential (axial) component of the magnetic field induced in the T-shaped WA by the AC passing through the aluminum imitator.

passing through the aluminum plate, has revealed the existence of density of the maximum concentration induction in the bottom parts of the WA (Fig. 4) and the presence of the phase angle between the alternating magnetic fields within $23^\circ \div 43^\circ$ $(0.18\pi \div 0.28\pi)$ (Fig. 7), which reduces the electromagnetic pressure by $1.5 \div 4.5$ kPa (from 5 to 15%): 70–180 mm pressure of the liquid aluminum alloy column.

The distribution by the magnetic field induced by the alternating electric current (Fig. 8) was obtained experimentally by simulating the MDI operation mostly in the pumping mode. The picture quality predetermines the redistribution component of the current density $j$ in the WA and its surroundings as a result of the interaction with the external magnetic field of the electromagnet and is characterized by displacement (pushing) of the flow lines in the area away from the projection of the poles of the electromagnet.

A characteristic feature of the MHD effect on the MDI performance is the significant differential values of the normal component of the magnetic induction in the WA, resulting in the formation of pressure fluctuations, and the magnitude of the volume electromagnetic forces therein. Topology analysis (Fig. 3*c*) shows that at a distance of 50–60 mm from the edge of the vertical projection on the horizontal pole of the electromagnet a decrease of the absolute value of the normal component of magnetic induction of up to 50% and at 80 mm up to 80% takes place. The decrease of induction vertically in the WA from the bottom edge of the electromagnet pole at a distance of 50 mm is over 85%. The result of this differential induction in the 2D-plane WA determines the difference value and the volume of the electromagnetic forces of the electromagnetic pressure in the T-shaped WA, where the melt flow rotates at $90^\circ$ and dynamic vortex structures form. These vortex structures have a wide range of impacts on the hydraulic characteristics of

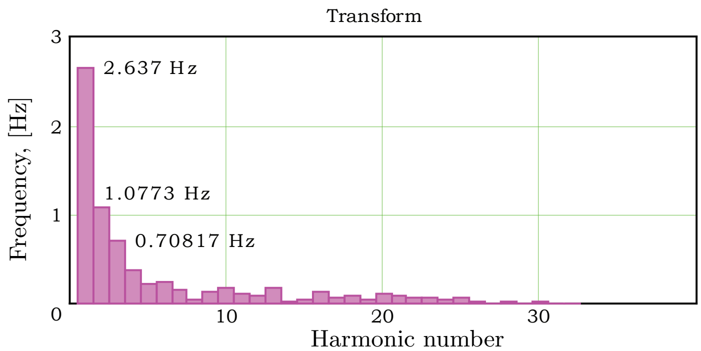



*Fig. 9.* Distribution of frequencies from the harmonics number of dosing oscillations.

the MDI and on hydrodynamic processes in the channels and in the WA, and with melt motion velocities up to 1 m/sec in the MDI channels and with high current densities in the channels pressure oscillations and electromagnetic pressure dynamics have been found increasing (by $10 \div 20\%$ from its nominal value at a frequency from 1 Hz up to 3 Hz) (Fig. 9). When the melt moved with medium velocities (>1 m/sec ) at high current densities, due to the flow turbulence in the WA and the output there from, the oscillation pressure characteristics, which did not to exceed 10–15%, were stabilized. However, the oscillation frequency becomes one or two additional (2nd and 3rd) harmonics: $0.4 \div 0.8$ Hz, $2.5 \div 3$ Hz, $3.4 \div 4$ Hz [6].

In the case of low values of the current density in the channels of the MDI and at low flow velocities in the pipes or channels in their absence, there is a pressure to destabilize the MDI performance by the development of an oscillating component, due to the development of powerful vortex structures in the vicinity of the WA that absorb a significant part of the energy generated in the WA by electromagnetic pressure.

(*a*)

(*b*)

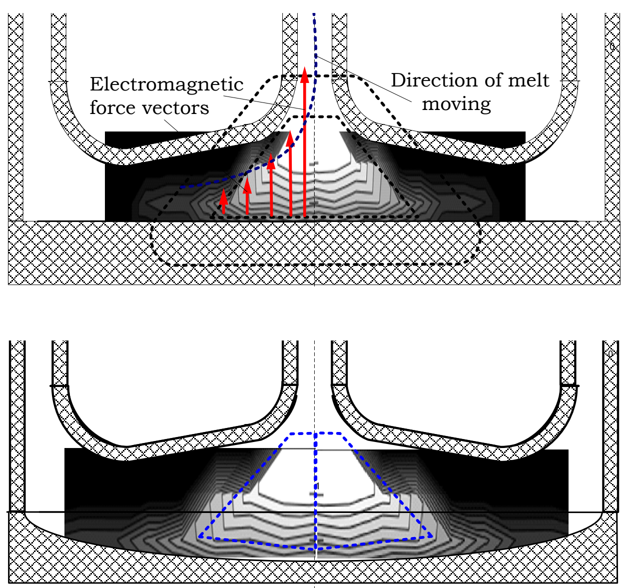



*Fig. 10.* Computer simulation of the distribution pattern with the normal component of magnetic field induction in the WA with a trapezoidal pole (*a*) and with indentations in the bottom part and U-shaped electromagnets (*b*).

In general, the process of maintaining excess pressure at the outlet of the WA may be accompanied by oscillations, with a transition zone in the "dip", that is the result of compression of counter-rotating vortex structures and their repulsion following from the distortion of the geometry from circle-shaped to ellipse-shaped [12].

Among the most promising problems for the further study are the optimization of the processes of redistribution of the normal component of magnetic induction in the WA and in its surroundings, with a view to a more rational use of the WA volume to create volumetric electromagnetic forces, as well as the optimization of magnetohydrodynamic processes there, stabilization and improvement of the operational and technical characteristics of magnetohydrodynamic systems.

To eliminate the harmful influence of the "anchor effect", the pole electromagnet geometry and its projection on the working area can be transformed from a parallelepiped, with 100% width of the width of the WA and 70% height of the height of the WA, to a trapezoidal form with the width of 40–50% of the upper base of the trapezoid and of 120–200% of the lower base and of 90–100% of the WA height (Fig. 10). This will ensure a forced change (90° angle rotation) in direction of the streamlines in the melt flow moving through the T-shaped WA, reduce hydraulic loss and prevent the formation of stable vortex structures.

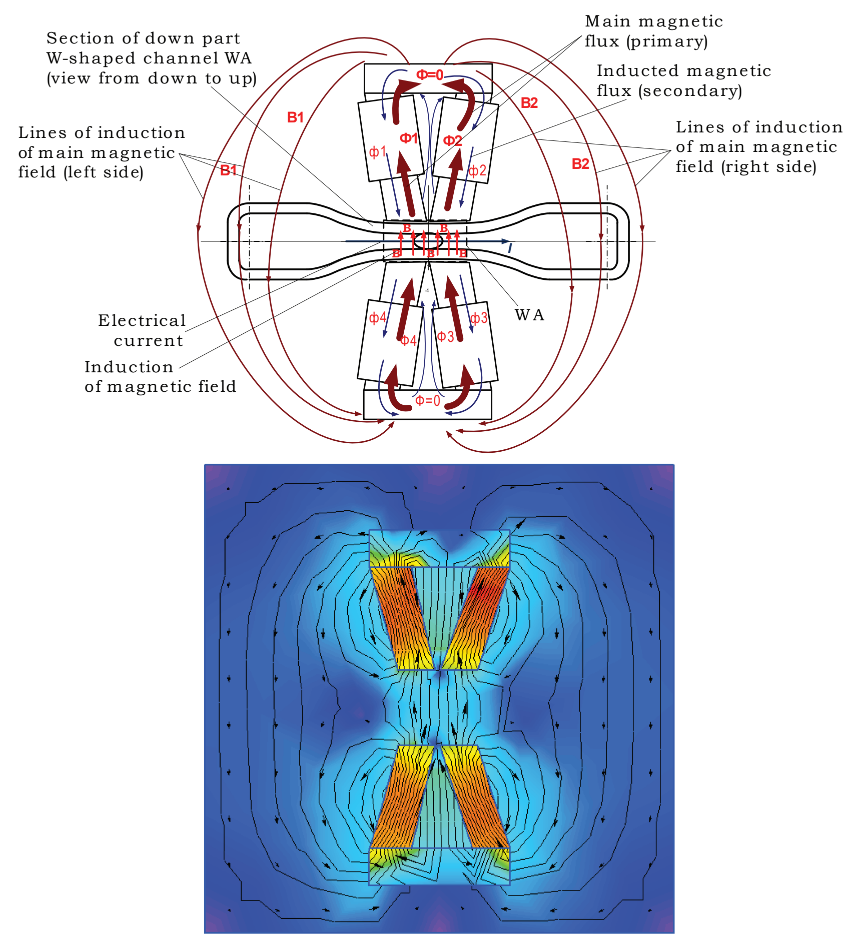



*Fig. 11.* The scheme and computer simulation of the generation the working component of magnetic induction in the WA and compensating of magnetic fluxes in the W-shaped channel induced by the current and electromagnetic force.

The MDI pressure characteristics MDI can be enhanced by increasing the depth of the WA base by $50 \div 60$ by performing indentations in the bottom part of the W-shaped channel. The estimated growth is promoted by the electromagnetic pressure, while maintaining the constant values of the current density, and the magnetic flux is up to $50 \div 60\%$.

To eliminate the melt "intaking" effect by creating a negative vector of the electromagnetic force in the working area, a special design of the MDI electromagnetic system has been developed as two U-shaped electromagnets with no connected core, with two windings on both, which is switched in the counter mode (Fig. 11).

The proposed solution avoids the interaction of the magnetic core of an electromagnet with the electrical current induced in the liquid metal coil and increases the pressure and flow characteristics by $15 \div 25\%$.

**2. Conclusion.** By analyzing the main factors which reduce the operating efficiency of the magnetohydrodynamic installations for aluminum alloys, it has been shown that the performance of the MDI can be enhanced by reducing the dispersion and increasing the concentration of magnetic fields in the T-shaped WA, as well as by reducing the negative influence of vortex structures at the WA boundaries. Experimental studies focused on the MHD processes in the MDI allowed to specify the role of the WA geometry, the location and geometry of the poles of the C-shaped electromagnet, and the redistribution component of the current density $j$ and the normal component of the external magnetic field in the projection of the T-shaped WA. The impact of MHD phenomena in the T-shaped WA on the efficiency, technical and operational characteristics of the MDI has been estimated. The possibility of substantial enhancement of the pressure characteristic in magnetodynamic installations, such as MDN-6A, has been shown.

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