EFFICIENCY OF THE INDUCTION INTERACTION OF A BLOB OF CONDUCTING GAS WITH AN ELECTRICAL CIRCUIT IN WHICH AN EXTERNAL ELECTROMOTIVE FORCE IS INCLUDED

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The possibility of increasing the efficiency of a magnetohydrodynamic energy conversion by including an external emf source in the operating winding is investigated. Values of the average electrical efficiency which can be obtained with the used operating winding are calculated. The possibility and the limits of regulating the efficiency by varying the magnitude of the external emf, the angle of the phase shift of the external emf relative to the currents in the ionized gas, and the magnitude of the excitation magnetic field for the known nature of the flow and the parameters of the gas are determined.

1. Formulation of the Problem. The power characteristics of magnetohydrodynamic interaction of an ionized gas blob moving through a constant magnetic field with the operating circuit connected to an ohmic load have been investigated in [1]. In this case the efficiency of energy conversion was found to be low and the electrical efficiency η did not exceed 3%.

A general investigation of the useful work of plasma against a magnetic field [2, 3] shows that for any type of MHD generator a matching of the induced electric fields E and uH/c is necessary in order to obtain an acceptable useful power and internal efficiency of conversion. As applied to an induction type MHD generator this requirement amounts to appropriate phase and amplitude relations between E and uH/c in the plasma. Therefore any device of this kind must have the possibility of regulating E in comparison with uH/c. One of the methods of accomplishing such regulation may be the inclusion of an external variable emf in the operating winding circuit.

The useful work of the plasma is given by the expression

$$A-Q=-\int\limits_T\int\limits_V jEdtdV$$

It follows then that in order for the useful work to be positive, i.e., in order that the plasma deliver energy to the external circuit, the vectors $\vec{E}$ and $\vec{j}$ must be oppositely directed in the plasma.

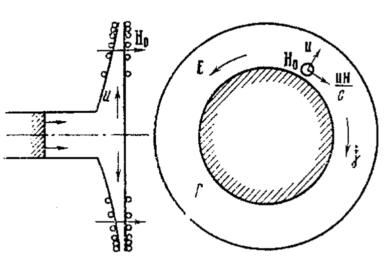

Fig. 1

2. Description of the Experimental Equipment. All the experiments were carried out on the equipment described in [1]. The difference was, firstly, in the use of an operating winding different from that used in [1] and, secondly, in the inclusion of the external emf generator in the circuit of the operating winding.

The geometry of the operating winding was so chosen that the current pulse of required polarity and duration produced in it by the inclu-

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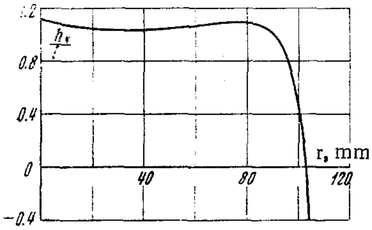

Fig. 2

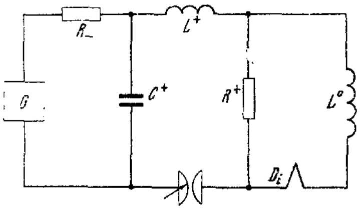

Fig. 3

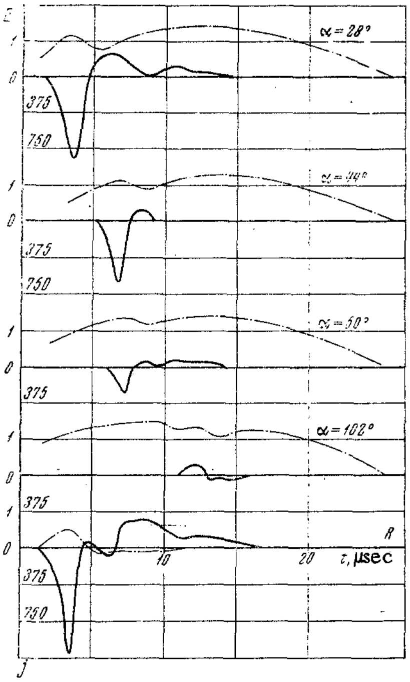

Fig. 4

sion of the external emf had the required relation between the vectors $\vec{E}$ and $u\vec{H}/c$. The position of the turns of the operating winding along the radius of the channel and the orientation of the vectors $\vec{E}$, $u\vec{H}/c$, $\vec{j}$, $\vec{H}_0$ in the gas are shown in Fig. 1 (the circle Γ is the plasma front). The turns are placed at radii r = 47, 76, 86, 95, 102, 106, 110 mm. The distribution of the magnetic field intensity h_k/I (Oe/A) in the MHD channel produced by the currents in the operating winding is shown in Fig. 2.

The circuit of the external emf generator and its inclusion is shown in Fig. 3, in which C^+, L^+, R_- are respectively the capacitance, induction, and the active resistance of the generator. L^0 is the inductance of the operating winding and D_i is the current sensor. The generator had a very small output resistance R_- (compared to the total resistance of the operating winding inductively coupled to the plasma). In this case the emf excited in the operating winding will not change the electric field intensity E produced by the generator and, therefore, a simple power computation of the work of the plasma in the circuit of the operating winding can be done.

The maximum value of the intensity produced by the generator in the operating winding was equal to 2.2 kV. The maximum intensity of the electric field E_k in the channel produced by the currents in the operating winding at a radius r = 67 mm was equal to 1.36 V/cm and could be changed smoothly with the change of the voltage at the condenser C^+. The possibility of obtaining high intensities was limited by the mechanical and electrical strength of the operating winding. The delay circuit made it possible to switch in the external emf generator at any time relative to the start of the main discharge.

3. Results of the Experiment. As in [1] the parameters of the conducting gas blob in the experiment were the following:

1) The velocity of the blob in the operating channel in a magnetic field $H_0 \approx 1000$ Oe was practically constant along the radius of the channel and was equal to ~10 km/sec;

2) the Reynolds number R_m computed for the characteristic dimension of the channel of 1 cm was equal to 0.4;

3) the maximum electrical conductivity of the gas was approximately the same for any radius of the channel and had the value $\sigma \approx 40\ \Omega^{-1}\cdot\mathrm{cm}^{-1}$. All experiments were conducted for four values of the field H_0 = 575, 860, 1150, 1430 Oe. Here and below the values of H_0 are given for the radius r = 67 mm.

The following quantities were measured during the experiment: the total electric field intensity E in the plasma, the distribution of the current density j along the radius of the channel and in time, and the variation of the current in the operating winding. The procedure of measurement of E and j have been described in detail in [1]; the current in the operating winding is measured with the use of a low-inductance current sensor.

The measurements showed a significant effect of the electromagnetic fields produced by currents in the operating winding on the current J in the plasma.

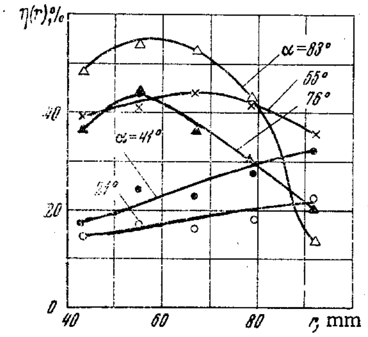

Fig. 5

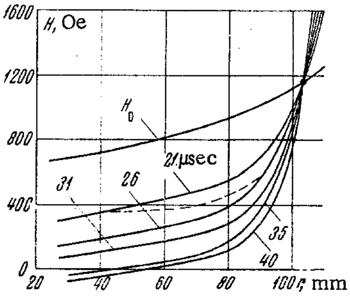

Fig. 6

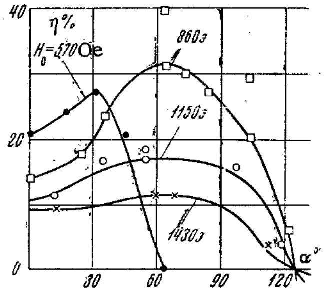

Fig. 7

The oscillograms of signals from E-turns and Rogowski loops recording the field intensity E, V/cm, (scale on the left) and the rate of change of currents J, A/μsec, (scale on the right) in the gas are shown in Fig. 4 as functions of the phase shift angle α between the injection of the plasma into the operating channel and the instant of switching of the external emf for r = 67 mm. The change of E and uH/c was accomplished by changing α. It is seen from these curves that the current magnitude J in the gas decreases due to the action of the external emf; for α = 102° the current even changes direction by 180°. The electric field intensity E in the gas is apparently higher than for the case of ohmic load (oscillograms R shown at the bottom of Fig. 4) [1] when there is no external emf. Thus, the inclusion of the external emf makes it possible to change E and J in the gas and the electrical efficiency of conversion η in wide ranges.

The average electrical efficiency of conversion is defined as the ratio of the useful work of the gas A−Q, averaged over a period and over the volume of the MHD channel, to the work A against the pondermotive forces of the magnetic field

$$\eta = A - Q / A = \int_T \int_V \mathbf{j}\mathbf{E}\, dt\, dV \left[\int_T \int_V (\mathbf{j} \times \mathbf{H})\, \mathbf{u}\, dt\, dV \right]^{-1}$$

The time variation of the time-average efficiency η(r) is shown in Fig. 5 as a function of the radius for different α. Here the maximum value of the ratio cE/uH changed from 0.1 to 0.7 on changing α from 21 to 83°. The most uniform η(r) along the radius is obtained for α = 55°. Therefore, for this angle η averaged over the volume has the highest value. For α > 55°, η(r) is very nonuniform and decreases rapidly at large radii. The decrease of η at large radii is due to the change of the magnetic field along the length of the channel and in time on including the external emf (the field h_k produced by the currents in the operating winding reduces the field H_0).

The pattern of distribution of the magnetic field along the radius of the channel and in time is shown in Fig. 6 for the regime corresponding to H_0 = 860 Oe and α = 55°. The leading front of the gas, where the path of motion is shown by the dashed curve, moves in almost constant magnetic field up to r = 91 mm. At the end of the channel it falls in the rapidly increasing magnetic field caused by characteristics of the operating winding shown in Fig. 2. It follows from this curve that if h_k is directed opposite to H_0 up to r = 105 mm, then starting from this radius h_k changes sign. This leads to a sharp increase of the magnetic field H at the end of the channel, a decrease of the ratio cE/uH at radius r = 100–110 mm, and a decrease of η at these radii.

Hence, it follows that in order to have high η in the entire volume the geometry of the operating winding must be chosen in such a way that there are no sharp gradients of the magnetic field in the operating channel or there is a possibility of a sharp increase of E in comparison with uH/c in the zone of the gradient.

There were no variations of the currents at r > 105 mm due to the constructional pecularities of the equipment. Therefore, there is no quantitative idea of the effect of the field increase at the end of the channel on η. However, it follows from the presented data that the decrease of η(r) at the end of the channel is a drawback of this operating winding and can be eliminated.

The electrical efficiency η was calculated by integration of the functions jE and juH/c over the entire volume and time. The magnetic field H(r, t) was found by summation of the field $H_0(r)$ and the field of the operating winding $h_k(r, t)$ computed from the measured current in the operating winding. The component of the field produced by the currents in the plasma $h_f \approx 0.1\ H_0$ and was not taken into consideration in the calculation. The total electric field E(r, t) was measured directly by E-loops. The values of the current density j(r, t) were determined at five points in the range of radii r = 40–100 mm.

The family of curves giving the dependence $\eta = \eta(\alpha)$ for different values of the magnetic field H_0 is shown in Fig. 7. It is seen from these curves that η decreases with the increase of H_0, since the possibility of mutual control of E and uH/c decreases with the increase of the magnetic field because the maximum value of the external emf fed to the operating winding was limited in the experiment by the mechanical and electrical strengths of the winding.

If the possibility of such regulation could be maintained on increasing H_0, then in this case the value of η for large fields could exceed the efficiency attained in the present experiment.

The dependence of η on the phase shift angle α and the maximum value of η = 30% obtained experimentally in the present work agree with the theoretical computation of the electrical efficiency carried out in [4] for small magnetic Reynolds numbers.

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