Current-voltage characteristics of a discharge in a supersonic flow of ionized air in permanent magnets field

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Abstract. The work is devoted to the development of direct conversion devices of energy of high-enthalpy hypersonic gas flow into electrical energy. The experiments were carried out to study the electrical characteristics of the gap between two electrodes filled with weakly ionized plasma of the airflow at the wind tunnel with a magnetogasdynamic accelerator SMGDU. The voltages induced in the field of permanent magnets and the corresponding induction currents were measured with an ohmic load in the external circuit. The current-voltage characteristics of the discharge are constructed for the case of an additional supply of a current pulse from an external source to the interelectrode gap. The conductivity of the medium in the gas flow and the MHD interaction parameter were estimated. The results obtained can be used in the design of surface MHD generators for the autonomous production of electrical power on board of a hypersonic aircraft.

There is an opportunity to extract electrical power from the kinetic energy of the airflow when a hypersonic vehicle flies in a weakly ionized atmosphere. If there is a system on board that generates a magnetic field in the area between the electrodes the voltage induced creates an electric current in the payload. Devices that use the principle of direct conversion of the energy of a high-enthalpy gas flow into electrical energy are well known [1]. A simulation of such a MHD generator was carried out as applied to real conditions of high-altitude flight in paper [2]. It was shown that the power generated can reach a megawatt level at moderate fields of 0.3-0.5 T and relatively small channel sizes. The use of similar generating devices as part of a flying body has its own specifics, since the elements of their structure should not affect the flow around the vehicle and its control.

Investigations of this work are aimed at creating surface MHD generators in which the magnetic field was formed near a plane, for example, a wing flown around by a supersonic flow, and the electrodes slightly protruded beyond the boundary layer.

The experiments were carried out on the set-up with a magnetogasdynamic accelerator SMGDU [3]. The air heated by the electric arc heater and supplemented with an ionizing additive passed through the channel of the MHD accelerator acquiring an additional speed in this wind tunnel. 35 pairs of electrodes of the heat-capacitive channel were involved. The total input power reached 400 kW. Finally, a square outlet nozzle produced a 25 mm wide supersonic flow. Numerous experiments and calculations have confirmed the high efficiency of this approach. For example, computer simulation of
one of the designs of the MHD accelerator showed that even with a smaller number of electrodes used and a lower energy input it is possible to achieve high parameters of a supersonic gas flow at the outlet of the MHD channel, namely: a flow velocity of 3.8 km/s at a Mach number of 3.6 and specific enthalpy over 11 MJ/kg [4].

The test model was mounted in the Eiffel chamber and contained the main units of the MHD generator: a magnetic system and electrodes. In this series of experiments magnetic field was created by permanent neodymium magnets. It should be noted that a strong magnetic field of a single magnet exists in a narrow layer at its edges. The field is small and rapidly decreases along the normal to the surface in central region. To enhance the field five permanent magnets were placed in one plane in a certain sequence in accordance with the so-called Halbach magnetic assembly [5]. The magnetization vectors of the individual magnets were rotated relative to each other by 90 degrees in this assembly. This led to the fact that the compensation of the magnetic flux from the bottom of the array aduced to its amplification from the top. As a result, the magnetic flux at the bottom was practically completely absent, and at the top it was almost twice as intense. Halbach array modeling in FEMM 4.2 revealed the following details. The magnetic field components that were perpendicular to the assembly surface and effect on the ionized gas flow were formed above two of the five magnets and were contrary to each other. The field was not homogeneous. Its induction was falling by 2 times at a distance of just over half the characteristic size of the magnet. The addition of a magnetic circuit shorting the magnetic flux in the bottom of the assembly further reduced the field to almost zero without changing its magnitude and distribution above the top of the assembly.

The magnetic system was mounted from 5 cubic elements with a side of 20 mm. Nd-Fe-B magnets of grade N38 were used. It should also be noted that the Halbach assembly was technically difficult to get together due to the noticeable repulsive forces between the magnets. To overcome these forces the magnets were setted in thick-walled textolite housing on a steel plate located below and acting as a magnetic circuit. All elements were additionally fixed with clamping bolts. The magnets were protected from the high-temperature flow by a 3 mm silicon nitride plate to avoid the loss of their properties due to overheating. The magnetic field was measured with an ATE-8702 teslameter after the magnets were installed. The measured and calculated dependences of the normal component of the magnetic field on the coordinate along the plane of the assembly for different distances from its surface are compared in Figure 1.

Figure 1. Distributions of induction of the normal component of the magnetic field along the Halbach assembly: black solid line - calculation results at a distance of 2 mm from the surface of the
magnets; blue triangular and red diamond points - data measured at a distance of 2 and 7 mm from the surface of the magnets, respectively.

The vertical solid lines correspond to the edges of the magnets. The measurement data repeated the field distributions obtained by calculation at 15% lower values of the magnetic flux. Most likely, these discrepancies are related to the difference between the magnetic properties of real materials and the characteristics included in the calculation. Despite this, the goal of creating a constant strong magnetic field was achieved. The induction of the field normal component on the assembly surface exceeded 0.6 T.

For efficient generation of electricity it is necessary that the vectors of the flow velocity, magnetic field induction and current density between the electrodes are mutually perpendicular. To meet these conditions electrodes were mounted on the container with magnets on either side of the conductive gas flow. Two pairs of electrodes were installed above the second and fourth magnets where the acting component of the magnetic field had the highest values. The distance between the electrodes of each pair across the flow was 25 mm.

A series of runs of the SMGDU wind tunnel was carried out to determine the electrical characteristics of the discharge gaps. The voltages induced on each pair of electrodes by the conducting gas moving in the permanent magnetic field as well as the electric current flowing between the first pair located closer to the nozzle were recorded in these experiments. The measured voltage on the first pair was negative and amounted to 6.0-6.5 V at the current of 1.0-1.1 A in a case when electrodes were shorted via 4.9 Ohm. Hence the resistance of this plasma gap was 1.1 Ohm. The voltage on the second pair was positive and did not exceed 1 V. The different polarity of the signals was due to the mutually opposite directions of the magnetic field in the zones where the electrodes were located. The lower voltage level on the second pair was apparently associated with its location in the shadow of the first pair that led to a significant change in the parameters of the gas flow around the second pair of electrodes.

Such measurements gave only one point on the current-voltage characteristic. It was necessary to change the ohmic load in the electrode circuit before each run to measure other points. This path was labor-intensive, limited by the resource of the set-up and the repeatability from run to run of the characteristics of the supersonic flow, for example, the plasma conductivity. A current pulse was applied to the first pair of electrodes from an external source in order to obtain a data set during one run. The current pulse was formed as a result of the discharge of the capacitor bank through the ballast resistor and the plasma gap. A sharp rise in the current at the beginning of the pulse was accompanied by a relatively slow decrease in its value later on. The discharge time constant was determined by the capacitance of the capacitors equal to 4.8 mF and the ohmic resistance of the circuit. The latter value was equal to 8 and 16 ohm in two series of experiments which corresponded to the time constant of the discharge about 40 and 80 ms at a maximum current of 120 and 60 A. The rate of the pulse rise was limited by an inductance of 250 µH.

Typical current and voltage waveforms between a pair of electrodes are shown in Figure 2. The signals clearly show the moments of the beginning and the end of the stage of the MHD accelerator operation with duration of 0.8 s. A current pulse was applied to the electrodes approximately in the middle of the run.

The integral volt-ampere characteristics were constructed (Figure 3) based on the preliminary smoothed data. Similar dependences can be described by a numerical model of a contracted discharge on a flat electrode [6, 7]. The interelectrode gap contains two layers therein. The space of the first wide layer is filled with a linear conductive medium with constant and sufficiently high electrical conductivity. The second layer is much narrower with low electrical conductivity. This resistive layer that breaks through is located on the surface of the electrode. Its resistivity is described by a function that nonlinearly depends on the current density. The current initially is diffuse one at a gradual increase in the voltage between the electrodes until its density reaches a critical value in a certain region of the resistive layer. Thereat the layer breakdown occurs and the entire discharge current is
collected in a thin cord. A further increase in voltage leads to the emergence of new micro-arcs. The transition from a diffuse current to an arc was experimentally observed earlier, for example, in a plasma flow of combustion products [8].

![Figure 2](image)

**Figure 2.** Oscillograms of the current (blue line) running through the plasma of a supersonic flow and the voltage (red line) that measured at the electrodes.

![Figure 3](image)

**Figure 3.** Examples of current-voltage characteristics obtained with different ballast resistors in the discharge circuit: red line - 8 Ohm, blue line - 16 Ohm.

Indeed, two parts of the current-voltage characteristic are easily distinguishable in Figure 3. The first part corresponded to the diffuse current flow between the electrodes. This part was characterized by an almost linear and slow rise in current with voltage increasing. The slope of the graph was constant and determined the ohmic resistance of the plasma section of the circuit. It can be seen that its value was about 1.3 Ohm and practically did not depend on the ballast resistor. The value determined
in this way was close to the electrical resistance obtained above without using an external source due to the measurement of current and voltage induced in the permanent magnetic field. Thus, the resistance of the plasma bulk was determined by two independent methods that increased the reliability of measurements. Then it was possible to estimate the conductivity of the medium in the gas flow, knowing the size of the electrodes and their location. Its value corresponded to the level of 100 Sm/m. The moments of appearance of the high-current micro-arcs are clearly visible in the form of sharp bends on the second much steeper part of the volt-ampere characteristics.

The existence of two modes of electric current flow was confirmed by frames of high-speed shooting of the supersonic air stream around the model (Figure 4). The secondary nozzle 1 is on the right and the Pitot tube 2 is on the left in this image. The supersonic flow is directed from right to left, respectively. The electrodes 3 (anode) and 4 (cathode) mounted on the model are at the top and at the bottom of the photo. The presence of contact spots 5 on the electrodes was observed only in the contracted discharge mode.

![Figure 4. A frame of high-speed shooting of a supersonic flow between the electrodes of the model. The directions of the vectors of the electric field strength $E$ and magnetic induction $B$ in the zone of strong magnetohydrodynamic interaction are shown.](image)

The values of conductivity obtained were 800-1300 Sm/m if assume that the value of 1.3 Ohm measured above corresponded to the resistance of a thin resistive layer and all the electric current flowed through one arc with a diameter of 0.6-1.1 mm. In fact these values were an order of magnitude lower since up to 10 traces of micro-arcs on the electrodes were clearly distinguishable in high-speed shooting frames.

The usefulness of measurements of current-voltage characteristics is that they allow you to evaluate some parameters of the medium in which the discharge occurs. In our case it became possible to determine the electrical conductivity of air ionized by a seed in the supersonic flow of SMGDU. This value in turn gave an opportunity to estimate the parameter of the magnetic interaction $S$, which is the criterion for assessing the effect of the electromagnetic field on the flow of a conducting gas [9]:

$$S = \frac{\sigma B^2 l}{\rho \omega},$$

where $\sigma=100$ Sm/m is the specific electrical conductivity of the medium determined above, $B=0.35$ T is the average value of the effective component of the permanent magnetic field in the MHD interaction region, $l=0.02$ m is the longitudinal size of this region, $\rho=0.01$ kg/m$^3$ is the density of the
medium and \(w=4000 \text{ m/s}\) is velocity of the supersonic flow. With these parameters, which are typical for the SMGDU wind tunnel, \(S = 0.006\).

It is required to achieve significantly higher values of the MHD interaction parameter to influence the supersonic flow in order to control its characteristics [10]. This can be achieved under the conditions of this experimental setup by a sharp increase in the magnetic induction and the size of the interaction region. The use of pulsed power supply systems for multi-turn coils provided an increase in magnetic field by an order of magnitude in a large volume within some milliseconds [11]. Nevertheless, magnetic systems mounted from strong permanent magnets can find their application for act the boundary layer formed when flowing around a body.

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