The operating mode of the water-cooled MHD accelerator of SMGDU with a magnetic field that changed along the channel

D S Baranov, V A Bityurin, A N Bocharov, S S Bychkov*, V A Grushin, E V Kusmartseva, N V Tretyakova, N I Batura, N G Zhurkin and N M Kolushov

1JIHT RAS, Moscow, Russia
2TsAGI, Zhukovsky, Russia

*serg-bychkov@yandex.ru

Abstract. The work is aimed at solving the problem of creating in laboratory conditions hypersonic high-enthalpy gas flows that parameters are kept constant for 5-10 seconds. For this purpose the test section of the MHD channel with water-cooled electrodes and side walls was under investigation at the set up with a magnetohydrodynamic accelerator in TsAGI. A new series of runs was performed in which the MHD-acceleration stage was successively increased to 5 seconds. It was determined that the electrical and gas-dynamic characteristics of the MHD accelerator did not depend on the duration of the run. It was first demonstrated that the use of a magnetic field special shaped along the axis of the channel made it possible to avoid catastrophic damage to the side walls of the channel at the entrance and exit of the MHD accelerator, which increased the service life of the installation.

The experiments were carried out at TsAGI on a unique in the world wind tunnel with a magnetogasdynamic accelerator (SMGDU). The feature of the test stand is that the acceleration of the conducting gas to hypersonic speeds is provided using the MHD accelerator that converts the main part of the electrical energy supplied from outside directly into the kinetic energy of the flow. The schematic diagram of such a tunnel with a heat-capacitive MHD channel and its characteristics are described in detail in paper [1]. The same review presents the experimentally obtained maximum values of the velocity of the hypersonic flow formed in the Eiffel chamber which reached 8 km/s with a Mach number of 15. Numerous researches have been performed at SMGDU over the years of its employment. The results of experimental investigation of airflow past simplest model bodies at different velocities are presented in [2], as example.

The use of a channel that accumulates heat in structural elements limits the time for the existence of a high-speed gas stream up to 1 second. The time-limit is due to the melting of copper electrodes and the rapid erosion of insulators exposed to high thermal and electrical loads. This circumstance significantly reduces the range of application of the facility for the study of promising technologies and materials. The possibility of increasing the duration of the acceleration stage by an order up to 10 seconds while maintaining the level of total pressure was demonstrated in [3, 4 and 5]. To achieve this goal the standard channel of the MHD accelerator was replaced by a new channel in which the electrodes and side walls were cooled with running water. However the destruction of the side walls at the ends of the channel was observed in separate runs when the energy input was increased. It is
known that end effects manifest themselves due to the inhomogeneity of the boundary conditions that have effect on the distribution of currents and potentials at the input and output of the MHD channel [6]. In our case the melting of the insulators and after them the metal walls up to the water circuit was caused apparently by electric currents arising as a result of shorting the induced Hall potential through an external circuit. This phenomenon was recorded only in the edge zones, where there were no longer loaded electrodes, but there was still a strong magnetic field.

The task of this work was to search for modes of trouble-free operation of the MHD accelerator equipped with a water-cooled channel. Measures were taken to weaken the magnetic field at the entrance and exit of the MHD accelerator not much changing it in the zone of the central loaded electrodes since the efficiency of acceleration increases rapidly with increasing magnetic flux density.

The magnetic field induction on the axis of the MHD accelerator was precomputed by the FEMM 4.2 software. Since the program considers only plane and axisymmetric tasks the cross section of the electromagnet was considered in which the dimensions of the core, the position of the coils, of the steel magnetic insertions and the MHD channel were specified. An example of the calculation for ten coils connected in series with a total number of turns 420 and a direct current of 200 A is demonstrated in Figure 1, in which the field distribution is shown by magnetic induction lines.

![Figure 1](image_url)

**Figure 1** A vertical section of the electromagnet with the results of the calculation of the magnetic field distribution.

The electromagnet of the installation was divided into two equal halves. Each of them was an E-type core assembled from electrical steel sheets. The MHD accelerator was located in the gap 1 between the poles of the central core 2 on which the coils of the current windings 3 were fixed. The MHD channel was bounded on sides by steel walls 4 insulated from a flow of conducting gas, and from above and below by sectioned electrode walls consisting of electrode-insulator pairs (are absent in Figure 1). The lateral walls were adjacent directly to the pole tips of the electromagnet. The gas flow was directed perpendicular to the plane of the drawing. Thus, the magnetic induction vector was oriented across the velocity vector of the working medium and the electric field intensity vector.

The magnetic field inside the channel was uniform in usual mode. The resistance of the magnetic circuit that is closed through the side parts of the magnetic core was increased due to the organization of the air gap to weak the field at the edges. This gap was filled with inserts of magnetically soft steel.
5 and 6 in the middle part of the electromagnet. Thus, the magnetic field had maximum value in the central zone of the MHD channel that covering approximately 11 electrode pairs.

The magnetic flux density distributions along the MHD channel axis were measured with a teslameter at two current values in the electromagnet winding: 117 and 200 A. The data obtained and their approximations by polynomials (solid lines) are shown in Figure 2.

![Figure 2](image)

**Figure 2** The distribution of the magnetic field along the axis of the MHD channel: dotted line - calculation; circles - measurements.

Zero on the z axis matches with the middle of the MHD channel. The dashed line is constructed according to the results of calculating the magnitude of the induction for two vertical cross-sections of the magnet core when 200 A electric current flowed in the winding. The central part of the graph corresponds to a cross-section in which all the gaps that appeared were filled with magnetic conductive material and the parts of the graph with lower values of induction that located to the left and to the right of it fits cross-sections where air gaps were originated. The magnetic field values calculated had exceeding slightly the data measured. The fact is that it was assumed in the calculation that the core and the inserts were made from pure iron that is the properties of real materials were not taken into account.

As a result of the preparatory work a case of a magnetic field changing along the gas path was realized. It was not constant and reached a maximum value only in the center of the channel. Nevertheless it is possible to distinguish three regions with different average values of induction: the central region where the field had the highest values and two regions symmetrically located along the edges of the channel in which the field was weaker by about 15%. Further the field had weakening quickly to the ends of the channel.

New series of runs were carried out at SMGDU wind tunnel with an MHD channel cooled by water and a magnetic field that varied along the axis of the MHD accelerator. The test unit was a quadrangular channel with two side insulating walls and with two electrode walls with sectioned electrodes. The number of electrode sections was 21. The sectioning step (total length of the electrode and insulator) was 13 mm. The width of the cooled copper electrode was 10 mm. The insulators were made of boron nitride. Their thickness was 3 mm. Steel side walls were also insulated from the flow with boron nitride plates. The 555 mm long channel expanded in the vertical direction from 15x15
mm² inlet cross-section to 15x25 mm² outlet cross-section. Each electrode pair of the MHD accelerator was connected to an independent power source according to the Faraday scheme.

Fifteen pairs of electrodes from 4 to 18 were involved during the runs. Extreme electrodes 1 through 3 and 19 through 21 were not connected to the power supplies. The maximum magnitude of the magnetic field at a current of 117 A in the electromagnet winding was about 1 T. All runs were performed under the same conditions and differed only in the duration of the gas flow acceleration stage. In each case the distributions of the main electrophysical parameters along the channel were recorded: currents and voltages between the electrodes, as well as Hall (longitudinal) voltage. The data obtained are presented in Figure 3 (currents) and Figure 4 (voltages) respectively as dependencies of the measured characteristics on the sequence number of loaded electrodes.

![Figure 3](image1.png)

**Figure 3** Currents between electrode pairs.

![Figure 4](image2.png)

**Figure 4** MHD accelerator electrode potentials.
The current quantity varied from 30 A for the first of the electrode gaps that loaded to 55 A for subsequent pairs of electrodes while the voltage between them reduced from a maximum level to 100 V. The growth in the electric current between electrode pairs corresponded to increase of current density from 20 A/cm² to 35 A/cm². The last value from mentioned was observed for most sections of the MHD accelerator.

For each run the lower curve in Figure 4 shows the distribution of the Hall potential measured on the cathode wall of the MHD channel relative to the first of the loaded electrodes (#4). The potentials of unloaded electrodes from the 1st to the 3rd and from the 19th to the 21st were not measured in this series of experiments. On the upper curve, the corresponding anodes potentials are plotted.

The input electric power determined for each electrode pair by multiplying the corresponding currents and voltages is represented in Figure 5.

![Graph of electric power supplied to each electrode pair](image)

**Figure 5** Electric power supplied to each electrode pair from an external source.

Charts marked with the identical color corresponded to the same run. The time of the MHD-acceleration stage was successively increased from 0.6 s (run #376) to 1.5 s (run #378), then to 3.2 s (run #379) and finally to 5.2 s (run #384). It can be seen that a good agreement between the experimental data was observed. The distributions on record in the run #384 slightly fall out of the rest of the curves bundle since this run was carried out another day when the initial conditions for experiments conducting at the SMGDU were slightly different apparently.

A special place in these studies was occupied by the run #383 conducted without the switching-on of a magnetic field. Enlarged interelectrode currents were observed and the Hall potential was close to zero in this run. Since the magnetic field was switched off it can be concluded that all the electrical power about 100 kW supplied from outside was spent on heating the gas, that is, the MHD accelerator worked as an additional air heater in this mode. In the case when the magnetic field was turned on the currents between the electrodes decreased, and the voltages increased so the total power applied to the discharge gaps of 15 pairs of electrodes was 170 kW.

The readings of total pressure sensor installed in the Eiffel chamber also were recorded in addition to electrophysical measurements. Figure 6 illustrates how the total pressure varied during MHD acceleration in a short time run (blue curve) and a long time one (red curve). The pressure sensor showed lower value in the first of these since the signal did not have time to reach its maximum value due to the inertia of the air duct connecting the Pitot tube to the sensor. To illustrate this circumstance a pressure signal recorded in the run of an intermediate duration (green curve) was added to the graphs.
Figure 6. It can be seen that the measured value reached the level corresponding to a 5 second run in about 1.5 seconds.

At the end of the experiments channel was opened. The destructions of the side walls were not detected after a thorough examination of the fire surfaces. A weak erosion of the copper electrodes was observed. However, a gradual spalling of ceramic insulators was noticed that eventually led to a decrease in resistance between electrode pairs up to a short circuit.

Figure 6 The signals of the total pressure sensor measured in the Eiffel chamber: run #376 – blue curve, run #378 – green curve and run #384 – red curve.

Summing up the research data we can draw the following conclusions. Firstly, it was found that the electrophysical and gas-dynamic characteristics of the MHD accelerator did not depend on the duration of the run. Secondly, a mode with a distribution of the magnetic field modified along the axis of the MHD channel was investigated in which the destruction of the side walls was not detected even in runs lasting several seconds. It is necessary to conduct additional research into the methods of interelectrode insulators protecting in order to further increase the resource of the water-cooled channel which provides for the generation of long in time high-speed flows.

Acknowledgments
The work was carried out with the support of the Russian Foundation for Basic Research (project 18-08-00890 A).

References
[1] V.I. Alferov. Current Status and Potentialities of Wind Tunnels with MHD Acceleration. High Temp. — 2000. Vol.38. No.2. P.300-313.
[2] V.I. Alferov, A.S. Bushmin, and I.V. Egorov. Experimental Investigation of Flow Past Simple Model Bodies in Hypersonic Wind Tunnels at Similar Values of the Mach and Reynolds Numbers but at Different Physical Flow Velocities. Fluid Dynamics. — 2015. Vol.50. No.1. P.109–117.
[3] N.I. Batura, E.B. Vasilevsky, N.M. Kolushov, N.G. Zhurkin, S.I. Inshakov, I.S. Inshakov, V.A. Bityurin, D.S. Baranov, S.S. Bychkov, V.A. Grushin, V.I. Zalkind, N.V. Tretyakova. New features in the study of thermal protection of materials on the stand with magnetogasdynamic acceleration // Materials of the XXVIII scientific and technical conference on aerodynamics.
[4] N.I. Batura, N.G. Zhurkin, E.B. Vasilevsky, V.A. Bityurin, A.N. Bocharov, P.P. Ivanov, V.I. Zalkind, V.A. Mozdykov, S.S. Bychkov, V.A. Grushin, D.S. Baranov, N.V. Tretyakova. Design and the first test results of the water-cooled MHD accelerator of SMGDU TsAGI. // Abstracts of the 16th International Workshop on Magneto-Plasma Aerodynamics. Moscow: JIHT RAS, 2017. — P.15-17.

[5] D.S. Baranov, V.A. Bityurin, A.N. Bocharov, S.S. Bychkov, V.A. Grushin, N.V. Tretyakova, N.I. Batura, E.B. Vasilevsky, N.G. Zhurkin, N.M. Kolushov. Flow characteristics in the water-cooled channel of the MHD accelerator. // Journal of Physics: Conf. Series — 2018. — Vol.1112. P.012017.

[6] Magnetohydrodynamic energy conversion. Physical and technical aspects. Edited by academician V.A. Kirillina, academician A.E. Sheindlin. — Moscow: Nauka, 1982. 386 p.