

MW-CLASS INDUCTIVE MPD THRUSTER USING NON-UNIFORM GAS-PLASMA FLOW

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ABSTARCT

Numerical simulations of nonstationary MHD process of the non-uniform gas-plasma flow acceleration in the electric propulsion (EP) channel in one-dimensional and two-dimensional approaches are performed. It is demonstrated that the T-layers used to generate the flow inhomogeneities in the form of plasma pistons allows to avoid the overheating instability development even at 1000 times increase of mass flow rate. The 1D simulation is performed for EP with inductive coupling of plasma clots with power source. It is shown the possibility of thrust attainment up to 1000 N with specific impulse about 4000 s. The 2D numerical simulation is realized in order to analyze the hydrodynamic instability of plasma clots piston-like structure. Several turbulence models are used for simulation. It is revealed that at certain conditions the turbulent viscosity suppresses the instability of gas-plasma boundary.

INTRODUCTION

The programs of the Near-Earth space exploration, building of the Lunar base, development of the regular human Mars mission, and so on will need the electric propulsion system with the level of thrust about 1000 N. The specific impulse of such EP may exceed 4000 s, correspondingly, required propellant supply in comparison with the existing rocket engine may be an order reduced. That will permit to organize a reusable space transport system use of which will reduce the financial expenditure in comparison with the single-mission spacecraft.

The existing EP is characterized by very low thrust level ¹ which now don't exceed 0.1 N for existing EP and will not exceed 1 N for advanced developments that is defined by the concept of work. Such EPs utilize steady-state plasma arcs accelerated by magnetohydrodynamic (MHD) force. The front of the ionization wave, through which the working medium passes and ionizes, may be stationary only in the condition of low-density gas. Otherwise the front breakdown will occur that will lead to the nonstationary processes development and the nonuniform structures forming. High value of Hall parameter at a low plasma pressure (about 100 Pa) defines the Hall type of MHD accelerator. This devise operates efficiently only in the stationary regime.

This exclusive circle may be broken by rejection of the stationarity requirement. The non-steady-state MHD effect of the stable plasma structures formation, so-called T-layers, is well known ². T-layers appear in the plasma flow moving in the transversal magnetic field as a result of the overheating instability development that in the condition of the MHD accelerator occurs inevitably as the plasma comes to the weakly ionized condition because of cooling by increasing gas flow rate. T-layers are plasma clots drifting with the gas flow. In this condition the density increasing and correspondingly gas flow rate raising do not switch the convective cooling of T-layer. T-layers are oriented along the electric field vector therefore one may utilize the plasma clots for the gas-plasma flow acceleration in the Faraday MHD channel. Results of the numerical simulation of the nonuniform gas-plasma flow acceleration process in the Faraday MHD channel were described in the paper ³. The possibility to obtain a high average velocity about 40 – 50 km/s on the channel outlet with propellant flow rate 10 – 50 g/s was revealed that provides thrust level in the range 400 – 2000 N. From the simulation results it was shown that the flow velocity asymptotically approaches to the value E/B that is typical for MHD process with high value of magnetic Reynolds number. It means that the energy transfer from the EP power supply to the T-layer plasma can be organized by the electrodeless technique through the

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inductive coupling. The purpose of present paper consists in the research of EP with plasma clots inductive coupled with the power supply system and in the analysis of hydrodynamic instabilities appearing during the T-layer interaction with the turbulent gas flow.

EP WITH TOROIDAL PLASMA CLOTS

Scheme of EP with T-layers forming azimuthal current rings can be shown according to Fig. 1. Here the MHD channel makes a cylindrical space between coaxial magnetic pole made of ferromagnetic material. The coil exciting the magnetic field is connected to external AC power supply that generates the alternating current and correspondingly, an alternating radial magnetic field is generated in the channel. In its turn, the time dependent magnetic field generates the azimuthal vortex electric field forming the arc discharge in the bulk of artificially established toroidal electroconductivity perturbation. In the present scheme of EP a transformer-like feed circuit of the plasma coils is practically realized. In the plasma clot in addition to ohmic heating there is an electrodynamic accelerating force. There is the formation under the action of heat and force factors of a plasma piston (T-layer) pushing the cold gas clot. The periodic initiation of T-layers forms the nonuniform flow structure. T-layer pushes the pressed cold gas clot whose density sharply drops at the domain of transition to the rarefaction wave appearing behind every T-layer.

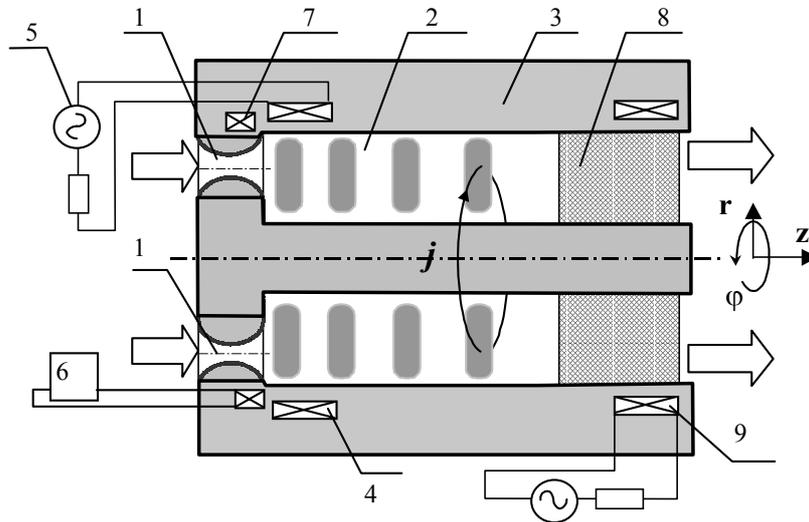


Figure 2. Schematic of EP with toroidal plasma clots: 1 - nozzle; 2 - MHD channel; 3 - magnetic core; 4 - primary current coil; 5 - power source; 6 - plasma clots initiation system; 7 - initiation coil; 8 - dielectric ribs; 9 - secondary current coil.

In the presented scheme the problem of T-layer quenching on the MHD channel outlet arises. Due to high magnetic Reynolds number in the T-layers an effect of magnetic field freezing-in would appear. The magnetic flux would be transferred out of the channel. At this moment accelerating regime has to turn into the generating one that will produce the magnetic field dissipation and fast T-layer plasma heating and braking. It is possible that similar mechanism underlie the solar flare phenomenon. To avoid this effect in the presented scheme it is proposed to set the dielectric ribs on the channel outlet. The surface of these ribs is disposed along the flow and therefore they do not make considerable resistance of flow. Dielectric ribs break the current in T-layer plasma and provoke the gas-discharge quenching. In addition for the magnetic field energy not be transferred into the T-layer, one more (secondary) energizing coil containing an additional EMF source and ohmic resistance is installed on the channel outlet. This coil absorbs the magnetic field energy by generating the vortex electric field opposite to the current direction.

Maintenance of the magnetic field above 1 T in the MHD channel bulk constricts the length of the MHD accelerator channel in the proposed EP scheme. The lateral surface of magnetic circuit internal cylinder must not essentially exceed the magnitude of the channel cross-section. If one accept the

maximum magnetic field value equal 2 T then the magnetic field in the channel will reduce proportionally by these area ratio. The mass flow rate limitation leads to the constriction of the cross section area. Evidently, to attain the magnetic field in the channel about 0.5 – 1.0 T it is necessary to keep the following proportion – the diameter of internal cylinder 10 cm, the MHD channel length 30 cm. For the numerical simulation of the MHD process we will consider that the channel height (gap between poles of magnetic coil) is equal 1 cm.

1D mathematical model of MHD process in the EP channel with azimuthal current layers

To simulate the process described above full set of the magnetohydrodynamic 1D equations were solved numerically. The governing equations include the equations of conservation of mass, momentum, energy and magnetic flux:

$$\frac{\partial}{\partial t} \begin{pmatrix} \rho \\ \rho u \\ \rho(\varepsilon + u^2/2) \end{pmatrix} + \frac{\partial}{\partial z} \begin{pmatrix} \rho u \\ p + \rho u^2 \\ (p + \rho\varepsilon + \rho u^2/2)u \end{pmatrix} = \begin{pmatrix} 0 \\ -j_\varphi B_r \\ j_\varphi E_\varphi - q_{rad} \end{pmatrix} \frac{\partial}{\partial t} B_r - \frac{\partial}{\partial z} E_\varphi = 0, \quad j_\varphi = \frac{1}{\mu_0} \frac{\partial}{\partial z} B_r = \sigma(E_\varphi + uB_r),$$

In the above expressions μ_0 – magnetic constant, E_φ - electric field, B_r – magnetic field, j_φ - current density, q_{rad} - volume energy losses due to radiation, ρ , u , p , ε - mass density, velocity, pressure and energy density of gas respectively, σ - electric conductivity.

The model of equilibrium hydrogen plasma is accepted. The electron number density is defined by the Saha equation. The volume energy losses from plasma due to radiation, which account even in rough approximation is very complicated problem, is taken into account as proportional to T^4 . The proportionality constant is chosen so that the energy radiation losses stabilize the plasma temperature in T-layer on level about $3 \cdot 10^4$ K. Such approach reflects the experimental data of plasma properties in the condition close to the present problem, for example in a plasmatron.

The boundary conditions for gasdynamics parameters have a form traditional for the nonstationary tasks with a supersonic flow: constant value at the inlet and zero coordinate derivative of all flow parameters at the outlet boundary.

The circuit equation with external EMF source inductively coupled with the plasma circuit has been solved to determine the boundary conditions for the magnetic field. Thus equation appears as:

$$RJ(t) - U(t) = -\frac{d}{dt} \Phi(t), \quad 2\pi a E(z, t) = -\frac{d}{dt} \Phi(t, z),$$

$$J(t) = a \ln\left(\frac{r_1}{r_0}\right) \frac{B(z=0, t)}{\mu_0}, \quad a = \sqrt{\frac{r_1^2 - r_0^2}{\ln(r_1/r_0)}}$$

where r_0 , r_1 – internal and external magnetic circuit radii, Φ - magnetic flux, R – circuit resistance, U – EMF, J – circuit current.

The azimuthal electric conductivity perturbations are set periodically in the gas flow at the channel inlet in the form of local isobaric temperature perturbances with $T_{max} = 10^4$ K.

In order to simulate the T-layer quenching at the MHD channel outlet, where plasma ring is cut by the dielectric ribs, equilibrium electric conductivity magnitude is multiplied by exponentially vanishing factor, which reduces the electric conductivity 1000 times on the interval from 25 cm to 30 cm.

The time dependence of source EMF feeding the exciting coil is chosen in accordance with the following factors:

1. The constant component should exist that provides the constant component of the magnetic field in the channel.
2. The growth of EMF support the acceleration regime, while the generation regime corresponds to the decreasing phase of EMF that should be avoided.
3. Adjustment of the vortex electric field value may be realized by the frequency and amplitude of EMF change.

Taking these into consideration as well as the result of numerous calculations the EMF time dependencies were chosen corresponding the oscillograms shown on Fig. 2a. The EMF changing period amounts to $5 \cdot 10^{-6}$ s that is equal to T-layer initiation period $4 \cdot 10^{-6}$ s.

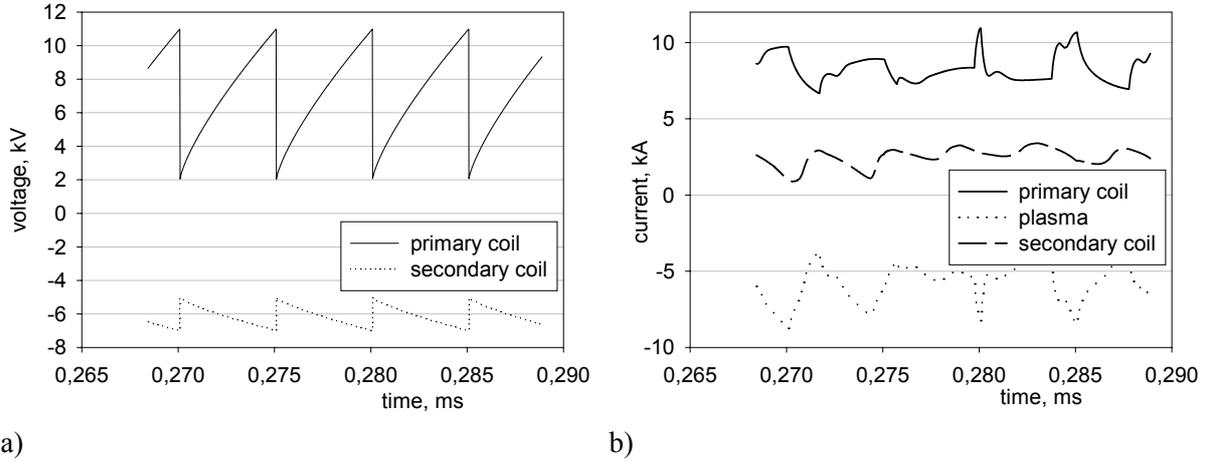


Fig. 2. Oscillograms of currents and voltages

The selection of propellant (hydrogen) is imposed by that the T-layer can appear only in the high density flow ($n_a \sim 10^{17} \text{cm}^{-3}$). This produces an excess high value of mass flow rate and correspondingly the requirement of exceedingly high power on-board energy installation. The hydrogen, as lightest gas, permits to minimize the required power. In the variant of calculated EP regime presented below the following working medium parameters on the channel inlet were set: static pressure and temperature – $1.15 \cdot 10^5$ Pa and 1000 K respectively, Mach number 1.5.

The result of simulation of non-steady-state process in the EP channel is shown on Fig. 3 in the form of instant distributions $T(x)$, $u(x)$, $\rho(x)$, $B(x)$, which correspond to established periodical regime. In order to represent the nonstationary process dynamics the distributions of all parameters are given for three sequential time moment. One can see from the curves features (Fig. 3a) that in the channel with length 30 cm two T-layers are present at any time moment. The temperature of T-layers attains $5 \cdot 10^4$ K at the initial stage and then is stabilized on level $3 \cdot 10^4$ K. The T-layers thickness is about 2-3 cm, that should ensure the hydrodynamic stability of the piston-like structure at the channel width 1 cm. The velocity distribution in the working medium flow (Fig. 3b) has a nonuniform structure, in which the velocity drop corresponds to left boundary of T-layer, i.e. gas in the rarefaction wave does not keep pace with the plasma clot. As a result density in this flow region (Fig. 3c) practically goes down to zero. T-layer interaction with gas flow results in the mass clots formation, which on Fig. 3c look like series of density picks. Comparing the location of temperature and density maximums we see that they are shifted by T-layer thickness approximately, i.e. the mass clot pressed by plasma piston is formed. The magnetic field distribution in the channel is shown on Fig. 3d. By this curve one can see that stepwise structure with sharp decrease of magnetic field on T-layers is formed. It should be noted, the first T-layer (nearest to exiting coil) does not screen total magnetic field that keeps the magnitude high enough to provide an effective acceleration regime on second T-layer.

The established oscillograms (Fig. 2a) provide weakly varying currents of constant signs in the exciting coil and in the T-layer plasma (Fig. 2b). These currents are opposite by sign but similar by magnitude. The electrodynamics interaction of the currents generates the accelerating force acting in the T-layer plasma. The EMF of secondary exciting coil, as it is shown on Fig. 2a, has the negative value while the current in this coil keeps positive value. Thus, energy from primary coil is transmitted to plasma while secondary coil absorb electromagnetic energy (generator regime). The energy generated by plasma may be utilized to generate the initial electric conductivity perturbations.

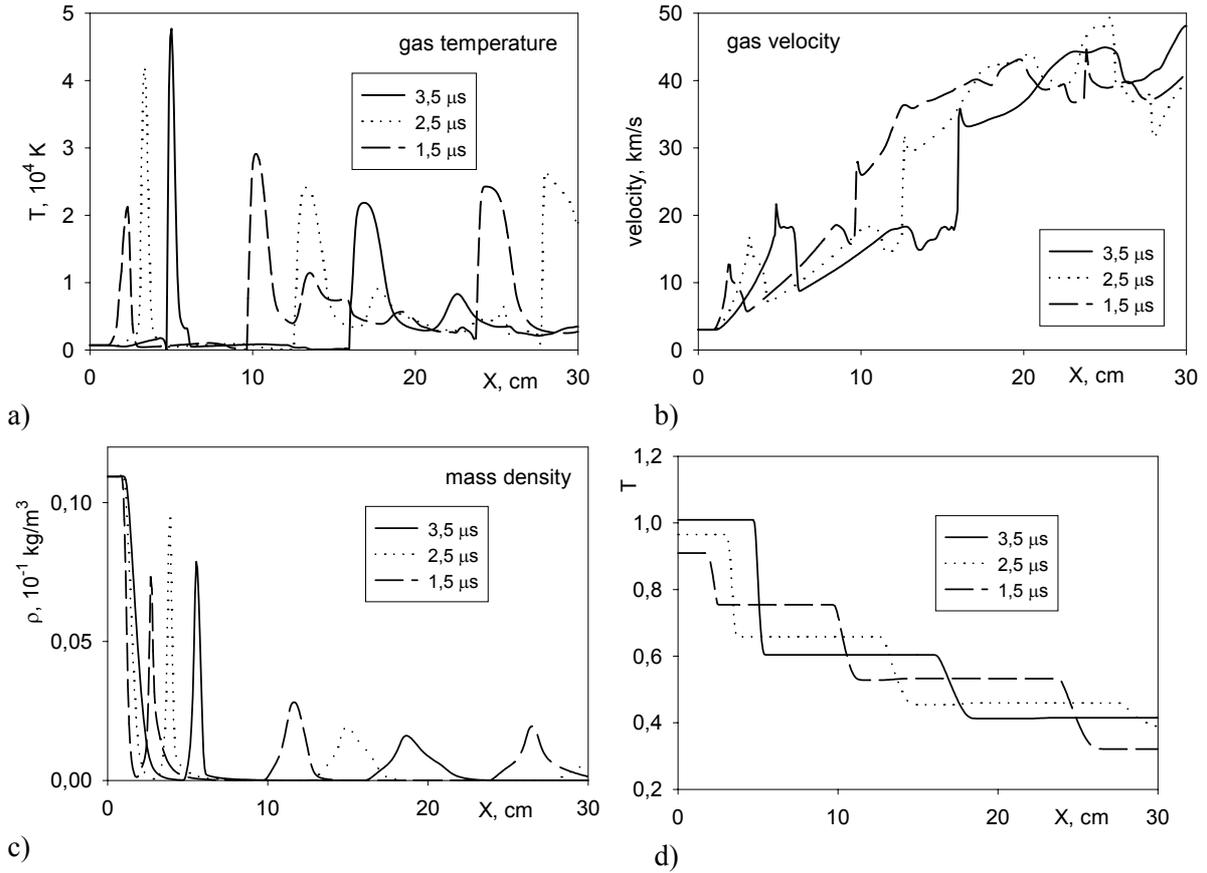


Fig. 3. Instant distributions in three sequential time moment.

In the course of numerical simulation the following average parameters have been calculated continuously: exhaust velocity u_{out} , propulsion thrust F , kinetic energy flux of jet K_{out} , kinetic energy flux of flow on channel inlet K_{in} , power of EMF source of primary coil P_{in} , power transferred to secondary coil P_{out} , enthalpy flux on EP inlet H_{in} .

At the mass flow rate = 35 g/s the following results have been obtained:

$$u_{out} = 43 \text{ km/s}; F = 1400 \text{ N}; K_{out} = 32 \text{ MW}; K_{in} = 0,5 \text{ MW}; P_{in} = 53 \text{ MW}; P_{out} = 15 \text{ MW}; H_{in} = 1 \text{ MW}.$$

To determine the EP efficiency the following adjectives have been calculated:

Specific weight of accelerator regime

$$\eta_p = \frac{P_{in} - P_{out}}{P_{in}} = 64\%$$

EP efficiency without utilization of P_{out}

$$\eta' = \frac{K_{out} - K_{in}}{H_{in} + P_{in}} = 60\%$$

EP efficiency with utilization of P_{out}

$$\eta = \frac{K_{out} - K_{in}}{H_{in} + P_{in} - P_{out}} = 70\%$$

Comparison of MHD processes in the channels of EPs with the electrode and inductive T-layers coupling with external power supply system

At first sight the electrode and inductive schemes are distinguished in principle by that in the first scheme we have uniform electric and magnetic fields distributions while in the second scheme these fields change stepwise on the T-layers. However, in the detailed analysis of the process nature it is discovered that at similar conditions of acceleration regime the gasdynamics distributions have the

similar structure (Fig. 5). It is curious that the x dependence of ratio E/B , to which the flow velocity value tends (Fig. 5 a, b), maintains monotonic and close by magnitude in the both schemes.

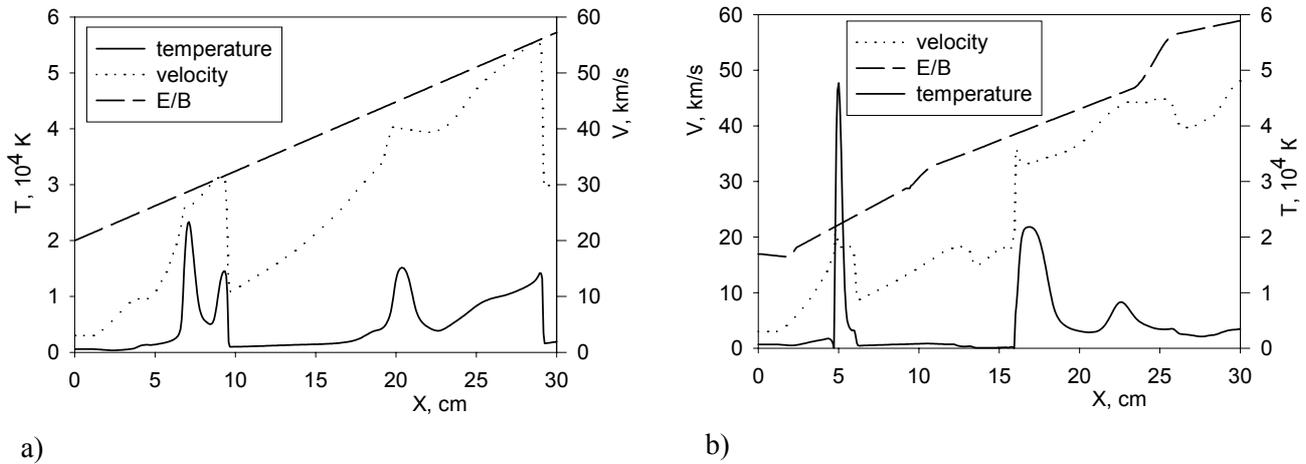


Fig. 5. Gasdynamic parameters distributions: a) electrode scheme; b) inductive scheme.

Conclusions on 1D analysis results

The EP, utilizing the T-layer effect, can provide specific impulse > 4000 s at thrust about 1000 N. However the operation of such engine will require the electric energy source with power level about 50 MW, that at present and in the foreseeable future seems problematical. In order to reduce the required power it is necessary to decrease the gas pressure at the EP inlet, but in this condition the effect of arc discharge localization, i.e. T-layer effect, may disappear. Definition of a lower bound of pressure is subject of prospective investigations that will demand the nonequilibrium processes consideration.

The 1D analysis does not answer the question about spatial stability of T-layer structure that may be realized by 2D simulation.

ANALYSIS OF 2D PROCESS IN THE NONUNIFORM GAS-PLASMA FLOW IN THE EP CHANNEL

Two-dimensional analysis of non-steady-state gasdynamic process in the nonuniform flow can reveal the development of the instability of boundary surface between gas and plasma which will appear in the form of standing waves. This instability may have various nature: acoustic instability, Rayleigh-Taylor instability, boundary layer instability. The last two instabilities are the most dangerous since they have large increment. At the nonlinear phase of development that instability form jets of cold gas breaking the plasma clots which is transformed to a set of arcs surrounded by gas flow. The instability development generate turbulent eddies of different scales that can essentially change the flow nature. It appears from this that the two-dimensional simulation will either confirm or refute the 1D simulation results.

The task formulation of 2D simulation is illustrated by scheme presented on fig 6. The channel composed of dielectric walls and electrodes is considered. The simulation domain is a rectangular area, which upper and lower boundaries correspond to the dielectric walls, and the left and the right ones correspond to the inlet and outlet sections. The vectors of flow velocity and magnetic flux are situated in the computational domain while the current density vector is orthogonal to computational domain. Inside the channel the T-layers are moving. In the initial condition the T-layers structure is assigned as one-dimensional (piston-like). The conditions in a non-perturbed flow correspond to the stationary flow of viscous non-electroconductive gas in the plane constant cross-section channel.

The wall boundary conditions are the “no-slip” and isothermic wall condition. The wall temperature is equal to the non-perturbed gas flow temperature. In the inlet cross-section the supersonic flow remains non-perturbed, therefore the stationary conditions for the turbulent non-

electroconductive gas remain constant. In the channel outlet the flow becomes nonstationary but remains supersonic, that allows using “soft” boundary conditions at the channel outlet.

In the thermal boundary layer gas temperature is decreasing to the wall temperature. Correspondingly in this domain the gas becomes nonelectroconductive that produces two-dimensional processes in the boundary layer.

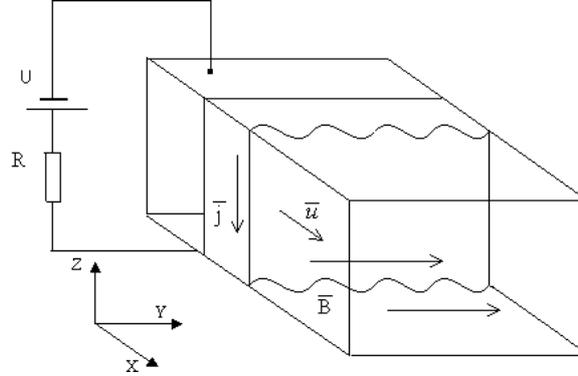


Fig. 6. Scheme of 2D simulation of MHD accelerator.

According to the problem formulated above, to confirm or refute the results of 1D computation, we can either just assign currents in T-layers and exclude consideration of the certain way of T-layer connection to power source (conduction or inductive) or consider a simplest conduction type, and attract attention to the gasdynamic process. In the presented below simulations we assumed the last approach.

The task was solved with use of three approaches for the investigation of two-dimensional flows with large Reynolds numbers. The first approach is the direct numerical simulation (DNS) on the base of full Navier-Stokes equations set where only the molecular viscosity and heat conductivity are taken into account. In the second approach the large-scale turbulence is simulated directly whereas the influence of subgrid flow scale is included by means of additional turbulent viscosity coefficient (LES). According the used in the presented calculations Smagorinsky method ⁴, this coefficient is defined as

$$\mu_t = \rho(c\Delta)^2 \left| \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)^2 \right|^{1/2}.$$

In the above expression the semi-empirical constant $c = 0.1$, Δ — spatial resolution of mesh.

The third approach is application of time averaged Navier-Stokes equations for compressible flow using the density as a weighting coefficient. As a closure model the one-parametric differential model v_t -92 ⁵ describing turbulent viscosity transport is used.

The governing equations for the formulated above task can be written in the form of MHD equations:

$$\frac{\partial \bar{U}}{\partial t} + \frac{\partial \bar{F}}{\partial x} + \frac{\partial \bar{G}}{\partial y} + \frac{\partial \bar{F}_v}{\partial x} + \frac{\partial \bar{G}_v}{\partial y} = \bar{S},$$

where

$$\bar{U} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \end{bmatrix}, \quad \bar{F} = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ u(e+p) \end{bmatrix}, \quad \bar{G} = \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ v(e+p) \end{bmatrix}, \quad \bar{S} = \begin{bmatrix} 0 \\ jB \\ 0 \\ jE - q_{rad} \end{bmatrix},$$

$$\bar{F}_v = \begin{bmatrix} 0 \\ -\tau_{xx} \\ -\tau_{xy} \\ q_x - (u\tau_{xx} + v\tau_{xy}) \end{bmatrix}, \quad \bar{G}_v = \begin{bmatrix} 0 \\ -\tau_{yx} \\ -\tau_{yy} \\ q_y - (u\tau_{yx} + v\tau_{yy}) \end{bmatrix}, \quad \begin{matrix} \tau_{ij} = \tau_{ij}^L + \tau_{ij}^T, \\ q_i = q_i^L + q_i^T \end{matrix}$$

$$q_i^L = -\frac{\gamma}{\gamma-1} \frac{\mu}{Pr} \frac{\partial T}{\partial x_i}, q_i^T = -\frac{\gamma}{\gamma-1} \frac{(\rho v_t)}{Pr_t} \frac{\partial T}{\partial x_i}, \quad i = x, y \quad j = x, y$$

Here τ_{ij}^L - the viscous stress tensor; τ_{ij}^T - the turbulent stress tensor; q_i^L, q_i^T - the molecular and turbulent heat conduction vectors respectively; μ, ν_t - the molecular and turbulent viscosity; γ - the ratio of specific heats; Pr, Pr_t - the molecular and turbulent Prandtl numbers; e - the energy per unit volume; T - the medium temperature. The turbulent stress tensor is defined analogously to viscous stress tensor with substitute of molecular viscosity to turbulent one.

In the case of application of one-parametric differential model the equations set is expanded by differential transport equation describing the evolution of turbulent viscosity:

$$\frac{\partial}{\partial t} \rho v_t + \frac{\partial}{\partial x} \rho u v_t + \frac{\partial}{\partial y} \rho v v_t - \frac{\partial}{\partial x} \left(\mu + \frac{\rho v_t}{\sigma_t} \right) \frac{\partial v_t}{\partial x} - \frac{\partial}{\partial y} \left(\mu + \frac{\rho v_t}{\sigma_t} \right) \frac{\partial v_t}{\partial y} = P_v - D_v$$

where $P_v - D_v$ - the terms of generation and dissipation of turbulent viscosity; σ_t - the model constant⁵.

Analysis of 2D process in channel of MHD accelerator with nonuniform gas-plasma flow

For numerical simulation three described above turbulent model were used: first – taking into account only molecular diffusion, second – LES model with turbulent viscosity generated by subgrid-scale turbulent eddy (which scale is less than spatial mesh size), and third – the one-parametric differential model of turbulence, in which the additional viscosity defined by a total spectrum of fluctuation averaging. Obviously, the effective viscosity value will increase when coming from the first approach to the third one.

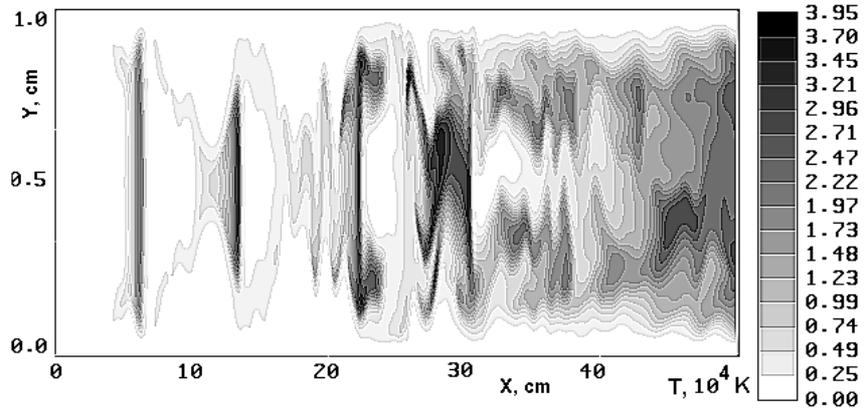


Fig. 7a). Instant isothermic domain distribution. Without taking turbulence. into account (DNS).

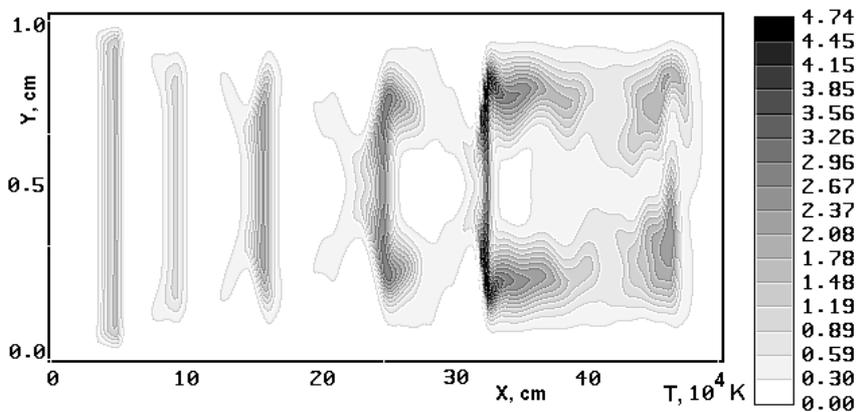


Fig. 7b). Instant isotherms distribution . The large eddy simulation (LES).

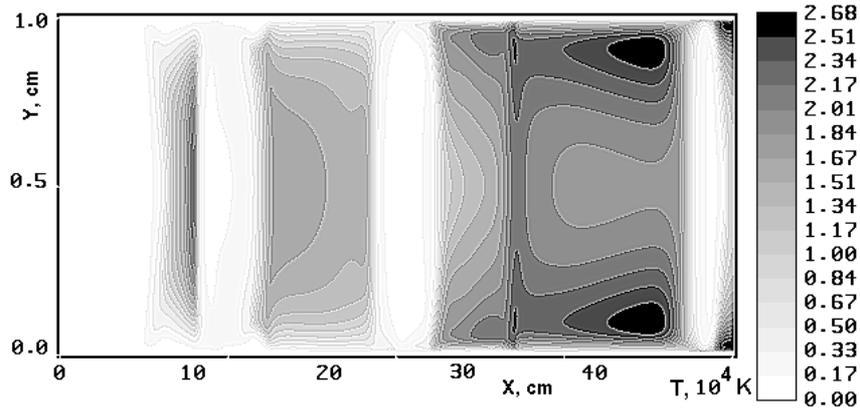


Fig. 7c). Instant isotherms distribution. The one-parametric differential model of turbulence.

On Fig. 7 a,b,c simulation results of three different variants, differing in turbulent model, are presented. The nature of two-dimensional structure on these figures is given in the form of the temperature distribution. On the pictures the size of computational domain in the “y” direction coordinate is 50 times stretched.

On the Fig. 7a regime without taking any turbulent viscosity into account are shown. One can see, the T-layer, formed at the MHD channel inlet (left side of domain), goes away from wall as passing ahead. Disturbed region in the form of typical wake appearing behind the moving T-layer. Furthermore, in the central flow region as a result of instability development a jet of cold gas is formed. The jet transfixes and breaks the T-layer. Consequently, the localized structure of T-layer disappears and the gas flow is filled up by turbulent eddy structure.

The flow structure calculated using the second turbulence model has a different nature (Fig. 7b). Here the Rayleigh-Taylor instability appears too. But due to the effective viscosity increase the instability intensity is weakened. As a result the T-layer life time grows. Under the influence of instability the T-layer is transformed into thin current clot, which is repelled away from wall by the cold gas flow.

The third turbulence model use leads to radical reconstruction of the T-layers structure. In this regime the influence of Rayleigh-Taylor instability is practically insignificant. The T-layer have the piston-like structure, which completely overlaps the channel cross-section. The one-dimensional character of T-layer generates the processes typical for one-dimensional structure². This appears as a formation of stabilization domain, from which the excess plasma mass is “discarded”. On the Fig. 7c in the region of third T-layer an internal peculiarity (temperature disruption) is observed, which separates the stabilized T-layer area (right side) from cooling mass (left side).

The character of variables distributions along the channel for the condition of third turbulence model is shown on Fig. 8. Curves demonstrate the temperature and velocity distributions on the central axis of the channel.

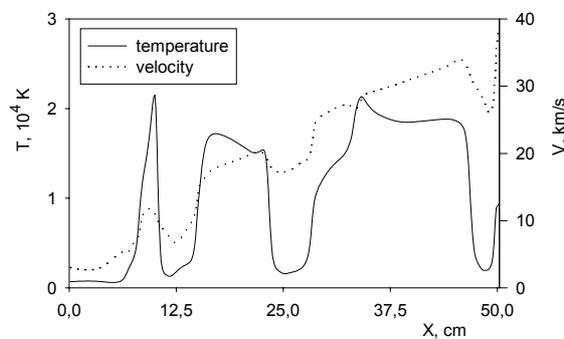


Fig. 8. Distributions of gasdynamic variables along channel

One can conclude from velocity value that the 2D model like one-dimensional (Fig. 5) provide a monotonic persistent flow acceleration. In the same time the dips in the velocity distribution become

smaller than in the 1D simulation. Seemingly, this is explained by that the gas mass, percolating through boundary layer in the T-layer domain, fills the rarefaction region.

The differential turbulence model used in this paper gives more magnitude of eddy viscosity than LES model. At larger magnitude of effective viscosity the flow character becomes practically one-dimensional that provides effective flow acceleration. However, for the condition of the presented problem formulation the LES model reproduces the real flow nature more accurately. The effect of piston-like structure stabilization depends not so great on the value of viscosity coefficient as on the viscosity influence on gasdynamics too. In the channel with length 0.3 m an average value of flow acceleration is $10^8 g$. At such electrodynamic action the viscous effects does not affect on the flow acceleration process even in narrow channels with width about 5 mm, but they can stabilize the piston-like plasma structure.

CONCLUSIONS

1. Use of T-layer effect will allow to design an effective high thrust EP with thrust up to 1000 N and with specific impulse about 5000 .
2. A high magnetic Reynolds number (~ 10) permits to realize an inductive coupling of plasma coil with external power supply system. Such electrodeless scheme will let to have an unlimited working life of EP.
3. The phenomenon of turbulence does not destroy the stratified gas-plasma flow structure and for the certain conditions turbulence can stabilize the plasma clots in the form of pistons impenetrable for gas flow, that accelerate the working medium of EP efficiently.
4. The T-layer is an MHD phenomenon appearing in the dense plasma ($n \sim 10^{17} \text{cm}^{-3}$), that determine the equilibrium character of such plasma. By plasma clots cooling in the channel outlet (in the diffuser of EP) the plasma recombination will occur and non-ionized gas will leave the EP. Thereby, in such propulsion the problems, concerned with plasma jet interaction on the spacecraft, will be absent.

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