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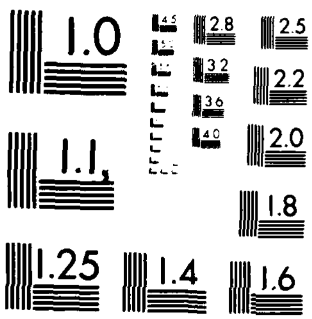

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FUTURE OF MAGNETOHYDRODYNAMIC SHIP PROPULSION

by

A.P. Baranov

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А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
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Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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FUTURE OF MAGNETOHYDRODYNAMIC SHIP PROPULSION

A. P. Baranov

The creation of powerful mechanism-free (without moving parts) generators [1] will open great possibilities for the electric propulsion of ships with the use both of ordinary electric paddle-wheel engines (GED) with a screw, and new types of engines without moving parts, based, for example, on the magnetohydrodynamic (MGD) principle of operation.

The magnetohydrodynamic method of ship propulsion with the use of ordinary permanent magnets and electromagnets was considered in works [2, 3] and was acknowledged as unsuitable due to the low efficiency and bulkiness of the propelling plant.

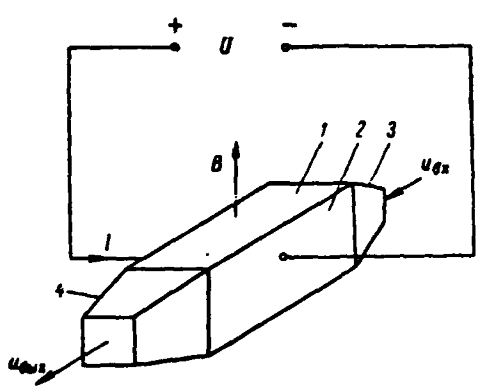
With the appearance of superconducting electromagnets [4, 5] the possibilities of obtaining stronger magnetic fields were expanded considerably, and, consequently, of realization of the magnetohydrodynamic method of propelling ships. In particular this is indicated in [6], where an analysis is made of the efficiency of a magnetohydrodynamic propeller (MGRD) depending on the speed of the vessel, geometry of the working channel, rate of movement of water on the inlet to the channel and magnitude of magnetic induction, and also the main problems which have to be solved in the development of this propelling device are listed: production of high-quality superconductors, removal of gases from the working channel, development of the optimal design of a Dewar flask (in which the cryogenic fluid is found), etc.

In this article, on the basis of certain approximate quantitative correlations and calculation, a comparison is made of the efficiency and compactness (power per unit of volume) of MGRD with a conventional electric-motor dc plant and evaluations are made of the outlook for using engines with a magnetohydrodynamic principle of operation.

In the simplest form an MGRD consists of a working channel and an electromagnet. The working channel (drawing) has a pump section (formed by two insulating walls 1, adjacent to the poles of the electromagnet, and two electrodes , 2)and a diffuser 3 and nozzle 4; subsequently the part of the working channel which arrives at the pole section we will call simply the channel.

For reducing the external magnetic field of the propelling device its structural fulfillment should be such that the magnetic field remains inside it.

If the working channel is filled with sea water and voltage is applied to the electrodes, then with an excited electromagnet the water in the channel will begin to shift under the action of force F, directed perpendicular to the magnetic field with induction B and current I, passing through the water. The water will enter the diffuser at a rate of $u_{вх}$, and at the outlet will exceed this rate ($u_{вых} > u_{вх}$). Due to the difference of velocities and pressures at the inlet to the diffuser and the outlet from the nozzle thrust is created in the propeller system.



Schematic layout of the MGRD.

1 - insulating walls, 2 - electrodes, 3 - diffuser, 4 - nozzle.

For the derivation of certain quantitative correlations we will consider the simplest MGRD with the following assumptions:

1. The cross section of the diffuser along the entire length is unchanged and coincides with the cross section of the channel.

2. The sea water behaves in the channel as a solid conductor with specific conductivity σ; change in the conductivity of the water due to Joule heating can be disregarded.

3. Magnetic induction B, density of current in the water, and average rate of flow of water u in all points of the channel are constant in magnitude and mutually perpendicular.

4. There are no leakages of current in the channel.

5. Gases, formed at the electrodes during electrolysis of the sea water, are removed from them. Losses of voltage near the electrodes are equal to zero.

6. Losses of power for creation of the magnetic field can be disregarded.

7. Propulsive efficiency of the vessel is equal to the efficiency of the propelling device.

Under these conditions the strength of the current passing through the MGRD channel is equal to

$$I = \frac{U - E}{R}\ a, \qquad (1)$$

where U - voltage on the electrodes, V;

E - counterelectromotive force V, equal to $E = dBu10^{-4}$;

B - induction in the channel, G;

u - average rate of flow of water in the channel, m/s;

R - electrical resistance of sea water, ohms,

$$R = \frac{d}{\sigma hl}; \qquad (2)$$

d, h, l - distance between electrodes, height and length of channel, m.

Replacing E and B [?] in formula (1) by their values, we obtain

$$I = \frac{\sigma(U - dBu10^{-4})}{d} = \frac{1 - \eta_9}{\eta_9}\sigma Buhl10^{-4}, \qquad (3)$$

where $\eta_{\text{э}} = \frac{dBu 10^{-4}}{U}$.

The force, moving the water in the channel, is calculated using the formula

$$F = 0{,}102 dBl 10^{-4} = 0{,}102 \frac{1-\eta_{\text{э}}}{\eta_{\text{э}}} \sigma B^2 u V_{\text{к}} 10^{-8} \text{ kgf}, \qquad (4)$$

where V_k =dhl - volume of the channel, m^3.

The force F creates an excess pressure, equal to

$$\Delta p = \frac{F}{dh} 10^{-4} \text{ kgf/cm}^2. \qquad (5)$$

This excess pressure is expended for accelerating the water in the nozzle and for overcoming hydraulic losses in the working channel.

The mechanical power imparted to the water in the channel is equal to

$$P_{\text{м}} = 9{,}8 F u 10^{-3} = \frac{1-\eta_{\text{э}}}{\eta_{\text{э}}} \sigma B^2 u^2 V_{\text{к}} 10^{-11} \text{ kW} \qquad (6)$$

The mechanical power, passed on to a unit volume of water in the channel, is calculated using the formula

$$P_{\text{уд}} = \frac{P_{\text{м}}}{V_{\text{к}}} = \frac{1-\eta_{\text{э}}}{\eta_{\text{э}}} \sigma B^2 u^2 10^{-11} \text{ kW/m}^3. \qquad (7)$$

The electric power supplied to the channel is equal to

$$P_{\text{э}} = UI 10^{-8} = \frac{1-\eta_{\text{э}}}{\eta_{\text{э}}} U \sigma B u h l 10^{-7} \text{ kW}. \qquad (8)$$

The force of traction of the MGRD with the same pressure on the inlet to the diffuser and the outlet from the nozzle is determined from the expression

$$T = \rho Q \Delta u \text{ kgf}, \qquad (9)$$

where ρ - mass density, kgf s^2/m^4 (for sea water ρ =102 kgf s^2/m^4);

$Q=Su=dhu$ - volumetric flow rate of water, m^3/s;

$\Delta u = u_{выx} - u_{вx}$ ($u_{вx}$ - rate of movement of water on the inlet to the diffuser, m/s;

$u_{выx}$ - rate of movement of water on the outlet from the nozzle, m/s; the magnitude of $u_{выx}$ can change due to a change in the geometry of the nozzle within the limits of available excess pressure Δp).

The thrust, forming during operation of the propelling device, will be transferred to the hull of the ship through the excitation winding of the electromagnet and the Dewar vessel. In this case the propelling device should ensure that velocity of movement of the vessel, at which the force of resistance of the water to its movement will equal the thrust T which is developed by the propelling device.

The towing or effective power of the MGRD is equal to

$$N_e = \frac{Tv}{75} \text{ hp,} \tag{10}$$

where v - velocity of movement of the vessel, m/s, and specific towrope horsepower (for a unit of volume of the channel)

$$N_{e\,yд} = \frac{N_e}{V_к} \text{ hp/m}^3. \tag{11}$$

With a calculation of the volume of the electromagnet and the Dewar vessel the towrope horsepower for a unit of volume of the entire MGRD $N'_{e\,yд}$ will be less than the specific towrope horsepower for a unit of volume of the channel, i.e.,

$$N'_{e\,yд} = kN_{e\,yд}, \tag{12}$$

where k - constant coefficient, depending on the construction and dimensions of the electromagnet and the Dewar vessel.

The value of $N'_{e\,yд}$ can serve as a criterion for comparing the MGRD with propelling plants of other types.

The electrical efficiency of the propelling device is calculated using the formula

$$\eta_{э} = \frac{P_{м}}{P_{э}} = \frac{9{,}8Fu}{UI} = \frac{dBu10^{-4}}{U} = \frac{E}{U}, \qquad (13)$$

and its hydraulic efficiency using the formula

$$\eta_{г} = \frac{Tv}{Fu} \qquad (14)$$

or in the case of $u=v$

$$\eta_{г} = \frac{T}{F}. \qquad (15)$$

The overall efficiency of the propelling device will be equal to

$$\eta = \eta_{э}\eta_{г} = \frac{9{,}8Tv}{UI}. \qquad (16)$$

It follows from expression (7) that with a high value of $\eta_{э}$ a low specific mechanical power $P_{уд}$ is obtained, and, vice versa, a high value of $P_{уд}$ is achieved with a low value of $\eta_{э}$. The required relationship of these characteristics of the MGRD can be obtained at the expense of the appropriate selection of variables U and d.

The power of the MGRD, in contrast to a dc GED [electric paddle-wheel engine], is not limited by conditions of commutation.

As is evident from expressions (4) and (7), the force F and specific mechanical power $P_{уд}$ can be increased at the expense of increasing the values of σ, u and B.

In principle the specific conductivity of sea water in the channel (σ) can be raised by injection of a special additive into it. However, it is very difficult to realize this in practice.

The average rate of flow of water in the channel (u) depends on the rate of travel of the vessel and on hydraulic losses in the working channel of the propelling device.

When superconducting electromagnets are used the magnetic induction B in the channel can be brought up to 10^5 G and higher with a current density in the winding of an order of 10^5 A/cm^2 [4, 5].

Since Joule losses are absent in a superconductor, the density of the current in the winding made from a superconductor can be approximately 50 times greater than in a copper winding which is cooled by water [4]. The power expended for power supply and cooling of the electromagnet with a superoonductor apparently will not exceed 1% of the power supplied to the MGRD.

The use of superconducting windings will make it possible to reduce the weight of the electromagnet as many times as the current density in the superconducting winding is greater than the current density in the copper winding (with a higher efficiency value of the MGRD). True, the weight-dimension indices of the superconducting electromagnets are worsened due to the use of Dewar vessels.

A superconducting excitation winding permits operation both in the mode of external power supply and in the mode of a shorted circuit with power supply disconnected [5].

For evaluating the efficiency of using the magnetohydrodynamic principle of movement of vessels we will cite numerical examples of the calculation of an MGRD with a superconducting magnet.

Initial data for the calculation:

$d=2$ m; $h=1$ m; $U_1=200$ V; $U_2=1200$ V;
$u=u_{Bx}=v=25$ m/s; $l=5$ m; $\sigma=5$ ohms^{-1} m^{-1}; $B=10^5$ G;
$\eta_r=0.6$; $k_1=0.3$; $k_2=0.25$; $k_30=175$.

The results of the calculation are given in the table.

For a comparison we will point out that the electric-power plant of the atomic ice breaker "Lenin" [7, 8] with an overall volume of 296 m^3 (consisting of one dc GED with a power of 19,600 hp, voltage of 1200 V, electrical efficiency 95.5%, volume 120 m^3 and two on-board GED with a power of 9800 hp each, voltage 1200 V, electric efficiency 94.5%, volume 88 m^3) develops with the screw propellers in forward movement in the mooring mode a thrust of 330,000 kgf (velocity of movement in smooth water 18 knots or 9 m/s), i.e., without calculating the spaces taken up by the fans, water coolers, energizing aggregates and control panels for the main propulsion motors, this installation has

$$N'_{e\,y\partial} = \frac{330\,000\cdot 9}{75\cdot 296} = 134 \text{ hp/m3}.$$

Results of the calculation (using the formulas given above) for one working channel.

Расчетные величины (1)	(2) Условия расчета	
	$U_1 = 2000$ в	$U_2 = 1200$ в
3 — R, ом	0,08	0,08
4 — E, в	500	500
5 — I, а	18 750	8750
6 — F, кГ	38 300	17 850
7 — ΔP, кГ/см²	1,93	0,9
8 — $P_м$, квт	9400	4370
9 — $P_{уд}$, квт/м³	940	437
10 — $P_э$, квт	37 500	10 500
11 — T, кГ	23 000	10 700
12 — Δu, м/сек	4,5	2,1
13 — $u_{вых}$, м/сек	29,5	27,1
$\eta_э$	0,25	0,416
$\eta = \eta_э \eta_г$	0,15	0,249
14 — N_e, л. с.	7660	3570
15 — $N_{e\,уд}$, л. с./м³	766	357
$N'_{e\,уд}$, л. с./м³ (16) при (17) $k_1 = 0,3$	230	119
при $k_2 = 0,25$	193	92
при $k_3 = 0,175$	134	42,5

Key: (1) Calculated variables; (2) Conditions of calculation, V; (3) ohms; (4) V; (5) A; (6) kgf; (7) kgf/cm^2; (8) kW; (9) kW/m^3; (10) kW; (11) kgf; (12) m/s; (13) m/s; (14) hp; (15) hp/m^3; (16) hp/m^3; (17) when.

It is evident from the table that in spite of the lower electrical and overall efficiency, in the case of specific values of applied voltage, magnetic induction (of an order of 10^5 G) and coefficient $k > 0.175$ the MGRD can have an advantage over the standard electric-motor installation in respect to the magnitude of towrope horsepower per unit of volume of the installation. With a further increase of magnetic induction and the magnitude of coefficient k this advantage of the MGRD will increase.

Also evident from this table is the dependence of effectiveness of the MGRD under consideration on the magnitude of applied voltage.

Thus, with U_1=2000 V, k_1=0.3, N'_{eyA}=230 hp/m^3, η=0.15, and with U_2=1200 V, k_1=0.3, N'_{eyA}=119 hp/m^3 and η=0.249.

Regulation of the power of the MGRD and, consequently, the velocity of movement of the vessel is ensured by a change in the magnitude of voltage supplied to the electrodes, by a change in the magnitude of magnetic induction (due to adjustment of excitation current of the electromagnet in the mode of external power supply), and also by a change in the average rate of the water u (for example, by means of changing the form and dimensions of the inlet section of the diffuser).

In the case of successful development of methods of producing an additive, its input into the channel and recovery on the outlet, a change in the operation mode of the MGRD is also possible due to regulation of the amount of additive (on which conductivity σ depends).

In all, modes of operation of the MGRD the change of density of excitation current, magnetic induction and temperature of the excitation winding should be permitted in the limits, within which the property of superconductivity is reliably preserved. In the case of breakdown of superconductivity and transition of the excitation winding to a normal state, the electromagnetic energy stored in it is expended for Joule heat. Heating of the excitation winding can cause its overheating, and also the rapid boiling of the cryogeric fluid, which in turn can lead to mechanical shocks and breakdown of the Dewar vessel. In order to prevent this a device for control and protection should be provided in the system for control of the superconducting electromagnets [5].

In conclusion it should be stressed that prior to practical use of the MGRD it is necessary to solve the problems of developing superconducting electromagnets for large spaces and a cryogenic system, of transmission of thrust through the magnetic system to the Dewar vessel and from it to the hull of the ship, removal from the working channel of the products of electrolysis of sea water, compensation of magnetic pressure, and a number of others.

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