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LIMIT CHARACTERISTICS OF AN MHD GENERATOR WITH A NONEQUILIBRIUM PLASMA

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By using known relationships of the energy balance for electrons and dependence of the conductivity of a turbulent plasma on the Hall parameter, ~~we~~ obtained useful relationships which permit evaluating the maximum parameters of an MHD generator operating on a nonequilibrium plasma. It is shown that with argon having an addition of cesium vapors at an electric load coefficient of 0.8 the maximum pressure in the reactor must not exceed 100 atmospheres absolute, even at the presently practically limiting values of reactor outlet gas temperature approximately 2500 degrees K, magnetic field induction approximately 10 T, and power of a given single MHD generator channel. It is shown that with a reduction in M number from 2.0 to 0.5 the maximum permissible pressure in the reactor is reduced from 70 to approximately 20 atm aos. With an increase in initial temperature and the other parameters remaining constant, the maximum value of capacity of a single unit is reduced. The article contains four illustrations.

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LIMIT CHARACTERISTICS OF AN MHD GENERATOR WITH A NONEQUILIBRIUM PLASMA

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By using known relationships of the energy balance for electrons and dependence of the conductivity of a turbulent plasma on the Hall parameter, we obtained useful relationships which permit evaluating the maximum parameters of an MHD generator operating on a nonequilibrium plasma.

It is shown that with argon having an addition of cesium vapors at an electric load coefficient of 0.8 the maximum pressure in the reactor must not exceed 100 atmospheres absolute, even at the presently practically limiting values of reactor outlet gas temperature ~2500°K, magnetic field induction ~10 T, and power of a single MHD generator channel of $3 \cdot 10^6$ kW. It is shown that with a reduction in M number from 2.0 to 0.5 the maximum permissible pressure in the reactor is reduced from 70 to ~20 atm abs. With an increase in initial temperature and the other parameters remaining constant, the maximum value of capacity of a single unit is reduced. The article contains four illustrations and four references.

For closed MHD cycles, where a nuclear reactor with a gaseous heat exchanger is used as the source of thermal energy, it is necessary to utilize nonequilibrium ionization effects. Even rough evaluations show that maintaining nonequilibrium conductivity in the channel of a

MHD generator requires a higher flow speed and strong magnetic fields at a low level of pressure in the channel. Effective heat removal in the reactor, especially on fast neutrons, is possible only at adequately high pressures. This work is concerned with the question of compatibility of an MHD generator with nonequilibrium conductivity and a nuclear reactor with a gaseous heat-exchange agent (argon). Under steady-state conditions the following equation of the energy balance is valid [1]:

$$\sigma E_{x\rho}^2 = 3\frac{m_e}{m_a} k\delta_1 (T_e - T_a)\frac{n_e}{\tau}, \tag{1}$$

where δ_1 is a coefficient taking into account inelastic losses, T_e is electron temperature, and T_a is the temperature of the gas. In the region of practical interest the Saha equation for electron concentration is valid [2]:

$$\frac{\alpha^2}{1-\alpha} = \frac{1}{n_s}\left(\frac{m_e}{2\pi}\right)^{3/2}\frac{T_e^{3/2}}{h^3}\exp\left(-\frac{I_s}{T_e}\right), \tag{2}$$

where $\alpha = n_e/n_s$ is the degree of ionization of the admixture, n_s is admixture concentration, I_s is the ionization potential of the admixture, h is the Planck constant, and the conductivity of the plasma is defined by the relationship [3]

$$\sigma_x = \lambda(T_e)\frac{n_e e^2}{m_e}\tau, \tag{3}$$

where $\lambda(T_e)$ is a coefficient on the order of unity.

However, at sufficiently large values of $\Omega\tau$ (in strong magnetic fields) a different type of instability is developed in a nonequilibrium plasma. The plasma becomes turbulent and, as research has shown [4], saturation of the Hall field sets in: the ratio of the longitudinal field to the transverse $\langle E_x\rangle/\langle E_y\rangle \approx 2$. Here it turns out that when $\Omega\tau > 2$ it is possible to take in the first approximation the following relationship for conductivity:

$$\sigma_* = \sigma_x\frac{1+2\Omega\tau}{1+\Omega^2\tau^2}, \tag{4}$$

where σ_{τ} is the conductivity of the turbulent plasma and $\sigma_{л}$ is the conductivity of a laminar plasma, which is determined from (3).

From the relationship $k = E/uB$, where $E = uB - E_{rp}$, it is possible to obtain the following expression for E_{rp}:

$$E_{rp} = (1-k)B\sqrt{\gamma R T_{a} M^{2}/[1+(\gamma-1)M^{2}/2]}. \qquad (5)$$

Thus, when the gas temperature T_a, the concentration n_s of easily ionized additive (cesium), and the gas concentration n_a are known, it is possible to use (1-3) and (4a) to establish the dependence $E_{rp} = f(T_e)$; at a given value of the load coefficient k, (5) can be used to obtain the relationship $E_{rp} = f(M)$.

Considering that the total pressure on the input to the generator (the pressure in the reactor) is

$$p_{p} = n_{a} \bar{k} T_{p} (1 + (\gamma - 1) M^{2}/2)^{\gamma/(\gamma-1)}, \qquad (6)$$

where $\bar{k}$ is the Boltzmann constant, and by using (1-4) it is possible to construct the relationship $p_p = f(M)$ at a given value of the electric load coefficient k, gas stagnation temperature T_p (temperature in the reactor), admixture concentration n_s, electron temperature T_e, and induction B.

Figure 1 shows certain calculated relationships $p_p = f(M)$. It also presents relationships for the case of total ionization of the admixture ($\alpha \sim 0.95$), calculated on the assumption that in this case laminar conductivity of the plasma is realized. The concentration of cesium admixture is $n_s = 10^{14}$ cm^{-3}. Figure 2 shows the results of calculations for an admixture concentration $n_s = 10^{15}$ cm^{-3}. In both cases the load coefficient k equals 0.8. It was assumed that at this value of load coefficient the effectiveness of energy conversion is acceptable.

It can be seen that the maximum permissible pressure in the reactor grows with an increase in magnetic field induction B and reactor temperature T_p. The pressure in the reactor also grows with an increase in M. The relationship $p_p = f(M)$ has a minimum at $M \sim 1$ only in the

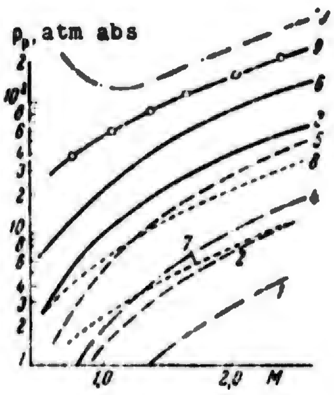


Fig. 1

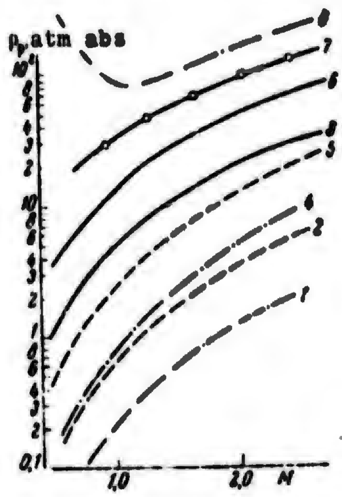


Fig. 2

Fig. 1. Dependence of pressure in the reactor on M number in the MHD generator channel (T_p = 1500°K, k = 0.8, $n_s = 10^{14}$ cm^{-3}): 1 – B = 4 T, T_e = 0.3 eV; 2 – B = 4 T, T_e = 0.25 eV; 3 – B = 4 T, T_e = 0.2 eV; 4 – B = 10 T, T_e = 0.3 eV; 5 – B = 10 T, T_e = 0.25 eV; 6 – B = 10 T, T_e = 0.2 eV; 7 – B = 4 T, α = 0.95, laminar conductivity; 8 – B = 10 T, α = 0.95, laminar conductivity; 9 – B = 10 T, T_e = 0.2 eV, T_p = 2000°K; 10 – B = 10 T, T_e = 0.2 eV, T_p = 2500°K.

Fig. 2. Dependence of pressure in the reactor on M number in the MHD generator channel (T_p = 1500°K, k = 0.8, $n_s = 10^{15}$ cm^{-3}): 1 – B = 4 T, T_e = 0.3 eV; 2 – B = 4 T, T_e = 0.25 eV; 3 – B = 4 T, T_e = 0.2 eV; 4 – B = 10 T, T_e = 0.3 eV; 5 – B = 10 T, T_e = 0.25 eV; 6 – B = 10 T, T_e = 0.2 eV; 7 – B = 10 T, T_e = 0.2 eV; T_p = 2000°K; 8 – B = 10 T, T_e = 0.2 eV, T_p = 2500°K.

weak nonequilibrium region (T_p = 2500°K and T_e = 0.2 eV). An increase in electron temperature T_e leads to an essential reduction in the maximum level of pressure. An increase in admixture concentration leads to a certain reduction of pressure in the reactor. In the area of practical interest the relationship $p_p = f(M)$ as calculated from conditions of total admixture ionization (laminar conductivity) lies lower than the calculated curve in the case of turbulent conductivity.

It is not difficult to obtain the following expression for generator length l_{κ}:

$$l_{\kappa} = \frac{S}{k(1-k)} \frac{1}{\gamma-1} \varepsilon_{n} \frac{1+(\gamma-1)M^2/2}{M^2}, \tag{7}$$

where S is stagnation length,

$$S = \frac{\rho U}{\sigma B^2} = \frac{p_p}{\sigma_e B^2 [1+(\gamma-1)M^2/2]^{(\gamma+1)/2(\gamma-1)}} \sqrt{\gamma M^2/RT_p}, \tag{8}$$

where $\varepsilon_{n} = \Delta T_0/T_0$ is the relative usable heat drop. Then, with given values of M, T_p, k, and p_p the flow G through the generator is written as follows:

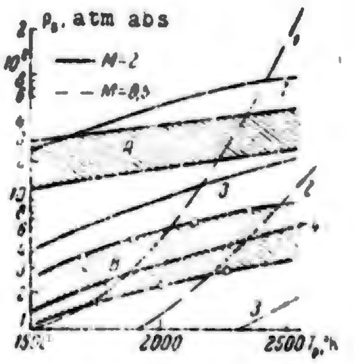
$$G \approx \left(\frac{l_{\kappa}}{\bar{\lambda}}\right)^2 \frac{p_p}{[1+(\gamma-1)M^2/2]^{(\gamma+1)/2(\gamma-1)}} \sqrt{\gamma M^2/RT_p}, \tag{9}$$

where $\bar{\lambda}$ is the relative length of the generator. In the final calculation it is possible to evaluate the total electrical capacity of the generator as

$$N_r \approx GC_p\varepsilon_n T_p. \tag{10}$$

Restricting the maximum values of the capacity of a single generator (for high energy it is possible to assume $10^5 \leq N_{\Gamma} \leq 3 \cdot 10^6$ kW), at a given ε_{n} and T_p we will find the range of change in G, and we shall determine the relationship $p_p = f(M)$ at given $l_{\kappa}/\bar{\lambda}$, T_p, T_e, B, and k.

Figures 3 and 4 show the dependence of pressure in the reactor on T_p at a given value k = 0.8, B, M, and $\bar{\lambda}$. T_e is a parameter. The shaded regions correspond to $10^5 \leq N_{\Gamma} \leq 3 \cdot 10^6$ kW. One can see that under subsonic conditions (M = 0.5) the maximum pressure in the reactor does not exceed 20 atm abs at T_p = 2500°K and B = 10 T; with supersonic flows (M ~ 2) the pressure can comprise 70 atm abs. It is a characteristic fact that at a given pressure p_p in the reactor and with $\bar{\lambda}$ = const the maximum capacity of a single generator is reduced with an increase in T_p.



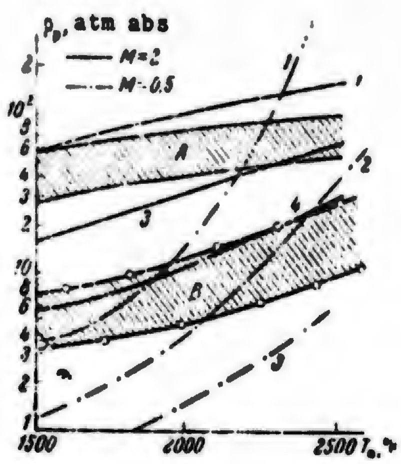


Fig. 3 Fig. 4

Fig. 3. Dependence of pressure in the reactor on temperature ($k = 0.8$, $\bar{\lambda} = 15$, $B = 4$ T, $n_s = 10^{15}$ cm^{-3}): 1 – $T_e = 0.2$; 2 – 0.225; 3 – 0.25; 4 – 0.3 eV; A – region $10^5 < N < 3 \cdot 10^6$ kW at $M = 2.0$; B – region $10^5 < N < 3 \cdot 10^6$ kW at $M = 0.5$.

Fig. 4. Dependence of pressure in the reactor on temperature ($k = 0.8$, $\bar{\lambda} = 15$, $B = 10$ T, $n_s = 10^{15}$ cm^{-3}): 1 – $T_e = 0.2$; 2 – 0.225; 3 – 0.25; 4 – 0.3 eV; A – region $10^5 < N < 3 \cdot 10^6$ kW at $M = 2.0$, B – region $10^5 < N < 3 \cdot 10^6$ kW at $M = 0.5$.

Conclusions

1. The obtained relationships make it possible to find the maximum pressure in the reactor when the plasma parameters are known and the geometric relationships of the MHD generator channel are rationally selected. At an electrical load coefficient of 0.8 the maximum pressure in the reactor for a laminar plasma is significantly lower than that for a turbulent plasma.

2. The concentration of cesium vapors in the argon has a weak influence on the magnitude of maximum pressure in the reactor. The maximum pressure is reduced with an increase in concentration.

3. With a given value of the electrical energy load coefficient and of generator capacity the maximum pressure strongly depends on the

magnetic field (proportional to ~B) and on the M number (with a change in M from 0.5 to 2.0 the maximum pressure grows by ~4 times).

4. The maximum pressure in the reactor grows with an increase in temperature. At a given pressure in the reactor and with the other characteristic parameters held constant, an increase in temperature leads to a reduction in the maximum permissible capacity of a single unit.

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