THE DISK MHD GENERATOR ON A NONEQUILIBRIUM Ar-Cs PLASMA FOR A MHD GAS-TURBINE (ELECTRIC) POWER PLANT

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ABSTRACT

The data on the numerical investigation, parametric optimization and preliminary design of main units and a 600 MW nonequilibrium argon-cesium plasma MHD generator, as a whole, intended for a pilot binary MHD gas-turbine electric power plant are presented. The operational parameters of the MHD generator with a disk two-section channel and a solenoidal superconducting magnetic system were as follows: an electric power of 675 MW (with a 10% reserve), a mass flow rate of 1700 kg/s, a cesium seed mole fraction of $1.6 \times 10^{-5}$, a stagnation temperature and pressure of 2200 K and 2 MPa, respectively, a Mach number of 0.9, a flow swirl degree of 1, a magnetic field induction $B_1=5.6$ T, $B_3=6.5$ T, inlet and outlet channel radii $r_1=1.12$ m and $r_3=2.8$ m, respectively, channel heights $h_1=0.16$ m and $h_4=0.164$ m, a voltage of 6.8 kV (section 1) and 13.0 kV a total, enthalpy extraction $\eta_{h}=34\%$, an internal (isentropic) efficiency $\eta_{e}=75\%$, a mass of $\approx 700$ t, a height of $\approx 7$ m and a diameter of $\approx 9$ m. The results obtained, the design developed and engineering solutions suggested have become the basis of a more detailed investigation, feasibility study and engineering design of disk MHD generators on a nonequilibrium plasma of various scales and purposes. The priority of further investigations headed for development of stationary disk nonequilibrium plasma MHD generators has been established.

INTRODUCTION

The work presents a concept of using compact MHD gas-turbine power stations with the aim of electric energy generation in gas-fields on gas-generation platforms on the shelf and in gas-bearing areas with depleted intrastratum gas pressures which are lower than those economically viable; then the electric energy could be transferred to regions with a developed infrastructure. It has been shown that such MHD power station can have an efficiency of $\approx 57\%$, a specific mass of $\approx 3.8$ t/MW, a specific volume of $\approx 60$ m$^3$/MW at a power of $\geq 4$ GW and $\geq 1$ GW of the energy plant and the disk MHD generator, respectively.

The given concept of the closed cycle disk MHD generator is based on using a subsonic ($M_1=0.9$) flow of nonequilibrium argon-cesium plasma with a completely ionized seed, elevated pressures (from 1 to 2.5 MPa) and magnetic field (6-7 T). Nowadays promising results ($\eta_e=20\%$ and $\eta_h=55\%$) have been obtained with large-scale experimental MHD generators (an electric power of up to 0.7 MW) which allow the disk MHD generators to be applicable in various fields of technology.

With the aim of finding operational parameters and an engineering structure of industrial scale stationary disk MHD generators on a nonequilibrium plasma ($T_e=2200$ K) establishing and considering physical and technological problems of their creation a number of theoretical investigations and engineering developments of basic components (units) and an MHD generator, as a whole, were carried out. The investigations involved calculations and estimates of gasdynamic, electric, thermal and lifetime properties and a construction - engineering development of a gasdynamic duct as well as a superconducting magnet system (SMS); a single-coil solenoidal system was chosen as SMS. Methods of thermal end electric insulation, a design and materials of anodes, cathode and multilayer walls for various gasdynamic sections and a cesium feed system were proposed. Parameters of a conductive, inductive and high frequency (capacitive) plasma preionizers were calculated. The obtained data and their analysis permitted setting a priority in further research. Problems of heating and providing argon purity as well as economical aspects were not considered.

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1. OPERATING PARAMETERS OF THE DISK CHANNEL MHD GENERATOR

1.1 Initial data

Argon seeded with cesium was considered as the working medium of the MHD generator at the following values of basic parameters: the mass flow rate of argon was 1700-1800 kg/s, the stagnation pressure \( p_{01} = 1.5-2.0 \) MPa, the stagnation temperature \( T_{01} = 2200 \) K, the factor of plasma inhomogeneity \( G = 1.1 \) in the MHD channel, and the ratio of radius and channel height in the inlet (form factor) \( r_1/h_1 = 7 \). The choice of the stagnation pressure value was caused by technological restrictions on the passage cross sections of the argon conveying pipelines and necessity for achieving high values (~10) of the Hall parameter at \( M_s \leq 1 \) and \( B < 8 \) T. The updated values of \( r_1/h_1 = 7 \) arise from the necessity for placing a preionizer and turning vanes of the nozzle in the pre-electrode area of the channel. Only subsonic flow modes were considered since they are characterized by minimum losses in the diffuser and, therefore, in the closed cycle. At a parametric optimization the following parameters were varied: Mach number \( M_1 \) in the channel inlet, cesium seed fraction \( c_0 \), magnetic field induction \( B_0 \), stagnation pressure \( p_{01} \) and level (angle tangent) of the swirl flow \( t_1 = u_{q1}/u_{t1} \) at the inlet, where \( u_{q1} \) and \( u_{t1} \) are the azimuthal and radial components of the gas flow velocity, respectively. Any influence of boundary layers and near-electrode voltage drops was neglected. Limitations on the stagnation pressure difference \( \rho_0 - p_{02} \) and number of calibers \( L_c/2h_{min} \leq 10 \) (\( h_{min} \) is the minimum channel height) were taken into account. For each set of the basic parameters an acceptable range of current (load coefficient) and voltage variations was found which provided a 10% reserve of electric power with ionizing stability of argon-cesium plasma \( B-G < B_{cr} \), where \( B_{cr} \) was the critical value of the Hall parameter.

1.2. The method of calculating the flow and performance of the nonequilibrium plasma disk generator

For the calculation of the gasdynamic duct dimensions, flow and energy properties and their parametric optimization a simple method was used based on a quasi-one-dimensional description of the flow in a disk channel at a constant radial Mach number (\( M_r = m_{t1} = \text{const} \)) at a given distribution of magnetic field induction (inverse problem). In the disk channel in such flow mode a potential energy (pressure) of the working medium and part of a kinetic energy of the subsonic flow related to an azimuthal velocity provided by the turning vanes of the nozzle unit convert into electric energy. The technique used gives approximate values of the flow and channel of the disk MHD generator parameters. It should be noted that uncertainty in the value and temperature dependence of transport cross-section of electron scattering by argon atoms which can be ~2 as well as the account of the Coulomb collision effect on \( \mu_r \) and \( \sigma \) (correction \( k_0 = \frac{\langle v_{ce} \rangle}{\langle v_{ce} \rangle} \)) can lead to a notable change in electron mobility and electric conductivity and, thus, the performance of the Hall MHD generator. This problem requires special consideration.

The computer code allows the MHD generator characteristics to be calculated at sub- and supersonic flows and in various modes of the MHD channel electric loading. The initial data were as follows: working media flow rate \( \bar{n} \), \( \tau = \frac{\bar{v}_p}{c_w} \), gas constant \( R \), stagnation temperature and pressure \( T_{01} \) and \( p_{01} \), Mach number \( M_1 \) at the channel inlet, inlet form factor \( f_1 = r_1/h_1 \) (\( h_1 \) is the height of the disk channel), load coefficient \( k_1 \), seed fraction \( c_0 \) and its type, swirl flow level \( t_1 \) at the inlet, relative distribution over radius of \( z \)-component of magnetic field induction and its absolute value in the center (on the axis), and parameter of plasma inhomogeneity \( G \) in the channel. A number of auxiliary parameters were also specified which required for the code operation and count stop at achieving physical-engineering limitations (\( M_2, P_2 \), etc).

In the first stage of the numerical investigation the calculations were performed for a model dimensionless over-radius distribution of the magnetic field induction \( B_0 \) (growing by ~15%). This model profile has been calculated earlier for a magnet system consisting of two coaxial parallel coils with the radius of their winding centers, \( r_2 = 4.72 \) m, and made dimensionless on relative to \( r_e \) and \( B_0 \) (\( B_0 \) is the induction on the magnet system axis). Fig.1 shows the profile of the model magnetic field for \( r_e = 5 \) m made dimensionless relative to the maximum outlet radius \( R_{max} = 3 \) m of the MHD channel (curve 1). The induction change in height of the MHD channel was not regarded since it did not exceed 0.012 T (~0.2%, see subheading 2.2, Fig.7).

1.3. Operating parameters of the optimal disk MHD generator

A great number of variants (~200) have been calculated at various combinations of basic parameters \( p_{01}, M_1, c_0, B_0, \) and \( t_1 \) and their following ranges of variations: 1.5 MPa \( \leq p_{01} \leq \) 2.5 MPa, 0.8 \( \leq M_1 \leq \) 0.9, \( 1 \times 10^{-5} \leq c_0 \leq 4 \times 10^{-5} \), 4 \( \leq B_0 \leq 7 \) T, 0.8 \( \leq t_1 \leq 1.1 \). The criterions for selection of optimum variants were: generated power \( N_e \), enthalpy extraction ratio \( \eta_{IN} \), power density (or working volume of the channel), internal (isentropic) efficiency \( \eta_{IN} \), channel electrode area length \( L_c \).
Variations in gas- and electrodynamic properties of the nonequilibrium Ar-Cs plasma flow along the radius of the disk channel are shown in Figs. 2-4.

In the stationary operation mode the rated reserve of power and enthalpy extraction ratio is about 10% and \( \eta_{\text{hi}} \) calculated without hydraulic losses taken into account achieves \( \approx 82\% \) at \( \eta_{\text{hi}} = 34\% \). The estimate of relative hydraulic losses in the gasdynamic duct (GD) (nozzle, channel and diffuser) yields not more than 8% (see subheading 2.1) which leads to a decrease of \( \eta_{\text{hi}} \) to \( \approx 82\% \). The potential difference between the first anode and the cathode (MHD channel exit) is 13 kV, i.e. the average longitudinal electric field on the insulating wall is about 80 V/cm.

**Table 1**

Optimal parameters of the two-section disk 600 MW MHD generator (\( \varrho_{\text{in}} = 1700 \text{ kg/s, } \alpha_{\text{e}} = 1.6 \times 10^{-5}, \tau_{\text{r}}/h_{\text{i}} = 7 \))

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>-0.04</td>
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The second stage involved the calculation of MHD channels with their electrode area being separated by an intermediate electrode into two sections: the first (internal), i.e. from the anode to the intermediate electrode, and the second (external) - from the latter to the cathode. The separation into sections was performed such that the intermediate electrode becomes the anode. This required that the electric current of the second section be larger than that of the first section. Variation of the loading mode of the second section of the MHD channel permitted the calculated power and enthalpy extraction ratio to be raised up to 670 MW and 35% respectively. The optimum parameters obtained for the two-section MHD channel found application in the design of a gasdynamic duct and, after defining its dimensions, in the calculation and project of a superconducting magnet system (SMS) and other units of the MHD generator. As a result of the SMS development for the chosen variant of the MHD generator main parameters of a solenoidal SMS and distribution of the operating component of the magnetic field induction \( B_{r}(r) \) (Fig. 1, curve 2) have been obtained. This distribution differed from the model and was used in conducting refined calculations of the two-section MHD channels. Final values of operating parameters for the base 600 MW MHD generator are given in Table 1.
magnet" system has shown that making GD and SMS in the form of independent modules (GD is located within SMS and their structural units never intersect) proves to be the most optimal in view of long-term operation (≥5000 h) of the stationary MHD facility, GD and SMS maintenance and electric strength of the MHD channel.

As initial data for designing the disk MHD generator the calculated electrical and thermodynamic flow parameters in the MHD channel were used (Table 1). Maximum thermal, thermochemical and power loads on the GD walls were assumed to be realized in the start-up mode of the MHD generator when the load is switched off and cesium seed is not injected to the working medium flow. In this mode a flow temperature of 2200 K over the whole GD length and a static pressure of ≃2 MPa can be attained.

In the optimization of the structural model and construction of the MHD generator GD the following requirements have been regarded:

- mole fraction of impurities entering the working medium flow (Ar+1.6×10⁻³Cs) at sublimation of fire wall surfaces materials (i.e. partial vapor pressure) should not exceed 10% of easy-ionizing seed concentration;

- degradation of insulation of the GD unearthed fire surfaces and electric breakdown of the plasma volume or between the construction surfaces which are under a plasma potential or to the load-bearing mainframe are not permissible.

- electrothermochemical erosion of the MHD channel walls and electrodes during operation cycle (≥5000 h) should not cause an increase of more than ≃5% in the MHD channel height compared to an initial value;

- stiffness of the construction at a static pressure load should not result in uncontrollable changes of more than ≃5% of calculated values in the nozzle unit (NU), disk MHD channel and diffuser;

- achievement of minimum hydraulic and thermal losses in GD, i.e. a maximum value of internal relative efficiency (η₀) of the MHD generator;

- achievement of a minimum overall dimension diameter of GD which defines a diameter of a "warm" window of SMS;

- convenience of GD and SMS mounting and maintenance under operation conditions.

Designing the gastodynamic duct of the disk MHD generator (Fig.5) involved calculation and development of a construction of eight main components (units). With the purpose of providing
minimum hydraulic and thermal losses in GD in making a choice of fire wall materials preference was given to technically smooth walls with a fire surface temperature close to that of stagnation of the working medium flow.

The inlet electric insulation section 0.8 m long (Fig.5) where a pure argon flux (v=70 m/s, p=2 MPa, T=2200 K, \( \eta \equiv 1700 \) kg/s) is present provides electric insulation of the downstream zone of the working medium preparation and the MHD channel which are under a potential of about 13 kV relative to the outer (load-bearing) grounded MHD generator mainframe. Volumetric insulation is attained with pure argon which has a breakdown voltage of 7.4×10⁵ V/m at T=2200 K and p=2 MPa. ⁵ Hence, the main problem is to provide the electric insulation along the fire wall surface and the surface itself from the mainframe in Ar. ⁶

The GD wall has a module-ceramic structure and is assembled from three-layer electroinsulating modules of 50±80 mm size that is defined by conditions of thermal strength and lifetime. The fire layer =10 mm thick is made from dense ThO₂ as at T=2000 K it has sufficiently high specific electric and thermal resistances (p=10⁷ Ω·m, \( \lambda=1 \) W/(m·K)) and its vapor pressure is 100 times less than a partial pressure of the Cs seed (≈23 Pa). The thermal resistance of this ceramics is higher than that of made on the basis of Al₂O₃ and ZrO₂ ⁷,⁸ and affords stable long-term operation of GD fire surfaces. This layer is monolithically baked with a thermal insulating gas-permeable layer =65 mm thick made of Al₂O₃ porous ceramics also having low thermal conductivity \( \lambda=1 \) W/(m·K). At this \( \lambda \) and a temperature of ≈300 K on the outer surface of the ceramic wall the thermal flux to the wall is ≈2×10⁻⁶ W/m². ⁷,⁹ Provisions are made for conveying cold argon with its mass flow rate chosen such that its heating up to ≈500 K at its filtrating through a porous layer compensates a thermal flux to the ceramics from the fire layer. At a porous ceramics (Al₂O₃) heat conductivity of ≈1 W/(m·K) a required value of argon flow rate through the porous layer is about 0.23 kg/(m²·s). Then the conveyed argon is removed through intermediate clearances onto the fire surface and further into the working medium flow. The construction of module attachments to the steel GD housing allows their electrical insulation from the latter.

The unit (section) of cesium injection and working medium preparation (Fig.5). At the beginning of this section there are injectors and swirling devices 10 for injecting cesium seed in the form of a mixture of argon (a flow rate of ≈9 kg/s) and cesium vapor (a flow rate of ≈0.08 kg/s) to the main argon flux. The length of the cylindrical section where argon and the seed are mixed is about 1.5 m. A conical confuser section of transition from axisymmetrical flowing to radial one lies downstream. The profile of transition from cylinder to cone and, further, to the inlet of the radial nozzle unit is made as an arc with a radius of 0.35 m. The Mach number in the minimal cross-section (Ω₁₁₆₀ mm) of the axisymmetrical section achieves ≈0.5 (Fig.5). At the radial nozzle unit the flow accelerates up to M=0.6 mainly in radial direction (the resulting Mach number M=0.9 and the tangent of the swirl angle t=1); this gives small values of relative profile vane thickness and, thus, low pressure losses at flowing along the vanes as well as their low weight.²¹

The construction of the ceramic module wall in this section is similar to that on the insulating area. Since the electric field has only a normal component in the boundary of the volume of the equilibrium Ar-Cs plasma (conductivity of ≈7 S/m) the inner fire layer fabricated from dense ceramics on the basis of stabilized ZrO₂. The next layer of the module is made of ZrO₂ porous ceramics with a porosity of ≈75% and a low thermal conductivity of ≈0.1 W/(m·K) which, in practice, completely chokes the thermal flux to the wall. Cold argon conveyed to the module collectors provides a reliable electric insulation between the fire surfaces of the ceramic modules and the hermetic GD housing of the MHD generator GD.

The nozzle unit (NU, Fig.5) performs initial swirling of the working medium \( t_s=\omega_s/\omega_r=1 \) at \( M_s=0.9 \) and presents a radial noncooled grid of 60 vanes made from high-strength molybdenum alloy which holds its strength and has low vapor pressure at T=2200 K. The geometry and quantity of the NU vanes was calculated in terms of minimum hydraulic losses.¹⁰ The unit of the anode and NU attachment is tightly connected with the steel housing of GD through a high voltage insulator 7 (Fig.5) made from high strength glass-reinforced plastic. The conveying pipe of the seed injection unit goes through the attachment unit along the axis into flow. The pipe is performed from ceramic pipe sections (Al₂O₃) joined together with stainless steel rings by use of high-temperature brazing (4, Fig.5).

The preionizer located downstream behind NU is a circular region of the insulating wall between the first anode A1 and NU outlet with a length of≈140 mm (about one caliber). On its walls inductive preionizer turns or segmented electrodes of the conductive preionizer with dc/ac can be located.

The disk MHD channel consists of upper and lower module type electroinsulating walls and circular electrodes placed on them – the first anode A1, the second anode A2 and the cathode (Fig.5). The fire
wall surfaces specify the geometry of the flowing path of the MHD channel and must provide its long-term electric strength at a radial electric field strength of \(8 \times 10^2\) V/m in the flow core and a potential of \(13\) kV in the working medium core at the channel inlet relative to load-bearing mainframe of the MHD generator. The construction of the channel insulating walls is similar to that of the inlet electroinsulating section and the electric strength of the walls is provided by pure argon conveying into collectors and intermodule clearances.

The anode A1 is placed on the upper and lower walls of the MHD channel (Fig.5). Its upper part is performed as a thin (\(\approx 5\) mm thick) circular molybdenum plate electrically connected to the NU attachment unit (Fig.5) which is one of the anode current leads. The average current density on the working surface of A1 is about \(4.5 \times 10^4\) A/m\(^2\). The lower anode A1 part is of similar design; it is segmented with a pitch of \(0.2\) m. Each segment has a current lead insulated from the GD housing. Such design allows the anode A1 unit to be used as a conductive or capacitative preionizer of working medium at the MHD channel inlet.

The upper and lower parts of the anode A2 80 mm wide along radius are not segmented and connected with each other by molybdenum rods 10 mm in diameter which are in the working medium flow. The anodes A1 and A2 have the same design of their working components. The anode A2 current leads 6 are insulated from the GD housing (Fig.5).

The upper and lower annulus parts of the cathode are made from porous tungsten plates 10 mm thick and brazed with thin-wall collector-buses where an Ar+ +15% (mole)Cs mixture of vapor with a temperature of \(1000\) K is conveyed through the pipelines serving, at the same time, as current leads. The cathode admits segmenting along azimuth. The cathode potential is close to zero relative to the grounded GD housing. Blowing in an argon-cesium mixture through the porous cathode body is intended for realization of a diffuse mode of current flow on the cathode at an operation current density of \(1.6 \times 10^4\) A/m\(^2\) and in order to avoid arc erosion of its surface and provide small values of cathode sputtering and, thus, to prevent its contour from contamination and achieve a rated operating time of \(\geq 5000\) hours.

Behind the MHD channel a radial diffuser D1 is placed downstream (Fig.5) which has a linear profile and a 1.75 expansion ratio which affords flow deceleration from \(M=0.64\) at the MHD channel outlet to \(M=0.35\) at the D1 outlet. The total expansion angle is equal to \(10^\circ\). As the plasma potential at the outlet of the MHD channel relative to the GD housing is zero, the construction of the module thermal insulating wall in these areas is easier than in proceeding ones.

Behind the diffuser D1 there is a unit of changing a radial flow into a circular axisymmetric flow; the unit consists of a levelling region with a constant height of the passage cross-section and a successive region of flow turning (by \(90^\circ\)) by use of turning vanes. Then the flow moves along the circular levelling section of constant cross-section before the inlet of the diffuser D2. Four turning vanes are taken to provide minimum hydraulic losses of a stagnation pressure of \(\leq 0.5\%\). The vanes are made of a molybdenum alloy and sectionalized over azimuth. Clearances are allowed between sections to compensate thermal expansion.

After the levelling section there is a ring diffuser D2 (Fig.5) with a linear profile of walls and a \(\approx 10^\circ\) optimum angle of their linear expansion. The full expansion of the diffuser D1 and D2 cross-sections is \(5.3\) which gives the flow deceleration from \(M=0.64\) at the inlet to \(M\leq 0.1\) (a velocity of \(\approx 70\) m/s). The construction of the module thermal-protecting ceramic walls in these regions is the same as in the diffuser D1; and external cooling of the GD housing by ambient air convection (free or forced) is sufficient for cooling the entire GD construction.

The GD outlet is mated with a built-up collector not shown in Fig.5.

A general problem in designing a sealed GD housing of a disk MHD generator is achieving a required stiffness of the construction which under operation pressure conditions would not result in an inaccessible uncontrollable increase of height (\(\geq 5\%\)) between the insulating walls which are, in essence, membranes tightened round the periphery with 24 cooled load-bearing studs 9 (Fig.5) \(\approx 70\) mm in diameter. One of the possible solutions to the problem is introduction of stiffening ribs 8 and cross-bar girders 2 (Fig.5) into the GD construction; the ribs and girders rest on support load-bearing rings 1 located on the GD housing from the side of the upper insulating wall and on the side surfaces of the section of conveying and preparing the working medium. The cross-bar girders 2 are also located on the upper and lower insulating walls and carried by load-bearing support rings located on the GD housing from the side of the lower insulating wall and the inner side of the diffuser D2. The number of stiffening ribs and cross-bar girders over the azimuth of the disk MHD channel is established as a result of the test analysis of the GD housing for stiffness. The cooled load-bearing studs 9 in the diffusers D1 and D2 which pierce the flowing part of GD are protected with ceramic rings of modular structure as in the case of the fire surfaces of the diffusers.
Fig. 5. Axial section view of the gasdynamic duct of the disk MHD generator
Pressure losses in GD were considered as the sum of losses in the functional GD sections of the MHD generator, i.e. \( \Delta p = \sum \Delta p_i \), where \( i \) is the number of the extended or local region with hydraulic resistance. The pressure losses \( \Delta p_i \) are determined from the formula \( \Delta p_i = \zeta_i \rho_i u_i^2 / 2 \), where \( \rho_i \) and \( u_i \) are the characteristic density and velocity in the cross-section of the local hydraulic resistance or in the extended region and \( \zeta_i \) is the integral coefficient of hydraulic resistance.

In calculating \( \zeta_i \), design techniques and recommendations from works \(^{10,12,13,15,16}\) were used. In accordance with a preliminary estimation the losses by stagnation pressure in GD which are not related directly with the process of MHD conversion were \( \approx 0.16 \) MPa or \( \approx 8\% \) of the stagnation pressure at the GD inlet. An optimization of the swirl geometry, sections of transition from an axisymmetric flow to radial before NU and turn of the flow between diffusers D1 and D2 can reduce hydraulic losses in GD.

2.2. Constructive-engineering solutions and performance of the superconducting magnet system

In this work for a pilot MHD generator a simple SMS configuration close to solenoidal is offered which is a single coil and requires no thick load-bearing bandage and stops to compensate great (thousands of tons) attractive forces acting between two coils in a Helmholtz-type magnet system \(^{1,2}\).

The superconducting magnet must satisfy the following parameters: a free inner volume diameter of 8 m, inside and outside diameters of the disk channel working volume of 1.1 m and 2.9 m, respectively, a height (a thickness) of 0.2 m and a magnetic field of about 6 T in the MHD channel with an acceptable nonuniformity of \( \pm 2\% \) in height and \( \pm 8\% \) in radius. In spite of an uprated volume of magnetic field attributed to its occurrence in the subsonic diffuser area SMS of solenoidal type proves to be more preferable as it is in good configuration with the axial feed and removal of the working medium, easy to manufacture and convenient to service. However the weight of the solenoidal SMS can be less than that of dipole SMS.

The diagram of the winding is given in Fig.6A. Proceeding from reducing a superconducting wire cost and winding technology a niobium-titanium alloy was chosen as a superconducting material. An acceptable current-carrying capability of the wire was achieved due to a significant decrease of the constructive current density in the end sections. This technique permitted generating almost equal fields (8.0-8.4 T) in the inner turns of all pancakes (Fig.6B). Fig.7 shows a topography of the field z-component in the area of the MHD channel. The winding consists of five sections: central, two end with an increased number of turns (aimed at improving the field uniformity) and two intermediate with a decreased number of turns (aimed at limiting the field peak in the winding). Between the end and intermediate sections of the windings there provided placement of load bearing plates which rest on a pipe support relieving the main part of the winding from compressive forces acting, above all, in the end sections.

![Diagram of the solenoidal SMS winding (A) and magnetic field module distribution in its turns (B)](image1)

A concept of non-degrading windings has been developed only for pancake windings, i.e. those consisting of a set of flat sections with a spiral-shaped wire in each of them. In such construction mechanical stresses decrease in the superconductor itself and there form no thermal perturbations of large amplitude which are capable of giving rise to development of mechanical-thermal and magnetic-thermal instabilities.

The magnet winding includes five blocks consisting, in turn, of multipancake sections and each of them is wound by a continuous wire length. Each pancake is stuck to a hard stainless steel disk which supports radial force of each turn. In the winding of such design stresses are uniformly distributed over radius. The radial pressure on the wire is not in excess of 80 kN/m\(^2\). Adhesive bonding will provide transfer of these stresses to the disk with a 4-7-fold reserve.

![Topography of the z-component of the magnetic field induction in the area of the MHD channel](image2)
Aluminum panels cooled by a liquid helium flow circulating in tubes due to a thermosiphon effect are stuck to the inner surface of the winding. The panel thermal conductivity affords cooling the entire winding.

The superconducting magnet is powered by a stabilized thyristor rectifier. Current is carried to the magnet through combined leads with inserts made of a high-temperature superconducting strip. A frozen-current mode is the main operation mode of the winding. The magnet itself is protected against occurrence of a normal zone by causing a forced transition of the winding to a normal state that affords an uniform energy distribution in it and its warming-up to not higher than 100 K. To improve security of the magnet winding at the advent of the normal zone a protection variant is allowed where a normal zone is induced by heaters located in the winding.

Preliminary cooling of the winding is carried by liquid coolants conveyed in tanks. Helium evaporating in standard operation condenses by a microliquifier and the heat shields are cooled by gas flows from cryocoolers that enable the magnet to operate practically autonomously for a year. The cryogenic equipment includes a helium compressor, a reservoir with liquid nitrogen and a heat-exchanger, a two-level cryocooler, a helium feeder, a gasholder, pipelines and cryogenic tubes.

The performance of SMS for the pilot disk MHD generator is given in Table 2. The total SMS mass together with the cryogenic equipment and outside constructions is about 460 t.

### Table 2
The performance of the SMS solenoid for the disk MHD generator

<table>
<thead>
<tr>
<th>Winding dimensions:</th>
<th>8330</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter of middle section winding, mm</td>
<td>8320</td>
</tr>
<tr>
<td>Outside diameter of lateral section winding, mm</td>
<td>5040</td>
</tr>
<tr>
<td>Number of blocks</td>
<td>5</td>
</tr>
<tr>
<td>Total number of pancakes</td>
<td>184</td>
</tr>
<tr>
<td>Full consumptions of wire, km</td>
<td>4252</td>
</tr>
<tr>
<td>Inductance, H</td>
<td>113.5</td>
</tr>
<tr>
<td>Nominal operating current, kA</td>
<td>140</td>
</tr>
<tr>
<td>Nominal induction on winding, T</td>
<td>10</td>
</tr>
<tr>
<td>Nominal induction in operating area, T</td>
<td>8.4</td>
</tr>
<tr>
<td>Rated operation temperature, K</td>
<td>6.0</td>
</tr>
<tr>
<td>Stored energy at nominal current, GJ</td>
<td>4.3</td>
</tr>
<tr>
<td>Cooled mass, t</td>
<td>360</td>
</tr>
</tbody>
</table>

#### 2.3. Pre-ionization of argon-cesium plasma

Producing a uniform nonequilibrium plasma state with a high degree of seed ionization in the MHD channel due to Joule heating requires a preliminary pre-ionization which proceeds in the ionizer placed between the nozzle and the MHD channel. The estimations show that at relative ionization “cost” of $\chi<10$, a power fraction of $P/N_e^2<2\times10^{-3}\chi$ is necessary for obtaining a total ionization of $\alpha<10^{-5}$ and $T_0>2000$ K, i.e. less than 1% of the produced power $N_e$. However, the power of the preionizer power supply is significantly greater and depends on the method of ionization and preionizer scheme.

The Ar-Cs plasma at the inlet to the nozzle is actually equilibrium: $T_e=T_0=2200$ K, $p=p_0=2$ MPa, $\sigma=6$ S/m, $n_e=6\times10^{20}$ m$^{-3}$, $n_i=1.8\times10^{19}$ m$^{-3}$, and the characteristic time of gas flight $\tau_e=L_v/v_0=0.4$ ms. At flowing through the nozzle there occur deviations of electron concentration and temperature as well as gas temperature from equilibrium values; the deviations are described by the system of equations for above-mentioned parameters.

Equation of electron balance was obtained for the conditions of threefold electron and ion recombination and meeting the Saha equation in the stationary process that leads to an expression of ionization coefficient in the form

With the aim of determining characteristic times and length of relaxation, $T_e$ and $n_e$, a model problem was under consideration when the gas temperature instantaneously dropped from 2200 K to the temperature of balance expansion at the nozzle outlet, $T_e=1730$ K. The data from the relaxation calculation, $T_e$ and $n_e$, in a dimensionless form ($X=T_e/T_0$, $Y=n_e/n_0$) are demonstrated in Figs.8,9. The transition from time- to spatial dependence ($t\rightarrow r$) proceeds through a kinematic ration of $r^2=v rt$. The electron temperature falls from 2200 K ($X=1.27$) to 1870 K ($X=1.08$) in own cooling time $\tau_e=(m_e/m_0)v_0^{-1}10^{-6}$ s. However, starting from a temperature of 1870 K the characteristic cooling time is $10^{-3}$ s due to the electron heat up on account of recombination energy. In this time a decrease of electron concentration to a balance value takes place. This large time of reaching the balance concentration of electrons is caused by a small coefficient of threefold recombination. Under stationary conditions at $T_e=1730$ K the electron concentration is $7.8\times10^{17}$ m$^{-3}$ ($Y=10^3$), and that of argon atoms is $n_a=4\times10^{-5}$ m$^{-3}$. As it is seen from Fig.8 at $t=1.5\times10^3$ s the value of $Y=5\times10^3$ which is consistent with $n_a=4\times10^{-8}$ m$^{-3}$. The obtained values of electron concentration justify using the electron balance equation. The gas atom temperature
turned out to be unchangeable in this time. The values obtained are input parameters for the preionizer.

The most allowable for the conditions under consideration were three types of electric preionizers and their characteristics were calculated using equations (1) and (2).

The structural model of a conductive preionizer where the direct current flows transverse to the gas flow and along the magnetic field has good energy characteristics, as the Joule heating power $P_j=\sigma E^2$ and the electric conductivity is a scalar value ($E_\text{m}=\text{const}$, $E_\text{p}=0$). Figs. 10 and 11 show radius dependencies of electron temperature and cesium atoms ionization degree for a heating mode with the electric field strength $E=8$ V/cm and $\delta=1.5$ (initial values are $X_0=1.003$ and $Y_0=0.005$). In this mode an electron temperature of 4320 K and an ionization degree of 0.98 were achieved.

The initial temperature growth proceeds very fast in a time of $t_0=10^6$ s both at heating of electrons and their cooling. In fact, the total ionization of seed atoms occurs at a length of 0.011 m (at a flow velocity of $\approx 700$ m/s). A total voltage of 160 V in the arc (with no electrode voltage drops taken into account), a total current of 5 kA and a full power of 0.75 MW were found. An increase of the inelastic loss coefficient $\delta$ up to 3 leads to an increase of electric field up to 12.5 V/cm. The total voltage grows to 225 V, the current to 7 kA and the power to 1.5 MW.

In another model of the conductive preionizer where the current flows along the gas flow and transverse to the magnetic field ($E_\text{p}=0$, $P_j=\sigma j^2/\sigma$) a great power of $\approx 40$ MW (7 kA, 5.5 kV) is required for attaining a seed ionization degree of 0.97. This is contributed to a low effective plasma electric conductivity (from 0.006 S/m to 2.25 S/m at the outlet and $\beta=10$).

The conductive preionizer is capable of operating also with alternating current with a period of oscillations supposed to be several times less than the time of gas flight over the preionizer area, $\tau_0=0.4$ ms. So a calculation of electron heating and seed ionization at a frequency of 0.2 MHz was conducted. The character of $T_e$ and $n_e$ variations along the length is similar to those with dc current (Figs. 10, 11). At a voltage amplitude of 220 V at the electrodes an ionization degree of 0.98 is achieved at a length of 1.5 cm at an average power of 0.9 MW in the ac generator. Thus the power of the preionizer power supply is several megawatts, i.e. <1% of the MHD generator power.

An inductive preionizer includes circular ac turns spaced symmetrically over each other on the upper and low walls of the disk channel at its inlet and insulated from plasma (inductor).\(^\text{17}\) At $\sigma=150$ S/m, the skin-layer thickness $l_\sigma=1/(\sigma \omega)^{0.5}$-$h=0.1$ m the acceptable current frequency $\omega=1$ MHz in the inductor. At an electric field amplitude of 12.5 V/cm and $\delta=1.5$ the variations of $T_e$ and $n_e$ along the preionizer radius are similar to those given in Figs. 10, 11 ($T_\text{m}=4220$ K, $n_e/n_0=0.97$); the ionization area length is 1.1 cm and the effective power is 0.7 MW. At increasing $\delta$ to 3 the required field amplitude and heating power achieve 18 V/m and 1.8 MW, respectively. An electrotechnical approach has...
been used in a calculation of the power of energy supply.\textsuperscript{30,31} A system of six circular turns was considered (13 coefficients of self-induction and mutual induction): two turns of the inductor of copper (a resistance of 0.017 Ω), two circular anodes of molybdenum (0.006 Ω), plasma turns of the preionizer (25 Ω) and MHD channel (0.5 Ω). A minimal power of 29 MW required for producing a voltage of 8 kV on the plasma turn and a Joule dissipation of ≈1 MW in it is attained by segmenting the annular turns of the anode (R_a=1 kΩ). An frequency increase up to ≈2 MHz allows the power supply power to be reduced by a factor of two, i.e. to 15 MW.

In the high-frequency capacitive preionizer electron heating and cesium atom ionization proceed in a stationary (pulse-periodic also possible) high-frequency gas discharge (usually it is 13.6 MHz) between two plane-parallel metal plates which are placed on the walls and can be insulated from plasma. The calculation of such preionizer was similar to that of a conductive one with a charge along the magnetic field. At a frequency of 20 MHz of an ac electric field the pattern of \( T_a \) and \( n_e \) dependence upon distance is of the form given in Figs.10,11. In this mode an ionization degree of 0.98 is achieved on a length of 1.5 cm at a full voltage amplitude on electrodes of 220 V and that agrees completely with the calculation results obtained with a frequency of 0.2 MHz. The calculation of mean power of the power supply was conducted in an approximation of a “simple” equivalent electric circuit consisted of series-connected active resistance (0.036 Ω) of the plasma gap in the preionizer, two capacitors of near-electrode layers, and a summary discharge and current lead inductance. At a frequency of 20 MHz a required voltage of 220 V on the plasma resistance is maintained with a generator of a power of 0.25 MW at a current amplitude of 6 kA and a voltage amplitude of 120 kV. The phase shift between current and voltage is close to π/2.

The calculation data obtained with different preionizer types have shown that the power consumption is of the order of 2% and less of the MHD generator power. The power of the power supply of the inductive preionizer is higher than that of the conductive one. However the inductive preionizer maintains the azimuthal plasma uniformity at the MHD channel inlet that is not easy to obtain in the conductive preionizer due to current contraction. An arc electrode discharge of the conductive preionizer can lead to appearance of impurities in the inert gas plasma because of arc erosion of electrodes (cathode sputtering). Highly perspective could be a preionizer with a h.f. discharge although it requires a powerful (~1 MW) h.f. and h.v. generator with a long-term operation resource.

**CONCLUSION**

As a result of the investigation conducted operation parameters of the MHD generator intended for a pilot MHD gas-turbine electric power station including a two-section disk channel and a superconducting magnet system have been determined as follows: an electric power of 675 MW (with a 10% reserve), a working medium mass flow rate of 1700 kg/s, a cesium seed mole fraction of 1.6×10\(^5\), a stagnation temperature and pressure of 2200 K and 2 MPa, respectively, Mach number of 0.9, a flow swirl degree of 1, a magnetic field induction B_1 of 5.6 T and B_2=6.5 T, an inlet channel radius r_1 of 1.12 m, an outlet r_2=2.8 m, channel heights of h_1=0.16 m, h_2=0.164 m, a voltage of 6.8 kV between the first and second anodes (the first section) and between the first anode and cathode of 13 kV, an enthalpy extraction of ≈34%, an inner relative (isentropic) coefficient of ≈75%, a mass of 700 t, a height of ≈7 m, and a diameter of ≈9 m.

Calculated, designed and offered are constructive engineering solutions concerning main components (units) of a disk MHD generator, techniques of thermal and electric insulation, a construction and material of multi-layer walls for different gasdynamic duct sections, a system of cesium injection and a plasma preionizer. The obtained results and the base design are the basis for more detailed investigations, a feasibility study and a design of disk MHD generators of various scales and purposes operating on a non-equilibrium plasma.

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**REFERENCES**


