# The physics of MHD generators

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A brief popular review is presented of physical phenomena in MHD plasma generators of electric power. The interaction between a current of weakly ionized gas and a transverse magnetic field is described. Qualitative explanations are given of the leading instabilities of this current and of certain phenomena near the electrodes. The characteristic properties of the plasma in MHD generators with nonequilibrium conductivity are noted. They include ionization turbulence, motion of the ionization front through a weakly ionized gas, and its stabilization at entry into the MHD duct. Data characterizing the scientific and technological achievements in the development of MHD generators are cited.

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## INTRODUCTION

The principle of transformation of thermal energy into electric power with the aid of magnetohydrodynamic generators and without the use of conventional machinery is quite simple. It is based on the replacement of the metal conductor by a current of plasma moving in a transverse magnetic field. Patents concerned with the principle of the magnetohydrodynamic generator were taken out during the first half of this century. However, extensive work on this method of electric-power generation began only during the last ten to fifteen years. This was connected, on the one hand, with successes in rocket technology (which ensured that the practical application of the idea became realistic) and with the development of powerful superconducting magnets and, on the other hand, with attempts to increase the efficiency of thermal electric power stations in which the efficiency of conventional turbogenerators had practically reached its limit (~40%). In the first-generation MHD electric power stations, the efficiency should increase to 50%. There is also considerable interest in the idea of the magnetohydrodynamic generator in nuclear power engineering in connection with the possibility of gas-cooled high-temperature power-producing fission reactors.

There is at present an enormous literature on magnetohydrodynamics and MHD generators. It includes not less than ten monographs,[1–10] the proceedings of numerous international and national conferences, and many thousands of articles in periodical publications. However, the MHD generator has not so far been widely used. The Lorho generator, which has a short operating cycle, has been used in the USA for supplying plasmotrons which, in turn, heat the gas in a large wind tunnel. Mobile MHD generators have begun to be used in the Soviet Union as pulsed supply sources for geophysical studies[11] and, finally, the industrial test set U-25 incorporating an MHD generator is working in Moscow and periodically feeds electric power into the urban grid. The first stage in the adoption of the U-25 has been discussed in the literature in some detail.[12] During this stage, the electric power output of the MHD generator was raised to 6 MW. At present, it has reached 20 MW. Just like any other major scientific and technological problem, the development of the MHD generator has been a synthesis of contributions from very different branches of science. The subject of the present paper, i.e., the physical phenomena occurring in the MHD generator, is, of course, one of the most important.

There are two classes: the so-called open- and closed-cycle MHD generators. The open-cycle MHD generators use the plasma of the combustion products produced by burning organic fuel as the working medium. The closed-cycle MHD generators use an inert gas raised to the necessary temperature in a special heater (it is hoped that this heater will be a future nuclear or thermonuclear reactor).

To ensure that the working gas has sufficient electrical conductivity, it must be partially ionized. At the temperatures that have so far been reached in MHD generators, appreciable ionization can be achieved only

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by using an admixture of the easily ionizable alkali-metal atoms. In the open-cycle MHD generators, the temperature of the combustion products is of the order of 2500–3500 degrees and this is sufficient for the necessary thermal ionization of the alkali admixture. In the closed-cycle MHD generator, the situation is more complicated because the heating of the gas to the above temperatures in a reactor with solid elements is impossible. The closed-cycle MHD generators are, therefore, based on the use of nonequilibrium plasma, i.e., they are operated so that the electron temperature is appreciably higher than the temperature of the main gas. This can be achieved through Joule heating of the electron gas by impeding the energy transfer between electrons and the inert-gas atoms, which proceeds through elastic collisions between electrons and atoms.

The idea of using nonequilibrium conductivity in closed-cycle MHD generators was proposed by Kerrebrock in 1961. The necessary conditions for attaining this situation can easily be obtained from the electron energy balance equation[13]

$$\sigma\left(\frac{uB}{c}\right)^2(1-K)^2=\frac{3m_e}{M_g}\,\delta\frac{n_e(T_e-T_g)}{\tau_e}. \tag{1}$$

The left-hand side of this equation gives the product of the conductivity by the square of the electric field heating the electrons. It is less than the induced field $uB/c$ by a factor of $(1-K)^{-1}$, where $u$ is the plasma velocity, $B$ is the magnetic induction, and $K$ is the load factor of the generator. The right-hand side gives the energy loss during collisions between electrons and heavy particles ($n_e$ is the electron concentration, $\tau_e$ is the mean free time of electrons, and $\delta$ is a coefficient representing the fact that energy transfer may be greater than in the case of elastic collisions). Hence, the ratio of the electron-to-gas temperature is

$$\frac{T_e}{T_g}=1+\frac{\gamma}{3\delta}\mathbf{M}^2(\omega\tau)_e^2(1-K)^2 \tag{2}$$

where $\mathbf{M}$ is the Mach number and $\omega_e$ the electron cyclotron frequency. The static gas temperature in the MHD channel is related to the temperature in the heater by the following well-known result:

$$T_g=T_h\left(1+\frac{\gamma-1}{2}\mathbf{M}^2\right)^{-1}.$$

Equation (2) leads to the important result that the MHD generator with nonequilibrium conductivity requires a high degree of magnetization of the plasma, i.e., the ratio of the electron cyclotron frequency to the mean frequency of collisions with the heavy component of the plasma must be high, $(\omega\tau)_e \gtrsim 3$.

It is clear that this condition will also remain in force for the other methods of maintaining the electron temperature which have occasionally been discussed in the literature if electric power is expended in heating the electrons. The production of nonisothermal plasma in the MHD generator is possible in practise subject to the condition that the electron energy losses are close to other losses. In open-cycle MHD generators, the interaction between electrons and impurity atoms, on the one hand, and the molecules of the working body on the other leads to considerable inelastic losses, so that the plasma in such generators is an equilibrium plasma (except, possibly, for small regions near the electrodes). An important characteristic of the MHD generator plasma is its electrical conductivity. For the plasma of combustion products, calculations of the electrical conductivity can now be carried out with satisfactory precision that has been checked experimentally. To analyze the complex composition of the combustion products and the electron mobility, one has to use numerous characteristics of the various elementary processes such as binding energy of the various plasma components, electron scattering cross sections of these components, and so on. The concentration of free electrons in the plasma is determined from the condition of ionization equilibrium, *taking into account the production of negative* ions. In closed-cycle MHD generators, the electron concentration is usually also determined by ionization equilibrium for the actual dimensions of the MHD channels and the impurity concentrations employed, but at the electron temperature.

The present paper is intended for a broad circle of potential readers and is concerned with the fundamental physical phenomena in plasma MHD generators and does not cover flow calculations, end effects, and certain other important problems that have been successfully resolved by magnetohydrodynamics, or problems in solid state physics relating to the constructional materials.

## OVERALL PHYSICAL PICTURE OF THE PROCESS

A particular feature of plasma is the appearance of the Hall effect, so that the current flowing through it is given by the generalized Ohm's law:

$$\mathbf{j}+\mathbf{j}\times\beta=\sigma(\mathbf{E}+\mathbf{u}\times\mathbf{B}/c)\,. \tag{3}$$

For closed-cycle MHD generators, the parameter $\beta$, also called Hall's number, is given by

$$\beta\approx\omega_e\tau_e=\frac{eB}{m_ec}\tau_e=\mu_e\frac{B}{c},$$
$$\sigma=e\mu_en_e$$

where $\mu_e$ is the mobility. Therefore, as we have seen, the nonequilibrium MHD generator will operate successfully only at high Hall numbers. This also applies to open-cycle generators which should be used with thermal electric power stations. The point is that the plasma conductivity falls sharply with decreasing temperature ($\sigma \sim T^{12}$). This means that only a small fraction of the total enthalpy of the current can be transformed into electric power. The application of MHD generators to power engineering is thus seen to presuppose the subsequent utilization of the energy of the gases transmitted through the MHD channel in a conventional steam-turbine cycle producing electric power. This generator-turbine combination requires, for constructional reasons, that the plasma pressure at exit from the MHD generator be of the order of 1 atm. For typical combustion products, the Hall parameter is $\beta=0.5B/p-$

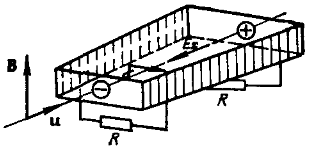

FIG. 1.

$0.8B/p$, where $B$ is in tesla and $p$ in atmospheres. The corresponding magnetic induction is 3.5–5 tesla. Hence, it is clear that the MHD generator for an electric power station should operate with a relatively small Hall parameter, amounting to a few units. In U-25, the magnetic induction is 2 tesla and $\beta \approx 1.5$. It is then clear from (3) that, in the plane perpendicular to the magnetic field, the current flows at an angle $\alpha$ to the acting electric field and $\alpha = \arctan\beta$. The slowing down of the plasma is produced under the action of the ponderomotive Ampere force $(\mathbf{j} \cdot \mathbf{B}/c)$. Since the plasma is weakly ionized and the concentration of ions and electrons in it is smaller by four to five orders of magnitude as compared with the concentration of neutral atoms or molecules, the thermal energy of the current is stored in the neutral component. In relation to the neutral molecules, the force $(\mathbf{j} \cdot \mathbf{B}/c)$ is realized through their collisions with ions and electrons which, in turn, experience the electric and magnetic fields. For example, in the MHD generator with a large number of sectionalized electrodes, each pair of which has an electrical load connected across it, one can ensure conditions under which the current flows strictly at right-angles to the direction of the plasma velocity $\mathbf{u}$ (Fig. 1). As a result of the Hall effect, this will be accompanied by a longitudinal electric field in the MHD generator channel due to the separation of charges: the ions are carried downward by the flow and the electrons are partially retarded by the transverse magnetic field. This longitudinal electric field, whose direction is opposite to that of the flow, communicates momentum to the plasma ions which transfer this momentum to neutral atoms and molecules in the course of collisions.

It is clear from (3) that, when

$$j_x = 0, \quad E_x = \beta\left(\frac{u}{c}B - E_y\right),$$

the force acting on the ions per unit volume of the plasma is

$$eE_x n_i = e\mu_e \frac{B}{c}\left(\frac{u}{c}B - E_y\right) n,$$

which is exactly equal to $j_y B/c$. In the other extreme case, when the electrodes in the MHD duct are continuous, $E_x = 0$ and there is no longitudinal force acting on the ions. However, there is then an electron current flowing along the channel, such that the electrons move against the flow of gas, and the retarding force due to these electrons on the flow can easily be shown to be equal to $j_y B/c$. In general, the ponderomotive force is produced by the combined action of both ions and electrons. For high $\beta$, the regime with longitudinal current which does no work but heats the plasma is, of course, inconvenient. Sectionalized electrons are therefore then essential. For a perfectly sectionalized channel, it is possible to estimate the longitudinal potential difference $V_x$ between its ends, due to the Hall effect. The work done by an element of the plasma against this field in the channel is $e\tilde{n}V_x$, where $\tilde{n}$ is the mean ion concentration. If we divide this work by the enthalpy of the element $(W = \alpha n_g T_g)$, which is equal to the product of the coefficient $\alpha$ by the concentration of neutrals and their thermal energy, we obtain the fraction of enthalpy transformed into electric power. For inert gases, $\alpha = \frac{5}{2}$ and, for the combustion products, $\alpha \approx 4-6$ because of the energy of partial dissociation of the component gases. Thus, $n_g/\tilde{n} \sim (3\times10^4 - 10\times10^4)$.

For the overall efficiency of the electric power station to be about 50%, the fraction of enthalpy used in the MHD generator should be not less than 0.2 (the total efficiency of the station is equal to the fraction of enthalpy spent in the MHD channel plus the remaining enthalpy transformed into electric power with the efficiency of the steam turbine cycle). The order of magnitude of the Hall potential difference is given by

$$V_x \sim 0.2\alpha \frac{n_g}{\tilde{n}} \frac{T_g}{e} \sim 10^4 B.$$

A potential difference of this order produces well-known technical difficulties relating to electrical insulation between the channel elements and between the combustion chamber (with its supply systems for the fuel, oxidizer, and the easily ionized impurity) and the ground.

The plasma MHD generators developed so far produce constant current which is extracted by electrodes in contact with the plasma. Before this can be used in power systems, the current must be converted into an alternating current. Inductive extraction of power is unrealistic because the magnetic field due to the current induced in the generator is relatively low:

$$\operatorname{curl} \tilde{H} \approx \frac{4\pi}{c^2} \sigma u B, \quad \text{whence} \quad \frac{\tilde{H}}{B} \approx \frac{uL4\pi\sigma}{c^2}.$$

This ratio (the magnetic Reynolds number) turns out to be much less than unity for typical parameters ($u \sim 10^5$ cm/sec, $\sigma \sim 10^{11}$, characteristic linear size $L \sim 100$ cm). A magnetic Reynolds number of the order of unity can be achieved only in shock tubes in which the plasma moves with a velocity up to $10^6$ cm/sec and the electrical conductivity is of the order of $10^{12}-10^{13}$ cgs esu. For usual parameter values, this can be achieved by increasing the size $L$, but this implies an increase in power to the relatively fantastic level of a few tens of gigawatts.

## INSTABILITIES IN THE MHD-GENERATOR PLASMA

The replacement of the solid metal conductor by the plasma conductor means that one of the central problems in this area is the stability of current flow in a transverse magnetic field. Theoretical analyses of plasma stability are most readily carried out in terms of the model of homogeneous and quasistationary plasma described by the gasdynamic equations. The plasma can then be looked upon as if it consisted of two fluids, namely, the light electron component and the heavy component consisting of ions and atoms. The interaction between them results in friction and energy transfer during elastic and inelastic collisions of electrons. This system of equations should include the equations of continuity, momentum conservation, energy balance of these components, continuity of electric current, and the condition for the magnetic field to be stationary. Moreover, they must be augmented with the equation of state of the gas and the equations characterizing the degree of ionization. As usual, this system of equations can be linearized with respect to small perturbations of one-dimensional plane waves of the form $\exp[i(\mathbf{k}\cdot\mathbf{r} - \omega t)]$, propagating in the plane perpendicular to the magnetic field. The assumption that the plasma is quasistationary and spatially homogeneous restricts the possible values of the frequency $\omega$. Thus, the latter must be much greater than $\gamma_B = \sigma B^2/\rho c^2$ and $\gamma_h = j^2/\sigma c_p T$, where $\gamma_B$ is the reciprocal of the characteristic time $\tau_B$ for the slowing down of the gas by induction currents, known as magnetic viscosity, and $\gamma_h$ is the Joule heating time $\tau_h$ of the ion-atom gas. The equations listed above can be used to obtain a dispersion relation for small-amplitude waves. It turns out to be of the fourth degree in $\omega$, i.e., in general, there are four different oscillation frequencies for a given wave number $k$. Under certain definite conditions, they may all have a positive imaginary part, i.e., turn out to be unstable. If we neglect the heating of the gas and the magnetic viscosity, one of the roots of the dispersion equation is $\omega_1 = 0$ and the two others, $\omega_{2,3} = \pm ka$, describe acoustic waves propagating in two directions, without attenuation or amplification, with velocity $a$. The fourth root is unstable in nonisothermal plasma with characteristic instability-development time $\tau_I = In_e\sigma/j^2$, where $I$ is the ionization energy. It is easily seen that $\tau_I$ is the plasma ionization time, and the instability itself is of ionization origin and is due to the fact that Joule energy dissipation increases in zones with enhanced concentration and, consequently, there is an enhancement of ionization. This mechanism is connected with the Hall effect and, for it to be seen, the Hall parameter must exceed the threshold value $\beta_k \sim 1$. The additional Joule dissipation is due to currents that are connected with nonuniform conductivity and are closed in the plasma. Their existence becomes obvious if we take the divergence of both sides of (3):

$$\beta \operatorname{curl} \mathbf{j} = \nabla\sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}/c)\,. \tag{4}$$

As noted above, the condition for a nonequilibrium plasma in the MHD generator is $\beta > 3$, i.e., this plasma is unstable with respect to ionization provided only a situation has not been set up in which the readily-ionized admixture is fully ionized.

The inclusion of thermal effects will transform the trivial first root into a complex expression, the imaginary part of which describes the overheating instability whose growth rate for isothermal plasma is of the order of $\gamma_h d\ln\sigma/d\ln T$. This instability, for which there is more current through the hotter areas, is frequently seen in plasma, even in the absence of the magnetic field. The configuration of the most unstable perturbations depends on the properties of the plasma, the Hall parameter, the energy dependence of the electron scattering cross section, and so on. The ponderomotive force due to the additional current flowing through the overheated region compresses the gas in front of the inhomogeneity (Fig. 2). This compression is accompanied by an increase in the gas temperature and a change (usually an increase) in the electrical conductivity. The presence of regions with enhanced and reduced conductivity on different sides of the inhomogeneous regions leads to a displacement of the fluctuation currents and hance of the overheated zone relative to the gas. The direction of motion of the inhomogeneity will depend on whether the conductivity deteriorates or is improved during the compression process. Since the velocity of the overheated regions relative to the gas flow is small, these regions drift with the flow. However, in large enough and powerful enough MHD generators, the overheating instability may succeed in developing during the time taken by the plasma to traverse the duct.

Oscillations in electrical conductivity and the Hall parameter are due to periodic variations in the density and temperature of the medium in acoustic oscillations. They, in turn, produce fluctuations in the current density at the same frequency. The fluctuating currents affect the acoustic oscillations in two ways. Firstly, they give rise to a fluctuating ponderomotive force which, under certain conditions, can do positive work during the oscillations of the medium. On the other hand, the fluctuating currents produce fluctuations in the Joule heating $q = j^2/\sigma$. When the heat release or the work done by ponderomotive forces per period is greater than zero, the acoustic waves will grow. (The overheating mechanism was noted a long time ago by Rayleigh for $dq/dT > 0$.) The instability of acoustic waves in crossed fields develops when the instability growth rate exceeds the effect of the magnetic viscosity, which always damps the oscillations. The instability development time is, therefore, of the order of the time $\tau_B$ of the magnetic interaction. The time taken by the plasma to traverse the duct is of the same order. If there were no sharp changes in the gasdynamic characteristics of the flow at the ends of the MHD duct, the acoustic instability would not present a particular danger. However, partial reflection of the waves from inhomogeneities at the ends may lead to the accumulation of acoustic energy in generators with subsonic flow. For acoustic waves whose phase velocity has a component along the magnetic field, the instability growth rate is greater because the motion of the gas in the direction of the magnetic field is unaffected by the magnetic viscosity. The most dangerous are the oblique standing waves,

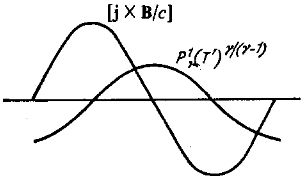

FIG. 2. Pressure and temperature perturbations due to perturbations in the ponderomotive force.

whose wave vector lies in the $(\mathbf{u}, \mathbf{B})$ plane, so that the component of the wave velocity in the direction of motion of the plasma is $-u$. These waves are stationary relative to the walls and their motion does not transport energy.

The plasma in the MHD duct, which is inhomogeneous along $B$, is also subject to an instability analogous to the Rayleigh–Taylor instability in a heavy inhomogeneous medium. It is well known that, during the adiabatic displacement of an element of a fluid from a position of hydrostatic equilibrium, the element experiences the Archimedes force due to its thermal expansion, and this either returns the element of the fluid to its position of equilibrium (this is accompanied by internal waves) or tends to take the element even further away from the position of equilibrium, and this is accompanied by free convection. The second situation occurs if the entropy $S_0$ increases in the direction of the gravitational force in the state of mechanical equilibrium. In a conducting medium carrying a current in a magnetic field, the gravitational forces are replaced by the electromagnetic force $\mathbf{j}\times\mathbf{B}/c$ and the thermal expansion is replaced by the temperature dependence of electrical conductivity. The underlying mechanism responsible for the phenomenon is then essentially reduced to the following. When an element of the medium is displaced down the conductivity gradient, which is due, for example, to a temperature gradient, its conductivity becomes different from that of the ambient medium. This gives rise to a perturbation of the current flowing across the conductivity gradient and to the appearance of the additional force $\mathbf{j}\times\mathbf{B}/c$ analogous to the Archimedes force. Depending on the direction, this force will return the element of the medium to its position of equilibrium or it will remove it even further from it. In the former case, a gravitational-type wave appears and, in the latter, we have an instability of the form of free convection. A stationary entropy gradient is present in the MHD duct because the flow carries the liberated Joule heat with it. For the simplest geometry of the velocity and temperature perturbations in the plasma, which vary only in the direction of the magnetic field, it is possible to obtain the following linearized equation (neglecting induced current and Joule heat in the energy equation):

$$\frac{\partial^2 T'}{\partial t^2}=\gamma_c^2 T', \qquad (5)$$

where

$$\gamma_c^2=\frac{jB}{\rho c}\,\frac{T}{c_p}\,\frac{d\ln\sigma}{dT}\,\frac{dS_0}{dx}$$

is the square of the growth rate of the convective instability which appears for $dS_0/dx>0$, i.e., in an MHD generator in which the entropy increases in the direction opposite to that of the force $\mathbf{j}\times\mathbf{B}/c$. The difference between the sign of the entropy gradient in the steady state and the sign in the ordinary liquid is due to the fact that the electrical conductivity of conducting media increases with temperature, whereas the density of ordinary liquids and gases decreases with temperature. For the above simple case, the instability limit is determined by the critical value of the load factor of the MHD generator $K_0=1-\sqrt{\alpha}$, where $\alpha=c_p/u^2(d\ln\sigma/dT)$.

When the Hall effect is taken into account, the instability region expands because the variable induced current producing the magnetic viscosity is reduced by the factor $(1+\beta^2)$. The closed longitudinal Hall currents then ensure that $\operatorname{curl}\mathbf{E}=0$.

Nonlinear analysis of the instability development shows that oscillations in the longitudinal velocity (Fig. 3), amounting to some tens of percent of the velocity of the main flow, may develop. This should be accompanied by an appreciable change in the average characteristics of the generator.

Insofar as the experimental confirmation of the above theoretical results is concerned, the ionization instability has fared best. It has been extensively investigated both in discharges in which crossed $E$ and $B$ fields were applied to a stationary gas and in discharges induced by motion.[13] The acoustic instability has been observed in some gas discharge model experiments.

The instabilities in open-cycle MHD generators have not been systematically investigated. They should be more appreciable in the larger installations. As mentioned in the Introduction, there are very few such installations and, in the first instance, most of the work on them has been confined to engineering development. At least, there has been no clear experimental evidence for instabilities that could be segregated from the complex overall picture of the process. The fraction of utilized enthalpy in open-cycle generators should increase by a substantial factor in the future (from the 5–7% achieved so far) and this will require an enhancement of the MHD interaction between the plasma flow and the magnetic field, which will result from an increase in the currents, fields, and linear dimensions. All this should facilitate the development of overheating and acoustic instabilities and, therefore, there is an urgent need for studies of the instability problem.

## IONIZATION TURBULENCE OF NONEQUILIBRIUM PLASMA[13]

When the threshold $\beta_{cr}$ for ionization instability is reached, the average characteristics of the nonequilibrium plasma undergo a sharp change. The observed effective conductivity and Hall parameter averaged over the volume are shown in Fig. 4 as functions of $(\omega\tau)_e$. For $(\omega\tau)_e>\beta_{cr}$, ionization oscillations are found to occur in the plasma. As the magnetic field increases, their frequency spectrum expands and "instantaneous" photo-

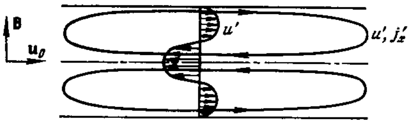

FIG. 3. Schematic illustration of additional motion and Hall currents during the development of overheating-convective instability.

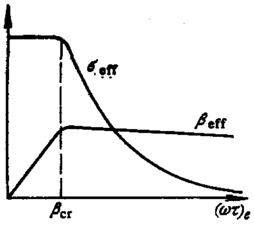

FIG. 4. Effective conductivity and Hall parameter as functions of $(\omega\tau)_e$ during the development of ionization turbulence in nonequilibrium plasma.

graphs show that the structure of the plasma gradually becomes quite irregular. The plasma goes into a new state of ionization turbulence, in which the degree of ionization, the electric current, and the fields undergo a spontaneous variation in space and time. The motion of the medium during the development of turbulence can usually be neglected.

The distinguishing feature of this plasma is the very weak dependence of $\beta_{eff}$ on $B$ and the associated reduction in $\sigma_{eff}$ for large $\omega\tau$:

$$\sigma_{eff} \approx \langle\sigma\rangle \frac{\beta_{eff}}{(\omega\tau)_e}. \tag{6}$$

The striking property of turbulent plasma which follows from (6) is that the electrical conductivity is independent of the electron collision frequency. The flow of current is ensured by the drift of electrons in the crossed fields:

$$\langle j_y\rangle \approx e\langle n\rangle \frac{\langle Ex\rangle}{B} c,$$

where the magnitude of $\langle E_x\rangle$ is automatically controlled by the fluctuating current.

Ionization turbulence is fundamentally different from ordinary hydrodynamic turbulence. It develops in an initially homogeneous plasma, and external geometric scales are unimportant for it. Current vortices in the turbulence interact through their influence on the average electrical parameters which depend on the root mean square fluctuations of the plasma concentration.

The variation of $\sigma_{eff}$ given by (6) produces an order of magnitude increase in the internal resistance of the nonequilibrium MHD generator and modifies the fundamental inhomogeneity condition (1). However, a nonequilibrium MHD generator can be produced at the expense of reducing the working pressures and increasing the values of $(\omega\tau)_e$. Since 1968, when the first successful generation of electric power in an external load was achieved, reaching 10% of the enthalpy flux in the duct, various models of nonequilibrium MHD generators have been successfully tested in different countries. All use plasma with ionization turbulence. Up to now, only nonequilibrium generators have succeeded in converting 20% or more of the enthalpy flux into electric power.

## STABILIZATION OF THE IONIZATION FRONT AT ENTRY TO THE NONEQUILIBRIUM MHD GENERATOR[13]

A substantial part of the volume of this generator can be occupied by the transition region in which the degree of ionization increases from small values at entry to the stationary state which is determined by the electron energy balance in the induced electric field. This part of the volume is inefficiently used and can be substantially reduced by stabilizing the ionization region at entry into the MHD duct. In the case of an MHD generator in which the temperature of the gas flow is low and there is practically no ionization, this stabilization of the ionization threshold is also necessary as is the stabilization of the combustion front in high-velocity flows of the fuel mixtures.

By analogy with the combustion front of a chemical fuel, the discharge region propagates through the unionized gas placed in an electric field which is sufficient to maintain the discharge but is not high enough to produce breakdown. Figure 5 shows the concentration profile of the plasma on its free boundary. On the right of this figure, we have the plasma region and on the left the unionized cold gas. Well away from the boundary, the electron temperature is determined by the balance of Joule heat and elastic losses in collisions with heavy particles:

$$\frac{e^2 n_\infty \tau_e}{m_e} E_0^2 \approx \frac{m_e}{M_g} \frac{n_\infty T_\infty}{\tau_e}. \tag{7}$$

Near the boundary of the plasma, the concentration and temperature of electrons are reduced (it may be supposed that they satisfy the Saha ionization equation)

$$\frac{n_e^2}{n_a} = AT_e^{3/2} e^{-I/T_e} \tag{8}$$

where $n_a$ is the concentration of admixture atoms. Equation (7) is then no longer satisfied because the left-hand side becomes greater than the right-hand side.

The surplus energy received by the electrons is transported in one way or the other to the boundary and is lost largely through ionization which results in the formation of $n_\infty v$ new electrons and ions per second, where $v$ is the velocity of the ionization front. Hence, $In_\infty v \approx \sigma E_0^2 l$. The characteristic length for a change in concentration depends on the mechanism responsible for heat transport. For electron thermal conductivity in a transverse magnetic field,

$$l \sim \left(\frac{1}{n}\frac{dn}{dx}\right)^{-1} \approx \left(\frac{M_g}{I}\right)^{1/2} \frac{T_\infty \tau_e}{m_e} [1 + (\omega\tau)_e^2]^{-1/2},$$

and

$$v \approx \left(\frac{T_\infty}{I}\right)^{3/2} \left(\sqrt{\frac{T_\infty}{M_g}}\right)^{1/2} [1 + (\omega\tau)_e^2]^{-1/2}, \tag{9}$$

which is lower by two orders of magnitude than the velocity of sound $\sqrt{\gamma T_g/M_g}$, i.e., it is much less than the necessary velocity at entry into the MHD duct. Equation (9) has been confirmed by experiments on dis-

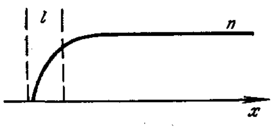

FIG. 5.

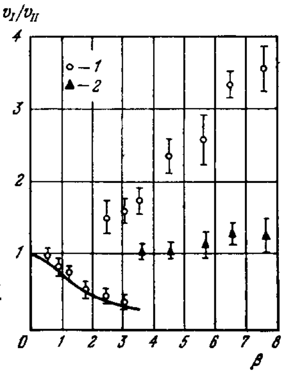

FIG. 6. Velocity of ionization front relative to the gas in a transverse magnetic field (argon with a cesium impurity). 1—Normal to the boundary parallel to $\mathbf{j}\times\mathbf{B}/c$, 2—normal antiparallel to $\mathbf{j}\times\mathbf{B}/c$.

charges in stationary gases with and without magnetic fields. The real situations prevailing in MHD generators, however, are substantially different from the assumptions leading to (9). Thus, the development of ionization instability in the interior of the plasma leads to a jump in the velocity of the ionization front relative to the gas (Fig. 6). This phenomenon is obviously connected with the additional transport of heat by Hall currents which close near the boundary.

The electric or gasdynamic turbulence of plasma may substantially increase the transport coefficient and the linear scale $l$, increasing the velocity of the ionization front in comparison with (9) by an order of magnitude or more. This may explain the experimental result that, in real MHD generators with nonequilibrium conductivity, the ionization front may travel at velocity of the order of $10^5$ cm/sec relative to the ionized gas. Special electrical preionizers which, one way or the other, give rise to enhanced ionization at entry into the MHD duct are usually employed in experiments with nonequilibrium MHD generators.

## PHENOMENA NEAR ELECTRODES

The problems associated with phenomena occurring near the electrodes and with the choice of electrode material are, unfortunately, the most complicated in the MHD generator technology, at least for long-operation closed-cycle MHD generators.

Since the combustion products form an oxidizing medium, electrodes made of high-melting metals, oxide-coated electrodes, and other types of electrode widely employed in electronic engineering cannot be used.

According to the generalized Ohm's law (3), the current flows at a certain angle to the equipotential surfaces including the electrode surface. This means that the current is concentrated at the edges of the electrodes, as shown in Fig. 7.

If the electrode temperature is appreciably lower than the temperature of the main plasma flow, very considerable temperature and conductivity gradients will appear near the electrodes.

It follows from (4) that this will give rise to a closed Hall current in the plasma, which may have a deleterious effect on the generator parameters for $\beta > 1$. It is clear that the influence of the inhomogeneity in conductivity can be sharply reduced by increasing the electrode temperature. This method was used, for example, in the U-25 system, in which a power output of 6–6.5 MW was achieved by increasing the electrode temperature to 1500–1800°K, and an output of 20 MW was obtained at a temperature of about 2250°K. Specially doped zirconium dioxide electrodes were employed.

The actual distribution of current near the electrode surface is radically different from the two-dimensional picture shown in Fig. 7. Both on the cathodes and on the anodes, the current pinches into small areas known as "microarcs" in the literature.

The contraction of the current to a small area leads to an increase in resistance which is inversely proportional to its linear size. In this case, this size (of the order of a millimeter) is a very complicated function of the current because it is determined by the Joule heating of the gas. The increase in resistance is very dependent on the practical absence from the spot zone of the Hall electric field which is shorted by currents closing in the plane parallel to the electrode surface.

The physical reasons for the appearance of the current spots on hot electrodes are essentially analogous to those that produce the thermal pinching of a current in semiconductors and in gas discharges. To elucidate this situation, consider, for example, the thermal balance on the anode surface. As a result of thermal conduction, this surface receives an energy flux from the plasma and there is also a Joule heat release in the region of the boundary layer (Fig. 8a). This heat flux is removed by thermal conduction through the body of the electrode and partly by radiation. The concentration of free electrons and the conductivity of plasma near the surface are regulated by the ionization equilibrium (8) with temperature $T \approx T_{e1}$.

Figure 8b shows schematically the rate of gain and loss of heat as a function of temperature. Because of the nonlinearity introduced by the degree of ionization, there are states with one or three points of intersection between the curves. In the latter case, the middle point is unstable and the other two correspond to two equilib-

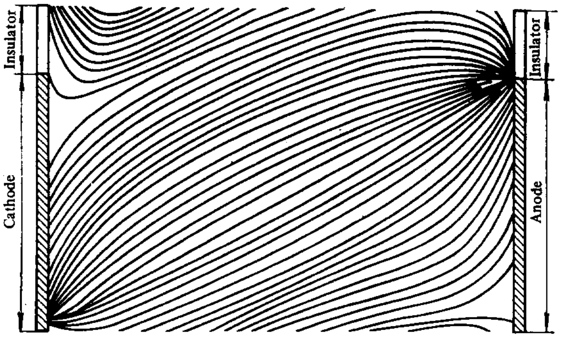

FIG. 7. Calculated current distribution near the electrodes in the presence of the Hall effect.

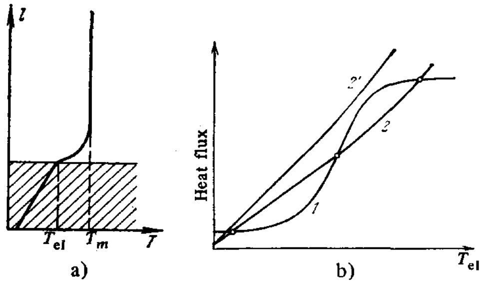

FIG. 8. Schematic illustration of the temperature distribution in plasma and electrode (a) and the dependence of the temperature of the anode surface on the heat flow (b). 1—Heat flowing from the plasma, 2—heat removed by conduction and radiation.

rium "phases." The appearance of spots on the electrode surface under certain critical conditions is, in fact, associated with the appearance of the second phase with a high current density. (The situation is analogous to the appearance of two phases, i.e., vapor and liquid, as described by the van der Waals equation when the temperature is varied).

Apart from the increase in the electrode potential drop due to the presence of the microarcs, the conditions governing the flow of current to the electrodes will also have a negative effect on the operation of the system. Arc discharges under the action of the Hall electric field between neighboring sectionalized electrodes may damage the insulating gaps between them. This type of discharge between neighboring electrodes is more dangerous at the anode wall of the MHD duct where the force j×B presses the arc against the insulator. At higher wall temperatures, the electrodes must be even more highly sectionalized, i.e., the linear size of the electrode along the duct must be reduced in order to reduce the Hall voltage acting between neighboring electrodes.

The development of a long-operation open-cycle MHD generator has necessitated the solution of many problems in materials science, electrochemistry, thermal physics, and mechanical engineering. The gradual solution of these problems has resulted in an increase in the duration of tests. The MHD generator in the U-25 has been operated continuously for 100 h.

## CONCLUSIONS

The history and basic results of tests carried out on open-cycle MHD generators up to the beginning of 1976 are shown in Fig. 9 which has been compiled by the Staff of the Institute of High Temperatures of the Academy of Sciences of the USSR. These investigations were begun in the USA by the Avco Everett Research Laboratories on the initiative of A. R. Kantrowitz. This work demonstrated that substantial amounts of electric power could be generated over short periods of time. Under these conditions, the transverse magnetic field could be produced with the aid of iron-free noncooled coils. The then record output power of 32 MW was achieved in experiments with the Mark-V installation. The MHD generator was operated under self-excitation conditions under which a proportion of the generated power (8 MW) was used to set up the magnetic field.

The Soviet program is being directed by V. A. Kirillin and A. E. Sheĭndlin and is distinguished by, firstly, the emphasis on the development of long-operation generators right from the outset and, secondly, by the fact that it is based on experimental systems simulating all the main elements of a possible electric power station. The first complex model system was the U-02 which prepared the technological groundwork for the first experimental industrial set, U-25 (Fig. 10). They use magnetic systems of stationary operation with iron magnetic circuits.

Figure 9 shows the achievements of the various scientific groups working on the development of stationary electric power sources incorporating MHD generators and the gap that must be bridged before mass-produced MHD power stations become possible. From the point of view of economics, such stations become realistic only when superconducting magnetic systems are employed and this, in itself, is a complicated independent problem in science and technology.

In contrast to the open-cycle MHD generators, the closed-cycle generators do not at present have a definite development program. Their physical principles have, on the whole, been developed but, as yet, there are no corresponding high-temperature gas-cooled nuclear reactors. Such reactors may be of considerable interest not for electric power generation but for those branches of industry that consume heat under high-temperature conditions. There has been recent discussion of the possibility of developing high-temperature fusion reactors using MHD generators with nonequilibrium conductivity. However, practical realization of such projects would not appear to be possible in this century.

Short-operation open-cycle MHD generators may find extensive practical applications. A good example of

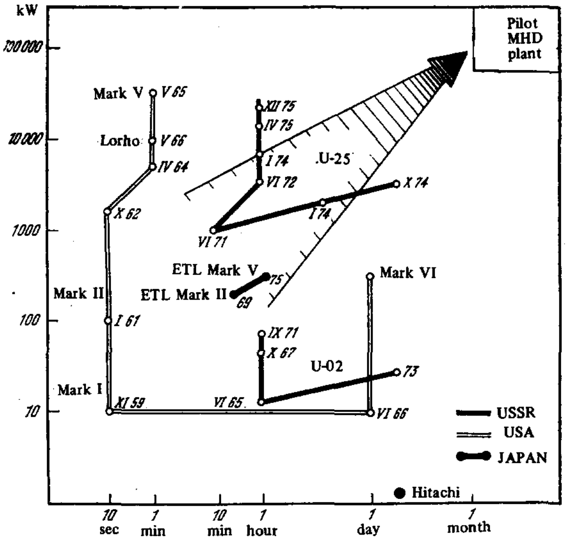

FIG. 9. Summary of results of tests on power-producing MHD generators. The horizontal axis gives the time of continuous operation of the generators and the vertical axis shows the electric power (both scales are logarithmic).

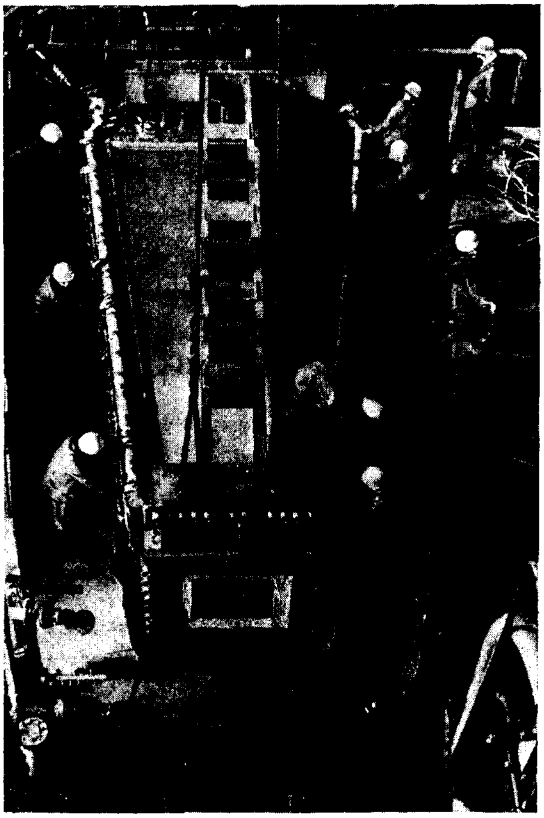

FIG. 10. Assembly of the MHD generator in the U-25 installation.

this is the use of pulsed MHD generators using the combustion products of solid fuels with alkali-metal admixtures for deep electromagnetic sounding of the earth's crust.

The MHD installation, Pamir-1, has two ducts located between three flat current coils producing a transverse magnetic field of up to 4.5 tesla. The length of the electrode zone of the MHD ducts is 1 m. Each generates up to 15 MW over an operating cycle of 3 sec, and the fuel enthalpy conversion efficiency is up to 12%.

The initial magnetic field is generated by discharging the capacitor bank. The current produced by the generator is used to enhance the field, and the generator itself is operated in the self-excitation regime. For this to be achieved, the product of the electrical conductivity by the square of the flow velocity at the beginning of the MHD duct $(\sigma u_0^2)$ must be large enough. The magnetic induction does not enter the self-excitation condition since both the generated power and the magnetic field energy are proportional to $B^2$.

The Pamir-1 system has been used for sounding the earth's crust down to depths of 12–20 km, which are inaccessible to energy sources previously available in geophysics. The system is self-contained and compact, so that it can be used in regions that are difficult to reach.

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