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Magnetohydrodynamic pumps for molten salts in cooling loops of high-temperature nuclear reactors

***Abstract**. Possibilities of using the magnetohydrodynamic (MHD) effect for pumping molten salts in cooling loops of high-temperature nuclear reactors are analyzed. Two basic ways of producing magnetic field in the pump (saddle coils and permanent magnets) are evaluated with respect to the total Lorentz force and resultant pumping head of the device. The corresponding mathematical models are solved numerically*

***Streszczenie.** W pracy przeanalizowano możliwość zastosowania efektu magnetohydrodynamicznego (MHD) do pompowania płynnych soli w obwodach chłodzących wysokotemperaturowych reaktorów jądrowych. Zbadano dwa podstawowe sposoby wytwarzania pola elektromagnetycznego (cewki siodłowe i magnesy trwałe) pod kątem całkowitej siły Lorentza i wytwarzanego ciśnienia względnego. Do porównania wykorzystano numeryczny model efektu MHD. (**Pompy magnetohydrodynamiczne do pompowania płynnych soli w obwodach chłodzących wysokotemperaturowych reaktorów jądrowych**)*

Keywords: magnetohydrodynamic pump, molten salt, electric field, magnetic field, temperature field, numerical analysis.
Słowa kluczowe: pompa magnetohydrodynamiczna, pole magnetyczne, analiza numeryczna

Introduction

High-temperature nuclear reactors use for transfer of heat from the active zones either molten metals and their alloys (Na, Pb, Pb-Bi, etc.) or molten salts (such as fluoride salts). Pumping of these liquid media by classical mechanical radial or axial pumps is, however, rather difficult and the lifetime of such devices is relatively low.

More prospective are, therefore, electromagnetic pumps without any movable parts. The simplest devices of this kind are magnetohydrodynamic (MHD) pumps with magnetic field generated either by a system of appropriately arranged saddle coils carrying direct current or by a system of permanent magnets.

Such pumps (these times applied only for molten metals) were first mentioned in 1957–1959 in both Soviet Union and United States [1–3].

The authors presented the analysis and basic characteristics of such MHD pumps during the conference CPEE 2008 that took place in Crimea, Alusta [4]. In this case, however, just the transport of molten metals (Na and Pb) was investigated, thus materials with a high electrical conductivity, which is from the viewpoint of MHD pumps highly advantageous.

Unlike the mentioned work, the paper is devoted to an illustrative evaluation (based on numerous testing computations) of possibilities of applying these pumps for transport of molten salts. Molten salts are, in comparison with metals, characterized by much smaller electrical conductivities, but on the other side, they are highly advantageous from the thermodynamic viewpoint (very high specific heat, which results in small amount of this medium to be transported). Such a property seems to be highly desirable in case of their employment in high-temperature nuclear reactors that are expected to appear in a near future. Application of the MHD pumps in this sphere, therefore, is very prospective.

Formulation of the problem

A. *Principle of operation of MHD pumps*

The principle of the MHD effect for pumping electrically conductive nonferromagnetic liquids (nonferromagnetic molten metals, molten salts or also ionic liquids) follows from Fig. 1. Perpendicularly to the channel with the working medium **1** there flows direct current I_e between two nonferromagnetic (and in case of molten metals and salts also heatproof) electrodes **E1** and **E2**. The vector of its density $\boldsymbol{J}_e(x,y)$ is prevailingly oriented in parallel with the x-axis, thus perpendicularly to the z-axis of the channel.

As for magnetic field, its magnetic flux density $\boldsymbol{B}_m(x,y)$ must prevailingly be oriented in parallel with axis y, thus practically perpendicularly to the z-axis of the channel and to the vector $\boldsymbol{J}_e(x,y)$.

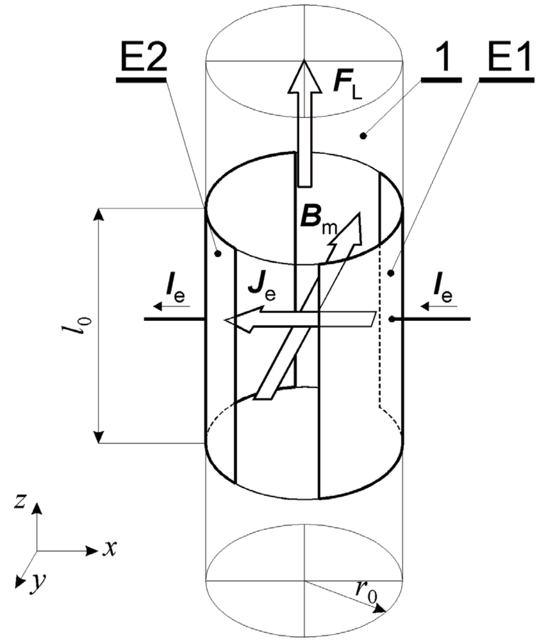

Fig. 1. Principal scheme of MHD pump **1**–channel with working medium, **E1**, **E2**–electrodes

The mutual interaction of these two vectors in the working channel of length l_0 gives rise to the following physical quantities:

- electromagnetic pressure p_{em} given by the formula

(1) $$p_{em} = \int_{l_0} (\boldsymbol{J}_e \times \boldsymbol{B}_m) \cdot d\boldsymbol{l},$$

- and total Lorentz force whose vector $\boldsymbol{F}_L$ is parallel to the z-axis and that is given by the integral

(2) $$\boldsymbol{F}_{\mathrm{L}} = \int_{V_0} \left(\boldsymbol{J}_{\mathrm{e}} \times \boldsymbol{B}_{\mathrm{m}} \right) \mathrm{d}V ,$$

where V_0 is the volume of the working channel.

The Lorentz force pushes the heat-transporting medium (molten salt) upwards along the working channel and, therefore, the whole cooling loop of the reactor. During this movement it must surpass hydraulic resistances in particular parts of the loop, and in specific cases also the hydrostatic pressure of the column of heat-transporting medium in this loop.

B. ***Basic structural arrangement of the MHD pumps***

Electric field (producing in the working channel of the MHD pump the current density $\boldsymbol{J}_{\mathrm{e}}(x, y)$) may be produced by

- one pair of appropriately shaped electrodes (Fig. 2 left),
- several independent pairs of such electrodes (Fig. 2 right).

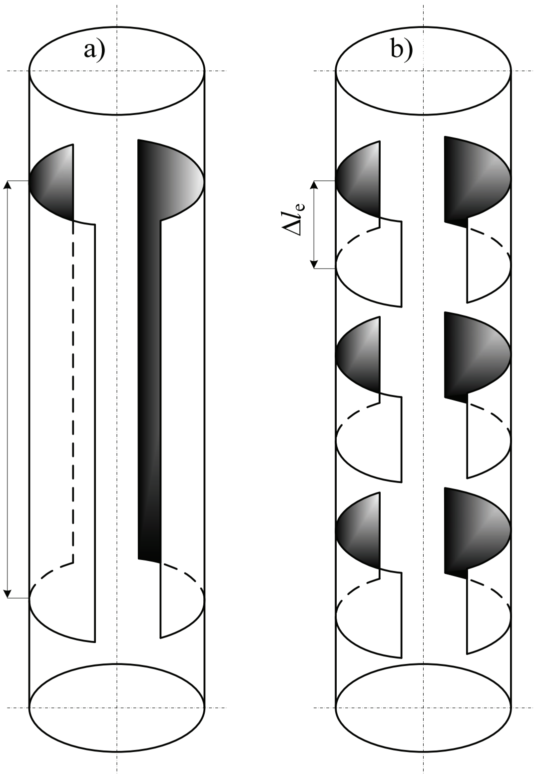

Fig. 2. Arrangement of an MHD pump a)–with one part of electrodes, b)–more pairs of electrodes

The multipair arrangement is more complicated, but it may be considered advantageous from the following viewpoints:

- Thermoelastic strains and stresses due to contact of the electrode material with melt of high temperature (see Tab. 1),
- Electrode currents I_{e} necessary for producing current density $\boldsymbol{J}_{\mathrm{e}}$ in the working channel need not be too high. The values of these currents are usually on the order of 10 kA (limitation follows fro available current sources and cooled conductors). Nevertheless, [1] mentions MHD pumps with currents reaching even $1 \div 2 \times 10^3$ kA.

Magnetic field of magnetic flux density $\boldsymbol{B}_{\mathrm{m}}$ in the channel can be produced

- by a system of suitably arranged permanent magnets,
- by an electromagnet or by a system of appropriately arranged saddle coils.

Arrangements with a system of permanent magnets (see Fig. 5) are relatively simple (from both operational and structural viewpoints) but they are usable just for smaller pumps. The only problem may be with ensuring a good thermal insulation (as the temperature of molten fluoride salts in the working channel is $T_{\mathrm{work}} \approx 700$ °C, while the maximum operation temperature of the permanent magnets $T_{\mathrm{w}} \approx 150$ °C).

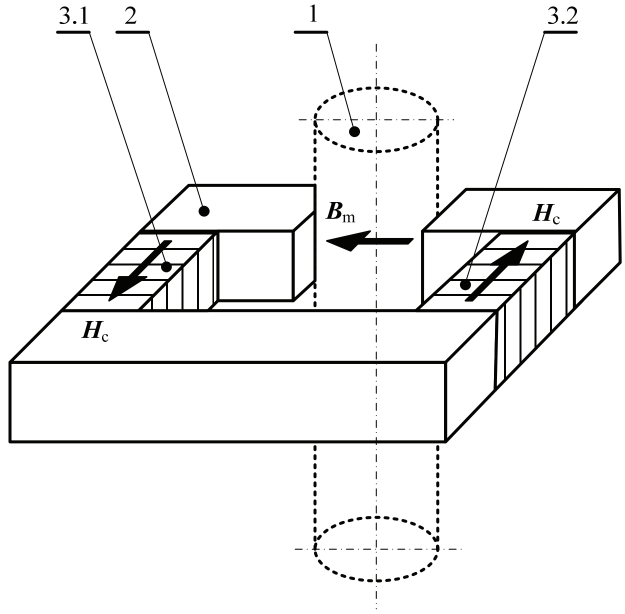

Fig. 3. Arrangement of an MHD pump with the magnetic circuit containing permanent magnets: **1**–channel with cooling medium, **2**–focusators of magnetic flux, **3.1, 3.2**–permanent magnets

Arrangements with suitable electromagnets, particularly with the systems of saddle coils (see Fig. 6) are more complicated (they require suitable sources of direct current on the order of 10 kA), nevertheless, they are suitable for large pumps with amounts of melt [1] round 100 m^3/hod. Again, it is necessary to check the temperatures of individual parts of the system, but in case of hollow conductors cooled by water the temperature rise may be kept in acceptable range.

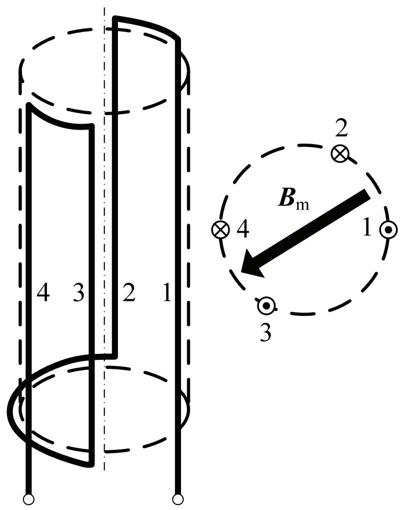

Fig. 6. Typical arrangement of the saddle coil (carrying DC current) In an MHD pump

Mathematical model of the problem

Provided that the operation regime of the considered MHD pump is stationary (independent of time), the vectors $\boldsymbol{J}_\mathrm{e}$ and $\boldsymbol{B}_\mathrm{m}$ are also stationary. These fields can, therefore, be described by a system of partial differential equations describing [5]

- electric field

(3) $$\Delta\varphi = 0$$

and

(4) $$\boldsymbol{J}_\mathrm{e} = -\gamma_\mathrm{e} \cdot \mathrm{grad}\varphi \,.$$

- magnetic field:

If it is produced by a system of *permanent magnets* of coercive force $\boldsymbol{H}_\mathrm{c}$ and remanence $\boldsymbol{B}_\mathrm{r}$

(5) $$\mathrm{curl}\left(\frac{1}{\mu}\mathrm{curl}\,\boldsymbol{A} - \boldsymbol{H}_\mathrm{c}\right) = \boldsymbol{0}$$

where

$$\mu = \frac{B_\mathrm{r}}{H_\mathrm{c}} = \mathrm{const}$$

and

(6) $$\boldsymbol{B}_\mathrm{m} = \mathrm{curl}\,\boldsymbol{A} \,.$$

If it is produced by a system of direct current carrying saddle coils, there holds

(7) $$\mathrm{curlcurl}\,\boldsymbol{A} = \mu_0 \boldsymbol{J}_\mathrm{m}$$

and again

$$\boldsymbol{B}_\mathrm{m} = \mathrm{curl}\,\boldsymbol{A} \,.$$

- stationary temperature field:

(8) $$\mathrm{div}\left(\lambda\, \mathrm{grad}\,T\right) = -\boldsymbol{J}_\mathrm{e}^2 / \gamma_\mathrm{el}$$

Equations (3), (5), (7) and (8) supplemented with correct boundary conditions may be solved by some of professional codes (see the next paragraph). The result is distribution of quantities $\varphi, \boldsymbol{A}, T$ and, consequently $\boldsymbol{J}_\mathrm{e}$ and $\boldsymbol{B}_\mathrm{m}$.

Values of the electromagnetic pressure p_em and electromagnetic force $\boldsymbol{F}_\mathrm{L}$ acting on the medium in the working channel can be found by numerical evaluation of (1) and (2).

Numerical solution and computer model

The mathematical model was solved as a 2D (x, y) problem. The computations were realized by code QuickField (version 5.6) [6], 3D arrangements may be solved, for instance, by Comsol Multiphysics [7]. The aim was fast determining necessary partial information (electric, magnetic and temperature fields) about the pump. Particular attention was paid to monitoring of the convergence of solution – for results valid in three significant digits it was necessary to use meshes with approximately

- 150×10^3 nodes for magnetic field,
- 60×10^3 nodes for electric field,
- 120×10^3 nodes for temperature field.

Except for these rather qualitative data, the results also provide even important quantitative results, particular numerical values discussed in the following paragraph.

Illustrative examples

The aim of the presented examples is to show the possibility of pumping molten fluoride salts by two basic kinds of MHD pumps, i.e., by pumps excited by a system of permanent magnets and pumps working wit a system of saddle coils.

In both examples, the heat-transporting medium is molten fluoride salt FLiNaK (LiF–NaF–KF with percentual ratio 45.3–13.2–41.5 %/mol), its operation temperature being $T_\mathrm{work} = 690$ °C. This medium is characterized by physical parameters listed in Tab. 1.

If some parts of the considered pumps are made of ferromagnetic material, it is always a carbon steel CSN 12 040 whose physical parameters are taken from [8]. The physical parameters of other materials used either in the first or second pump are given in Tables 2 and 3.

Table 1: Physical parameters of fluoride salt FLiNaK

operation temperature	T_work	(°C)	690
specific mass	ρ	(kg/m^3)	1972
electrical conductivity	γ_e	(S/m)	501.3
thermal conductivity	λ	(W/mK)	0.9194
specific heat	c_p	(J/kgK)	18.50
kinematic viscosity	ν	(m^2/s)	1.225×10^{-6}

A. ***MHD pumps with a system of permanent magnets***

A.1 *Arrangement of the pump*

The starting arrangement of the magnetic circuit (producing magnetic field $\boldsymbol{B}_\mathrm{m}$ by means of a system of permanent magnets) of the pump is (together with some important geometric dimensions) depicted in Fig. 7. Analogously, the arrangement of electrodes is shown in Fig. 8. The value of angle $\alpha = 150^\circ$ providing sufficiently uniform of distribution of current density $\boldsymbol{J}_\mathrm{e}$ is taken over from [4]. The physical parameters of individual parts of the pump are given in Table 2.

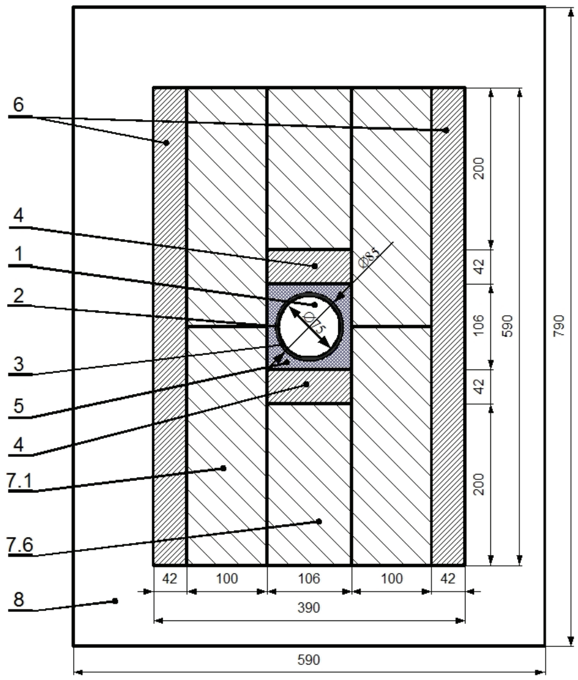

Fig.7. Cross-section of an MHD pump with magnetic field generated by a system of permanent magnets: **1**–transported molten fluoride salt, **2**–pipe (molten basalt), **3**–electrodes (graphite reinforced with glass fibers), **4–**ferromagnetic focusators (carbon steel 12 040), **5**–thermal insulation of magnets (glass wool), **6**–ferromagnetic bypasses of magnetic flux (carbon steel CSN 12 040), **7–**permanent magnets (NdFeB Magnet, Grade GSN-40), **8**-cooling water

A.2 *Results and their discussion*

The results were obtained for the following input parameters:

- $l_{\mathrm{p}} = 0.1$ m, one pair of the working electrodes (Figs. 4a and 8),
- Permanent magnets NdFeB Magnet, Grade GSN-40 [9] with $H_{\mathrm{c}} = 9.555 \times 10^5$ A/m in the arrangement depicted in Fig. 8.

These results may be divided into qualitative and quantitative ones.

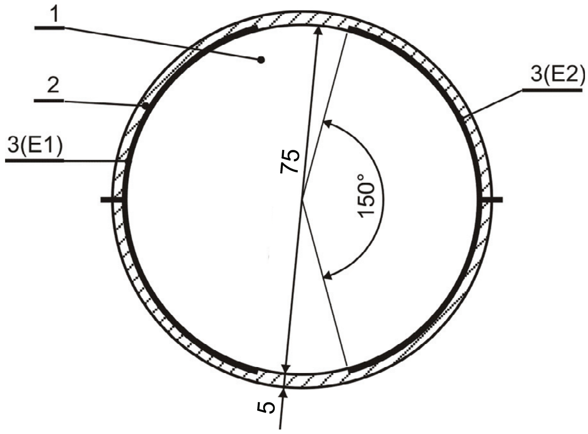

Fig. 8. Electric circuit of the considered MHD: **1**-transported molten salt, **2**-pipe (molten basalt), **3**-electrodes

Table 2. Physical parameters of individual parts of the pump (see Fig. 7)

Item	material	characteristic values
1	transported medium	see Tab. 1
2	molten basalt	$\gamma_{\mathrm{e}} = 10^{-6}$ S/m $\mu_{\mathrm{r}} = 1$ $\lambda = 2$ W/mK
3	graphite	$\gamma_{\mathrm{e}} = 1.5 \times 10^6$ S/m $\mu_{\mathrm{r}} = 1$
4	carbon steel 12 040	μ_{r} see Fig. 9 λ see Fig. 10
5	glass wool	$\gamma_{\mathrm{e}} = 10^{-6}$ S/m $\mu_{\mathrm{r}} = 1$ $\lambda = 2$ W/mK
6	carbon steel 12 040	μ_{r} see Fig. 9 λ see Fig. 10
7	NeFeB magnets Grade GSN-40	$H_{\mathrm{c}} = 9.555 \times 10^5$ A/m $B_{\mathrm{r}} = 1.27$ T $T_{\mathrm{w}} = 150$ °C $\mu_{\mathrm{r}} = 1.0577$
8	cooling water	$\mu_{\mathrm{r}} = 1$ $T_0 = 20$ **°C**

The qualitative results are depicted in Figs 11a, 11b, and 11c. Fig. 11a depicts the distribution of the force lines of magnetic field in the working channel of the pump. The lines are almost parallel, which means that the field is there almost uniform. This has a positive influence on flow of the medium. The calculated average value of the y th component of magnetic flux density in the channel is in this case $B_{\mathrm{a},y} \approx 1.533$ T.

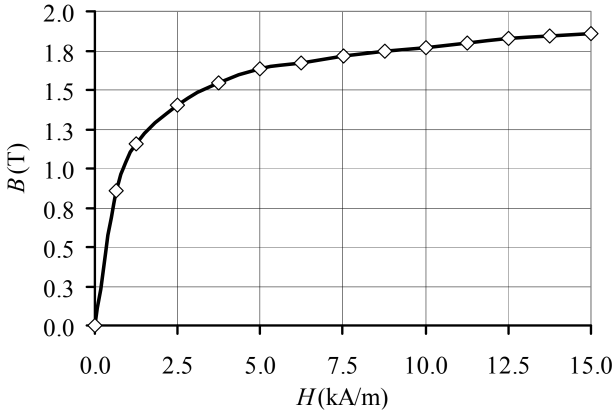

Fig. 9. Magnetization characteristic $B(H)$ of carbon steel 12 040

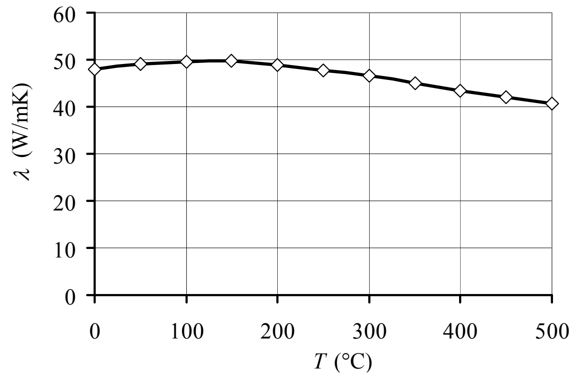

Fig. 10. Dependence $\lambda(T)$ for carbon steel 12 040

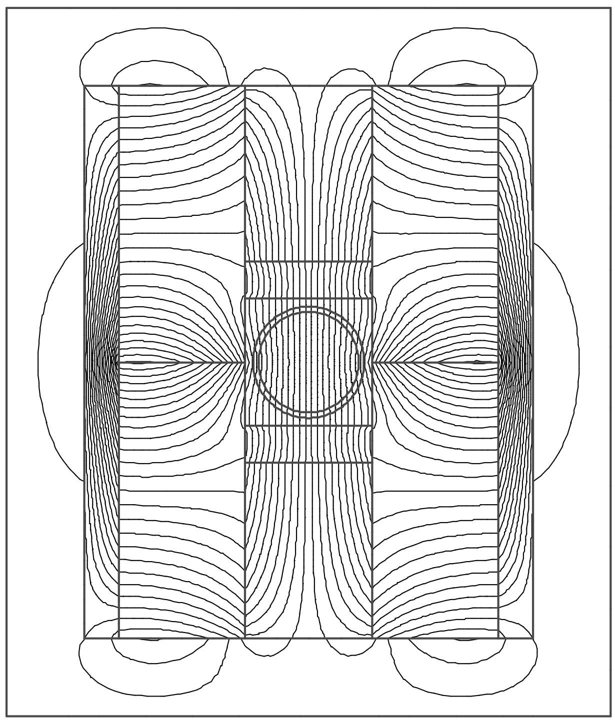

Fig. 11a. Distribution of magnetic force lines in the system

Fig. 11b shows the distribution of the force lines of electric field in the system. These are also practically parallel, so that this field is also highly homogeneous (which is also advantageous from the viewpoint of flow). The current source is supposed to deliver direct current

$I_e = 51.88$ A, which corresponds to current density $J_{a,x} \approx 6.918 \times 10^2$ A/m^2.

Finally, Fig. 11c shows that the thermal insulation in the space of the pump is quite satisfactory. The operation temperature of the molten salt $T_{work} = 690$ °C reduces to $T_{min} \approx 60$ °C (the difference between the neighboring isotherms being $\Delta T = 90$ °C), which is, from the viewpoint of used permanent magnets, quite satisfactory.

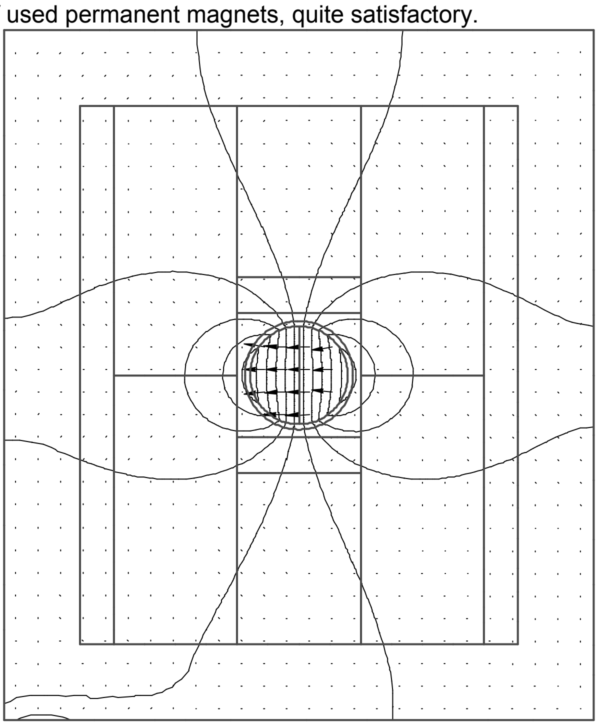

Fig. 11b. Distribution of electric force lines in the system for $J_{a,x} \approx 6.918 \times 10^2$ A/m^2

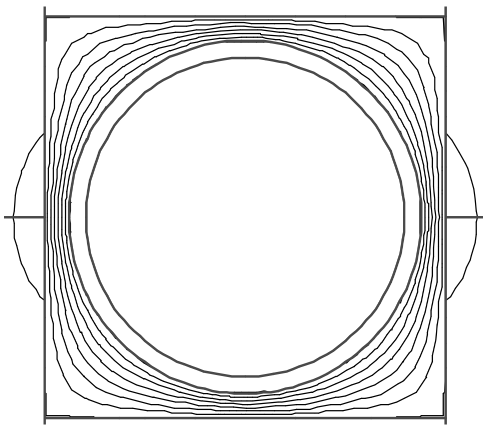

Fig. 11c. Distribution of temperature field in the space of the channel ($T_{max} = T_{work} = 690$ °C, $\Delta T = 90$ °C)

The average values of magnetic flux density $B_{a,y} \approx 1.533$ T and current density $J_{a,x} \approx 6.918 \times 10^2$ A/m^2 cause electromagnetic pressure $p_{em} = 1.074 \times 10^2$ N/m^2 and total Lorentz force $F_L = 4.685$ N. The total Lorentz force can easily be increased by an increase of current I_e. On the other hand, the current I_e could be reduced by using several pairs of electrodes (see Fig. 4b).

B. ***MHD pumps with a system of saddle coils***

B.1 *Arrangement of the pump*

The arrangement of the magnetic circuit (generating field $\boldsymbol{B}_m$ by the system of saddle coils) is depicted (together with the principal dimensions) in Fig. 12. The arrangement of the electrodes is similar to that in Fig. 8, but now the diameter of the working channel is 130 mm. The physical parameters of the individual parts of the pump are listed in Tab. 3.

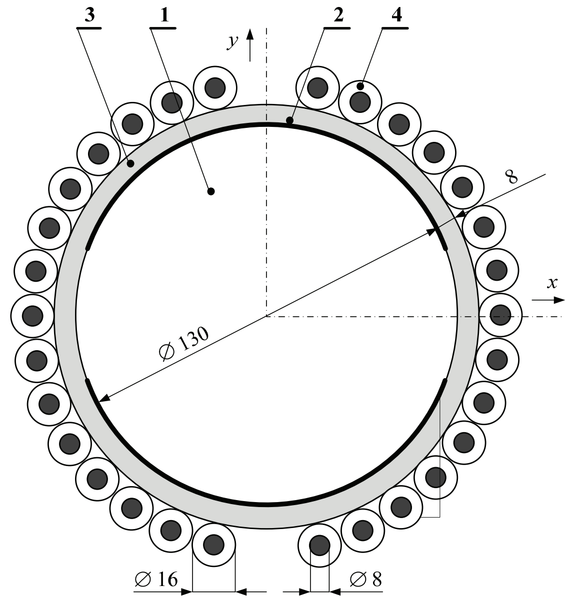

Fig.12. Cross-section of an MHD pump with magnetic field generated by a system of permanent magnets: **1**–transported medium (molten fluoride salt), **2**–electrodes, **3**–pipe (molten basalt), **4**–saddle coils

Table 3. Basic technical parameters of the MHD pump with a system of saddle coils

Item	material	characteristic values
1	transported medium	see Tab. 1
2	austenitic steel CSN 17 030	$\gamma_e = 1.5 \times 10^6$ S/m $\mu_r = 1$
3	molten basalt	$\gamma_e = 10^{-6}$ S/m, $\mu_r = 1$ $\lambda = 2$ W/mK
4	Cu	$\mu_r = 1$, $\gamma_e = 57 \times 10^6$ **S/m** $\lambda = 395$ W/mK

B.2 *Results and their discussion*

The results were obtained for the following input parameters:

- $l_p = 0.5$ *m*m, one pair of the working electrodes (Figs. 4b and 8),
- saddle coils, see Fig. 6 and Fig. 12.

These results may again be divided into qualitative and quantitative ones.

The qualitative results are presented in the following figures:

Fig 13a shows that the distribution of the force lines of magnetic field in the working channel of the pump. The lines are again almost parallel, which means that the field is there almost uniform. This has a positive influence on flow of the medium. The calculated maximum value of the y th component of magnetic flux density in the channel is in this case $B_{a,y} \approx 0.4261$ T for direct current $I_m = 10^4$ A passing through the saddle coils of the pump.

Fig. 13b depicts the current lines in the system. These are also practically parallel, so that this field is also highly homogeneous (which is also advantageous from the viewpoint of flow). Now we consider the voltage source with the difference at the electrodes $\triangle U = \pm 10$ V. The corresponding maximum value of current density in the channel $J_{a,x} \approx 1.889 \times 10^5$ A/m^2.

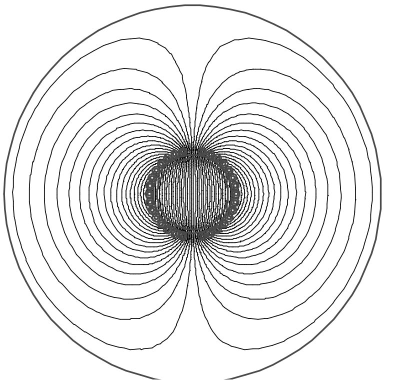

Fig. 13a: Magnetic field in the pump with saddle coils ($l_p = 0.5$ m, $B_{a,y} \approx 0.4261$ T)

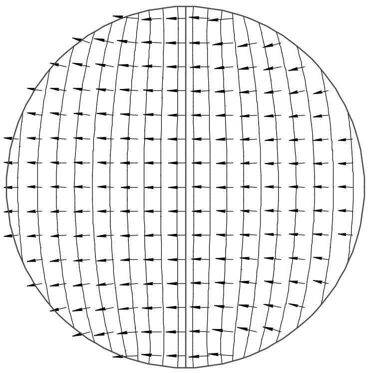

Fig. 13b: Current field in the same MHD pump ($J_{a,x} \approx 1.303 \times 10^5$ A/m^2)

Finally, Fig. 13c presents the temperature field on the following input data:

- The conductors of the saddle coil are cooled by water, the voltage difference on the electrodes being $\triangle U = \pm 10$ V.
- Velocity of the water in the conductors $w_{H_2O} = 3$ m/s its input temperature being $T_{min,H_2O} = 10$ °C, output temperature $T_{max,H_2O} = 90$ °C and corresponding [10] Reynolds number $Re \approx 1.2 \times 10^4$ (the flow is strongly turbulent, which means a practically perfect contact between the cooling water and wall of the conductor).

The temperature of conductors of the saddle coils, is, therefore, quite acceptable, just little higher than the temperature of cooling water. But, on the other side, it is necessary to appropriately propose the length of the cooling sections in order to avoid boiling water in them. But details are beyond the scope of this paper.

The quantitative results show that the above values $B_{a,y} \approx 0.4261$ T and current density $J_{a,x} \approx 1.889 \times 10^5$ A/m^2 cause electromagnetic pressure $p_{em} = 4.025 \times 10^4$ N/m^2 and total Lorentz force $F_L = 534$ N. The total Lorentz force could easily be increased by an increase of the voltage difference ΔU or current I_m. On the other hand, a substantial reduction of both above quantities could be reached by using several pairs of electrodes (see Fig. 4b).

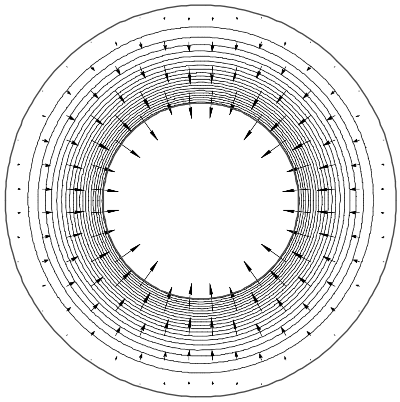

Fig. 13c: Distribution of temperature in the cross section of one saddle loop conductor ($I_m = 10^4$ A, $w_{H_2O} = 3$ m/s, $T_{av,H_2O} = 50$ °C, $T_{max} = 62.4$ °C, $T_{min} = 60.2$ °C, $\Delta T = 0.1$ °C)

Conclusion

The paper is devoted to illustrative evaluation (based on a lot of testing computations) of possibilities of using appropriate MHD pumps for transport of molten salts, for example, in cooling loops of nuclear reactors. The result show (in the opinion of the authors) that such a possibility is quite real, the pumps provide the electromagnetic force and total Lorentz force in a large interval of values.

Nevertheless, it is crucial to do the consequent step and validate the results experimentally in appropriate cooling loops. Only after successful results of these experiments one could seriously consider about practical utilization of these MHD pumps for transport of molten salts as coolants in a certain class of nuclear reactors.

Acknowledgment

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