Abstract. This paper presents the results of a numerical analysis of gas- and electrodynamic behavior and integral characteristics of the “Sakhalin” pulsed MHD-generator for the conditions of run #1; a peak electric power of 510 MWe, strong MHD interaction at a Reynolds magnetic number of about 0.5 have been demonstrated. The investigation was carried out in a stationary quasi-one-dimensional approximation for a two-phase polydisperse real flow of gas and liquid particles Al_2O_3 (the “Kanal” code). The properties and characteristics of the MHD generator were determined; the effects of heat loss in the plasma generator, two-phase nonequilibrium, particle coagulation and breaking, boundary layers, induced magnetic field, near-electrode voltage drop and edge current leakages upon the MHD performance were established. Characteristic properties of the processes and their difference from similar ones proceeding in pulsed MHD generators of smaller scale were defined. The process of self-excitation and taking resistive load at its paralled connection to the MHD generator was designed. The information obtained is in satisfactory agreement with the experimental data on pressure, current and voltage as well as on their change in time.

Introduction

In paper [1] a discription of basic components of the pulsed MHD-generator operating on a solid plasma-generating (powder) propellant (SPP) and its integral characteristics for its six runs are presented. The experiments perfomed have confirmed, on the whole, design parameters of the facility which based on a quasi-one-dimensional (Q1D) approximation for a “pseudogas” flow.

However, a number of physical criterions, experimental data and their variation with time differ from those earlier obtained for other MHD-generators and seem to be unique. Thus under conditions of strong MHD interactions (the Stewart number is up to 1.3) at a magnetic Raynolds number of 0.5 in the mode of a peak power output for the pulsed SPP MHD-generators outstanding specific energy values have been obtained, i.e. $\eta = 11\%$ and $q_{sp} = 0.6 MJ/kg$ that provided a specific mass power of 0.1 t/MW. Determination of salient features and interrelations of the processes in a supersonic MHD generator of a similar scale where surface effects are rather small is of general importance in physics. There are lots of flow parameters of SPP plasma products and local electric characteristics left unknown and their numerical values could be found only in numerical experiments of high informative quality.

In an early stage of numerical investigations it is sufficient to use design techniques based on a Q1D approximation for a two-phase flow. As is known this approximation gives a satisfactory description of integral characteristics of supersonic MHD generators and their self-excitation [2,3] and has been already used in the design of the “Sakhalin” MHD-generator perfomance [4]. The results obtained can be used as the basis for a more detailed special discription of flow and processes with the help of mathematical models and codes of a higher level.

Below the data of the preliminary numerical analysis of plasma properties, flow parameters and self-excitation of the “Sakhalin” MHD generator with a peak power of 510MWe achieved under conditions of run #1 are presented.

1. Experimental Parameters of the “Sakhalin” MHD Generator and Initial Data for the Analysis

Fig.1 shows a gasdynamic duct (GD, or path flow) of the MHD-generator including a sub-, trans- and supersonic part of the nozzle, an MHD channel and a diffuser (or outlet branch pipe) [1].

![Fig.1. The profile of the gasdynamic duct and the distribution of relative induction of the external (1) and total (2, $<B_{ext}>_0=1.95$ T) magnetic fields.](image)
For a quasi-one-dimensional calculation \[3,4\] the real profile of the subsonic nozzle part was substituted with a model one of square-section \(a(x)-h(x)\) while keeping up the cross-section area unchanged. As initial data for the design purposes a minimum set of independent experimental results corresponding to run \#1 was used [1] (Fig.2): SPP generator (PG) at \(Q_1D\) approximation the extrapolation of the rated \(B>9\) (Fig.1, curve 1), a magnetic field induction \(B_{mes}\) measured at the point of intersection of the inner (to the MHD channel) coil plane and the z-axis passing through the channel center or an initial excitation current (see p.3.3).

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B, T & I, kA & V, V \\
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1 & 2 & 3 \\
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The experimental values of electric circuit parameters of a self-excited MHD generator were also used (Fig.3) and in run \#1, found to be the following: \(R_m=11\text{mOhm}, L_m=6.5\text{mH} \) (specified value), \(R_L=47.5\text{mOhm}, R_b=45.6\text{mOhm} \) and \(R_t=48.3\text{mOhm} \). In run \#1 a ballast resistor \(R_b\) intended for stabilization of the current at a given level was not connected to the magnet circuit.

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I, kA & V, V & J, A/cm^2 \\
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Fig.2. Time-dependence of experimental parameters of the self-exciting “Sakhalin” MHD generator (run \#1).

The total near-electrode voltage drop was described by a typical dependence for the SPP MHD generator channels at a maximum value of 200V (a limited expert evaluation): \(\Delta V_e=aj/j_{cr}\) at \(j\leq j_{cr}\).

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Fig.3. Principle circuit of the self-exciting MHD generator.

All four sections of the non-iron magnetic system in run \#1 were connected in parallel and did not change during the start-up period which gave a mean calculated value of the magnet constant four times less than with the case of series connection, i.e. \(\alpha_{ps}=4\times10^{-5}\text{T/A} \) [1]. The magnetic field induction was measured with a detector spaced in the central \((L/2)\) plane along the z-axis at a distance of 650mm from the channel axis. To determine an average (over cross-section) magnetic flux density required for calculations in a Q1D approximation the extrapolation of the rated distribution \(B(z)\) (more exact, \(\alpha(z)\)) to the detector area was used which gave a correction factor \(k_b=B>B_{mes}=0.95 \) [1]. Hence, the induction measured by the detector is consistent with its average value in the central \((L/2)\) channel cross-section \(<B><B_{mes}>k_bB_{mes}\).

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layer was supposed to form in a supersonic nozzle part spaced 0.1 m apart from the throat and the thickness of pulse loss is $\delta = 1 \text{mm}$. The temperature of fire surfaces of the GD walls was assumed to be constant and equal to 2300 K, which is confirmed by the calculation at a GD operation time of $>2 \text{s}$ [3]; the wall surface was considered sand rough with a scale of $k_i = 0.3 \text{mm}$ [3,6].

No influence of the induced magnetic field was taken into account in the calculation of edge current leakages.

2. Technique and Code of the Analysis

The technique and code known as the “Kanal” were employed for performing the calculations of pulsed MHD-generators [6,7,3]. The program is based on a Q1D approximation of the description of a two-phase polydisperse flow of combustion products with due regard for coagulation and break in the nozzles, MHD channels and diffuse.

The composition and properties of the combustion products consisting of gas and condensed phases were defined by pressure and enthalpy and designed using the technique and program given in work [8].

The boundary layers were designed by an integral method in a “pseudogas” approximation [6,3,9]. The flow design is restricted by conditions of the boundary layer separation or choking the nozzles [6,3,9]. The flow design is restricted by conditions of the boundary layer separation or choking the nozzles [6,3,9]. The flow design is restricted by conditions of the boundary layer separation or choking the nozzles [6,3,9].

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The average induction from plasma can achieve $20\%$ of an external field produced with a two-coil magnetic system. In this connection the distribution of the magnetic field induction in the working MHD channel volume has been estimated.

It was supposed that an average (over the channel cross-section) $x$-component of an induced field is produced by currents in plasma $<B>_x(x)$ and in current-collecting buses $<B>_x(x)$:

$$<B>_x(x)=<B>_y(x)+<B>_z(x).$$

The average induction from plasma current was estimated in an approximation of a flat current layer from the solution of the Maxwell one-dimensional equation:

$$d<B>/dx=-\mu_0j_z\varphi_p(x,y,z),$$

where $\varphi_p(x,y,z)<1$ is the coefficient of nonuniformity $B_z$ in the cross-section, related with finite current size in plasma. The coefficient was taken to be constant and equal to 0.5. At the inlet to the MHD channel the external magnetic field attunes by $<B>_z=\text{const}$, and at the outlet it increases by the same value $B_{z}=B_{\max}/2$, where $B_{\max} = \mu_0\frac{\mu_0}{\mu_0}I_{0}/dx$.

More complex is the estimation of the field produced by current-collecting buses. The current-collectors start from the inlet to the electrode area and extend 0.75 m downstream beyond the outlet electrode edges. The width of the buses is $a=0.45 \text{m}$ at the electrode width $a=1 \text{m}=\text{const}$. At the channel inlet the current $I_0=0$ and at the outlet $I_0=I_2$ and its variation along the channel $I_2(x)$ is estimated by the design and is close to linear (see p.3.1).

In an approximation of two long parallel (along the $x$-axis) buses with the width $a$, and current $I_2$ spaced a distance $h$ (Fig.1) apart the field induction in the channel cross-section is defined by superposition of the fields produced with each bus [11]:

$$B_{re}(y,z)=\frac{\mu_0I_2}{2\pi a_I}\left(\frac{\arctg \frac{a_1+2z}{2y} + \arctg \frac{a_1-2z}{2y}}{\arctg \frac{a_1}{2y}}\right).$$

(2)

For the field on the axis ($y=z=0$) we have $B_{re}(0,0)=\mu_0a_I/\pi a_1 \arctg(\alpha_a/h)$, i.e. for the conditions considered this formula gives the induction close to that on the axis of two linear wires (Bio-Savart’s formula) $B_{re}(y)=\mu_0I_2(y)/\pi h$.

The spacial nonuniformity of the field in the MHD channel was taken into account using the coefficient $\varphi_p(x,y,z)=\varphi_p(x,y,z)$, i.e. $<B>_z(x)=\mu_0I_2(x)\varphi_p(y,z)$.

It follows from (2) that the field distribution across the cross-section has a strong nonuniformity: it increases by three times in the $y$-direction to electrodes and falls by 1.5 times in the $z$-direction to insulation walls. The correction factor $\varphi_p(y,z)$ was taken to be constant and equal to $\varphi_p(y,z)=\varphi_p(y,z)$.

Since the buses have a finite length $L_1$, the field close to the axis at the inlet and outlet of the MHD channel is $B_{re}(0,0)=B_{re}(0,0)$, where $\varphi_{1,2}=\varphi_{1,2}=\varphi_{1,2}=\varphi_{1,2}$.

For the middle part of the channel $\varphi_{1,2}=\varphi_{1,2}=\varphi_{1,2}=\varphi_{1,2}$, the $\varphi_{1,2}$ relation was not regarded and its value was assumed to be equal to $\varphi_{1,2}=\varphi_{1,2}=\varphi_{1,2}=\varphi_{1,2}$. Thus, the correction factor $\varphi_{1,2}=\varphi_{1,2}=\varphi_{1,2}=\varphi_{1,2}$ was used in the analysis.

To calculate self-exitation a simplified electric circuit of a self-exciting MHD generator
was used (Fig.3). An initial magnetic field was generated with a system of initial excitation (IES) on the basis of a capacitor bank which was switched at the time $t_s=3.07$s from the start of SPP burning (Fig.2) [1].

For the sake of simplicity no calculation of the bank discharge was carried out [3]. In a time of 0.03$s the current in the magnet achieved such a value ($\approx 15$kA, $B>0.2$T) at which the MHD channel started feeding the magnetic system ($I_{sk}=I_{k}+I_{ES}$, $V_{k}=V_{k}+V_{ES}$), and at a positive feedback the channel current started rising. The numerical calculation of self-excitation was performed using equation $I(t+\Delta t)=I(t)\exp(\Delta t/\tau)$, where the constant time of the system $\tau_s=L_s/(V_{sk}/I_{sk}+R_s)$, $I(0)=I_{ Mb}$.

The algorithm of the self-excitation calculation is of the form: $\tau=t_s$, $I_{k}=I_{ MB}$ $\Rightarrow$ $<B>_0$ $\Rightarrow$ Voltage-Ampere characteristic $\Rightarrow$ $V_k(I_{sk},I_k)$ $\Rightarrow$ $\tau$, $I=I_{0}(t+\Delta t)$, where $<B>_{0 ext}=<\alpha>_0 IM$ (or $<B>_{0 ext}=B_{mes}$). At achieving a specified value $I_{k}=I_{sk}$ in parallel to the channel and magnetic system an ohmic resistor $R_s$ is connected. At an initial moment after switching load no changes in the circuit current and induction take place and the current, channel voltage and load current change in a very short time of $<10$s. The channel current and voltage are found iteratively with the help of current-voltage characteristics according to the following scheme.

The first approximation $I_{k}^{(1)}>I_{w}$ is specified and at a known $<B>_{0} V_k$ is determined by the current-voltage characteristics. From the equation of resistive load circuit $V_k=V_e=I_{sk}R_s$ and $I_{k}=I_{sk}+I_k$ the channel current is found to be $I_{k}^{(2)}=V_e/R_s + I_w$, and its value is used as the next approximation and so on. After electric values determined one finds $\tau$, and $I_{sk}$ the time constant of the system and current, respectively, at the next moment of time $t+\Delta t$. Then the procedure of finding $<B>_{0} V_k I_k$ and $I_{sk}$ iterates.

3. Results of Numerical Analysis

3.1. Gas- and Electrodynamic Parameters of the MHD Generator

With the aim of determining a quantitative effect of heat loss in PG as well as two-phase nonequilibrium with a flow in the nozzle upon the calculation results at the channel inlet the calculations were made for the combustion products with $p_i=0.46$ at $\chi_{r}=1$, 0.99, 0.98 and 0.97. For the calculations the codes called “Plasma” and “Kanal” have been used [3,7]. Their results for relative values of electric conductivity $\sigma$ in PG (1) and at the channel inlet (2) are shown in Fig.4.

Here, at $\chi_{r}=1$ $\sigma=126$S/m and $\sigma_1=54$S/m and at $\chi_{r}=0.985$ $\sigma_1$ and $\sigma_1$ are 115.5S/m and 44.8S/m, correspondingly. It is seen, that for the taken value of $\chi_{r}=0.985$ an conductivity of only 44.8S/m is observed, i.e. 17% less than its ideal value (54S/m and 10% less than rated 50S/m) [1].

The calculated by the model of an equilibrium ideal “pseudogas” flow (expansion) at $\chi_{r}=0.985$ and with allowance for a thickness of boundary layer displacement gives (see below) the following: a mass flow rate of 833kg/s, $p_1=0.306$MPa, $T_1=2780$K, $u_i=2030$m/s, $M_{mix}=2.37$, $\sigma_1=51.8$ S/m, $\mu_1=0.197$J, i.e. the two-phase nonequilibrium leads to a 12% decrease in conductivity.

The calculated data on the SPP BP-11 (a seed is Cs) [5] at a pressure of 46 at in PG are as follows: $T_s=3690$K; $\gamma_{mix}=1.16$; $R_{mix}=238$J/kgK; $z=0.345$; $R_p=363$J/kgK; $c_p=1685$J/kgK; $\eta_{f}=8.7-10^{-5}$Ns/m$^2$. The particles in PG were distributed as a logarithmic-normal law over 20 fractions at $d_{fr}=4$um and $\sigma=1.5$. Under these conditions a mass flow rate of 911kg/s was found, i.e. about 10% greater than at an equilibrium “pseudogas” flow. The gas phase parameters at the MHD channel inlet are the following (see the Table): $p_1=0.328$ MPa; $T_1=2710$K; $u_i=1960$m/s; $\sigma_1=44.8$S/m; $\mu_1=0.187$J.

For the numerical investigation of flow parameter variations under conditions of strong MHD interaction a limiting operation mode of the MHD generator was chosen which provided a peak power output close to the experimental value and observed at a still non-separation flow in the channel (within the integral method of the boundary layer calculation) (Fig.5, p.N) the voltage at the electrodes, $V=2550$V ($\delta=0.96$) at an average induction $<B>_{0 ext}=1.95$T, with an induced magnetic field $<B>_{0 ext}=1.99$T, measured by detector.
The distribution evolution of liquid particles $\text{Al}_2\text{O}_3$ along the GD length is shown in Fig.6 for continuous distributions of mass particles fraction $g(r)$, plotted in accordance with distribution $g_i(r_i)$ [7,8]. Here curve 1 shows the distribution in PG and curve 2 in the nozzle throat and curve 3 at the channel inlet and close to it everywhere downstream.

In the process of accelerating the working medium there occur coagulation of particles and their growth in size basically in sub- and transsonic parts of the nozzle before its cross-section with a relative expansion, $F/F_{th} \approx 1.2$ and $M_{in} \approx 1.1$. The mass fraction of particles of small fractions reduces by 5 times and more, and of large-sized ($d \geq 10 \mu m$) greatly increases that results in enlarging characteristic sizes of particles, e.g. $d_{14}$ (and $d_{12}$) from 4 \mu m to 20\mu m (Fig.7).

This permits discounting, in the first approximation, coagulation and breakage of liquid particles when analyzing the processes in the supersonic nozzle part and MHD channel.

Fig.8 demonstrates the variation of velocity $\delta \omega_i = (1-\omega_i)$, $\omega_i = u_i/u$ and temperature $\delta \theta_i = (1-\theta_i)$, $\theta_i = T_i/T$ nonequilibrium at the two-phase flow in the GD. The two phase nonequilibrium attains its maximum in the transsonic nozzle part. Up to the channel inlet a relative lag of particles behind the gas $\delta \omega$ falls to zero for $d_i = 1-2 \mu m$ and to
+8% ($d \geq 20 \text{ µm}$) and $\delta_0$ from 0% to 9%, respectively.

Fig.8. Variations of deviation of velocities and temperatures of particles of various fractions along the gasdynamic duct.

On average the relative lag of particles behind the gas is +9% and the excess of their temperature is −6% (Fig.7,8). With no magnetic field the two-phase non-equilibrium in the MHD channel varies insignificantly. The supersonic flow of the gas phase decelerates in the MHD-channel that, starting from a certain distance from the inlet ($x = 2.9 \text{ m}$ and $\delta_0 = 0$, Fig.7,8), results in a reversal of gas and flow interaction: the particles start leading the gas (up to −11%), entraining it due to friction and deceleration. In this case the friction force acts against a ponderomotive force. As a result there arise a volume effect of electromagnetic forces on the particles in the flow of electroconductive gas. The effect is the most characteristic of small-size particles (to 5 µm) and, therefore, small mass. If a velocity of small-size particles is close to that of the gas (the gas velocity in the channel falls by 35%), an effect of MHD deceleration on the velocity of the large-size particles ($t \geq 20 \text{ µm}$) proves to be less significant (their velocity drops only by 20%).

More complex is a variation of the temperature nonequilibrium which depends on the gas temperature distribution in the channel. For instance, small and large particles can be in thermal equilibrium with the gas to the outlet of the MHD channel. This can be explained by temperature relaxation of small particles to the gas temperature and a rise of this temperature up to that of slowly cooling down large particles in the process of MHD interaction. Thus, under conditions given in Fig.7,8 the large particle temperature decreases by 3% (from 2920K to 2810K) in the MHD-channel, but the small particle temperature as well as the gas one increases up to 5% (from 2720K to 2870K). These dependencies are qualitatively consistent with those obtained earlier for the “Pamir” MHD generator with an electric power of $\approx 10 \text{ MW}$ and a mass flow rate of $\approx 25 \text{ kg/s}$ [6].

Fig.9 shows the variation of temperature, velocity and Mach number for the gas phase along the GD $x$-axis, and Fig.10 of pressures along the axis, and the anode ($p_a$) and cathode ($p_c$) walls.

Fig.9. Gasdynamic parameter distributions along the gasdynamic duct.

The Table demonstrates basic parameters at the inlet and outlet of the MHD-channel obtained for a gasdynamic flow ($B = 0$) and strong MHD interaction with and without account of an induced magnetic field.

As is seen the MHD deceleration of the flow is strong ($S_{ef}= v \cdot B/(p u^2) \approx B/(a p u^2) = 0.3$) and leads to a decrease of velocity by 33% ($u_2/u_1 = 0.67$) and of kinetic energy by 55%. The calculated Mach number for the gas phase is already $M = 1.13$ ($M_{in} = 1.5$), i.e. it proves to be transsonic and close to a mode gasdynamic choking.

At a voltage of $< 2500 \text{ V}$ there appear separation of the boundary layer. It has been shown earlier [3,6], that the calculation of the boundary layer in a two-dimensional approximation demonstrates a decrease in the critical current by 5%-10%.

The gas temperature notably increases that leads to rising conductivity by 1.5 times with respect to the input value and MHD interaction downstream that seems to be negative.

The static pressure, first, slightly falls along the channel length and in the outlet area $\approx 1 \text{ m}$ long starts rising ($dp/dx \approx 3 \cdot 10^3 \text{ Pa/m}$) which facilitates and causes the separation of the boundary layer (Fig.10). The negative and small positive pressure gradients in the channel are realized only at currents less than $\approx 130 \text{ kA}$. From the inlet to the MHD-channel with continuous electrodes due to Hall currents a transverse nonuniformity of the parameters starts its development. The transverse nonuniformity of
pressure which grows with an increase of the magnetic field induction was calculated in a Q1D approximation [2]. At a current of ≈200kA its magnitude achieves ≈0.1 at (Fig.10), i.e. the pressure gradient between the cathode and anode (dp/dy=d/dy=0.5·10^5 Pa/m) is comparable or even exceeds the longitudinal pressure gradient. Therefore, under these conditions a calculation in the Q1D approximation can result in great errors.

Fig.10. Pressure distribution along the axis and anode (pA) and cathode (pC) walls.

It should be noted that the experimental value of pressure at the inlet to channel considerably (by 25%) less than that calculated and somewhat rises with current. The effect is likely to be due to a nonuniform spacial structure of the flow in the inlet area of the MHD channel. A decrease of induction in the inlet area of the MHD channel and its increase in the outlet due to an induced field and location of current-collecting buses in the diffuser area lead to a nonuniform distribution of local parameters, first of all, a pressure of about 0.2 at and intensity of the MHD interaction (Fig.9, 10, Table).

If the induced magnetic field is not taken into account the parameter distribution over the GD length becomes more uniform and the calculated separation of the boundary layer occurs at a higher current (by ≈10%, Fig.5).

Fig.11 shows a variation of the characteristic boundary layer thickness, the form factor f=8*[(lnu)/dx] and the heat flux density obtained with an integral method according to Kutateladze-Leontiev’s theory [10,3].

For the gasdynamic flow (B=0) calculations were also performed in a two-dimensional approximation using a differential equation for turbulent viscosity [6]; they give more prominent values (up to 1.5 times) of the characteristic boundary layer thickness and lower values of the heat flux density to the wall.

At MHD interaction the thickness of the boundary layer on the electrode increases by a factor of 10 and on the insulating wall by 2 times, i.e. the near-electrode layer becomes 5 times as much as the insulating wall.

In the considered mode of limiting deceleration the form factor f attains -0.004 at a critical value (fcr) of -0.006 (x=6m, Fig.11). The 2D calculation of the boundary layer usually shifts the separation area down to the region of lower values of total current by 10%-20% which results in a decrease of electric power (see p.3) [3]. The level of heat fluxes and their distribution is typical for “rough” (k=0.5 mm) walls of GD of pulsed MHD generators and drops over the channel length from 600W/cm² to 280W/cm² (Fig.11) [3,6]. A greater decrease of the heat flux density gives the 2D calculation of the boundary layer.

Fig.12 demonstrates a variation of electrodynamic parameters along the GD length including the electric conductivity and the Hall parameter β=μ_eB.

Fig.12. Distributions of electrodynamic parameters along the gasdynamic duct.
It is seen that these values are typical of pulsed MHD generators. As \( \beta^2<0.15<<1 \) a negative effect of the Hall currents on the power characteristics of the Faraday channel with continuous electrodes is insignificant. The Faraday current and magnetic field induction and, therefore, the ponderomotive force density are minimal for pulsed MHD generators (Fig.12). However, due to a large channel length high values of specific energy \( q_{sp}=0.6 \text{MJ/kg} \) and the enthalpy extraction ratio \( \eta_{en}=11\% \) were observed. The load factor \( \sim 1/B \) in the main part of the channel varies as \( \langle k\rangle=0.7 \). The total current and power grow linearly over the channel length.

The induced magnetic field changes the distribution of local electrodynamic parameters at the inlet and outlet (see Table) channel regions and, first of all, a load factor, current density and electric conductivity (to 5\%).

The distribution obtained for the current density and total current over the length permitted evaluating the induced field distribution by formula (3); a maximum induced field of 0.19T is attained at a distance of 0.7m from the channel outlet, i.e. 12\% of an external field in this area. Fig.1 shows relative distributions of the z-component of induction of both the external magnetic field \( (b_{ext}=\langle B>_{ext}(x)\cdot<\langle B>_{ext}=1.95T, \text{curve 1}) \) and total field \( (b_{z}=\langle B>_{z}(x)<\langle B>_{z}=1.99T, \text{curve 2}) \) which were obtained after two iterations and showed agreement with the calculated \( B_{mes}=2.09 \text{T} \).

3.2. Integral Characteristics of the MHD Generator

Figs.5 and 13 and the Table present voltage - ampere, load and several other integral characteristics of the “Sakhalin” MHD generator obtained with (solid curves) and without account (dashed curve) of the induced magnetic field.

It is seen that a peak power at an induction of \( >1.3 \text{T} \) is restricted by occurrence of separation flows. Characteristically, that calculated values of maximal electric power correspond to a pre-separation or close-to-it mode of loading the MHD generator and well agrees with the experimental data (Fig.2, the time counts from the start up of PG). Putting an ohmic load in parallel with the magnetic system at the moment \( t=4.4s \) (Fig.2) resulted in a decrease in the total ohmic resistance of the MHD channel from 14.1mOhm to 10.9mOhm and the channel current jump from 130kA to 178kA. As a result, a sharp growth of the MHD interaction and positive pressure gradient in the second half of the channel occurred and, obviously, initiated a boundary layer separation in the outlet area of the MHD channel.

A tendency to further power growth due to enhancement of MHD interaction (a voltage (load factor) decrease) and the magnetic field \( B=\alpha_{en}I_{en}-I_k \) increase leads to a developed separation flow in the MHD channel and saturation of integral electric characteristic at a level of 500MWe (Fig.2) as is the case of other self-exciting pulsed MHD generators [3,12]. Such self-concordant mode of flow and electric characteristics of a self-exciting MHD generator is known as the effect of gasdynamic stabilization [2,12] and used for obtaining time-constant integral parameters. However, in this case power parameters prove to be \( \sim 30\% \) less than in the mode of a limiting non-separation flow.

An increase in MHD interaction at \( B_{mes}=2.09 \text{T} \) at a voltage decrease (\( V_k<2500 \text{V}, \langle k\rangle<0.6 \) leads to supercritical operation modes and a decrease of power [2,3,12]. Power parameters of the MHD generator operating in supercritical modes were estimated approximately, by empirical method [3,12]. The data from such estimations are shown in Fig.9,10 by dotted lines. It should be noted that a characteristic value of the short-circuit current at \( B_{mes}=2.2T \) qualitatively conform with an experimental value of \( \sim 290kA \) obtained in run #2.

As follows from comparison of solid and dashed-dotted curves for \( <B>_{test}=1.9 \text{T} \) (Fig.5,13) an account of the induced field (solid curve) results in an increase of electric power of more than 3\% and the boundary layer separation occurs at lower (by 10\%) currents. This is caused by a predominant effect of a 2\% increase of induction (in the middle of the channel) on a notable deformation of its characteristic at a level of 500MWe (Fig.2) as is the case of other self-exciting pulsed MHD generators [3,12]. Such self-concordant mode of flow and electric characteristics of a self-exciting MHD generator is known as the effect of gasdynamic stabilization [2,12] and used for obtaining time-constant integral parameters. However, in this case power parameters prove to be \( \sim 30\% \) less than in the mode of a limiting non-separation flow.

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in operating modes close to short-circuit an induced magnetic field can distinctly influence the flow and electric characteristics. Thus, at $<B>_\text{ext}=0.75T$ and $I_k=200kA$, a 20% induced field contribution and a 10% electric characteristics difference were found.

Comparison of the calculation data with and without edge current leakages taken into account (Fig.5,13 and, correspondingly, curves 1 and 2 for $<B>_\text{ext}=1.95T$) shows that for conditions under consideration the edge effect on power characteristics proves to be great. For nominal conditions the calculated (within the Q1D approximation) values of edge current leakages in the channel rise with an increase of magnetic field from several percent to $\approx 15\%$ (in the “Pamir” MHD facility $3\%-5\%$, the “Soyuz” MHD facility $\approx 7\%$). Their value for the conditions considered is likely to be too high assuming that the near-electrode voltage drop does not exceed 100V only a $\approx 2\%$ power increase will be obtained.

The current and voltage values obtained in the Q1D approximation for non-separation flows well agree with the experimental data accurate up to 5%-10%.

### 3.3 Self-Excitation of the MHD Generator

In the calculation and analysis of the MHD generator self-excitation process an experimental value of total magnet circuit resistance $R_m=R_o+R_t=14.1\, \text{mOhm}$ was used (see p.1, Fig.3) and for the magnetic system inductance its calculated value $L_m=6.5\, \text{mOhm}$ was taken [1]. Pressure variations in PG during the process were neglected.

Fig.14 presents experimental voltage and current of the MHD channel in the process of self-excitation (the curve segment from p.S to p.L) and voltage drop on both the ohmic resistance $V_R=I_mR_m$ and inductance $V_L=L_mdI_m/dt$ of the magnetic system.

The corresponding calculated dependence is shown with a dotted curve. From comparison of calculated and experimental curves it follows that the numerical model of self-excitation gives a satisfactory description of the experimental data. Up to a time of 4.3s the current $I_k=I_m$ (in the experiment the difference between $I_m$ and $I_k$ is about 2%) rose to 125kA and the induction $<B>_\text{ext}$ increased to $1.62T$. In the time $t_1=4.38s$ the resistive load $R_\text{in}=47.5\, \text{mOhm}$ was connected in parallel with the channel and magnetic system. This led to a decrease in the equivalent resistance to $R_\text{eq}=10.9\, \text{mOhm}$ of the external MHD channel circuit and in voltage over the electrodes and inductance $V_L$, as well as to an increase in the total current, MHD interaction and time-constant of the system (to $\approx 3s$).
in supercritical operation modes was evaluated by an empirical relation (see p.3.1, dotted curves in Fig.5,13) [3,8,12].

Conclusion

As a result of the conducted numerical analysis the following peculiarities of the processes in the pulsed “Sakhalin” MHD generator have been established.

- Heat losses in PG and two-phase losses in nozzle significantly reduce both conductivity (down to 17% at $\chi_\rho=0.985$) and energy complex $\alpha u^2$ at the MHD channel inlet.
- Coagulation $Al_2O_3$ particle of at flow in the nozzle leads to an increase in their diameters up to values maximal for SPP MHD generators ($d_{43}=\approx20\mu m$) that is due to large size of the nozzle throat.
- The mean value of velocity and temperature nonequilibrium attains +5% and -6%, respectively, at channel inlet and that is close to typical values.
- Electric power of a self-exciting MHD generator is restricted by appearance of a separation flow. The calculated value of the flow velocity decreases by $\approx30\%$ and the kinetic energy by $\approx50\%$. The indicated high levels of MHD interaction are achieved on account of large channel length that gives the Stewart number $S=1.3$ (effective value 0.3).
- In the performance of strong MHD interaction the Hall currents produce a cross pressure gradient which facilitates appearance and development of separation flows and, possibly, secondary ones.
- In spite of a significant value of the Reynolds magnetic number $Re_\mu=0.5$, the effect of the induced magnetic field on power characteristics of the MHD generator by load factor $>0.5$ is not in excess of $\approx5\%$.
- Edge current leakages in the channel reach (within the Q1D approximation) a very big value of $\approx15\%$ and considerably exceed the induced field effect. So it seems necessary to make a study of edge effects in the channel of the “Sakhalin” MHD generator with the help of Q2D and 3D codes.
- The calculated data on local and integral characteristics of the “Sakhalin” MHD facility, obtained in the Q1D approximation for the area of non-separation flows fairly well agree with the experimental results with a measuring accuracy of 5%-10%. This approximation gives a satisfactory description of the self-exitation process too.

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References