Introduction

This work was initiated by Ajax program [1, 2] which treats the problem to provide the onboard MHD generator in a hypersonic aircraft at the Mach number \( M<8 \) during the flight and to introduce MHD methods of control of the hypersonic flights. For these purposes it was intended to ionize air with external energy source. This work is aimed to produce the means for air ionization and to study the mechanisms inherent to MHD interaction maintaining pre-induced ionization.

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The work consists from two sections. The first refers to thermal ionization of air involved by the shock waves. A general aim to be accomplished is to determine the capability of selective heating of the electrons in the magneto-induced field to reduce the electron recombination rate.

The second deals with aim to accomplish non-thermal ionization of air with pulse-periodical discharge. In this study, the problem to be advanced is to ignite a high-current uniform pulse discharge in a supersonic air flow and to determine a rate of ionization degradation, being produced in a bulk of gas by such a discharge, when gas moves downstream. A special attention must be paid to manufacturing the pin electrodes able to secure the uniform current flowing.

The Experiments with Thermal Plasma

**Experimental conditions**

The experiments were performed in disk-shaped MHD channel conjugated with a shock tube. Mainly, gas ionization proceeds into a shock-compressed plug when decelerating during a flow turn from a shock tube towards a disk-shaped channel. Experimental setup and methods of measurement were described in [2-4]. Figure 1 shows the setup’s schematic. A flow from a shock tube of 50 mm in diameter enters a disk-shaped channel of 280 mm in diameter with a gap of 10mm between the disks. The disks are made from organic glass, Hall current is not closed. The magnetic field was introduced by a constant electromagnet, being below \( B=0.8T \) in the experiment under question.

This experiment was carried out in pure air as well as in air-Argon mixtures. Three runs of the experiments were accomplished with three different compositions of working gas: 100% air + 0% Ar, 50% air + 50% Ar, 20% air + 80% Ar. The Mach number of the shock into the shock tube is \( (9.3\pm0.3) \), initial gas pressure into the low-pressure chamber was 6.5 Torr. In the experiment, a gas pressure \( p \), flow velocity \( u \) were measured, a density of azimuthal current \( j_0 \) was measured through the local inductive coils, a Hall field strength \( E_r \) was measured with aid of the electrodes. For the channel under question, the Ohm law takes form as follows:

\[
 j_r = -\alpha n B , \quad E_r = 0 \]

\[
 j_0 = 0, \quad E_r = \beta n B .
\]

With these formulas one can determine the values of conductivity \( \sigma = j_0/\mu B \) and Hall parameter for the electrons \( \beta = E_r/\mu B \) using the experimental data. The calculation of conductivity and Hall parameter was carried out in an «elementary approximation»:
\[
\sigma = e^2 n_e / m_e v; \quad \beta_e = \omega_e / v, \quad (3)
\]

where \( \omega_e = eB / m_e \). The measurements of the density of the coil current and Hall field strength gave the electron concentrations: \( n_e = j_e B / eE_c \). When calculating the mean cross-sections of momentum transfer \( \nu \), the elastic part of the velocity distribution function of the electrons was assumed to be the Maxwellian.

The numerical estimations showed that the values of the plasma parameters into the disk channel were within the ranges as follows: gas density \( \rho = (0.06 \pm 0.02) \text{kg/m}^3 \), mean concentration of a heavy component \( n_0 = (0.5 \pm 1.0) \times 10^{-4} \text{m}^3 \), gas temperature \( T_0 = 6000 \text{K} \pm 2000 \text{K} \), flow velocity \( u = (1 \pm 2) \times 10^3 \text{m/s} \), values of conductivity were within \( \sigma = 1 \pm 10 \text{Sm/m} \), values of the Hall parameter were \( \beta < 10 \). The parameter of MHD interaction \( \Theta = \alpha B L / \rho u < 0.01 \) was relatively small, thus, any noticeable deceleration of the flow was not observed.

A ratio of the magneto-induced electric field to particle concentration \( uB / n_0 < 10^{-16} \text{ (B/cm) cm}^{-3} \) was also so small that any additional non-thermal ionization of a gas did not occur. Thus, the main effect of MHD interaction was a selective heating of the electrons which can be noticed due to a change in frequency of momentum transfer, the latter affecting the values of conductivity and Hall parameter.

**Kinetics of thermal ionization of air**

The laws of the ionization and dissociation kinetics of air were treated in [5-7]. At the high temperatures which arose past the strong shock waves, a partial \( O_2 \) and \( N_2 \) dissociation occur as well as formation of the \( NO \) molecules. According to the estimations, under conditions of the given experiment, at \( T < 8000 \), the main mechanism of ionization was associative ionization of \( NO \) molecules but the main mechanism of a loss of the electrons was the dissociative recombination of \( NO^+ \) ions, and, at the low temperatures \( (T < 2000 \text{K}) \), it was adherence to \( O_2 \) which became ineffective because of an inadherence due to the collisions of \( O_2 \) ions with other particles. When calculating the rates of direct and reverse reactions, the values of the rate constants were taken from [5-7]. Below, the main reactions are shown.

The dissociation reactions:

\[
O_2 + M \longleftrightarrow O + O + M \quad (4)
\]

\[
N_2 + M \longleftrightarrow N + N + M \quad (5)
\]

\[
NO + M \longleftrightarrow N + O + M \quad (6)
\]

\[
O + N_2 \longleftrightarrow NO + N \quad (7)
\]

\[
N + O_2 \longleftrightarrow NO + O \quad (8)
\]

\[
N_2 + O_2 \longleftrightarrow NO + NO \quad (9)
\]

The reactions of associative ionization and dissociative recombination:

\[
O + N \longleftrightarrow NO^+ + e \quad (10)
\]

To take the values of the coefficients of the associative ionization \( K_i \) and dissociative recombination \( K_r \):

\[
K_i = 5 \times 10^{-11} T_h^{-0.5} \exp(-32500 / T_h) \quad (11)
\]

\[
K_r = 3 \times 10^{-3} T_e^{-1.5} \quad (12)
\]

The dimension of \( K_{i,r} \) is cm\(^3\)/c.

The most expanded data on formation and disintegration of \( O_2 \) ions are in [8]

\[
e + O_2 + M \longleftrightarrow O_2^- + M \quad (13)
\]

Thus, under taken conditions there are three charged components of plasma: \( NO^+ \), \( e \) and \( O_2^- \).

\[
|NO^+| = |e| + |O_2^-| \quad (14)
\]

The gas mixture included the heavy components as follows: \( O_2 \), \( O \), \( N_2 \), \( N \), \( NO \), \( NO^+ \), \( O_2^- \), and \( Ar \). Denote a concentration of the particles of “l” kind to be \( n_l \), its relative concentration to be \( x_l \). Internal energy of a single particle \( e_l \) includes energy of translational degrees of freedom, the rotational and oscillatory ones, and dissociation energy. The total values for which are attributed the MHD equations: mean mass of a particle \( m \), mixture’s density \( \rho \), gas pressure \( p \), mean energy \( \varepsilon \) of the particles, mean frequency of momentum transfer \( \nu \) at collision of an electron of a mean velocity \( c_e \) with a particle \( l \) having a mean scattering cross-section \( Q_{ln} \), are expressed as follows

\[
m = \sum_{l=1}^{8} m_l x_l; \quad \rho = \sum_{l=1}^{8} m_l n_l; \quad p = \sum_{l=1}^{8} \eta_l T_l;
\]

\[
\varepsilon = \sum_{l=1}^{8} x_l \varepsilon_l; \quad \nu = \sum_{l=1}^{8} n_l c_e Q_{lc} \quad (15)
\]

The reactions (10), (13) determine the equation of the charged particles. The energy equation is reduced to the equality of the Joule
heating power of the electrons and the energy transfer rate to the heavy component at elastic and inelastic collisions in which the energy losses refer to excitation of the rotational and oscillatory degrees of freedom and are characterized by a factor $\delta$ of the inelastic losses.

Now, the energy equation of the electrons can be expressed as follows

$$e\alpha^2 B^2 = \sum_{l=1}^{8} \delta_l n_e \frac{3}{m_l} \left(T_e - T_h \right)$$

For monatomic gases $\delta=1$, but for the two-atomic gases, especially, $N_2$ and $NO$, the value of $\delta$ can be several hundreds. The values a factor of the inelastic losses are affected by the velocity distribution function of the electrons as well as the distribution of occupancy of the different levels. Data on $\delta$ in literature are in rather poor agreement.

To estimate a selective heating of the electrons we applied the values of $\delta$ for $N_2$ and $NO$ given in [9]. The mutual solution of the conservation equation for electron component and MHD equations for a whole gas [2] provided the distributions of the parameters in the disk-shaped MHD channel.

The experimental results

The calculated data pointed out a tendency in changing the concentration of the electrons along the channel for three mixture compositions are presented in Fig.2. The concentration of the electrons drops along the channel due to gas expansion as well as the dissociative recombination of $NO^+$ ions.

![Fig.2. A change in the concentration of the electrons along a channel for the different mixtures of the components.](image)

In the experiment, the emphasis was on seeking the peculiarities in the behavior of the electrophysical parameters of plasma in a fixed point of the channel when changing the magnitude of the magnetic induction. The measurement was carried out at the middle point of the channel at $r = 6$ cm.

Figure 3 shows the dependence of the values of Hall parameter, the experimental ones as well as the calculated ones at the different values of the magnetic inductions for the air- Ar mixtures. At the constant temperature of the electrons, at the condition of the experiment under question, Hall parameter should grow linearly with increase in magnetic induction. However, one can see from Fig.3 that this dependence is less pronounced with a field’s growth because of the selective heating of the electrons. The dependence of Hall parameter on the temperature is determined by a frequency of momentum transfer which shows an increase with a growth in the mean velocities of the electrons as well as a mean cross-section of the momentum transfer. The calculation showed that, e.g., the temperature of the electrons in a mixture of 20% air + 80% Ar at $B=0.6$ T is as high as approx. 8000K.

![Fig.3. The values of Hall parameter at the different values of the magnetic induction for three mixtures. The curves refer to calculations, the points represent the experiment under question.](image)

Obviously, selective heating is essentially lower in the mixture with greater air content. Moreover, the frequency of momentum transfer is relatively weakly affected by the temperature of the electrons in air.

Figure 4 shows the values of conductivity at different values of the magnetic induction. The drop in conductivity experimentally observed with a growth in magnetic induction evidences, firstly, on a growth in a frequency of momentum transfer due to selective heating of the electrons. However, one can see that this drop is smaller in $Ar$-mixtures than a deviation from a linear dependence of Hall parameter that evidences on a growth in electron
concentration. In pure air, conductivity is smaller than that in the mixtures with Ar, for good reason. In addition, as one can see in Fig.4, the measurement error shows an increase concerning the small values of conductivity.

![Fig.4](image-url)

**Fig.4.** The plasma conductivity of the different mixtures as a function of magnetic induction. The curves refer to calculations, the points represent the experiment under question.

![Fig.5](image-url)

**Fig.5.** A change in the concentration of the electrons when changing the magnetic induction.

The behavior of the electron’s concentration in a given point of the disk-shaped channel is shown in Fig.5. In a mixture 50% air + 50% Ar, the electron’s concentration does not change, in practice, as well as in pure air. In a Ar-rich mixture, rising a higher selective heating of the electrons, one can see a growth in concentration of the electrons because of a field growth. This occurs due to fall in velocity of the dissociative recombination with a growth in the electron temperature, for what reason the drop in the electron concentration becomes less pronounced along a channel.

**Discussion and conclusions**

Firstly, it should be noted the difference in selective heating of the electrons in a cold gas-discharge air plasma and hot air. At the experimental conditions in pure air, $E/p (B/(cm\text{-}Torr)) = 2$ in the terms of gas-discharge plasma. Here $E=\mu B$. According to the data in [7], in the gas discharge where the temperature of a heavy component $T_h = 300K$, temperature stratification reaches a large value, in this case $T_e/T_h=20$. In the hot-air experiment, a value of $T_e/T_h$ proves to be little different from 1.

The selective heating is to be more pronounced with lower air pressure. The experiment in Ar-mixture with 20% air, in the first approximation, can be interpreted as an experiment at 1/5 times air pressure. Thus, in the experiment $E/p_{air} =10$, data analysis having demonstrated that $T_e/T_h \approx 2.5$, whereas this ratio proves to be 20 times larger in gas-discharge plasma.

The difference in the experimental conditions is in rather complicated pre-history of a flow in MHD channel: at the beginning of MHD interaction zone, the air temperature was as high as 4500K. At the cross-section under study, the temperature of the translational degrees of freedom drops to 2150K., the air state being extremely non-equilibrium, concentration of the products of the chemical reactions, e.g., NO content being significantly higher at the cross-section under study as compared with relevant equilibrium values.

Thus, it was shown in this work that, in hot air, the temperature stratification of the light and heavy components of plasma is essentially lower than that in cold gas-discharge plasma. It was revealed that there is deceleration of the process of a loss of the charged particles in MHD channel as a result of the selective heating of the electrons.

**Ionization of Air in External Electric Field**

**State of the problem**

One can show that thermal ionization of air may be used for the purposes of MHD energy conversion only at high Mach numbers of a flight ($M>12$). In the range of our interest ($M<8$), the external sources are required to air ionization. Further, we project to realize ionization in air with pulse periodical electric field. As the first step toward this purpose we show the results of the experiments with a single pulse. The aim of this experiment is to produce a uniform high-current short discharge to ionize a gas volume downstream.
in a supersonic air flow up to the high degrees of ionization \((10^{-3}-10^{-4})\) and carry out the studies how the preliminary induced ionization would fade when this volume of gas moves downstream. As an electrode system, it was intended the pin electrodes and the purpose was to determine the conditions under which a relatively uniform discharge can be ignited.

**Organization of the experiment**

The experiment is performed in a shock tube. The working section of square cross-section (50 mm × 50 mm) is manufactured from organic glass. There are pin cathodes and anodes on inner surface of the opposite walls in such manner as it is shown in Fig.6, the cathodes being located on the top wall, the anodes being located on the bottom one.

Every cathode or anode includes several pin of 0.5 mm width and 2.5 mm length inserted into a flow by 2 mm isolated from each other. In Fig.6 they are presented as the short horizontal lines. At 1 cm² area of the electrode, there are 3-4 pins. A high-voltage pulse of 10-15 kV of approx. 1µs duration supplies the first pair of the electrodes (Fig.6). The second and third pairs of the electrodes are intended to detect residual ionization. For this purpose, they are supplied with small voltage and record a current. A schematic of the pin connections in a single electrode as well as the

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**Fig.6. A schematic of a working section.**

**Fig.7. A schematic of the pin electrode connections: a) ionization electrodes, b) electrodes for measurement.**

**Fig.8. Illumination of an ionizing pulse: a) p=30 Torr, b) p=5 Torr.**
schematics of the supply of the ionization electrodes and the fixating ones are shown in Fig. 7. A ballast resistance $R_b$ is adjusted for each regime. As it was shown in the experiment, the degree of the discharge uniformity depends on a gas pressure, electrode voltage, and ballast resistance.

Figure 8 shows the discharge structures obtained in a gas at rest at the different pressures under an electrode voltage $V=12$ kV. One can see in Fig.8-a that the discharge at $p=30$ Torr is essentially non-uniform. It consists from several channels of current with different intensities. Figure 8-b shows more uniform discharge realized in a pressure range $p=(2\div6)$Torr.

Figure 9 shows the current’s and illumination’s oscillograms of the ionizing pulse. For $p=3$ Torr, $V=12$ kV, Figure 9 shows the current’s oscillograms of the ionizing pulse and illumination’s oscillogram. Plasma illumination is observed for several $\mu$s during 1 $\mu$s current. The experiment in a moving flow was accomplished under conditions as follows: Mach number of the front of the incident shock wave is 7.5, initial air pressure in the low-pressure chamber is 1 Torr. Air density past the shock wave grew up to 5.5 times the initial value, it corresponds to a pressure $R_g.d. =5.5$ Torr, air concentration past the shock wave was $2\cdot10^{-3}$ m$^{-3}$, the value of the temperature was approx. 2700K, flow velocity was 1.85 km/s in terms of a gas discharge.

Figure 10 shows a change in conductivity of the pre-ionized gas volume as it was moving along the channel. The effective conductivity in an ionizing discharge is as high as approx. 80 Sm/m corresponding to the value of a degree of ionization averaged over volume $\sigma=10^{-7}$. When moving downstream for a time of 25 $\mu$s, the effective conductivity in pre-ionized gas volume drops to that of approx. one order of value. This signifies that a degree of ionization is also of one order lower.

Thus, as a result of our work, we succeed in obtaining rather uniform pulse high-current discharge giving a degree of air ionization of the order of $10^{-4}$ and in evaluating the fading of previously obtained ionization in a supersonic flow. Also, it is of importance that, our work being in progress, the ways to realize a uniform discharge at higher pressure as well as to obtain higher temperature in an ionizing discharge with lower energy consumption can be directed.

References