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MHD GENERATOR OF ELECTRICAL ENERGY WORKING ON THE GASIFICATION PRODUCTS OF LIGNITES

V. A. Derevyanko, V. S. Slavin, and V. S. Sokolov

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One of the main trends in the development of present-day thermoelectric power engineering is its continuing reorientation toward the use of low-quality coals. At the same time, such coals are also being considered for the production of motor fuel. In our opinion, one promising means for the complex processing of coal with the simultaneous production of electrical energy and chemical products is the use of MHD converters of energy. The fundamental premises of this approach are set forth in [1]; therefore, the present article touches only on processes connected with the building of the MHD generator itself. The concept under consideration is based on the phenomenon of a T-layer (current layer) which was studied in [2-9]. A sufficiently clear understanding of the physical essence of this phenomenon makes it possible to approach with complete confidence the development of the theory of a generator as a gas-dynamic, heat, and electrical machine. A significant supplement to these considerations is provided by experimental investigations of an artifically initiated T-layer in a linear channel, the preliminary results of which are set forth in our present article.

1. Experimental Investigation of Models of MHD Generators with a T-Layer. Experiments on the artificial initiation of a T-layer were made in a unit having a rectangular MHD channel with solid electrodes. The cross section of the channel was 50 × 50 mm, the length of the electrode part was 200 mm, and the external magnetic field $B_0 \leqslant 1$ T. The flow of the working gas (helium with a hydrogen impurity) with the parameters $T \simeq 4000°K$, $p \simeq 1$ atm, and $u = 5$ km/sec was set up by an electric-discharge shock tube, and has steady-state parameters at the inlet to the MHD channel for a period of 10^{-4} sec. The temperature inhomogeneity, at which a T-layer is formed in the MHD channel, was set up at the inlet to the MHD channel by the discharge of a condenser battery. Figure 1 gives photographs of the consecutive phases of the motion of the T-layer in the MHD channel.

The experiments made demonstrated the possibility of obtaining a spatially stable structure of the T-layer and made it possible to determine its main parameters: the velocity, the conductivity, and the temperature. However, in view of the limitations inherent in this experimental unit, certain questions remained unclear: above all, the stability of the T-layer with its motion along the MHD channel, with a long interaction, and the conditions of the formation of a T-layer in the combustion products. The resolution of these questions made it necessary to build a qualitatively new unit, which would make it possible to carry out the above experiments and to compare them with calculated results. The parameters of the newly built pulsed unit were the following: working gas air or imitation combustion products; mass flow rate, 1 kg/sec; temperature ahead of nozzle, 2500°K; pressure ahead of nozzle 20 atm; duration of flow, $2 \cdot 10^{-3}$ sec; velocity of flow, 1.5 km/sec; cross section of MHD channel, 40 × 80 mm; length of electrode part, 2000 mm; induction of magnetic field, 2 T. The unit makes it possible to carry out the basic physical investigations needed to build an MHD generator working under periodic conditions. Simultaneously, work was started on the investigation of conditions for the periodic formation of a T-layer in a steady-state flow of gas.

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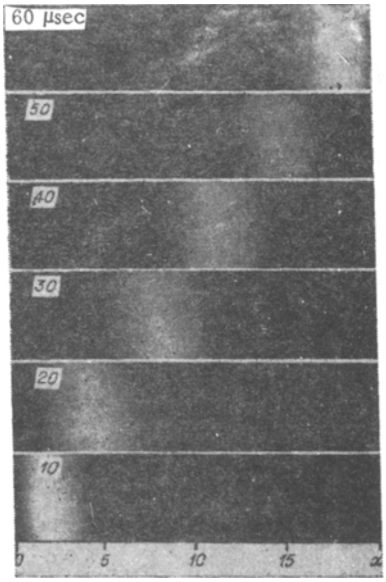

Fig. 1

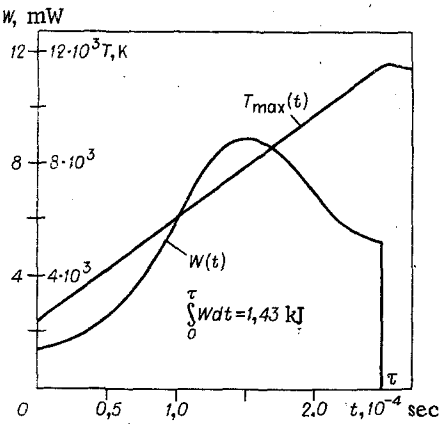

Fig. 2

2. Numerical Modeling of an Unsteady-State Process in the Channel of an MHD Generator with a T-Layer. We give the results of a numerical experiment, preceding actual tests of a model of an MHD generator in a T-layer. It is assumed that the model will work on a mixture of molecular gases, simulating the combustion products of gasified coal. The heat source of the model is a plasmotron, which makes it possible to investigate a broad range of different working bodies over a wide range of their parameters. It was proposed to make the first start-ups on air. Therefore, air was considered to be the working body in the calculation.

The external source of energy is the preheating of a local section of the flow. In the calculation, the preheating was modeled by the assignment of volumetric sources of energy, localized in a determined section of the flow and moving together with it. The power of the energy sources was varied with the time, in order to assure a constant rate of rise of the temperature.

Before the appearance of a plasma bunch, the flow in the channel practically did not interact with the magnetic field. Therefore, the natural initial condition for this problem is the steady-state flow of a nonelectrically conducting gas. The properties of the air flow are the following: stagnation pressure at inlet, 5 atm; stagnation temperature, 3000°K; mass flow rate, 0.56 kg/sec.

We write a system of quasisteady equations, describing an unsteady-state generating process in a hydraulic approximation [10]:

$$\frac{\partial \rho}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}(A\rho u) = 0; \qquad (2.1)$$

$$\rho\frac{\partial u}{\partial t} + \rho u\frac{\partial u}{\partial x} = -\frac{\partial p}{\partial x} + jB + \tau_w; \qquad (2.2)$$

$$\rho\frac{\partial}{\partial t}\left(e + \frac{u^2}{2}\right) + \rho u\frac{\partial}{\partial x}\left(e + \frac{u^2}{2}\right) = -\frac{1}{A}\frac{\partial}{\partial x}(Apu) + jE - q_w - q_r; \qquad (2.3)$$

$$\frac{1}{A}\frac{\partial}{\partial x}(AE) = -F\frac{\partial B}{\partial t}; \qquad (2.4)$$

$$\frac{\partial B}{\partial x} = -\mu_0 j; \qquad (2.5)$$

$$j = \sigma(E - uB)$$

$$e(\rho, T);\ p(\rho, T);\ \sigma(\rho, T);\ \varkappa(\rho, T);\ \lambda(\rho, T);\ q_r(\rho, T). \qquad (2.6)$$

The parameter F in Eq. (2.4) is a previously calculated function F(x) (in our case ≈0.5), determining the decrease in the flow of the induced magnetic field through the electrode loop of the MHD channel due to the finite width of the electrodes. τ_w and q_w are the force of viscous friction with the walls and the heat flux at the wall of the channel, referred to a unit of volume

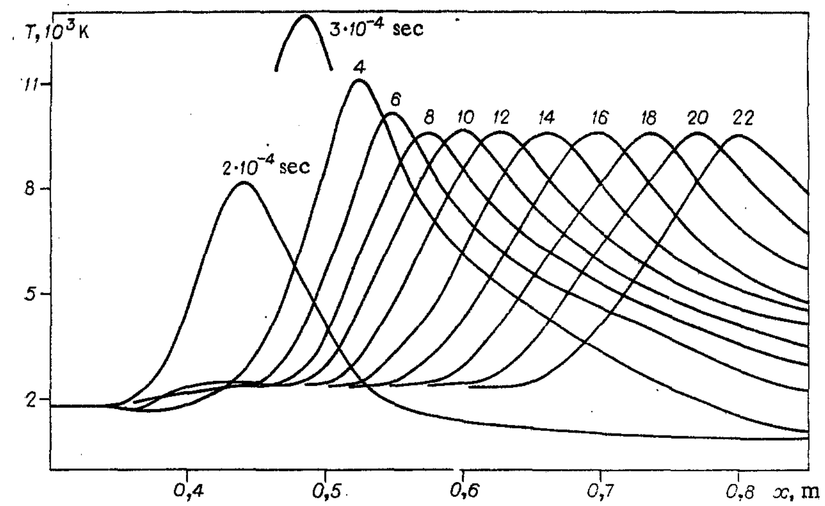

Fig. 3

$$\tau_w = \eta \frac{\rho u^2}{2} \frac{4}{D}, \quad q_w = \alpha \rho u (h - h_w) \frac{4}{D},$$

where D = 4A/s is the effective diameter; h = p/ρ + e. The coefficients of friction and heat transfer η and α are determined in accordance with [11] using the formulas

$$\eta = 0.092 \left(\frac{\rho u D}{\varkappa}\right)^{-0.2}, \quad \alpha = 0.092 \left(\frac{\rho u D}{\varkappa}\right)^{-0.2} \left(\frac{C_p \varkappa}{\lambda}\right)^{-0.66},$$

which are obtained for turbulent flow conditions ($Re_D \geq 10^3$). The dependence e(ρ, T), p(ρ, T), and q_r(ρ, T) for an air plasma were taken from [12, 13], and the dependence of the coefficients of the electrical conductivity σ(ρ, T), the viscosity ϰ(ρ, T), and the thermal conductivity λ(ρ, T), from [14].

The flow conditions at the inlet to the channel are supersonic; therefore, the gasdynamic parameters in the inlet cross section remain constant. In the inlet cross section, the boundary conditions are determined from the characteristic relationships for adiabatic flow.

For the equations of electrodynamics, the boundary conditions in the MHD channel are obtained from the equation of the circuit (the plasma, the electrodes, the load). The relationship for the cross section x_R, in which the load is applied,

$$E = \frac{R}{R_0} BF(x_R), \text{ where } R_0 = 4\pi \frac{l(x_R)}{a} \cdot 10^{-4}\ \Omega.$$

For the opposite end $B = B_0$.

The total system of equations of magnetic gasdynamics (2.1)-(2.6) was solved numerically, using an algorithm described in [9].

Figure 2 shows the time dependence of the power of the external source of energy, preheating a local perturbation. The initial level of the power, determined from the relationship $C_p(T_0)\rho_0\Delta T_i/\tau$, must be increased by almost an order of magnitude in the course of the process, which is connected with overcoming the dissociation peak of the heat capacity with temperature of ~8000°K. The heating process lasts 280 μsec, and ends when the maximal temperature in the heating zone reaches $12 \cdot 10^3$ °K. As calculations have shown, under the conditions in question, the level of the temperature must be regarded as optimal since, for a lower value of the temperature, the electrical conductivity of a bunch is found to be insufficient for Joule dissipation $\sigma(E - uB)^2$ to maintain the temperature in the bunch. With a higher temperature, the radiation cools the gas at a high rate, and the temperature is lowered to a level equal to that attained with heating to $12 \cdot 10^3$ °K, i.e., excess preheating is advisable from an energy point of view.

Figure 3 shows the dynamics of the formation of a T-layer and the arrival of the T-layer at the working section of the MHD channel. From the character of the shift in the temperature peak, it can be seen that at the moment of the short-circuiting of the electrically conducting bunch, there is a sudden stagnation at the electrodes of the forming cross section.

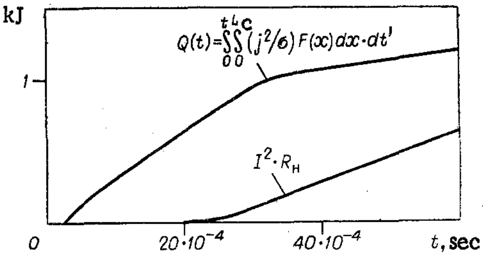

Fig. 4

With the formation of a plug of compressed gas behind the shock wave, there is a weak acceleration of the T-layer. Under these conditions, the temperature, falling from a value of $12 \cdot 10^3$ °K, is stabilized at a level of $9.5 \cdot 10^3$ °K due to Joule dissipation. Here, the thermal inertness of the molecular gas is found to be a favorable property.

Figure 4 shows the integral energy characteristics of the MHD process:

$$Q(t)=\int_0^t\int_{x_0}^{x_N}(j^2/\sigma)\,A\,dx\,dt,\quad E(t)=\int_0^t\int_{x_0}^{x_N}(jE)\,A\,dx\,dt.$$

The thermal inertness of the combustion products stabilizes the parameters of a conducting bunch. As a result, the dependences E(t) and Q(t) are practically linear functions. From the figure it can be seen that, with a length of the working part of ≈1.5 m, the energy evolved in the load compensates the expenditures of energy for the initial preheating.

If we have in mind the building of an MHD generator of alternating current of industrial frequency, this determines the length of the working part of such a generator, since $L_c = u\tau_p \approx 500/50 = 10$ m. Consequently, after expenditures for inherent needs have been covered in a length of 1.5 m, there still remain ≈8.5 m for useful work.

It is interesting to compare the power of the Joule dissipation with the power of the radiant losses in different stages of the process. Figure 5 gives the specific powers of the Joule dissipation q_J and the losses of energy due to radiation q_r for the section of the flow with a maximal temperature. The power of the external source, inducing the temperature perturbation, is shown on the left. After short-circuiting at the electrodes of the MHD channel there is a drop in the temperature; in this case $q_r > q_J$. However, the cooling is connected predominantly with the gasdynamic broadening of the temperature peak, and when it ends, the temperature is stabilized. Under fully established conditions, the heat balance q_J q_r is satisfied. The difference between these values, negligibly small in comparison with q_J, is the result of convective heat transfer. It is important to note that the time required for the establishment of a steady state $\tau_e \ll L_c/u$, which makes it possible to construct a simple physical model of an MHD generator with a T-layer.

3. Elementary Theory of an MHD Generator, Using the Phenomenon of a Self-Sustaining Current Layer. In the channel of an MHD generator, as is shown by calculations of an unsteady-state process, there is a reorganization of the gasdynamic parameters of the flow. The formation of a stable structure is completed in a time $\sim\delta/\sqrt{T}$ (Fig. 6); it can be seen that, from the T-layer, as from the stagnant piston upstream, a shock wave goes out, while on the other side there is a rarefaction wave. The pressure drop arising Δp determines the force of the action of the gas flow on the current layer, which is compensated by the electrodynamic force, i.e.,

$$\Delta pA = jBA\delta, \tag{3.1}$$

where A is the transverse cross section of the channel; B, induction of the magnetic field; j, mean current density in the T-layer.

Dynamic equilibrium (3.1) is accompanied by the establishment of an energy equilibrium, where

$$(j^2/\sigma)A\delta = \sigma u^2B^2(1-K)^2\delta A = Q_r \approx 4\varepsilon\sigma_{C-B}\,T^4A, \tag{3.2}$$

where σ is the mean electrical conductivity in the T-layer; K, load coefficient; ε, integral radiating power over the spectrum of a hemispherical volume of gas, heated up to the temperature of the T-layer T; the coefficient 4 is obtained with a transition from hemispherical volumes to a parallelepiped, irradiated over all its faces [13].

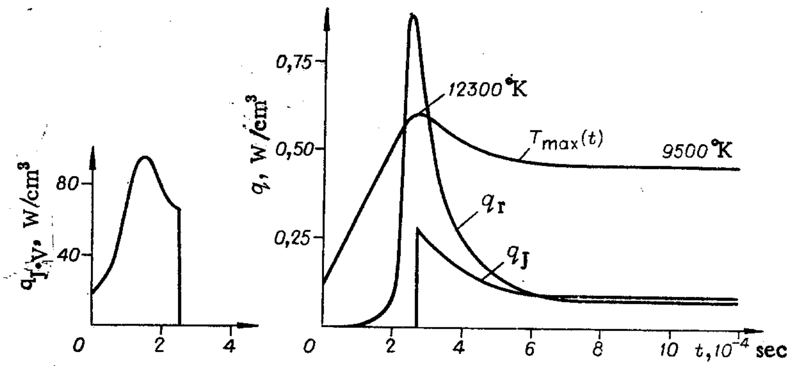

Fig. 5

In the relationship (3.2) it is assumed that, in the volume of the T-layer, the temperature field is homogeneous. This can raise the true losses due to radiation by 1.5-2 times. In addition, we neglect losses of heat with heat transfer with the surrounding cold gas and the walls of the channel. As calculations showed, the washing-out of the temperature peak due to molecular thermal conductivity after the characteristic time is negligibly small, and the heat fluxes to the wall, connected with convective transfer in the turbulent boundary layer, constitute not more than 5% of the transfer by radiation.

The balance equations (3.1), (3.2) make it possible to analyze the efficiency of the work of an MHD generator as a converter of heat energy into electrical energy. We shall define the ideal degree of conversion as the ratio

$$\eta_N' = \frac{\Delta p u A}{\rho^* u^* A^* \left(C_p T^* + \frac{u^{*2}}{2}\right)}, \tag{3.3}$$

where u is the velocity of the T-layer; ρ^*, u^*, and T^* are the parameters of the flow in the critical cross section A^* of a supersonic channel.

The pressure drop in the T-layer is determined from the relationship

$$\Delta p = p_1 - p_2,$$

where p_1 is the pressure behind the front of the shock wave; p_2 is the pressure at the boundary of the rarefaction wave in contact with the T-layer.

The parameters p_1 and p_2 are determined from the following relationships:

$$p_1 = p_0\left(\frac{2\gamma}{\gamma+1}\mathrm{M}_1^2 + \frac{\gamma-1}{\gamma+1}\right); \tag{3.4}$$

$$p_2 = p_0 (c_2/c_0)^{2\gamma/(\gamma-1)}, \tag{3.5}$$

where $M_1 = (u_0 - D)/c_0$ is the Mach number of the shock wave; $c_2 = c_0 - [(\gamma - 1)/2](u_0 - u)$ is the velocity of sound in the rarefaction wave. The velocity of the front of the shock wave D is determined from the equation of continuity

$$\frac{u_0 - D}{u - D} = \frac{\rho}{\rho_0} = \frac{\frac{\gamma+1}{2}\mathrm{M}_1^2}{1 + \frac{\gamma-1}{2}\mathrm{M}_1^2} = \frac{\frac{\gamma+1}{2}\left(\frac{u_0 - D}{c_0}\right)^2}{1 + \frac{\gamma-1}{2}\left(\frac{u_0 - D}{c_0}\right)^2}, \tag{3.6}$$

for the combustion products we can set $\gamma = 1.2$; then, solving (3.6) for D, we obtain

$$D = \frac{1.1u + 0.9u_0}{2} - \sqrt{\frac{(1.1u + 0.9u_0)^2}{4} + c_0^2 + 0.1u_0^2 - 1.1u_0 u}. \tag{3.7}$$

We find the parameters in the unperturbed flow u_0, c_0, p_0 from the stagnation parameters p_{00} and T_{00}, the pressure and the temperature in the combustion chamber, and from the M number of the unperturbed flow

$$p_0 = p_{00}\left(1 + \frac{\gamma-1}{2}\mathrm{M}^2\right)^{-\gamma/(\gamma-1)},$$
$$T_0 = T_{00}\left(1 + \frac{\gamma-1}{2}\mathrm{M}^2\right)^{-1}, \quad c_0 = \sqrt{\gamma R T_0}, \quad u_0 = c_0 \mathrm{M}. \tag{3.8}$$

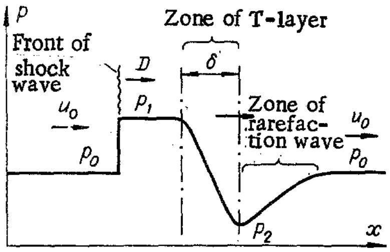

Fig. 6

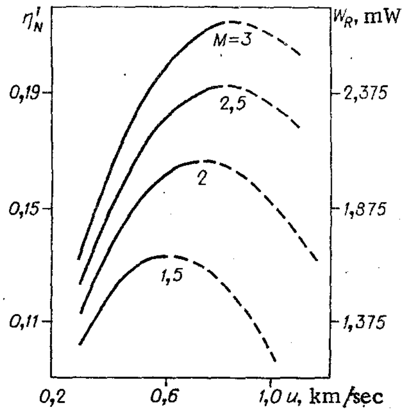

Fig. 7

Thus, relationships (3.4)-(3.8) make it possible to calculate the degree of conversion in an MHD generator with one T-layer, if there are given the stagnation parameters p_{oo} and T_{oo}, the velocity of the T-layer, and the expansion of the channel, which is uniquely determined by the M number in the unperturbed gas:

$$\frac{A}{A^*} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \frac{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M}.$$

For the subsequent analysis, $\eta'_N(M, u)$ is calculated with the condition p_{oo} = 3 atm and T_{oo} = 3000°K. The result of the calculation is shown in Fig. 7 in the plane $\eta'_N - u$ by a set of curves, where M is a parameter. All the curves have a clearly expressed maximum, which separates the region of stable conditions with $\partial\eta'_N/\partial u \geqslant 0$ (continuous curves) from the region of unstable conditions (dashed lines) with

$$\partial\eta'_N/\partial u < 0. \tag{3.9}$$

The stability condition (3.9) reflects the fact that, with a variational rise in the velocity with the condition $\partial\eta'_N/\partial u > 0$, there is an increase in the power Δpu and in the constant part of this power Q_J. This leads to an increase in the electrical conductivity and, consequently, of the current J and of the braking force **J•B**, as a result of which the velocity should decrease to the starting level.

On the right-hand vertical axis of the figure there is plotted the useful power in the load for a channel with a mass flow rate of the working body G = 5 kg/sec, working under conditions of the withdrawal of the maximal power, i.e., the load coefficient $K = R_l/(R_{use} = R_l) = 0.5$.

Let us now examine the energy balance of the T-layer, for which we rewrite conditions (3.1), (3.2) in the form

$$\Delta p = jB\delta,\ \sigma uB(1-K)uB(1-K)\delta = jB\delta u(1-K) = \Delta pu(1-K) = 4\varepsilon\sigma_{C-B}T^4 = q_r. \tag{3.10}$$

We obtain an energy balance referred to a unit of surface of the T-layer. The dependence $\varepsilon(T)$ was taken from [13], which gives a table of the radiating powers of hemispherical gas volumes of a mixture of 90% CO_2 and 10% N_2.

Figure 8b gives the power of the radiation $q_r(T)$, referred to a unit of surface of the T-layer. The upper layer relates to a layer of thickness 10 cm and the lower to a thickness 1 cm, both with a pressure of 1 atm.

Equations (3.4)-(3.8) were solved to determine $q_J = \Delta pu(1-K)$ in Eq. (3.10). The result of a calculation for the parameters p_{oo} = 3 atm, T_{oo} = 3000°K, and K = 0.5 is shown in Fig. 8a in the form of a dependence of q_J on u. The physical sense of the parameter $\Delta pu(1-K)$ is the power expended by the gas flow to cover the loss of energy from a steady-state T-layer. It is interesting to note that the conditions for an increase in the efficiency of the generator process and the condition for maintenance of the T-layer are found to be contradictory. While the first condition for an increase in η_N requires an increase in the Mach number M, i.e., a large expansion of the channel, the second condition, interpreted as an

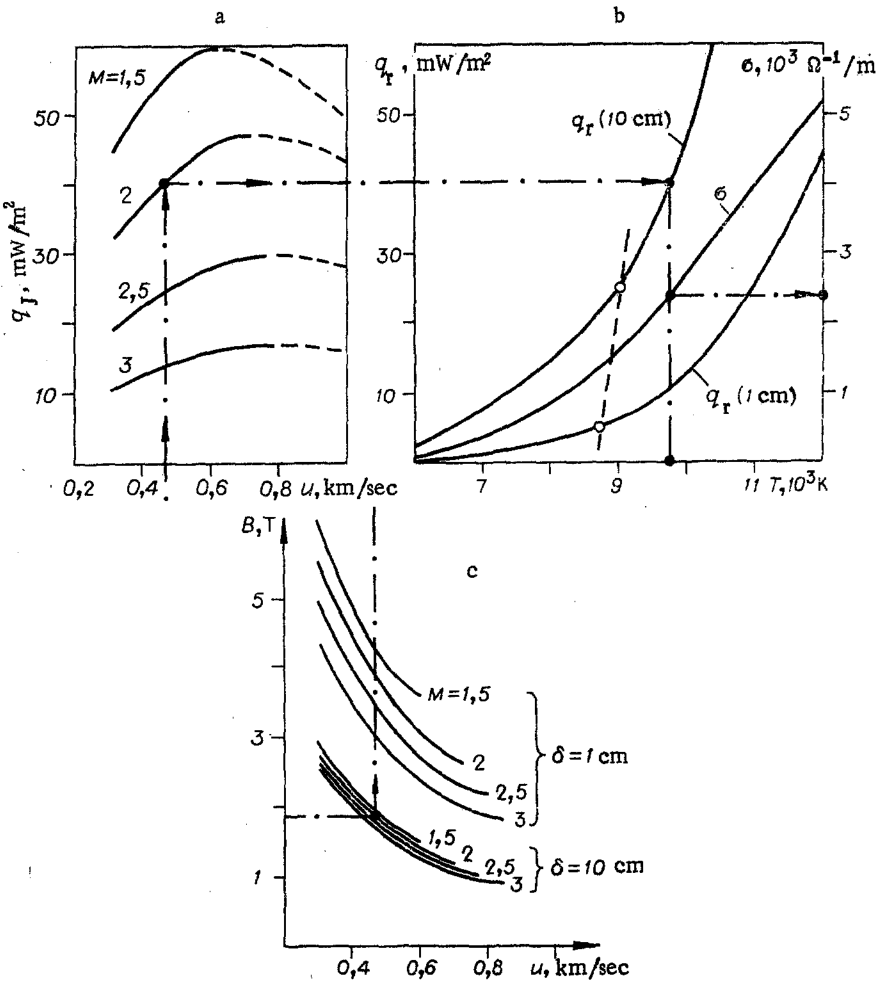

Fig. 8

increase of the Joule dissipation in unit volume, requires a decrease in the M number. The parameters q_J in Fig. 8a and q_r in Fig. 8b are referred to a common scale, which makes it possible to solve Eq. (3.10) graphically with respect to the temperature of the steady-state T-layer. We write once again the balance equation (3.2) as

$$\sigma u^2 B^2 (1 - K)^2 \delta = q_r. \tag{3.11}$$

The dependence σ(T) is plotted on Fig. 8c on a temperature scale, in common with q_r, which makes possible a simultaneous determination of σ.

Thus, with a given thickness of the T-layer δ and a given choice of the supersonic conditions, i.e., of the Mach number, relationships (3.10), (3.11) make it possible to connect such parameters of the T-layer as the velocity u, the magnetic field B, and the temperature T. Figure 8c gives the result of a solution of Eq. (3.11) for B. The dot-dash line connecting the points of the curves of Fig. 8a-c shows one of the possible variants of the solution of Eqs. (3.10), (3.11).

The question of the thickness of the T-layer δ remains open. In the general case, this parameter cannot be given arbitrarily, since it is determined by the internal physical nature of the T-layer. But if we look on the steady-state T-layer as an electric arc, stabilized by radiation, we obtain the condition for the stable combustion of such an arc within given dimensions, as

$$\partial q_J / \partial T \leqslant \partial q_r / \partial T. \tag{3.12}$$

If this condition is not satisfied, then there is a thermal contraction of the T-layer to smaller dimensions, where the increasing transparency increases the volumetric losses due to radiation. On the curves of q_r (10 cm) and q_r (1 cm) points are found at which the relationship (3.12) is satisfied as an equality. The lack of information on the radiating properties of the combustion products did not permit a clear delineation of the region of stable conditions; therefore, an arbitrary limit is drawn through these two points. The region lying to the right of this line should be regarded as stable.

The elementary theory makes it possible to select working conditions for the work of an MHD generator which will be a reasonable compromise between the requirements of high efficiency and stability of the T-layer.

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