Measurement of heat flux to model surface in the wind tunnel SMGDU

V A Bityurin¹, A N Bocharov¹, S S Bychkov¹*, T N Kuznetsova¹, N V Tretyakova¹, N I Batura² and N G Zhurkin²

¹JIHT RAS, Izhorskaya 13 Bd 2, Moscow 127412, Russia
²TsAGI, Zhukovsky, Russia

Abstract. The results of studies of heat fluxes that can occur in the gas supersonic flow created in the wind tunnel with a magnetogasdynamic accelerator are presented. For two operation modes of the installation, measurements of heat fluxes to the surface of a calorimetric model were performed. The dependences of these parameters on induction of magnetic field on axis of the MHD accelerator were obtained for the first time. It was found that their values reached a level of 6 MW/m². The experimental data were compared with the results of a numerical simulation of a longitudinal flow past cylinder with a flat face in the real conditions of the wind tunnel, that allowed to calculate other characteristics of the gas flow. As a result, it is shown that this setup is enabled to create high-speed gas flows with high enthalpy that can be used in the development of prospective hypersonic aircrafts.

The problem of the creation of gas flow corresponding to high-altitude flight conditions in the atmosphere is of particular importance to date. It is equally important to know the characteristics of the flow formed in the wind tunnel. A standard set of diagnostic tools used at the experimental setup with a magnetogasdynamic accelerator (SMGDU) [1-5] usually included the measurement of the total pressure behind the shock wave and the video shooting of the flow. Spectra and shadow pattern were recorded in certain runs, also. However, to solve a number of actual problems, in particular, for testing of thermal protection materials, this information is not enough. It was necessary to carry out calculations simulating the flow under real experimental conditions to obtain a more complete data set in details. The purpose of the work is to expand the list of parameters registered in the air stream generated in this experimental setup and their comparison with calculations in order to determine the total enthalpy of hypersonic flow. The results of a series of SMGDU runs to determine the heat flux to the model surface are presented below.

The energy supply to the gas was carried out by two devices in the wind tunnel SMGDU. First, the air (pressure was 0.2 MPa) was warmed up by the electric-arc heater in the plenum. After the addition of the K-Na seed (weight fraction was about 1%), the gas entered to the Faraday segmented MHD accelerator through the primary supersonic nozzle (the Mach number was 2). In the accelerator channel, amount of energy supplied outside was spent for additional acceleration of the gas. Finally, the hypersonic gas flow in the working part of the installation was formed by a secondary nozzle.

A special calorimetric model was used to measure heat fluxes. The model was a copper cylinder with a flat end facing the oncoming gas flow. The model diameter was 20 mm. At its end there were symmetrically arranged two heat flux sensors at 6 mm distance from the axis. Sensitive elements of
the sensors were copper calorimeters of cylindrical shape with 1.5 mm diameter and 5 mm length. The sensors were well insulated from the body of the model, and their inner ends were connected to the chromel-copel thermocouples. The hole in the center was intended for gas sampling in order to measure the pressure behind the direct shock wave. Its diameter was 1 mm.

The model was placed on the axis of the supersonic flow at a distance of 10 mm from the outlet of the secondary nozzle. The nozzle had a rectangular cross-section of 100 mm high and 70 mm wide. The signals recorded by the sensors of the calorimetric model during the run are shown in figure 1. The fragment of the oscillograms recording can be divided into three stages in time. The initial stage I was characterized by a steady-state total pressure $p_0'$ about 6 kPa, and a slow increase in temperature $T_1$ and $T_2$ of the two calorimetric sensors. At that time only the electric-arc heater worked. In the next stage II MHD accelerator was turned on. During its operation that continued 0.7 s there was a sharp rise in pressure to 12 kPa and a much faster increase in temperature. Finally, the phase of gradual relaxation of signals came after the accelerated flow regime (stage III).

![Figure 1](image_url)  
**Figure 1** Signals of the sensors of the calorimetric model:  
a) total pressure behind the shock wave;  
b) temperature of the copper calorimeters.

In the measurement method used, the average heat flux to the surface of the model $q$ is proportional to change of the hot junction temperature $dT_s$ during the time interval $dt$ selected:

$$q = K_d \frac{du}{dt} = K_d K_t \frac{dT_s}{dt},$$

where $K_t$ is proportionality factor, $U$ is the voltage measured between the cold ends of the thermocouple and $K_t = 0.067$ mV/°K is conversion factor for chromel-copel thermocouple. The proportionality factors for two calorimetric sensors were determined on a special pulse thermal installation that generated a stepped pulse of a calibrated convective heat flux. As a result of the calibration, the coefficients $K_d$ measured was equal 35 W·s/cm²·mV for the first sensor and 37 W·s/cm² for the second one. The calibration accuracy was about 3%.

The results of this recalculation performed for the first and second stages of the run are shown in figure 2. The data are presented as a function of the external magnetic field induction on the axis of the
MHD accelerator. The blue color indicates the experimental points corresponding to the gas heating mode by the electro-arc heater only. Red points are obtained when the heater and accelerator are working together. All points were determined by averaging over the time intervals selected. For the stage II this interval was equal to the time of the MHD accelerator operation. The heat flux to the surface of the model did not depend on the magnetic field in the operation mode when only electro-arc heater operated, as expected. On the contrary, this value grew more than an order of magnitude with magnetic induction increasing and reached a value about 6 MW/m², if the MHD accelerator was additionally turned on. Such a growth in the heat flux associates with a rise in total enthalpy supplied to the MHD accelerator from the external electric circuit.

![Graph](image)

**Figure 2** Heat fluxes measured at different stages of the run.

Other airflow characteristics can be estimated from the numerical simulation of ambient flow around the cylinder. For these purposes, the PlasmaAero software package [6,7] adapted to real conditions of the SMGDU wind tunnel was used. First, a two-dimensional axisymmetric flow in the facility duct was calculated. It was considered that the area of the circular cross-section was equal to the area of the real rectangular section. To calculate such an "effective" flow in the MHD channel, the bulk ponder motive force $F$ and total power supplied $W$ (source terms in the equations of motion and energy) were set like that the integral pulse and energy corresponded to the quantities defined earlier. These values were obtained as a result of calculation of the gas flow in the MHD channel consisting of 35 electrode pairs. A current of 35 A was set at each pair. The induction of the magnetic field was 2.4 T. In the example considered below the values were taken as $F = 55$ N and $W = 280$ kW, respectively. Then it was calculated the flow around the cylinder with a radius of 10 mm which end surface was 10 mm from the secondary nozzle outlet. Some results of the simulation are presented in figure 3. Also, there is an image of airflow around the calorimetric model in the Eiffel chamber of SMGDU in figure 3 on the left to compare calculated distributions with experimental data. The image was obtained during the video shooting with a high-speed camera. Exposure time of the frame was 500 μs.
a) A frame of high-speed shooting of supersonic flow around the model.

b) Pressure distribution:

\[ P_{\text{min}} = 147 \text{ Pa}, \]
\[ P_{\text{max}} = 26530 \text{ Pa} \]

c) Temperature distribution:

\[ T_{\text{min}} = 1550^\circ \text{K}, \]
\[ T_{\text{max}} = 13100^\circ \text{K} \]

Figure 3 Longitudinal airflow around the copper cylinder with a flat end at SMGDU:

a) an experimental pattern; b) and c) some results of simulating.

The next figure 4 demonstrates the radial distributions of the heat flux over the surface of the cylinder for two cases. The operating mode of the SMGDU when there was no additional pulse \((F = 0)\) and energy \((W = 0)\) input in the facility duct is shown in blue. This case corresponded to the turning on of the arc heater, only. For another mode, when also the MHD accelerator is turned on the distribution is shown in red.

Figure 4 Heat flux distributions on the surface of the cylinder.

The same figure shows the points of experimental measurements of heat fluxes obtained under maximum value of magnetic field \(B_n = 2.4 \text{ T}\) by means of two calorimetric sensors. The blue dot includes both measurements, since in this mode the readings of the sensors were practically the same.
When the MHD accelerator was turned on, the measured heat fluxes differed by approximately 20% (red dots). Apparently, this circumstance indicated the asymmetry of the gas flow since the calibration accuracy is much higher.

As the experimental data are in good agreement with the results of numerical simulation, it is possible to determine other characteristics of the hypersonic flow in the test part of the SMGDU. Radial profiles of gas flow velocity (the Mach number on “effective” flow axis is 5.4) and specific total enthalpy in the outlet section of the secondary nozzle are shown in figure 5, as example.

![Figure 5](image.png)

**Figure 5** Radial distributions of flow characteristics at the nozzle exit cross-section: velocity (solid lines) and specific total enthalpy (dotted line).

Thus, it is possible to determine the characteristics of the supersonic gas flow formed by the wind tunnel SMGDU when measurements of heat fluxes are accompanied by mathematical modeling. Air flow with such parameters can be applied in the ground-based research needed to create new hypersonic devices.

**Acknowledgments**

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

**References**

[1] Alferov V I 2000 Current status and potentialities of wind tunnels with MHD acceleration. *High Temp.***38** 300

[2] Alferov V I, Bushmin A S and Egorov 2015 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 Dyn.***50** 109

[3] Alfyorov V I, Dmitriev L M, Egorov B V, Markachev Yu E and Rudakova A P 2001 The possibility of simulating in wind tunnels the parameters of hypersonic flow and the conditions in the combustor of hypersonic scramjet engine *High Temp.* **5** 688

[4] Bityurin V, Bocharov A, Baranov D and Bychkov S 2007 Power Extraction Experiment with a Surface MHD Generator in Hypersonic Airflow *38th AIAA Plasmadynamics and Lasers Conf. In conjunction with the 16th Int. Conf. on MHD Energy Conversion, Miami, FL, June 25-28 2007 AIAA-2007-3882.*

[5] Bityurin V A and Bocharov A N 2009 Hypersonic MHD: Features and Problems *Proceedings of the 17th Int. Conf. on MHD Energy Conversion, 14 – 17 September 2009, Shonan Village Center, Kanagawa, Japan IK1-1.*
[6] Bityurin V and Bocharov A 2006 Magnetohydrodynamic interaction in hypersonic air flow past a blunt body. *Fluid Dyn.* **41** 843

[7] Bityurin V A and Bocharov A N 2018 MHD heat flux mitigation in hypersonic flow around a blunt body with ablating surface *J. Phys. D: Appl. Phys.* **51** 264001