Flow characteristics in the water-cooled channel of the MHD accelerator

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Abstract. Many problems related with the development of a hypersonic vehicle and development of new thermal protection materials are directly related to the possibility of conducting a wide range of laboratory researches under conditions that are close to the real flight conditions as possible. In this connection, the work on the formation of high-enthalpy and high-speed gas flows in ground-based installations is of special importance. It is shown in this paper that the flow characteristics required can be achieved using the experimental setup with a magnetohydrodynamic accelerator after its updating. The feature of this research facility is that more than half of the electric energy supplied from electric circuit is converted directly into the kinetic energy of the flow. Preliminary analytical and experimental studies of the MHD accelerator with a water-cooled channel allow one to conclude that a hypersonic flow with duration up to 10 s is formed at the SMGDU path. The total enthalpy in the core of the flow is close to 20 MJ/kg, while a required high level of total pressure is being maintained. The facility with such flow parameters becomes unique and allows one to significantly expand the range of ground-based testing, for example, testing of thermal protection systems, and testing of novel contactless flow control methods for hypersonic flight conditions.

Introduction
The hypersonic flight control and thermal protection of a hypersonic vehicle surface is one of the topics of special interest. Apart from traditional tools for vehicle trajectory control, the plasma technologies become more and more attractive. Attractiveness of plasma technologies relies on their feasibility to change flow characteristics by means of electric and magnetic field in so called non-intrusive manner. The latter implies that no control elements are subject to direct flow action. In addition to feasibility for flow control, there are two other topics related with applying of on-board magnet: namely, surface heat load mitigation and direct conversion of kinetic energy of the hypersonic flow to electric power. To study all these possibilities in ground-based facilities close-to-real flight conditions should be created, which is a problem of great challenge. The free-stream velocities should be as high as 6 – 8 km/s, the specific enthalpy of the flow should exceed 10 MJ/kg, the time duration of test run should exceed 1s (1-10 s).

The TsAGI Magneto Hydro Dynamic (MHD) Wind Tunnel Facility has been created to meet the needs for hypersonic flow conditions as close as possible [1,2]. For example, the free-stream flow velocities in the range of 8 – 15 km/s have been reached in earlier studies. Later, in 1999-2006, principal
studies on magnetic field flow control have been carried out on this facility. The results of these studies are summarized in [3]. While high-velocity flow has been realized, the drawback of the facility is small duration time of the run (0.5-0.7s). The current efforts are intended to increase this time and make the facility suitable for both MHD flow control research and experimental studies on thermal protection systems. The upgraded facility is thought to exceed some key parameters achieved on currently the most powerful Facility PWT-Scirocco [4-6], in which the hypersonic flow (Mach number – 6, total pressure is up to 6 Bar, specific enthalpy is up to 20 MJ/kg) is generated by arc heater. The objectives of the current efforts on TsAGI MHD Facility is to obtain flow with total pressure up to 10 Bar, specific enthalpy more than 20 MJ/kg, and duration time up to 10s.

The high velocity, high enthalpy flow is achieved by means of using a) preliminary heating of the flow by the arc rotating in magnetic field, and b) consequent magneto hydrodynamic acceleration of the flow followed by the nozzle.

In the current paper, the first experimental results obtained on the upgraded facility are presented. The physical and computational model developed to analyze the flow in the facility duct and in the test section is formulated. The preliminary numerical results on MHD flow in the facility duct are given.

Experimental data
The segmented Faraday-type MHD channel is the unit that experiences the highest electrical and thermal loads. For this reason, the duration of the supersonic flow was limited by 0.7 seconds in the standard mode. The research potential of the setup can be significantly improved by means of the using a new channel with water cooling. For this purpose, a test section of the channel was developed and manufactured in the JIHT RAS. In new channel, the copper electrodes and side walls are cooled by water. Some characteristics of both channels are given in Table 1.

| Type of channel | Number of electrode pairs | Electrode width, mm | Insulator gap, mm | Cross-section of the channel at the inlet/outlet, mm |
|----------------|--------------------------|---------------------|-------------------|-----------------------------------------------|
| standard       | 35                       | 5                   | 3                 | 15x15/25x15                                  |
| water-cooled   | 21                       | 10                  | 3                 | 15x15/25x15                                  |

Figure 1 shows the results of electrical parameters measurements for two runs of TsAGI MHD Wind Tunnel Facility with channels of different design. The number of electrode sections is indicated on the abscissa axis. The red lines correspond to the run of standard channel for 0.7 s. The blue lines correspond to the run of the water-cooled channel for 3 s. Both runs were conducted under the same conditions. The working gas was air. The gas flow rate was 12.4 g/s. The weight fraction of K-Na seed was 1%. The electrodes were loaded with the same voltage sources. It can be seen from the figure that the distributions of the quantities measured for two channels are close in form but differ in absolute values. The difference is explained by the fact that in the water-cooled case the magnetic field inside the MHD accelerator was weaker due to the design features. Thus, total inputted electrical power reduced to 21 electrode pairs was 270 kW for standard channel and 180 kW for water-cooled one, respectively. Series of runs with this power operation mode was carried out for water-cooled channel, and the time of trouble-free operation of the MHD accelerator was extended from 0.7 to 10 seconds.
Figure 1 Comparison of electrical characteristics of two channels.

a) – electrode current, A  
b) – electrode Faraday voltage, V  
c) – electrode Hall voltage, V  
d) – electrical power input, W

Computational model

The layout of the TsAGI MHD Wind Tunnel Facility is presented in Fig. 2. 250 kWt arc heater provides a supersonic flow at the inlet of MHD acceleration section. To provide functioning of MHD accelerator NaK eutectic is injected.

![Diagram of MHD Wind Tunnel Facility](image)

Figure 2 Layout of the flow in TsAGI MHD Wind Tunnel Facility duct.

Some parameters of the Facility and flow are given below. MHD accelerator inlet cross-section is $15 \times 15$ mm, outlet cross-section is $25 \times 15$ mm (extension in Y direction), length of MHD accelerator (in flow direction, X) is $550$ mm, nozzle outlet cross-section is $70 \times 100$ mm, nozzle length is $350$ mm.

The flow characteristics at the MHD accelerator inlet are taken to be as follows:

- static pressure is $25$ kPa,
- static temperature is $2500$ K,
- velocity is $2000$ m/s,
- Mach number is 2.

Chemical composition in mole fractions:

$x_{N2} = 0.78, x_{O2} = 0.20, x_e = x_{K_e} = 0.0133$, (1)
We shall consider the flow of chemically reacting air with the seed. So, seven chemical substances are assumed to take part in the chemical conversions: N$_2$, O$_2$, NO, N, O, K, K', e (electron). Reduced chemical kinetics of Park [9] is used to simulate the flow in the duct.

**Governing equations**

To numerically simulate the flow in the facility duct, consider the following set of governing equations.

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{U}) = 0 \tag{3}
\]

\[
\frac{\partial \rho \mathbf{E}^0}{\partial t} + \nabla (\rho \mathbf{U} \mathbf{E}^0) + \nabla \mathbf{q} = -\nabla \mathbf{P} + \mathbf{J} \times \mathbf{B} \tag{4}
\]

\[
\frac{\partial \rho \mathbf{H}^0}{\partial t} + \nabla (\rho \mathbf{U} \mathbf{H}^0) + \nabla (\rho \mathbf{U} \mathbf{r}) + \nabla \mathbf{q} = \mathbf{J} \mathbf{E} \tag{5}
\]

\[
\frac{\partial \rho_i}{\partial t} + \nabla (\rho_i \mathbf{U}) + \nabla \mathbf{q}_i = \dot{\omega}_i, \quad \dot{\omega}_i = \frac{\partial \rho_i}{\partial t} + \nabla (\rho_i \mathbf{U}) + \nabla \mathbf{q}_i \tag{6}
\]

\[
\frac{\partial \mathbf{v}}{\partial t} = \rho \frac{\partial \mathbf{U}}{\partial t} + \nabla \mathbf{p} + \mathbf{J} \times \mathbf{B} \quad \mathbf{v} = \frac{\partial \mathbf{U}}{\partial t} + \frac{1}{\rho^0} \frac{\partial \rho^0}{\partial t} \tag{7}
\]

\[
\mathbf{h}^0 = e^0 + \frac{p}{\rho}, \quad e^0 = e + \frac{\nu^2}{2}, \quad h = e + \frac{p}{\rho} = \sum_i Y_i h_i, \quad h_i = h_{i,f} + f^T_{i,ref} C_{pi} dT \tag{8}
\]

\[
P = \sum_i P_i, \quad P_i = \rho_i R_i T, \quad R_i = \frac{R^0}{\omega_i} \tag{9}
\]

Equations (3) – (5) govern the transport of total mass, momentum and total specific energy. Equation (6) specifies the transport of the mass of each chemical species. The transport equations are closed with the equations of state, (8) – (10). In equations (3) – (10) $\rho$ is density, $\mathbf{U}$ is velocity, $P$ is pressure, $T$ is translational temperature, $e^0$ is total specific energy, $e$ is internal specific energy, $h^0$ is total specific enthalpy, $h$ is internal specific enthalpy, $\rho_i$ is the density of $i$-th chemical species ($\rho = \sum \rho_i$), $\dot{\omega}_i$ is $i$-th species rate of production in chemical conversions, $Y_i$ is mass fraction of $i$-th species, $Y_i = \frac{\rho_i}{\rho}$, $P_i$ is $i$-th species partial pressure, $h_i$ is $i$-th species internal enthalpy, $C_{pi}$ is $i$-th species heat capacity at constant pressure. Operators in (7) are gradient and divergence operator, respectively. $\mathbf{n}_x \mathbf{n}_y \mathbf{n}_z$ denote basic unit vectors, index $\xi = 0$ corresponds to cartesian coordinate system, and $\xi = 1$ corresponds to cylindrical one.

Electrodynamic part of the whole system is assumed to describe by the following equations including Maxwell’s equations for quasi-steady electrodynamics and generalized Ohm’s law.

\[
\nabla \mathbf{J} = \mathbf{0}, \quad \mathbf{E} = \frac{-\partial \mathbf{v}}{\partial t} \tag{11}
\]

\[
\mathbf{J} + \frac{\beta}{\mathbf{B}} (\mathbf{J} \times \mathbf{B}) = -2(1-s)^2 \frac{\beta \beta^T}{B^2} (\mathbf{J} \times \mathbf{B} \times \mathbf{B}) = \sigma (\mathbf{E} + \mathbf{U} \times \mathbf{B}) \tag{12}
\]

In equations (11) – (12) $\mathbf{J}$ is electric current density, $\mathbf{E}$ is electric field strength, $\sigma$ is scalar electric potential, $\sigma$ is electric conductivity, $\mathbf{B}$ is magnetic flux density (magnetic induction), $\beta$ is Hall parameter for electrons, $\beta^T$ is ionic Hall parameter, $s$ is ionization degree. Electromagnetic field effects on the flow through electromagnetic force $\mathbf{J} \times \mathbf{B}$ (Equation 4) and through the energy yield $\mathbf{J} \mathbf{E}$ (equation 5). Equations (11), (12) can be reduced to partial differential equation for electric potential [6].

The fluxes in equations (3) – (6) are determined as follows. Mass diffusion flux and heat flux read as:

\[
\mathbf{q}_i = -\rho D_i \frac{\partial Y_i}{\partial r} + \sum_i h_i \mathbf{f}_i \tag{13}
\]

Here, $D_i$ is effective diffusion coefficient of $i$-th species, $\lambda$ is heat conductivity of the mixture. The viscous stress tensor is specified as follows:

\[
\tau_{ij} = \frac{2}{3} \eta \delta_{ij} \nabla \mathbf{U} - \eta \left( \frac{\partial Y_i}{\partial x_j} + \frac{\partial Y_j}{\partial x_i} \right) \tag{14}
\]

In (14) $\delta_{ij}$ is Kronecker symbol. The transport coefficients $D_i, \lambda$ and $\eta$ are calculated in accordance with the model presented, for example, in papers [9, 10]. Electric conductivity is determined by the following relationships:
\[
\sigma = e \mu_e n_e, \mu_e = e \frac{\tau_e}{m_e} \equiv \frac{B}{\tau_e} e^{-1}, \nu_e = \sum v_{ej}, v_{ej} = n_j u_e Q_{ej} \\
\mu_i = e \frac{\tau_i}{m_i} \equiv \frac{B}{\tau_i} i^{-1}, \nu_i = \sum v_{ij}, v_{ij} = n_j u_i Q_{ij}
\]

Here, \(e\) is electron charge, \(m_e\) and \(m_i\) are electron and ion mass, respectively, \(b_e\) \(b_i\) are electron and ion mobilities, \(v_{ej}\) \(v_{ij}\) are mean electron and ion collision frequencies, \(n_j\) is the number density of particles of \(j\)-th kind, \(u_e\) \(u_i\) are mean thermal electron and ion velocities, \(Q_{ej}\) \(Q_{ij}\) are collision cross-section for collisions of electrons and ions with particles of \(j\)-th kind.

### Chemical kinetics model

The rate of production of \(i\)-th chemical component due to chemical reactions in gaseous phase is given as:

\[
\dot{\omega}_i = W_i \sum_{r=1}^{N_r} \left[ \chi_{i,r}^{*} - \chi_{i,r}'' \right] \left( k_{fr} \prod_{l=1}^{N_l} c_l^{X_{l,r}} - k_{br} \prod_{l=1}^{N_l} c_l^{X_{l,r}'} \right)
\]

\[
c_i = \frac{b_i}{W_i}, k_{fr} = a \cdot T^b \cdot \exp\left(-E_a/T\right)
\]

Here, \(c_i\) is molar concentration of \(i\)-th component, \(W_i\) is its molecular mass. \(\chi_{i,r}^{*}\), \(\chi_{i,r}''\) are stoichiometric coefficients of reagents and products in \(r\)-th reaction. \(k_{fr}\) \(k_{br}\) are forward and backward reaction rate constants, respectively; \(a, b, E_a\) are reaction parameters, \(N_r\) is total number of reactions, \(N\) is total number of components. For thermal kinetics, \(E_a\) is activation energy. \(T_w = 1800K\)

### Initial and boundary conditions

The boundary conditions for transport equations (3) – (6) are set as follows. The supersonic conditions (1), (2) are specified at the inlet boundary. At the outlet boundary (nozzle exit), all variables are extrapolated from the interior. At the wall the temperature is assumed to given, \(T_w = 1800K\), corresponding to water-cooled wall. Initial conditions are not needed when steady-state solutions are sought. However, they are required in unsteady calculations. Typically, solution obtained for some conditions of external electric loading is used as initial one when these external electric loading is changed.

In general, the boundary conditions for electrodynamics equations (11), (12) may be non-local (functional) and time-dependent. The inlet and outlet boundaries are considered as insulating boundaries. Here zero normal current is set to zero, \(\int n \cdot J = 0\). The same conditions are set at the insulators separating electrodes. Electric potential is specified at the electrode boundaries. The value of potential at each electrode is calculated from the relationships determining external electric loading of the MHD channel. Currently, the electrode currents are assumed to be known as functions of time. Taking this into account, the boundary conditions for electrodynamics problem read as follows (17), (18):

\[
\begin{align*}
&\dot{\varphi} = P_k \\
&\int nJ dS = I_k(t), k = 1, \ldots, N_k
\end{align*}
\]

In (18) \(I_k(t)\) is the total current into \(k\)-th electrode, \(t\) is time, \(N_k\) is the number of electrodes. We consider the case of water-cooled channel, for which \(N_k = 42\), i.e. 21 electrodes on both bottom and top wall. Relationships (18) is one of the simplest manner to specify boundary conditions for MHD channel electrodynamics. As a role, more sophisticated relations are required to link electrodynamic characteristics in the channel and those in external circuits. The solution technique applied to solve for electrodynamics problem allows one to specify any physically reasonable relations between the currents and potentials.

### Solution technique

The complete set of governing equations is solved using different techniques for different equations. Explicit time-integration technique is used to advance flow solution in time. The source-terms are treated as averaged over time-step value determined by gasdynamic characteristic times rather than chemical
ones. This implies that chemical kinetics equations (16, 17) are integrated over gasdynamic time-step using implicit stiff ODE solver.

At every time-step electrodynamics problem (11), (12), (17), (18) is solved with multi-grid solver [11]. LU-factorization is used as a driving method on each iteration of three-level flexible-cycle multi-grid solver, and direct method is applied on the coarsest grid. Acceleration technique can be applied due to the manner, in which the external circuit conditions are treated. This technique allows a stable solution of the whole equation set even when electrodynamic equations are solved only at every \( n \)-th time-step. Typically, \( n \) varied from 10 to 100, which depends on the external circuit conditions.

Discretization of governing equations is carried out with control-volume method on the structured computational grid. Inviscid fluxes are calculated with several AUSM-techniques [12, 13], which provide low-diffusion carbuncle-free solutions. Viscous fluxes in equations (3) through (6) are calculated with the scheme analogous to central-difference one (see, for example, paper [14]). A bit different discretization scheme is used in solving electrodynamic problem to accurately take into account Hall effect.

**Preliminary numerical results on the flow in MHD Wind Tunnel Facility**

First estimations of capabilities of upgraded facility were carried out in papers [15 – 17]. Here, we shall consider preliminary numerical results obtained with the computational model discussed above. Consider the MHD channel which characteristics are listed in Table 1. The electric loading is presented by 21 electrode pairs, which realizes the old scheme, i.e. Faraday-type MHD channel is considered. Every section of each pair consists of 7 mm electrode and 3 mm insulator. For the first time, 50 A current per electrode section was specified. Total current is 1050 A. Magnetic field was specified in a simplest manner: \( \mathbf{B} = (0,0,B) \). Distribution of \( \mathbf{B} \) is shown in Fig.3 or Fig.4. The distributions of wall potentials and current stream functions are shown in Fig.3 and Fig.4, respectively. It was assumed that the nozzle is maintained at grad potential. Horizontal parts of potential curves correspond to equipotential boundaries of electrodes. The stream function curve represents the current distribution in the channel. Notice that stream function is defined as:

\[
\frac{\partial \psi}{\partial x} = -J_y, \frac{\partial \psi}{\partial y} = J_x.
\]

Integral of stream function over any line segment is the total current passing through this segment.

The total power supplied to the MHD channel is determined by the expression \( W = \int J E dV \). We consider an operation mode with moderate power supply \( W = 106 \text{ kW} \). The power of ponderomotive force \( A = \int (\mathbf{J} \times \mathbf{B}) \mathbf{U} dV = 80.6 \text{ kW} \). So, efficiency of MHD acceleration can estimated as \( \eta_E = A/W = \ldots \)
The operation mode just discussed is not an optimal one. The power supply is almost three times less than those allowed by the external circuit and desirable from the view point of hypersonic thermodynamics. Also, Hall effect seems to be significant, which diminishes the efficiency of MHD interaction. Further efforts could be done to optimize the external electric circuit.

Fig. 5 presents the distribution of axial velocity and Mach number along the axis of the duct (y = 0). The effect of MHD interaction is exposed as drastic increase of these quantities in the region of MHD channel.

Distributions of total pressure and total specific enthalpy are shown in Fig. 6. Even for non-optimal operation mode the total enthalpy reaches the value exceeding 10 MJ/kg, which is considered as the lowest one for hypersonic operation mode. Main characteristics of the flow at the nozzle exit station are presented in Fig. 7 and Fig. 8.

Finally, two-dimensional fields of basic flow quantities are presented in Figures 9 – 11.
**Concluding remarks**

The following three circumstances could be noticed.

First. The flow in the MHD channel is not symmetric one. This is due to the presence of Hall current (or leakage current) directed against the flow. This leakage current generates the force directed from bottom to top, i.e. in the direction of main (Faraday) current. One of the means to prevent or to diminish the influence of the leakage currents (and to diminish the flow asymmetry) is to reconfigure the external circuit in favor of Hall-type or Montardi-type MHD unit. Another possible solution is to diminish Hall parameter, specifically in near-electrode regions, where Joule heating is especially high. This could be done by increasing the ionization degree. Increase in ionization degree leads to increase of mean electron collision frequency because of growing of the role of column collisions.

Second. The level of specific total enthalpy (see Fig.6 and 8, for example) is sufficient for required hypersonic flow. However, distribution of this quantity is quite non-uniform across the nozzle exit. This undesirable property of the flow is thought to be mitigated by optimization of the geometry and initial flow conditions.

Third. It can be seen from Figures 7, 8 that the hypersonic flow of interest takes place in the core of the flow which is of order of 3 – 4 cm in height. The near-wall layers, also rather thick, are both high-enthalpy and high-temperature ones (~6000K). We hope the new water-cooled channel will capable of managing with these hard thermal conditions.

These preliminary estimates show that the main result – generation of long-term high-enthalpy hypersonic flow by means of MHD acceleration – can certainly be achieved.

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