THEORY AND PRACTICE OF ENERGETIC MATERIALS

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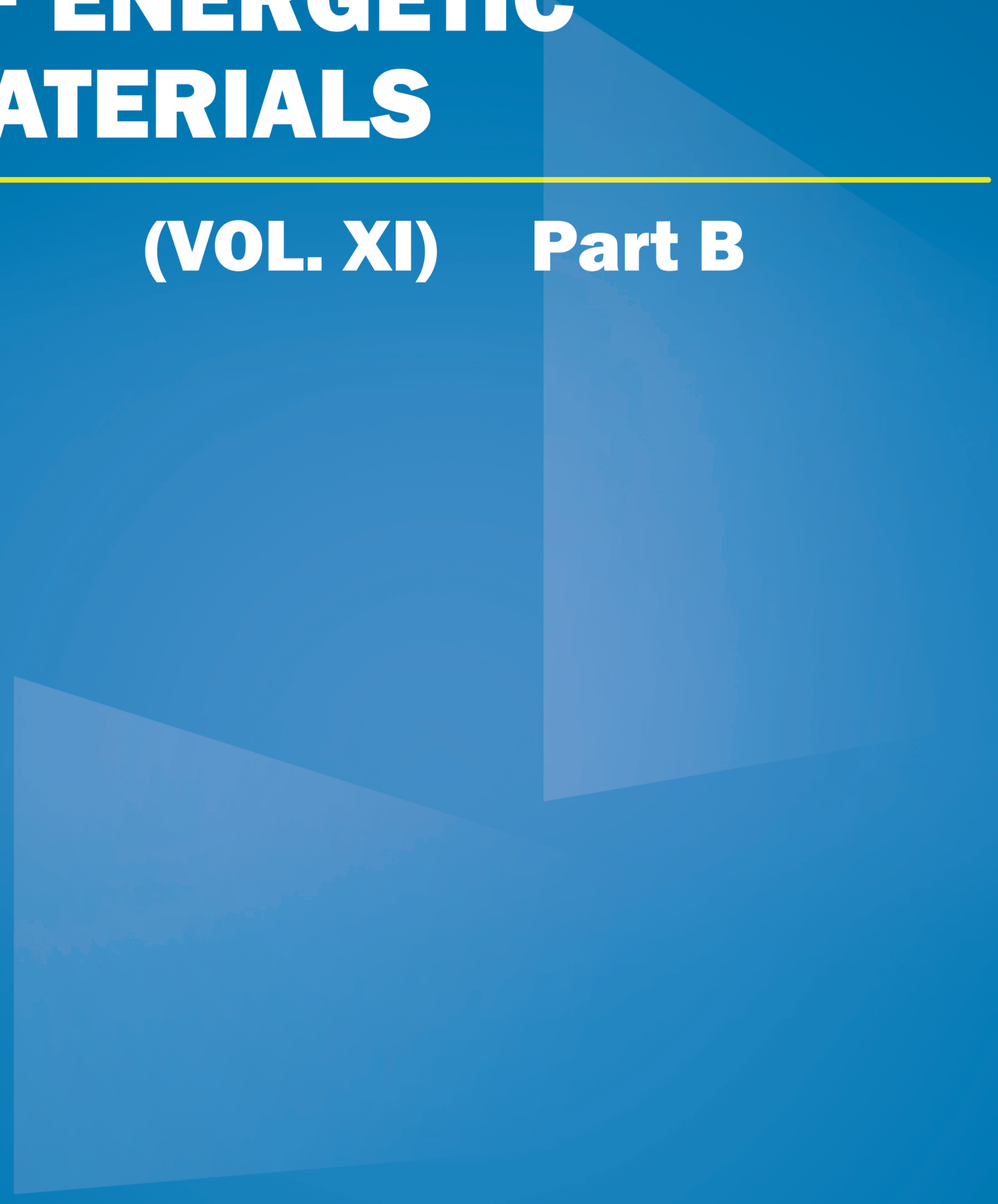

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SECTION THREE

COMBUSTION AND DETONATION

Rapid Fire Railguns Powered by Pulsed MHD Generators Using Plasma-Generating Solid Propellants

A. G. AFONIN[1], V. G. BUTOV[1], V. P. PANCHENKO[2], S. V. SINYAEV[1],
V. A. SOLONENKO[1], G. A. SHVETSOV[3], A. A. YAKUSHEV[2]
(1 Research Institute of Applied Mathematics and Mechanics, Tomsk State University, pr. Lenina 36, Tomsk, 634050 Russia
2 TRINITI Troitsk Institute for Innovation & Fusion Research, State Research Center of Russian Federation,
ul. Pushkovykh 1, Troitsk, Moscow region, 142190 Russia
3 Lavrentyev Institute of Hydrodynamics, SB RAS, pr. Lavrentyeva 15, Novosibirsk, 630090 Russia)

Abstract. The possibilities of using a pulsed MHD generator operating on a plasma-generating solid propellant as an electrical energy source for a rapid fire multirail electromagnetic launcher have been studied by mathematical modeling. Results of this study show that the use of pulsed MHD generators operating on plasma-generating solid propellants as a power supply for rapid fire high-velocity railguns provides great opportunities for accelerating solid projectiles weighing tens of grams to several hundred grams to velocities above 2–3 km/s.

Keywords: MHD generator, plasma-generating propellant, multirail launcher, cyclic load, simultaneous calculation, supersonic shock-free flow

1 Introduction

In most published studies of electromagnetic launchers, electrical energy was produced by capacitor banks, which have relatively low weight and volume energy characteristics and hence cannot be used to produce mobile transportable sources with energies of tens and hundreds of megajoules required to accelerate projectiles to velocities of 2−3 km/s.

The possibilities of using pulsed MHD generators (PMHDG) to power railgun launchers were studied in[1, 2].

One of the key problems in the development of rapid fire electromagnetic railguns[3–5] is the design and production of specialized sources of electrical energy for them.

Pulsed MHD generators are compact, self-contained sources of electrical energy with specific energy parameters many times higher than the specific energy characteristic of capacitors, and the time of their start and warm-up period does not exceed a few seconds. The power of pulsed MHD generators reaches hundreds of megawatts[7]. This allows them to be considered as a promising direct source of power supply for high-velocity railguns.

This paper presents the results of mathematical modeling of the rapid fire launching of solid projectiles from a multirail electromagnetic launcher (MREL)[8] with direct power supply from two parallel-connected “Sakhalin” type MHD generators with a total power of 1 GW. The calculations were performed for a plasma-generating propellant with a relatively high consumption[9]. The use of modern propellants [6] allows a considerable (manifold) reduction in the weight, size, and flow characteristics of MHD devices, which has motivated the development special high-energy propellants and pulsed MHD generators for MRELs.

When a cyclically time-varying active-inductive load (launcher) is powered from power supply from an MHD generator, the supersonic equilibrium plasma flow in the MHD channel and the electrical characteristics of the MHD generator will change significantly[10]. Hence, the problem arises of determining the stability and continuity (shock-free nature) of the supersonic flow in the MHD channel under conditions of cyclic variation of the characteristics of the “MHD generator– rail launcher” electrotechnical system.

2 Formulation of the Problem

Figure 1 shows a schematic diagram of the simulated device in which a multirail launcher with a metal armature[8] is powered directly from a system of two parallel-connected PMHDGs via a high-speed switch K. The plasma flow in the PMHDGs is produced by combustion of solid plasma-generating propellant and contains a gas phase and a condensed phase with a mass concentration Z = 0.36–0.46. The condensed phase consists of liquid particles of alumina Al_2O_7 with melting and boiling points of 2320 K and 3250 K, respectively. It is formed by combustion of a composite solid propellant containing a fine aluminum powder. The condensed-phase particles have radii of 0.5–2 μm[11]. The gas phase in the MHD channel is a chemically reactive mixture of molecules of CO (mole fraction of 45%), H_2 (25%), N_2 (14%), H (4%), H_2O (4%), and CO_2 (1%) and vapor of K, Cs, Mg, and Fe

(≤1%)[9]. The main source of free electrons in the gas phase is the alkali metal atoms in the ionizing additive to the propellant, which have a low ionization potential. The remaining components of the gas phase are not substantially ionized[10].

In the gas-dynamic channel of the MHD generator, the gas is accelerated by the pressure gradient, and the condensed-phase particles are accelerated by aerodynamic forces and lose their heat content only in the viscous flow of the gas phase. During acceleration of the two-phase flow, there is velocity and temperature nonequilibrium: the gas particles lag behind the gas and become more heated during motion than the gas. In the MHD channel, where the gas is decelerated in the magnetic field, the particles may overtake the gas. In general, however, the velocity and temperature nonequilibrium between the gas and condensed phase is negligible in the MHD channel, so that in the calculation it can be neglected[10].

The rail unit of the launcher consists of several pairs of guide rails, separated from each other by insulating inserts and connected in series by electrically conducting bridges in the inlet section of the launcher. The projectile armature consists of several identical isolated from each other by metal brackets with two peripheral current-collecting parts. Each bracket of the armature closes the corresponding pair of guide rails of the launcher.

Projectiles are fed into the MREL channel in succession, and, before entry into the rail unit, they can be accelerated as a rigid assembly[3]. Before leaving the launcher, the armature of each projectile is de-energized due to current interception by the armature of each successive projectile (which is fed into the launcher before the preceding projectile leaves it) and the resistive bridges at the launcher exit. Thus, there is an alternation of acceleration regimes, in which either one projectile or a combination of two projectiles is accelerated in the MREL channel. Equivalent electrical circuits for these two regimes are shown in Fig. 1b and Fig. 1c, respectively. The first projectile is fed into the launcher channel during no-load operation of the PMHDG. The launcher operation model is constructed under the following simplifying assumptions: the current is distributed uniformly over the cross sections of the rails; the electrical resistivity of the rail material is linearly dependent on temperature; the influence of heat conduction in the rails and heat dissipation into the environment during launcher operation can be neglected; the electrical contacts between the armatures and the guide rails are arcless; the inductance of the rails is calculated in a quasi-stationary approximation using a rectangular finite element method with a uniformly distributed current[12] which is a generalization of[13]. It is also assumed that the currents through each metal bracket are the same in each armature. In this case, the currents through each de-energizing bridge will also be identical for series-connection of each pair of the rails (see Fig. 1a).

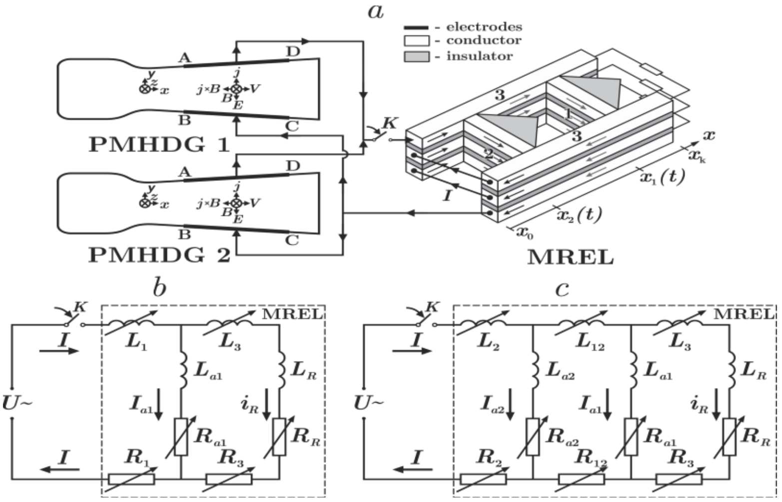

Fig.1 Schematic diagram with direct power of the launcher from the PMHDG: 1, 2 – projectiles; 3 – multirail launcher; b) electrical circuit for launching one projectile; c) for simultaneous launching two projectiles

In the fire-rapid operation mode, the launcher is an active-inductive load with cyclically varying electrotechnical parameters: inductance *L* and active resistance *R*. A non-stationary quasi-two-dimensional model of the device in question was developed to study the effect of this load on the supersonic flow mode in the PMHDG channel and its output characteristics. The flow of the electrically conductive two-phase working fluid in the channel of the MHD generator is modeled in the nonstationary quasi-two-dimensional approximation of ideal pseudogas[14] derived from the three-dimensional equations of magnetohydrodynamics by averaging over the *z* coordinate directed along the magnetic field (see Fig. 1a). The calculations are performed in the quasi-stationary approximation for the electromagnetic field in the MHD channel. A semi-empirical approach[10] is used with an experimentally measured magnetic induction profile in the channel. Its distribution normalized to the maximum induction value (2.2 T) is described by curve 1 in Fig. 2. Here curves 2 and 3 show the profiles of the electrode and insulator walls of the channel, referred to half the distance between the electrode walls at the outlet of the computational domain (0.9 m). The inlet boundary of the computational domain is the section $x = 1.12$ m. The values of the parameters at the inlet boundary are determined in the approximation of quasi-one-dimensional isentropic flow in the booster nozzle. The pressure and temperature values in the combustion chamber required to determine them are 4.76 MPa and 3750 K, respectively. The plasma parameters in the chamber are specified taking into account the equilibrium chemical reactions in the boost phase of the gas-dynamic duct of the PMHDG. The mass fraction of the condensed phase in the flow is 0.35. The effective values of the adiabatic exponent and the gas constant of the pseudogas are 1.16 and 238 J/(kg K), respectively[15].

According to estimates, the change in the thermophysical parameters of the flow in the supersonic region is insignificant, so that their values are assumed to be constant. At the inlet of the computational domain, the following values are obtained for the pressure, temperature, and velocity: 0.682 MPa, 2917 K, and 1734 m/s, respectively.

The system of equations consistently describing the operation of the MHD generator and rail launcher, the initial and boundary conditions, necessary relations, the assumptions used, and a description of the calculation procedure are given in[17,18].

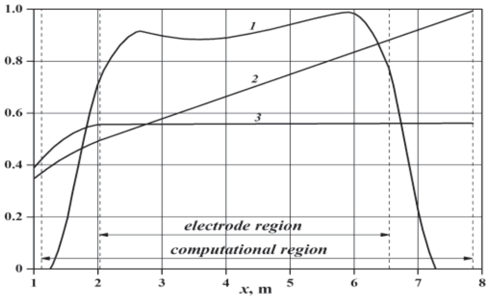

Fig.2 Profiles of the “Sakhalin” PMHDG channel walls of and magnetic field induction: 1 – magnetic induction; 2 – electrode wall; 3 – insulator wall

3 Results

Figure 3 shows the calculation results for the following launcher model: length of the rails 5.5 m, number of pairs of rails 5, cross-sectional area of each rail 8 cm^2, chromium copper rails, initial resistance of the bridges 8.5 milliohms, inductance of the bridges 0.4 μH, initial temperature of the rails and bridges 20°C, number of projectiles in succession 20, weights of the projectiles $m_1 = 550$ g, $m_2,\ldots,m_{19} = 470$ g, $m_{20} = 525$ g, and initial projectile velocity 50 m/s.

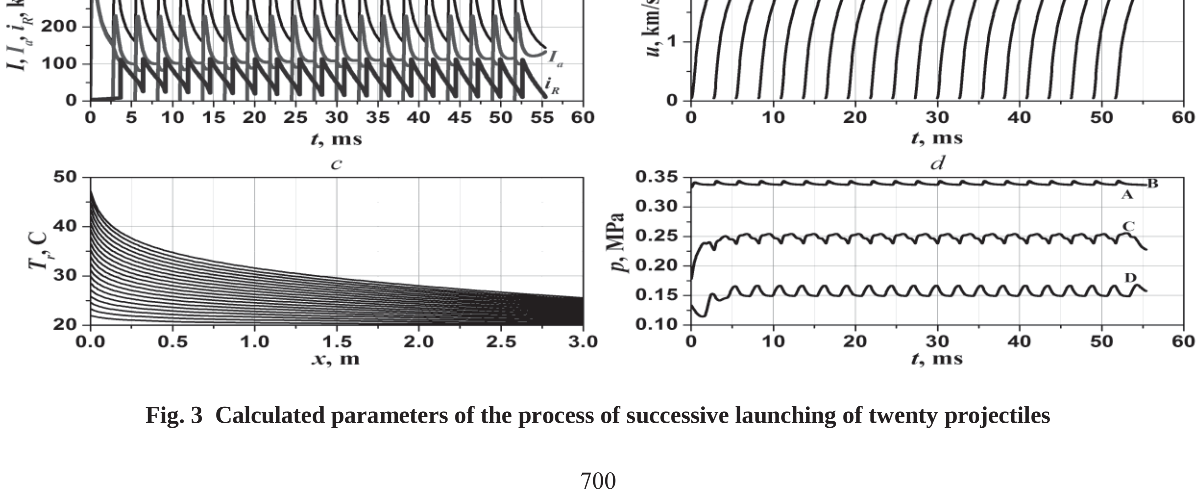

Fig. 3 Calculated parameters of the process of successive launching of twenty projectiles

Figure 3 shows the changes in the main characteristics of this embodiment of the PMHDG-MREL device: a – total discharge current I in the PMHDG and the currents through the armature I_a and the bridge i_R; b – projectile velocity; c – temperature profiles of the rail unit at the time of exit of each projectile from the launcher; d – pressure at four points of the MHD channel.

From the relations given in Fig. 3a, it follows that each successive armature acts as a dynamic crowbar[18], almost de-energizing the preceding armature by the time it leaves the launcher. Additional de-energizing of the projectile armatures is provided by resistive bridges at the exit of the rail unit. The exit velocity of all twenty projectiles from the launcher is 2.2 km/s. The launching modes of all projectiles are similar with a rate of 365 Hz. Stabilization of the launching modes of the first and last projectiles in succession is provided by increasing their mass. The initial distance between successively launched projectiles at the launcher exit is about 6 m. The number of projectiles in succession is limited by the maximum permissible temperature of the launcher rails in the exit section. In this calculation, the heating of the rails does not exceed 30℃, which makes it possible to increase the number of projectiles in succession. Figure 3d shows the corresponding pressure changes at four characteristic points of the MHD channel: points *A* and *B* at the entrance and points *D* and *C* at the exit of the anode and cathode, respectively (see Fig.1a). The pressure in the entrance section of the electrode zone is higher than the pressure in its exit section throughout the process, which suggests shock-free flow in the MHD channel[10].

Figures 4a and 4b show the calculated pressures in the MHD channel at the moment of maximum and minimum currents, respectively, through the armature of the fifth projectile (see Fig. 4c). This pressure distribution in the MHD channel is characteristic of the entire launching process, which also confirms that the supersonic flow is shock-free and, hence, that the generator has stable output characteristics when operating on the given cyclic load. Periodical increase in the (*L, R*) parameters of the load reduces the electromagnetic deceleration of the flow, which, in turn, prevents the formation of compression waves and shock waves in the generator channel**.**

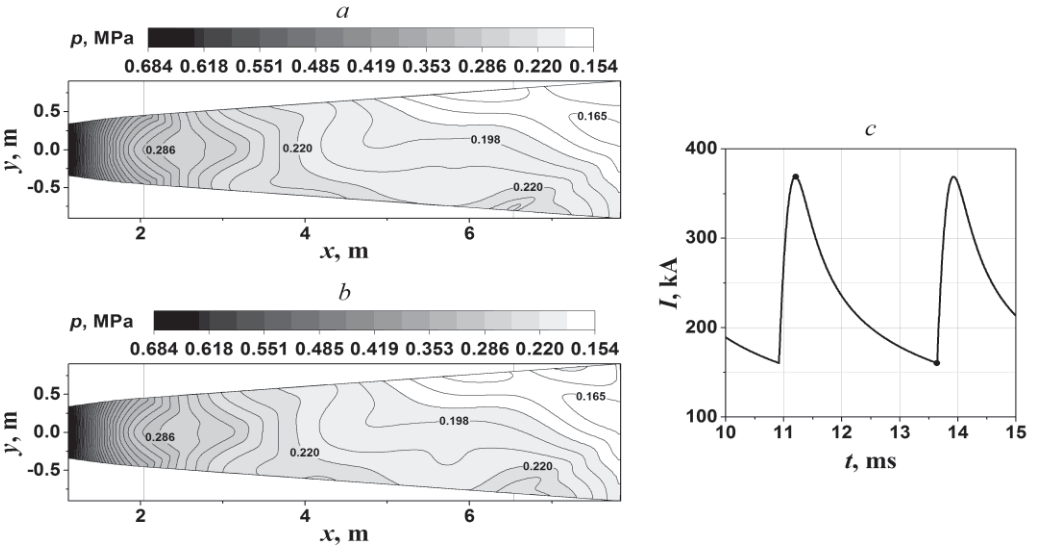

Fig..4 Pressure distribution in the MHD channel at the moments of maximum and minimum currents through the armature of the fifth projectile

Figure 5 shows the results of the calculation of the operation of the following launcher model: length of the launcher 3 m, number of pairs of rails 3, cross-sectional area of each rail 4 см^2, initial resistance of the bridges 14 mohm, inductance of the bridges 0.7 µH, number of projectiles in succession 20, weights of the projectiles m_1 = 90 g, $m_2,\ldots,m_{19}$ = 75 g, m_{20} = 120 g, and initial projectile velocity 150 m/s.

In this version of the calculation, launching of projectiles of substantially smaller weight with a higher initial velocity of entry into the launcher is considered. In this case, the firing rate increases considerably and reaches 1330 Hz. The exit velocity of all twenty projectiles from the launcher is 3.2 km/s. Due to the increased rate, the initial distance between the projectiles leaving the launcher is about 2.3 m. In this version of the calculation, the rail temperature in the entrance section reaches 100^{o} C, which is the maximum permissible value that limits the number of projectiles in succession. The pressure in the entrance section of the electrode zone is higher than the pressure in its exit section throughout the process (see Fig. 5d), which indicates shock-free flow in the MHD channel, but the cathode pressure at the channel exit is close to the pressure at its inlet. Therefore, this launching mode is ultimate for the device in question.

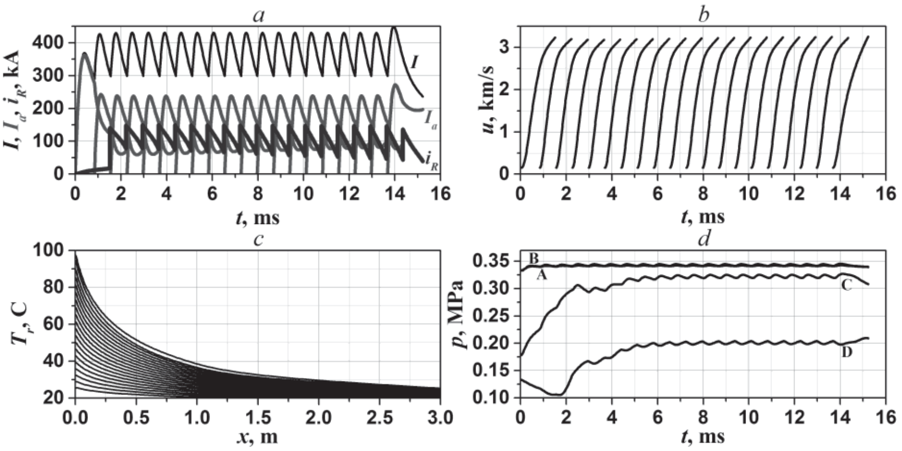

Fig.5 Calculated parameters of the process of successive launching of twenty projectiles

It should be noted that the “Sakhalin” PMHDG is a development of the seventies of the last century with a characteristic plasma conductivity of 30–80 S/m[9]. The propellant consumption in it is about 1 kg/ms. Using modern propellants[19], it is possible to generate a plasma with a conductivity of 120–160 S/m, which allows a reduction in the weight and size characteristics of the generator due to a decrease in the propellant consumption by a factor of more than two.

4 Conclusions

The problem of calculating the joint operation of an MHD device (total power of 1 GW) consisting of two “Sakhalin” PMHDGs and an arcless multirail launcher with cyclically varying resistance and inductance was formulated and solved.

It has been found that the cyclic operation of the launcher does not lead to the development of separated flows in the MHD channel and a qualitative change in the electrical characteristics of the MHD generator.

It has been shown that rapid-fire launching of twenty projectiles with a frequency of 350–1300 shots per second can be implemented with stably reproduced dynamic characteristics in each cycle of operation of the device.

The calculations illustrate the high adaptive capacity of the PMHDG powered by a rapid fire electrodynamic launcher.

Results of the study show that the use of pulsed MHD generators operating on plasma-generating solid propellants as a power supply for rapid fire high-velocity railguns provides great opportunities for launching solids weighing tens of grams to several hundred grams to velocities above 2–3 km/s.

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References

[1] Shvetsov G. A., Titov V. M., Bashkatov Yu. L., et al. Operation of a railgun accelerator for solid projectiles powered from an explosive MHD generator, in: Ultrahigh Magnetic Fields. Physics. Techniques. Applications. Proceedings of the Third International Conference on Megagauss Magnetic Field Generation and Related Topics. Nauka, Moscow, 1984. P. 177–182.

[2] Harada Nob. Space application of non-equilibrium MHD generator, 2nd Int. Workshop on Magnetoplasma Aerodynamics in Aerospace Applications. Moscow, Russia, 2000. P. 325−329.

[3] Sinyaev S. V., Burkin B. V., Pimonov E. Yu. Toward the development of a high-rate electrodynamic accelerator: Results of experimental and theoretical studies, in: Modern methods of design and development of missile and artillery weapon systems. Proc. Conf. of the Volga regional center of RARAN. Sarov, VNIIEF, 2000. P. 507–512.

[4] Schneider M., Wötzel M., Wenning W. The ISL Rapid Fire Railgun Project RAFIRA-Part II: First Results, IEEE Trans. Magn., 2009. V. 45, No. 1. P. 448–452.

[5] Schupper Ch., Alonahabi F., Schneider M. Electomechanical Aspects of Reliable Loading Procedures for Multishot Railguns, IEEE Trans. on Plasma Science, 2013. V. 41, No. 5. P. 1387–1391.

[6] Velikhov E. P., Dyogtev Yu. G., Dogadaev R..V., Panchenko V. P., et al. Experimental and Numerical Study of Properties of Combustion Products of Advanced Solid Plasma-Generating Propellant for Pulsed MHD Generators, Proc. 17th Int. Conf. on MHD. Kanagawa, Japan, 2009, P. 72–89.

[7] Velikhov E. P., Matveenko O. G., Panchenko V. P. et al. Pulsed MHD power system “Sakhalin”– the world largest solid propellant fueled MHD generator of 500 MWe electric power output. Proc. 13th Int. Conf. on MHD and HTT, China, Beijing, 1999. Vol. 2. P. 387–398.

[8] Poltanov A. E., Kondratenko A. K. et. al. Multi-Turn Railguns: The Concept Analysis and Experiments, IEEE Trans. Magn., 2001. V. 37. No. 1. P. 457–461.

[9] Gomozov V. A., Matveenko Z. I., Panchenko V. P. Experimental study of the characteristics of the condensed phase in the combustion products of pulsed MHD generators, Teplofiz. Vysok. Temper, 1992. Vol. 30. P. 1006–1011.

[10] Breev V. V. Gubarev A. V., Panchenko V. P. Supersonic MHD generators, Ed. by Gubarev A. V. Energoatomizdat, Moscow, 1988.

[11] Pulsed MHD converters of chemical energy into electrical energy, Ed. by Sheindlin A. E. and V. E. Fortov. Energoatomizdat, Moscow, 1997.

[12] Sinyaev S. V. Method of calculating the force and electromagnetic parameters of complex systems of conductors in problems of electrodynamics, Abstracts of the Third Siberian Congress on Industrial and Applied Mathematics. Publishing House of SB RAS, Novosibirsk. 1988, Part 3. P. 40.

[13] Honjo R. T., Del Vechio R. M. A program to compute magnetic fields and inductances due to solid rectangular conductors arbitrarily positioned in space, IEEE Trans. Magn., V. 22. No. 5. 1986. P. 1532–1535.

[14] Butov V. G., Galkin V. M., Golovizin V. M. et al. Numerical modeling of spatial two-phase flows in supersonic MHD generators, Preprint IAE-5276/16. Kurchatov Institute of Atomic Energy. Moscow. 1990.

[15] Panchenko V. P. Preliminary analysis of the “Sakhalin” world largest pulsed MHD generator, Proc. 14th Int. Conf. on MHD and HTT. USA, Maui, Hawaii. 2002. P. 193–202.

[16] Afonin A. G., Butov V. G., Sinyaev S. V. Mathematical modeling of the operation of a pulsed MHD generator with a cyclic load with variable electrotechnical parameters, Izv. Vuzov. Fizika 2008. V. 51. No. 8/2. P. 11–18.

[17] Afonin A. G., Butov V. G., Sinyaev S. V. Flows in the pulsed MHD generator channel in operation with various electromagnetic loads, Izv. Vuzov. Fizika. 2013. V. 56. No. 9/3. P. 5–8.

[18] Knopfel H. Pulsed high magnetic fields, American Elsevier, New York, 1972.

[19] Velikhov E. P., Dogadaev R. V., Panchenko V. P., Yakushev A. A., et al. Properties of the combustion products of solid (powder) plasma-generating propellant for pulsed MHD generators. Doklady Akad. Nauk, 2010, Vol. 434, No. 2, P. 1–6.