To on-board MHD power generation

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Abstract. The electric power generation in on-board MHD generator is considered under conditions of vehicle’s flight in Earth atmosphere. The physical and computational model of on-board MHD power generation is presented. It is shown that electric power of order of 18 – 20 MW (or ~ 100 W/cm³) can be extracted in ordinary Faraday-type segmented MHD generator. This high level of electric power is achieved at magnetic field about 0.3 – 0.4 tesla and constitutes nearly 9.5% of total enthalpy flux. The main factor limiting the rise of extracted power is a stall of flow due to MHD deceleration.

1. Introduction
The concept of on-board electrical power production with an MHD generator converting the kinetic energy of high-speed external flow to electricity has been proposed in early 1990th. The ensuing theoretical studies on this subject demonstrated the feasibility of extraction of power about 1 MW under re-entry flight conditions [1 – 3]. The principal ability to obtain electricity from the high-speed flow is due to ionization of air in the shock layer around the vehicle and rather high speed of the flow in it. Experimental studies in on-ground surface-based MHD Facility [7] demonstrated a power extraction of order of 60 W per 30 cm² of the surface. In those experiments, the flow Mach number was M=12, and 2 ms pulsed magnetic field amplitude was 2 T. Later, theoretical works [8, 9] demonstrated much higher power level in surface-based MHD generator under conditions of Earth’s re-entry flight.

In [4 – 6], the surface-based MHD generator was replaced with those representing air in-take unit. This modification of generator was successfully tested in Hall-type MHD generator [8], and 3 MW (or 5% of total enthalpy flux) of electric power was numerically obtained. Almost same scheme as in [8] is considered in the current paper. But some changes are suggested to increase the extracted electric power.

2. Problem setup
Consider an air flow between two thick plates organizing the MHD channel which represent the simplest in-take unit, see figure 1. Both plates have cylindrical ends. In the computational domain shown in figure 1(a), the flow is assumed to direct from left to right. The structured computational grid consists of 278 grid lines along the channel, and 123 grid lines across one. The thickness of the plates is taken as 0.1 m. The height of the channel at the inlet is 0.14 m, and it is 0.24 m at the exit of the channel. In 3rd direction (Z) the size of the channel is assumed to be 1 m. The total length of the channel is 1.95 m. figure 1(b) represents distribution of magnetic field Bz. Such magnetic field can be
induced by two current loops located below bottom and above top wall, respectively (see, for example, [8]). Also, the electrode walls of MHD channel are schematically shown, details will be discussed later.

![Diagram of flow in MHD generator](image)

**Figure 1.** Scheme of the flow in MHD generator (a) and distribution of magnetic field $B_z$ within the channel (b).

To estimate electric power extracted in MHD channel which is a part of in-take channel shown in figure 1 let’s consider the two-dimensional flow in the plane $x0y$ in figure 1. The physical and computational model of non-equilibrium MHD flow presented in papers [6, 12] seems to be suitable to describe the flow under consideration. In contrast to MHD generator scheme of [8] we consider classic Faraday-type MHD generator, in which plasma takes place due to ionization of air behind a system of strong shock waves. The latter are consequence of flow pattern in in-take unit, see, for example, figure 2. As in [6], let’s consider that quasi-steady electrodynamics equations along with generalized Ohm’s law are valid.

Here, we consider another kind of electric loading of the MHD generator than those considered in [8]. This is expressed in setting boundary conditions. In the current paper, the boundary conditions are specified as follows. Most of the wall including the round parts are considered as electric insulator, and zero current condition is set, $Jn=0$ ($n$ is unit normal vector). Electrode walls of length of 64 mm are subdivided by 10 segments (see figure 1). Every segment consists of electrode which has the length 48 mm and insulator which has the length 16 mm. Electric potential is set at each of 20 electrodes (10 electrodes are on the bottom wall, and 10 electrodes are on the upper wall). Each of 20 potential values are found from the conditions $I_k(t), k=1,…,20$. Here, $t$ is time, $I_k$ is the total current into the $k_{th}$ electrode. Time dependent current conditions are specified just to provide a stability of the solution.

3. Results

Let’s consider the MHD flow in in-take MHD channel for the following free-stream conditions: $\rho = 1.0 \cdot 10^{-3}$ kg/m$^3$, $p = 68.8$ Pa, $V = 11100$ m/s, $T = 238.5$ K, $M = 35$, $T_{wall} = 2500$K. We shall characterize the magnetic field (see figure 2) by the value $B^*$ in the center of MHD channel. Example of gasdynamic field is presented in figure 2 by pressure distributions.

Figure 2 demonstrates well known feature of MHD interaction in MHD channel, namely, a rise of pressure in the channel. Typical pattern of electrical characteristics in current-driven MHD generator
is presented in figure 3. The operation mode for the picture corresponds to the extracted electrical power \( W_e = 19 \text{ MW} \), which constitutes 9.5\% of the total enthalpy flux.

The nature of the flow in the mode of generating electric power is shown, for example, figure 3,4. These distributions correspond to the flow in the mode of generating a power of 19 MW, close to the maximum achieved. This power is achieved at a magnetic field \( B^* = 0.32 \text{ T} \) and full current \( I_{\text{tot}} = 200 \text{ kA} \). \( I_{\text{tot}} \) is a current flowing in the channel. According to the boundary conditions, this means that the total current for each of the 10 sections is 20 kA. It can be seen from figure 3 that voltage drop between the anode (upper wall) and the cathode is not very large, 163 V. That is, the electric fields are on average very small, and one should not expect the effects typical for high-voltage discharges (dissociation and ionization by a high field, not by a high temperature). We can say that we are dealing with a discharge similar to an arc.

**Figure 2.** Pressure field in in-take channel. No MHD case – upper plot; MHD power generation mode – bottom plot. \( B^* = 0.32 \text{ T}, I_{\text{tot}} = 200 \text{ kA}, W_e = 19.1 \text{ MW} \).

**Figure 3.** Electric potential (colored) and electric current stream function (black) for MHD power generation mode. \( B^* = 0.32 \text{ T}, I_{\text{tot}} = 200 \text{ kA}, W_e = 19.1 \text{ MW} \).
Figure 4. Specific power (colored) and ponderomotive force (black vectors) for MHD power generation mode. \(B^*=0.32\text{T}, I_{\text{tot}}=200\text{kA}, W_e=19.1\text{ MW.}\)

Figure 4 shows the electric power density \(J E\) (color fill) and the ponderomotive force density field \(J \times B\) (vector). This figure clearly shows where energy is generated (dark blue), and where it is dissipated (yellow-red areas near the electrodes). A small energy dissipation (heating) also occurs before and after the MHD channel. This is due to the boundary conditions of zero-current at the entrance to the channel (the system of jumps to the left of the MHD channel is a non-conducting boundary) and at the output boundary of the region. Figure 3 shows that the scale of the longitudinal current near these boundaries is small (the number of current lines in the electrode region is \(\sim 50\), the number of current lines near the boundaries is 1, i.e. the distortion of the solution by boundary conditions is not significant). We also note the insignificant influence of the MHD interaction on the flow at the entrance to the air intake (near the blunted plates). The (longitudinal) current flow in this distant zone is caused by the presence of an induced voltage between the MHD channel zone and the grounded section on the left border of the region.

Figure 5 is a typical power diagram for MHD generators of the Faraday type. The maximum power is reached at the values of the characteristic magnetic field of 0.32-0.4 T. As can be seen from figure 5, the maximum extracted power has a scale of 20 MW. This estimate can be obtained based on classical simple relations for the characteristic values of parameters and spatial scales.

Figure 5. Total electric power vs characteristic magnetic field and total current.

These characteristic values were taken as the average values of the corresponding parameters in the center of the channel, in the area of the maximum magnetic field. The following parameter estimates were used: \(Y^*=0.19\text{ m}, U^*=2500\text{ m/s}, \sigma^*=2750\text{ mho/m}, B^*=0.15\text{ T}, X^*=1\text{ m}, Z^*=1\text{ m}.\) These parameters are the result of solving the problem discussed above. For them, we obtain an estimate of
the power \( W^* = \frac{1}{4} \times \sigma^* (U^*)^2 (B^*)^2 X^* Y^* Z^* \approx 19.3 \text{ MW} \). Thus, in the MHD channel with a volume of \(~0.2 \text{ m}^3\), it is possible to obtain electrical power at the level of 100 W/cm\(^3\). Of course, such a good estimate is based on a successful choice of determining parameters, which themselves are the result of the solution. Finally, we note that the extracted electrical power is approximately 9.5% of the total enthalpy flow entering the MHD channel.

4. Conclusions
The main conclusion from the numerical studies of the MHD power generation in an in-take MHD generator is that the density of the extracted power at the level of \(10^{-100}\) W/cm\(^3\) is possible for the conditions of re-entry flight. This corresponds to the electric power of 20 MW for small-size MHD generator (0.2 m\(^3\)). In turn, this value constitutes 9.5% of the total enthalpy flow entering the MHD channel.

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References
[1] Bityurin V A, Zeigarnik V A, and Kuranov A L On a Perspective of MHD Technology in Aerospace Applications 1996 27th Plasmadynamics and Lasers Conference New Orleans: AIAA 96-2355
[2] E P Gurjanov and P T Harsha 1996 AJAX: New Directions in Hypersonic Technology 27th Plasmadynamics and Lasers Conference New Orleans: AIAA 1996-4609
[3] Bityurin V A, Lineberry J T, Potebnya V G, et al. Assessment of Hypersonic MHD Concepts June 23–25 1997 28th Plasmadynamics and Lasers Conference Atlanta, GA: AIAA 97–2393
[4] A N Bocharov, V A Bityurin, J Lineberry Study of MHD Interaction in Hypersonic Flows The Proc.15th International Conference on MHD Energy Conversion and the 24-27 May 2005 Proc. 6th International Workshop on MagnetoPlasma Aerodynamics IVTAN Moscow p 399
[5] V A Bityurin, A N Bocharov MHD Flow Control in Hypersonic Flight Proc. 15th International Conference on MHD Energy Conversion May 24-27 2005 Proc.6th International Workshop on Magneto-Plasma Aerodynamics, IVTAN, Moscow p 429
[6] Bityurin V A, Bocharov A N and Popov N A 2019 Magnetohydrodynamic Deceleration in the Earth’s Atmosphere, J. Phys. D: Appl. Phys. 52 354001 (pp 7)
[7] Bityurin V, Bocharov A, Baranov D and Bychkov S Power Extraction Experiment with a Surface MHD Generator in Hypersonic Airflow 38th AIAA Plasmadynamics and Lasers Conference In conjunction with the June 25-28 2007 16th International Conference on MHD Energy Conversion Miami FL AIAA(2007)3882
[8] V A Bityurin and A N Bocharov 2011 MHD Generator Onboard Space Capsule Technical Physics Letters 37 4 376–378
[9] Macheret S O, Shneider M N, Candler G V, Moses RW, Cline J F Magnetohydrodynamic Power Generation for Planetary Entry Vehicles 28 June–1 July 2004 35th AIAA Plasmadynamics and Lasers Conference Portland Oregon: AIAA (2004)2560
[10] Wan T, Candler G V, Macheret S O, Shneider M N, Miles R CFD Modeling and Simulations of MHD Power Generation During Re-Entry 28 June–1 July 2004 35th AIAA Plasmadynamics and Lasers Conference Portland Oregon: AIAA (2004)2562
[11] Bityurin V A and Bocharov A N 2006 MHD Interaction in Hypersonic Airflow Around a Blunt Body Fluid Dynamics 41 843
[12] A N Bocharov, V A Bityurin 2018 MHD heat flux mitigation in hypersonic flow around a blunt body with ablating surface Journal of Physics D: Applied Physics 51 26 264001