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THE MHD LABORATORY'S WORK IN NON-FERROUS METALLURGICAL APPLICATIONS

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During the last 15 years the MHD Laboratory (Kharkov, Ukraine) has worked out several proposals and starts-up for MHD systems for metallurgical applications. MHD systems provide pumping, transportation, and dosing of alloys or liquid metals with temperature up to 700°C (fluid media: aluminum-zinc alloy; metals: zinc, tin, lead, gallium, sodium, potassium, rubidium, lithium). The results of this work are original schemes and technologies created in the Laboratory and protected by 24 patents.

The novelty of the devices is that the main part of the system — the MHD pump — does not require external cooling; its cooling is realized by heat transfer to the liquid metal. In these machines high-temperature electrical insulation and special technologies have been used; this ensures the creation of reliable and highly productive MHD machines. This is the principal difference between our work and similar work carried out by other organizations.

At present, pumping devices based on mechanical force (coercion) on liquid metal are used in metallurgy – mechanical pumps, pneumatic grabs, ladles. The use of these devices is associated with high energy expenditures, considerable losses of metal, and low capacity and reliability. The main advantages of MHD pumps for metallurgical equipment compared with mechanical devices are:

1. Absence of mechanical moving parts contacting with the moved liquid metal, and full integrity of channel.
2. Direct control of metal flow performance by changing of electrical parameters (voltage and current).
3. Intensification of pumping process.

The equipment described here, based on an MHD pump, has the following areas of metallurgical applications:

- transfer of liquid metal from the work pot (bath) to the reserve pot for inspection of pot walls and in emergency situations;
- dosed supply of metal;
- casting of motor rotors by aluminum;
- units for obtaining pure alkaline metals.

1. SYSTEM OF MHD PUMPS FOR MOVING OFF THE LIQUID METAL FROM THE WORK POT

The technology of putting the hot coating on sheet rolling metal or machine parts by immersion into the liquid metal requires periodically moving off the liquid metal from the work (coating) pot during scheduled or forced stops.

At present, for moving off the melted metal from the pot, ladles or mechanical pumps are used. But the first method is unsuitable in emergency situations and dangerous for the men on duty; mechanical pumps are difficult to use and not reliable enough. In particular, the imported mechanical pumps used in the coating rolling shop of the "Severstal" Plant (Cherepovets, Russia) have limited guarantees. Replacement of the mechanical pumps by MHD (electromagnetic) pumps permits solving the problem of effectively moving off the melt with multiple use of the equipment.

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Table 1

Main parameters	AMHЦ-7	AMH-11AЦ	AMH-13Ц	AMH-14C
Working media	Zinc	Aluminum-zinc	Zinc	Lead
Temperature of media, °C	460	up to 710	460	550
Capacity, tons/h	400	300	160	200
Height of lift, m	3.8	3.8	2.7	4.5
Pump phase current, A	≤ 420	≤ 220	≤ 220	≤ 380
Line voltage, V	220	300	230	350
Period of permanent operation	1 h 15 min	20 min	30 min	Permanently
Pump mass, t	2.5	1.4	1.0	2.5
Dimensions of pump* $h \times a \times b$, mm	1500×345×525	1000×345×525	800×345×525	1500×345×525
Power supply source	Induction regulator ИР-74/40	Auto transformer АТРМК-250/0,5	Induction regulator ИР-59/22	Induction regulator ИР-59/32
Mass of pump system, tons	5	1.5	1.2	3
Pot melt capacity, tons	500	55	80	—

*Excluding dimensions of nozzles, cable pipes, and legs.

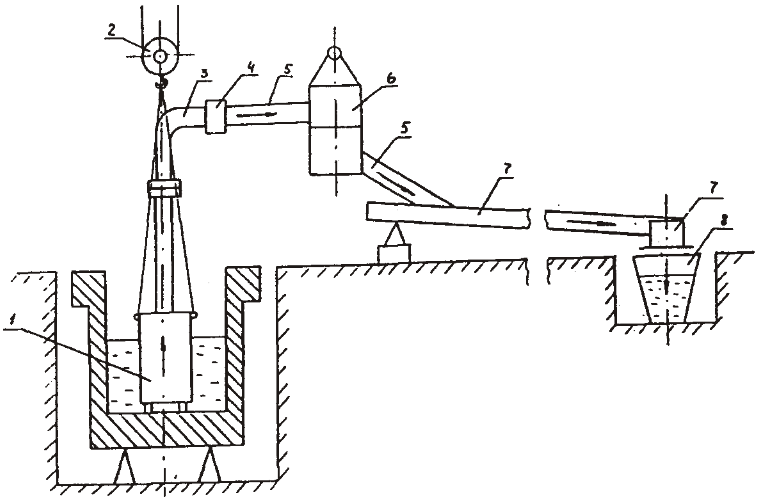


Fig. 1. Scheme of the immersible MHD pump system for transferring aluminum-zinc alloy in the coating workshop, at the "Everstal" Plant. *1* – MHD pump; *2* – suspension bracket unit; *3* – knee; *4* – flange connection; *5* – chutes; *6* – storage; *7* – trays; *8* – moulds.

The MHD pump system contains:

– an induction three-phase immersible MHD pump with cooling to the melt of the pot;

– power supply control devices (an induction regulator, control devices, a control desk), providing smooth regulation of the capacity from zero to rated value;

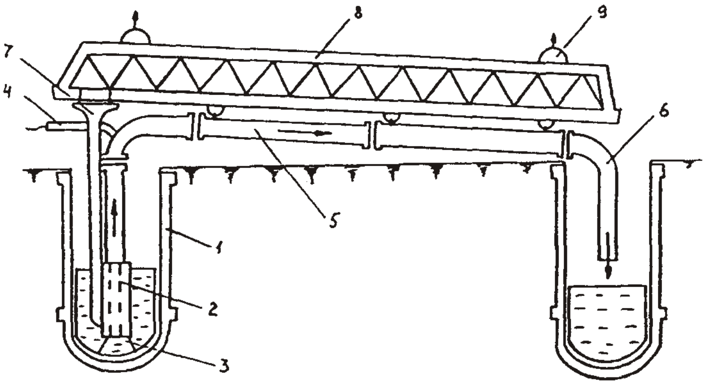


Fig. 2. Scheme of the immersible MHD pump system for transferring zinc melt in the coating workshop of the Pervomaysk Machine-Building Plant (Ukraine). *1* – pot (bath); *2* – MHD pump; *3* – inlet; *4* – terminals; *5* – heated tray; *6* – outlet nozzle; *7* – fixing; *8* – traverse; 9 – lift-transportation mechanism.

– a melt transportation tube connecting the MHD pump with the receiving vessels;

– a cross arm for lifting the pump and tubes and for control of their position in the pot.

From 1980 to 1993 the Laboratory developed, manufactured, tested, and delivered to its customers four systems of MHD pumps, which do not have, as far as we know, counterparts abroad:

1. An MHD pump system (AMHЦ-7) for pumping over the zinc melt from the work pot (bath) with a capacity of 500 tons to the reserve pot for a machine-building plant (Pervomaysk on the Bug River, Ukraine). The period of development and manufacture was 1980-1987, the start-up was in 1987, and the system has worked successfully for more than 8 years;
2. An MHD pump system (AMH-11AЦ) for pumping over the aluminum-zinc alloy (55% aluminum, 45% zinc) from the work pot with a capacity of 55 tons to the receiving vessels for the coating workshop of the "Severstal" Plant. The period of development and manufacture was 1989-1993, the start-up was in 1993, and the system has worked successfully for 2 years;
3. An MHD pump system (AMH-13Ц) for pumping over the zinc melt from the work pot with a capacity of 80 tons to the reserve pot, and vice versa, for the cold-rolling workshop of the Ilich Plant (Mariupol, Ukraine). The period of development and manufacture was 1992-1994, and the start-up was in 1994.
4. An MHD pump system (AMH-14) for permanent delivery of lead to the metering device feeder for the lead-zinc workshop of the "Ukrzinc" Plant (Konstantinovka, Ukraine). The period of development and manufacture was 1992-1993, and the unit was delivered to the customer at the end of 1993.

In Table 1 the main parameters of the systems are listed. The performances of the first three systems were obtained during their use.

The systems (units) differ from each other mainly in the kind of melt, the level of melt temperature, the dimensions of the immersible pump, and the kind of hydraulic tubes connecting the pump with the receiver vessels. The hydraulic tube in the Cherepovets and Mariupol schemes consists of chute, storage, and a system of trays. The tube is split because in the workshop part of it is often in use and is not connected with the lift-transportation mechanism (Fig. 1).

In the Pervomaysk scheme (first and most powerful) the hydraulic tube consists of a heated chute and an outlet tube which are connected to the pump by traverse fixing and a lift-transportation mechanism (Fig. 2). The MHD pump system for delivery lead melt is meant for work in the stationary regime; it is fastened to the pot and is connected by a flange to the chute (Fig. 3).

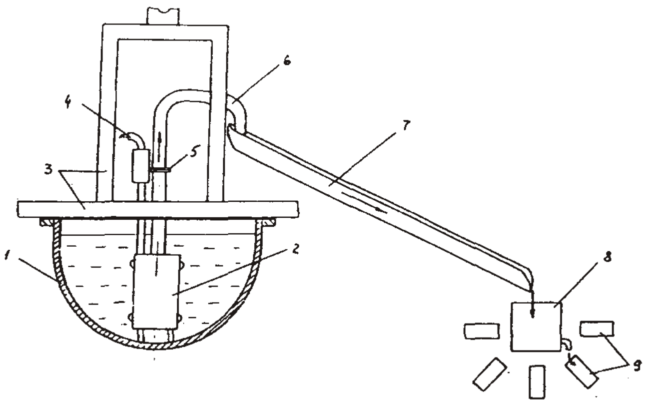


Fig. 3. Scheme of the immersible MHD pump system for permanent delivery of lead melt to the batcher at the "Krzinc" Plant. *1* – pot (bath); *2* – MHD pump; *3* – frame for fastening the pump to the pot; *4* – terminals; *5* – flange connection; *6* – chute; *7* – tray; *8* – batcher storage; *9* – moulds.

A common feature of the above systems is the construction of the pump. It is rectilinear, of the immersible type, without external cooling, and with vertical orientation. The construction of the Cherepovets pump was developed by designer V. E. Strizhak. The system consists of two inductors (MHD pump), pressure outlet, terminal box with cable pipes, and netting for the inlet of the pump. Each inductor has a laminated magnetic core, winding, and casing. The laminated core is made of electrical sheet steel with a coating working at temperatures up to 650°C. The winding is three-phase, double-layer, made from copper wire. The insulation is high-temperature (650°C) on a base of mica. The casing is welded and made from stainless steel.

At the time of design of the MHD pump the main dimensions of the pump are height of the channel on the liquid metal 2Δ, the thickness of the wall of the channel Δ_l, the width of the channel $2a$, the active length of the pump $2p\tau$, where τ is the pole pitch and p is the number of pole pairs [1]. Taking in account different initial data (capacity, height of melt lift, physical characteristics of the media, and so on) and given current loading, and keeping the main technological devices, the choice of the main dimensions comes down to determination of the parameters Δ, Δ_l, p.

From the theory of electromagnetic induction pumps it is known [2] that the ideal efficiency of the pump (without taking into account hydraulic losses and electrical losses in the inductors) is equal to

$$\eta_{\text{id}} = \frac{\Delta_S/\Delta(1-\Delta_S/\Delta)}{1+(\sigma_1\Delta_1)/(\sigma\Delta)-\Delta_S/\Delta},$$

where $\Delta_S = Q/8af\tau$ is constant for a given capacity Q, frequency of current f, and parameters $2a$, τ, chosen according to technological reasons; σ_1 is the electrical conductance of the channel wall; σ is the electrical conductance of the melt.

The maximum of the ideal efficiency

$$\eta_{\text{idm}} = \left(1+\sqrt{\frac{\sigma_1\Delta_1}{\sigma\Delta}}\right)^{-2}$$

is attained when $\Delta_m = \Delta_S + \sqrt{\sigma_1/\sigma\,\Delta_1\Delta_S}$.

In a variant of the Cherepovets pump $\Delta_S = 5\cdot10^{-3}$ m; $\sigma_l\Delta_l/\sigma = 3.75\cdot10^{-3}$ m; $2\Delta_m = 1.85\cdot10^{-3}$ m; $\eta_{\text{idm}} = 0.287$.

Table 2

Main parameters	AMH-7	AMH-11AЦ	AMH-13Ц	AMH-14C
Pole pitch τ, m	0.167	0.167	0.167	0.167
Width of channel $2a$, m	0.15	0.15	0.15	0.15
Liquid metal gap 2Δ, m	0.025	0.025	0.016	0.016
Thickness of channel wall Δ_l, m	0.01	0.0075	0.008	0.006
Material of channel walls	X18H10T	03X17H14M3	X18H10T	X18H10T
Material of casing	"	"	03X17H14M3	"
Full gap between inductors, m	0.046	0.0408	0.0328	0.0288
Number of poles $2p$	8	5	4	8
Full length of inductor, m	1.5	1.0	0.8	1.5
Winding factor	5/6	5/6	5/6	5/6
Number of teeth in one inductor	107	71	59	107
Tooth pitch, mm	13.9	13.9	13.9	13.9
Width of slot, mm	8.9	8.9	8.9	8.9
Height of slot, mm	69	69	69	69
Height of back, mm	30	30	30	30

If we take into account the fact that losses in the inductors and channel affect the maximum efficiency at the side of greater liquid metal gaps, a value of $\eta_{idm} = 0.287$ for wall thickness $7.5\cdot10^{-3}$ m and gap $2\Delta = 25\cdot10^{-3}$ m is optimal.

The number of pole pairs is equal to $2p = Ah/I^2$, where h is the height of the melt lift, I is the phase current, A is a constant determined by the physical parameters of the melt, the given channel geometry, and the data of the inductor winding. For the Cherepovets pump variant the value $A \cong 60\ 000$ A/m, $2p = 5$ (an integral).

The main dimensions of other systems of pumps were chosen the same way (see Table 2). Complicating the conditions for the use of pumps are the high cost of materials, including high-temperature insulation, and the demand for raw theoretical and experimental investigations connected with improving the calculation method, analysis of thermal and hydraulic regimes, and search for materials stable to the corresponding melts and temperatures. The results of these investigations were given in detail in [3-7]; here we mention briefly some of them.

I. In preliminary tests of the Pervomaysk MHD pump for the pumping of the melt from the pot to the same pot it was found that the capacity of the pump is two times greater than that predicted by calculation.

For improving the calculation method, specific peculiarities of the present pump were taken into account such as:

– relatively thick channel walls;

– availability of a large bulk of melt around the pump; the external melt plays the role of the connecting buses. It decreases the transverse end effect;

– heterogeneity of the magnetic field along the width of the channel and the polyharmonic character of the current load distribution along the length of the channel.

Accounting for the above factors enables one to obtain good agreement between calculation and experiment. Figure 4 shows the nominal point according to the previous calculation (point A). Curve *2* was calculated according to the specified method for experimental distribution of the magnetic field, and curve *3* was calculated according to the specified method with use of the calculated distribution of the magnetic field for the presented current loading. There is a good agreement between the experimental curve *1* and curves *2* and *3*.

The theoretical investigations of our MHD Laboratory co-worker, Dr. S. Yu. Reutsky, are based on modern calculation methods. This analysis, in particular published in [5-6], is unique. The method includes the solution of a three-dimensional problem on magnetic field distribution [6] and, following its approximation by polyharmonic functions, includes determination of the current density distribution, the electromagnetic forces in the liquid metal, and the energetic performances. Use of the method allows one to decrease by 1.5 times the dimensions of the Cherepovets pump and by 2.5 times those of the Mariupol pump, and to include in the dimensions of the Pervomaysk pump the pump for lead. It has led to a reduction in machine cost.

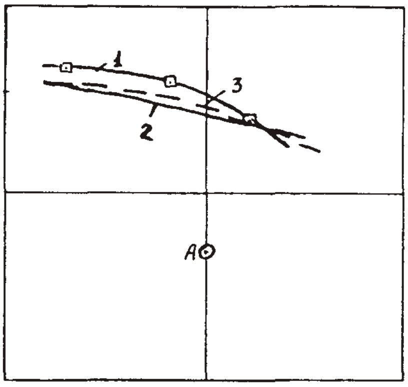


Fig. 4. Dependences of pressure (head) on capacity for the Pervomaysk MHD pump. *1* – experiment; 2 – calculated according to the specified method for experimental distribution of the magnetic field; 3 – calculated according to the specified method with use of the calculated distribution of the magnetic field for the presented current loading.

II. From a consideration of the heat regimes that arise when the pump is suddenly dropped into the melt, the influence of such factors as preliminary warming-up, moment of turn-on of the voltage, and velocity of immersion in the melt was shown.

The above regimes have been described in [4]; here we give the main results. Immersion of the cold inductor in the melt leads to intense conduction of heat away from the melt inside the channel up to hardening.

1. In particular, calculations made for the parameters of the Pervomaysk pump shows that for the "cold" pump immersed in liquid zinc, the liquid zinc inside the channel becomes hard after 3.2 min and will melt again after 4.5 h only.

2. The intensity of conduction of heat away from the melt inside the channel decreases if there is preliminary warm-up of the pump.

3. Preliminary warming-up is established by open-circuit pump currents without the melt in the channel. In this case the channel walls, owing to the eddy currents, warm up considerably faster than the inductors, reaching the melting-point (460°C) while the inductors remain relatively cold (210-230°C).

4. With increase in winding current the velocity of warming-up increases. Thus, if the phase current is equal to 60% of the nominal value, warming-up continues for about 2 h; this is allowed for scheduled moving off of the pot. If the phase current is equal to the nominal value, channel warming-up proceeds practically adiabatically, reaching the melting point of the melt in 3 min. This regime is admissible in an emergency situation, but it is extremely dangerous for channel integrity because the channel can melt.

III. In connection with the choice of materials for the immersible part of the pump, investigations were conducted on the corrosion resistance of type X18H10T stainless austenite steels in zinc melt at temperatures 450-500°C and types 03X17H14M3 and 316L (USA) in aluminum melt at temperatures 765-780°C, and some coatings that protect these steels [7].

The permeability P characterizing the material taken away was determined according to the loss in unit mass:

$$P = 87.6\Delta m/\gamma S t \ \text{(mm / year)},$$

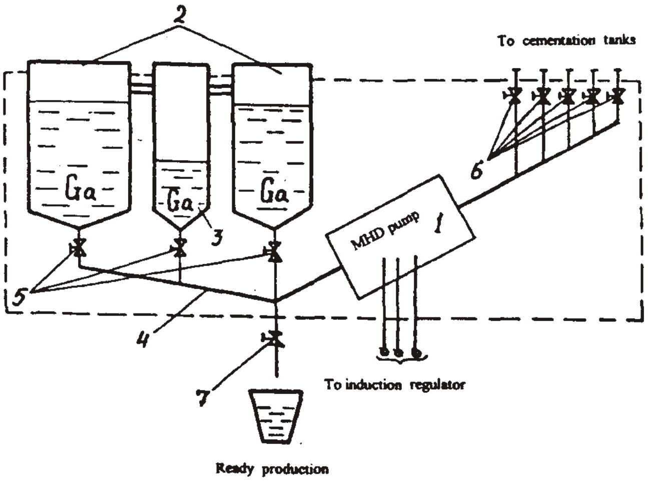


Fig. 5. Scheme of the MHD pump system for dosed supply of liquid rough gallium to the carburization tanks. *1* – MHD pump; *2* – measured tanks; *3* – sink tank; *4* – pipes; *5* – clutches for connection of flowing part with tanks; *6* – clutches for connection of flowing part with carburization tanks; *7* – clutch for sink of ready production.

where m is the loss in mass resulting from corrosion, g; γ is the material density, g/cm^3; S is the square of the surface of the unit in contact with the melt, cm^2; t is the duration of the test, h. Some results of the tests are listed below.

1. Under the conditions of the working hot zinc galvanizing pot with the temperature of the zinc melt at 460°C, the amount of steel X18H10T taken away was equal to 116.5-134 mm/year; but welded joints were in good condition and practically did not undergo corrosion. Based on these results, we estimate that the Pervomaysk pump is used for as much as 425 h. Taking into account that one moving off of pot melt has a duration of about 1 h 15 min, the above time is enough for 340 moving-off procedures (usually 1-2 movings off per year are necessary).

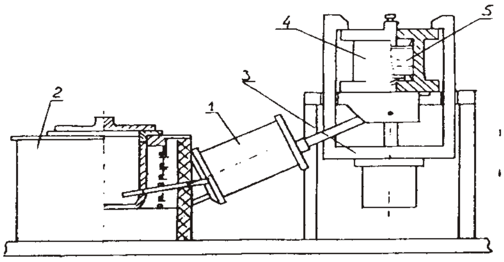
2. The amount of steels 03X17H14M3 and 316L (USA) in an aluminum melt taken off at temperatures 760-780°C is equal to 600 mm/year (non-hardened steel 03X17H14M3), 140 mm/year (hardened steel 03X17H14M3), and 160 mm/year (non-hardened steel 316L).

It is necessary to point out that the composition of steel 03X17H14M3 does not completely correspond to the standard (GOST 5632–72). The steel contains less nickel (10% instead of 13-15% according GOST) and little titanium (less than 1%). According to [9], if the content of nickel is less than 10%, the austenite state is unstable and, due to the high temperature and internal tensions, can change slightly to the martensite state. We observed this phenomenon: pieces of steel became magnetic somewhere. Adding a protective coating decreases the amount of material taken away, in particular in the aluminum melt, up to 6 mm/year.

In conclusion we note that the use of the MHD system led not only to a considerable decrease in the duration of the working cycle and a decrease in losses of the melt, but also to a basic change in the technology of pot filling of the bimetal.

2. DOSING OF LIQUID METAL

The MHD Laboratory has created two systems using an MHD pump for dosing of rough gallium. Gallium is extracted from the carburization tank and then a dose of gallium is pumped into the tank again with the subsequent sink of the remaining gallium as a ready product (Fig. 5). One of these systems was started up at the Bauxitogorsk Alumina Plant, Russia (1979); a second is meant for the Pavlodar Aluminum Plant. The unit has been manufactured, but has not been shipped.



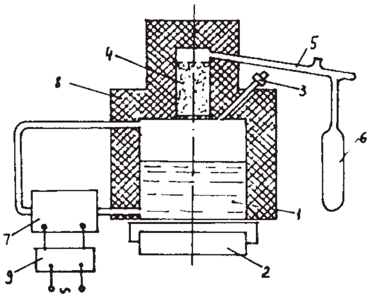


Fig. 6. Scheme of experimental stand for motor rotor potting. *1* – MHD pump; *2* – electric furnace; *3* – mechanism for press form locking; *4* – press form; *5* – laminated rotor.

Fig. 7. Scheme of unit for obtaining pure rubidium (cesium) at the Lovosersk ore mining and processing enterprise, Russia.

The two systems are similar, but there are some nonfundamental construction differences.

The main parameters of the batcher for the Pavlodar plant are: media – gallium with temperature up to 180°C; doses – 30, 60 kg; height of lift gallium – 4 m; duration of metal transfer – 50 sec.

The use of the unit decreases the gallium losses, improves the conditions of work, and mechanizes the manual labor.

3. CASTING OF MOTOR ROTORS BY ALUMINUM BY THE METHOD OF ADJUSTED PRESSURE

At present two methods for rotor casting (potting) are known: high-pressure casting and casting by gravity. Rotor casting by the method of adjusting the pressure uses the advantages of both methods. The adjusting of pressure is realized with the use of an MHD pump installed in the metal way between the furnace with the melt and the press form (Fig. 6).

The concept of the method of adjusting pressure belongs to the "UkrNiiLitMash" (Kharkov, Ukraine). This enterprise developed the experimental stand. The MHD Laboratory developed and manufactured the system of MHD pumps. The system of MHD pumps has realized the following:

- supply of the melt to the press form;
- pressing after filling of the press form;
- reversing the remainder of the liquid metal;
- barring of the metal way.

According to the above conditions the system consists of:

1. An MD pump, induction, three-phase, screw (spiral) channel;
2. A control board;
3. A standard adjustable voltage source.

The pump is dismountable, and the channel is replaceable during operation. The main construction units are:

- an external inductor with a rotating magnetic field. The magnetic core is laminated from *permendure*, an alloy based on cobalt, and has a high Curie point; the winding is three-phase, based on high-temperature insulation developed by VNIIEIM, Moscow, Russia. The winding was of steeped special high-temperature composition;
- an internal inductor, made of a magnetic core without winding;
- a screw (spiral) channel which has an inlet and an outlet for hydraulic connection with the remaining part of the metal way; the channel is made of stainless steel 3H943, which according to literature data is stable in aluminum melt at a temperature of 780°C;
- a pump casing with terminals box.

The main project system parameters are:

1) casting regime: capacity, $0.9 \cdot 10^{-3}$ m^3/sec; head, $2.5 \cdot 10^5$ N/m^2 = 2.5 atm; line voltage, 80 V; phase current, 40 A;

2) metal pressing regime: capacity, 0; maximum of head, 25 atm; line voltage, 140 V; phase current, 120 A (loading is short-term).

The pump was tested in the idling regime. The experimental data are in good agreement with the calculated data. In particular, the calculated nominal regime values of current, voltage, and induction at the center of the channel are 40 A, 80 V, and 0.2 T respectively. The experimental values are 40 A, 87 V, and 0.19 T. A hot test is planned in the near future.

4. MHD PUMPS IN UNITS FOR OBTAINING PURE ALKALINE METALS

In Fig. 7 is shown the scheme of the unit for obtaining pure rubidium (cesium) from the melt, coming from the ore of furnace origin. The unit was developed by E. P. Lokshin at the Lovosersk ore mining and processing enterprise. The melt is placed in distiller *1* with volume 20 liters made of stainless steel. The distiller is heated by electric heater *2* and filled with the melt through inlet *3*. Above the distiller the so-called dephlegmator *4* is placed. It is a column filled by special metal shavings (chips). At the top of the dephlegmator there is a condensation pipe *5* and glass or metal vessel *6*, in which rubidium drops. The distiller and dephlegmator are covered by thermal insulation *8*.

When the melt reaches 380-400°C it begins to boil, and the steam goes through the dephlegmator, where it cleans itself, then condenses in pipe *5* and gathers in vessel *6*.

To increase the efficiency of the unit it was decided to equip it with MHD pump *7* which picks up the melt from the bottom part of the distiller and transfers it to the top (height 250 mm). The MHD Laboratory designed in 1980 a unit single-phase alternating-current high-temperature (500°C) pump with a flow rate of 0.7 m^3/h and a head of 0.01 MPa. The pump employs a series excitation. The power is supplied by the bucking transformer *9*. The use of the pump increases the level of metal purity.

Systems of MHD pumps similar to that described, for specified technical conditions, can be developed, manufactured, and started up by our enterprise.

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