MHD Control of the Separation Phenomenon

in a Supersonic Xenon Plasma Flow

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MHD Control of the Separation Phenomenon

in a Supersonic Xenon Plasma Flow

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Introduction

The flow separation phenomenon is encountered practically in all areas of technology related to liquid or gas flows. Generally, the separation leads to harmful consequences such as an increase of the body drag, a decrease of the wing lift, unsteady loads, and at high supersonic velocities causes emergence of narrow zones with intense heat fluxes toward the vehicle surface. The flow separation at supersonic velocities is associated with the interaction between shock waves and boundary layers.

Shock-wave/boundary-layer interaction (SWBLI) has been a subject of many investigations over the past four decades aimed eventually at designing supersonic and hypersonic air intakes [1]. There are some convenient physical models allowing the researcher to study SWBLI experimentally under simple conditions by means of a relatively simple visualization technique. One of such models is a supersonic flow inside an inner dihedral angle (compression corner). SWBLI may cause the flow separation in the vicinity of a compression corner. Improvement of understanding of the mechanism of the control of that interaction and prevention of the separation can pave the way for solving the problem of designing an air intake for operation over a wide range of the flight velocities. According to the AJAX concept [2], a magnetohydrodynamic (MHD) approach to controlling a supersonic flow of an ionized gas seems very attractive and advantageous.

Formulation of the problem

The objective of this work is an experimental study of an MHD influence on the gasdynamic flow structure inside a compression corner where a flow separation is possible.

The emergence of a flow separation is conditioned by a positive pressure gradient in the boundary layer behind a shock wave. A typical pattern of the flow is shown in Fig. 1.

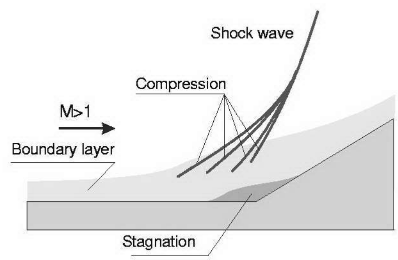

Fig. 1. Flow pattern inside a compression corner.

The character of such a flow inside a compression angle is governed, in general, by the flow deflection angle, mainstream Mach number M, and Reynolds number Re. From the above-said it is clear that influencing the separation is possible by means of varying these parameters. An MHD impact, in principle, allows one to change the mainstream parameters to influence the separation. However, an attempt to influence directly on the positive pressure gradient in the boundary layer by MHD impact seems more advantageous.

The direct objective of the study was elucidating conditions at which an MHD control does not cause a flow separation. This reasoning became the base for designing a test MHD channel and for a game plan of the experiment. The investigation was divided into two stages. The first stage was devoted to studying influence exerted on the supersonic flow by a current passing through the plasma without magnetic field, and the second – to the impact of an external magnetic field on the gasdynamic flow structure.

Experimental

The experiments were carried out using the equipment designed on the basis of the Big Shock Tube (BST) at the Ioffe Institute [3]. A layout of the experimental setup is shown in Fig. 2. The total length of the shock tube is 18 m and the inner diameter of its channel is 100 mm

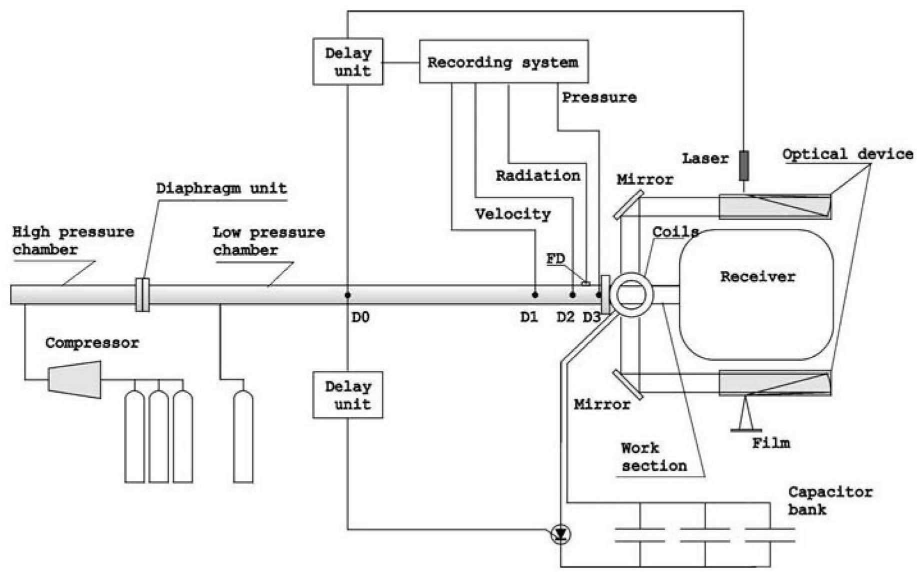

Fig. 2. Layout of the experimental equipment.

The high-pressure chamber of the BST filled in with hydrogen is separated from the low-pressure channel by a metallic diaphragm. The low-pressure channel is filled in with xenon as a working gas. Mach number of the incident shock wave in xenon is 7. The xenon is heated up to a temperature of ~9000 K by the shock wave reflected from the end of the low-pressure channel terminating in a wall separating the low-pressure channel from the test section. A slit in this wall of 10 mm in width and with the length equal to the channel width 75 mm is the throat of the supersonic plane nozzle. The test section has its second end connected by a metallic tube with the receiver of 6 m^3 in volume evacuated down to a forevacuum (~ $5 \cdot 10^{-2}$ mm Hg).

Diagnostic facilities for experimental investigations at the BST include the following set of means: an optical device for the flow visualization, as well as piezoelectric, photometric, and electric apparatus monitoring the gas flow parameters and properties.

Optical visualization in the present study is the basic means for the diagnostics of the separated flow. We use a standard industrial model of an optical Schlieren device IAB-451 with a view field of 230 mm in diameter and a focal length of 1.9 m. The test section is located between the illuminating and receiving parts of the Schlieren device. As a light source in the illuminating part we use OGM-20 Q-switched ruby laser with a light pulse duration of 30 ns. In the focal plane of the receiving part of the device there is a visualizing metallic diaphragm in the form of a "knife". This diaphragm screens light rays deflected by the gas nonuniformity and provides obtaining a Schlieren pattern in the image plane. We record the Shlieren pattern in a scale of 1:2 using high-speed film situated in a plane optically conjugated with the medial cross section of the test section. The Schlieren technique provides a high sensitivity to the light refraction in the gas under study, which is important in our case because the xenon density near the compression corner vertex is less than 1% of its magnitude at the atmospheric conditions. For measurements of the shock wave velocity we use piezoelectric transducers D2 and D3 located in the shock tube wall at a known distance between one another (Fig. 2).

The synchronization of the recording equipment is implemented using a pressure transducer pulse as well. The plasma state at the nozzle inlet can be monitored using signals from the pressure transducer D3 and the photodiode FD.

Gasdynamic parameters at the nozzle inlet are determined on the basis of a calculation within the framework of equilibrium gas ionization. The initial data for such a calculation are the shock wave velocity measured in the experiment and the initial gas pressure in the low-pressure channel. Mach number M_{s1} of the incident shock wave in the xenon, the initial xenon pressure p_1, and gas stagnation parameter behind the shock wave are presented in the Table.

Table

M_{s1}	P_1, (Torr)	P_0, (atm)	T_0, (K)	N_a, (cm^{-3})	α_0	σ_0, (mho/m)
7	35	10	9050	$8\cdot10^{19}$	0.02	1700

In the Table the following notations are used: p_0 and T_0 are the stagnation pressure and temperature, respectively; N_a is the concentration of heavy particles, α_0 is the ionization level, and σ_0 is the plasma conductivity.

Numerical calculation in the frame of a one-dimensional model of the nonequilibrium plasma expansion allowed us to obtain the following estimates of the plasma parameters in the exit nozzle cross section. Ratio of the temperature of heavy particles and electron temperatures to the stagnation temperature are equal to $T_a/T_0 \sim 0.2$

and $T_e/T_0 \sim 0.5$, respectively. Changes in the ionization level and conductivity at the nozzle outlet with respect to their magnitudes at the nozzle inlet amount $\alpha/\alpha_0 \sim 0.1$ and $\sigma/\sigma_0 \sim 0.3$, respectively. The duration of steady-state plasma flow through the nozzle amounts about 2 ms.

The test section schematic is shown in Fig.3. The test section is a channel of an internal rectangular cross section of 140×75 mm^2, containing a supersonic planar nozzle. The low-pressure channel is separated from the supersonic nozzle by a thin plastic diaphragm. To shape a compression corner we use a plate connected to the nozzle wall and deflecting the flow by angles of 15 or 30°.

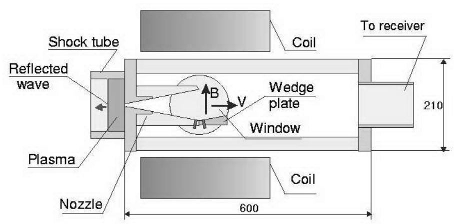

Fig.3. Line diagram of the test section.

The test section is located in-between two coaxially positioned coils inducing a magnetic field when discharging a capacitor bank through them with the total energy store up to 400 kJ. The maximum magnetic induction between the coils reaches $B = 1.5$ T.

Measurement technique

Electric measurements in the MHD channel are performed by means of recording voltage drops over different elements of a discharge circuit including the MHD channel itself. The aim of these measurements consists in determining the strength and form of current flowing through the plasma. To perform these measurements we use two couples of brass electrodes set in the nozzle wall in the vicinity of the compression corner vertex as it shown in Fig. 4. Dimensions of the electrode surfaces faced the flow are 6 mm along the stream and 4 mm in the transversal direction. The distance of the corner vertex from the upstream electrodes is 2 mm and from the other electrodes is 6 mm. Such positions of the electrodes are chosen with the aim to implement a local MHD impact on the flow directly upstream and, respectively, downstream from the corner vertex.

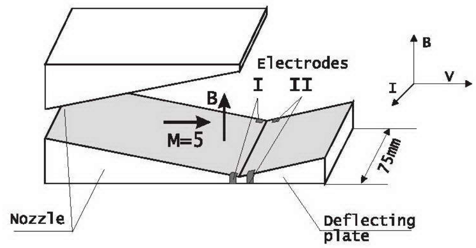

Fig. 4. Configuration of the supersonic nozzle with a deflecting plate and electrodes in the compression angle vicinity.

An MHD impact can be performed by connection of the electrodes to an external voltage source *U*. As an external voltage source we use a multi-cell *LC* circuit (see Fig.5) consisting of 14 identical cells; each of them has the parameters L = 3.5 μH and C= 300 μF.

The multi-cell *LC* circuit energized up to an initial voltage U_o is connected to the first or second pair of electrodes. After initiation of the flow through the nozzle, the interelectrode gap is filled in with a conducting plasma, and the multi-cell *LC* circuit discharges through the circuit with the parameters determined by the effective resistance of the channel, as well as by limiting resistor R_{lim} and load resistor R.

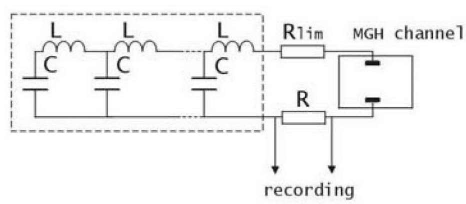

Fig. 5. Schematic diagram of the measurement system.

Series connection of the resistor R_{lim} in the *LC* circuit is caused by the necessity to have a voltage applied to the electrode which would be sufficient for the discharge initiation, on the one hand, and to vary the current strength independently, on the other hand.

In the experiment, we measured variations with time of the voltage drops U_R across the resistor $R = 0.04$ Ohm and U_c over the interelectrode gap. The voltage drop across the load resistor R was used for the calculation of the current flowing through the plasma, and the voltage drop U_c allowed the effective conductance of the MHD channel to be estimated.

Measurement results

Measurements without magnetic field

At the previous stage of the investigations we were studying the influence of the discharge current of the multi-cell *LC* circuit passing through the plasma on the flow structure in the channel with no magnetic field. The objective of those investigations was studying variations of the current through the channel with time, as well as the current influence exerted on the supersonic flow.

As a result of the investigation of the flow deflected by 15° two main observations were made:

1. The resistance of the channel remained practically invariable during the steady-state flow through the nozzle when the electric current increased up to 1000 A.
2. The shock wave pattern in the vicinity of a compression angle of 15° was also invariable in the current range studied.

In Fig. 6 a Schlieren pattern is shown corresponding to the steady-state phase of the flow with no separation inside 15° compression corner. The shock wave is depicted by practically straight line attached to the compression corner vertex.

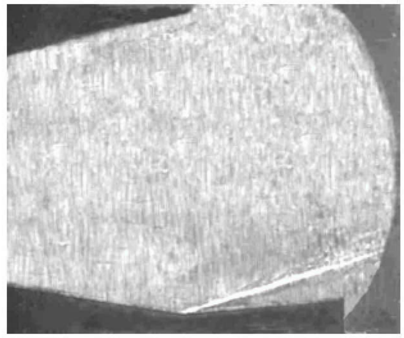

Fig. 6. Schlieren pattern of a flow with no separation inside a compression corner deflecting the flow through 15°.

The observations mentioned above do not contradict to one another – independence of the channel resistance on the flowing current means that the current practically does not change the plasma parameters, and, consequently, the shock wave pattern is not distorted. At the moment of publishing [4] this fact was supposed to be valid. Some doubts was caused by that in the vicinity of the electrodes the current density was sufficiently high and this resulted in an intensive visible radiation from the near-electrode region of the flow. Such a heating, in our opinion, could influence the flow structure. Just these circumstances forced us to analyze the discharge circuit in detail. An accurate checkup of the MHD channel design was performed, and a defect was found capable of causing an electric break-down bypassing the working channel section at sufficiently high voltages.

The defect found in the channel design was eliminated, and repeated experiments were carried out to detect the current influence on the flow structure without external magnetic field. It turned out that after reaching a certain current strength (more than 300 A) a separated flow is realized in the nozzle upstream from the compression corner vertex. In Fig. 7. a Schlieren pattern of such a flow is demonstrated. In the flow pattern the shock wave is depicted by a diffuse light line starting against the nozzle wall. The shock wave edge fuzziness can be explained by that the wave front is not plane inasmuch as it is formed by the separation zone with an intensive turbulence depicted by a dark band below the shock wave. A region abutting against the nozzle wall and plate shaping the compression corner looks light. The main reason for increasing the illumination in this region is an intensive visible radiation of the gas heated by the current flowing through the first (upstream) pair of electrodes. The gas radiation from this region exceeds sufficiently the total plasma radiation background throughout the flow field. In Fig. 8. there is a photo of the MHD channel obtained with the absence of a light source in the illuminating part of the Schlieren device.

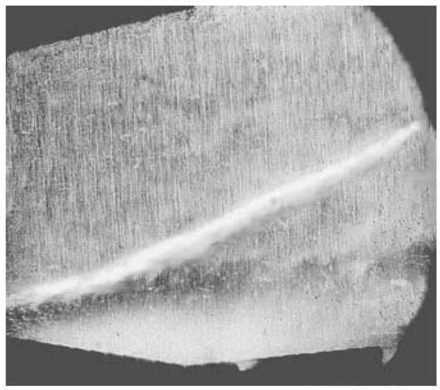

Fig. 7. Schlieren pattern of a separated flow insidea compression corner deflecting the flow through 15°.

The film was exposed only by the plasma radiation during the flow existence and duration of the discharge of the multi-cell *LC* circuit. A dark region near the lower channel wall (light-struck by the radiation) gives a notion on the current distribution in the flow.

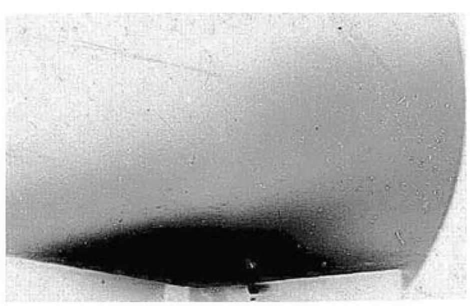

Fig. 8. Radiation of the plasma from the flow separation zone in the vicinity of electrodes.

As a reason for the separation onset at a certain magnitudes of the flowing electric current one can consider increasing the gas pressure in the vicinity of the compression corner vertex due to the heat release. In its turn, the transition to the separated flow is accompanied by a sufficient change in the current passage character.

Figure 9 displays oscillograms of the current flowing through the first pair of electrodes. The solid line corresponds to a flow with no separation and the dashed one – to a separated flow in a situation with no external magnetic field. In a separated flow the current pulse maximum is considerably larger and its duration is less as compared with the flow regime with no separation.

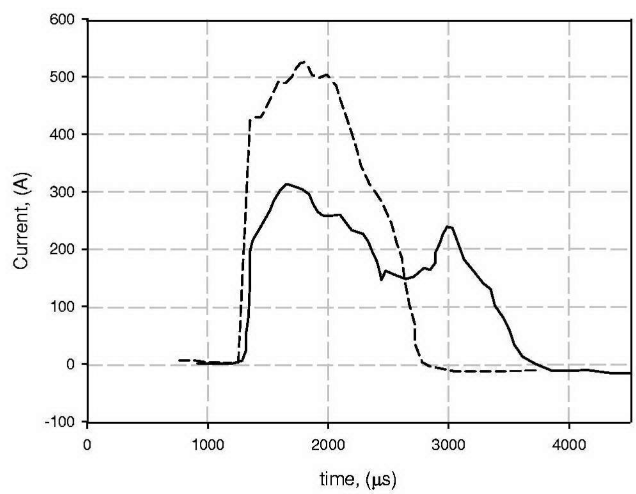

Fig. 9. Pulse shapes of the current passed through the channel in a separated flow (dashed line) and in a flow with no separation. The flow deflection angle is 15°.

From this it follows that in a flow with the separation a more intensive energy release occurs which results in a larger increase of the gas temperature and pressure near the electrodes. The current pulse duration in a flow with no separation approximately corresponds to the existence duration of the steady-state flow through the nozzle.

Naturally, the effective channel resistance is also dependent on the current passing through the plasma.

In Fig. 10. it is shown variations with time of the channel resistance at various magnitudes of the current flowing through the plasma. The solid line in the plot shows the channel resistance corresponding to a regime close to the flow separation, and the dashed line corresponds to a separated flow. It is seen that in the course of steady-state flow (time interval is 1300 – 2500 μs) in both cases the resistance changes insufficiently. The channel resistance in a separated flow (dashed line) is more than two times as less than that in a flow with no separation (solid line). The channel resistance increases as the current decreases. The dotted line corresponds to a flow with no separation at a less magnitude of the current flowing through the channel.

Investigations carried out with the use of a compression corner deflecting the flow through 15° showed that in the vicinity of the corner vertex a local separation zone emerged. In Fig. 11 there is a Schlieren pattern of a separated flow obtained with no current through the plasma. In the pattern it is seen that on drawing near the compression corner vertex, the shock wave front bends and recedes from the vertex, while the front strength decreases and the shock wave becomes almost invisible in the Schlieren pattern.

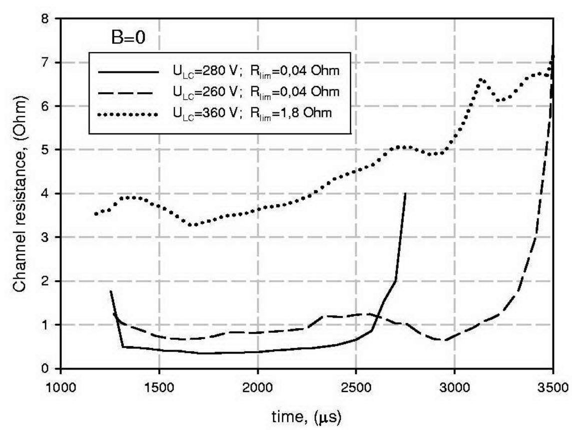

Fig. 10. Variation of the MHD channel resistance with time without magnetic field at different current strengths in regimes with no flow separation (chopped lines) and with a separation zone (solid line).

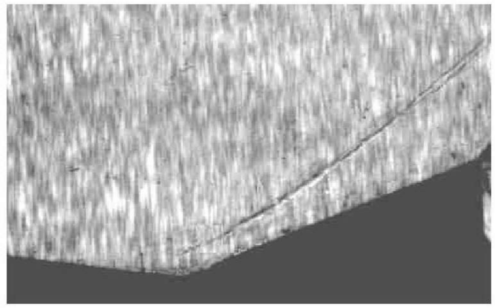

Fig. 11. Schlieren pattern of a flow with a local flow separation

When the electric current is passed through the second pair of electrodes located downstream from the corner vertex, bright luminosity is observed in the electrode vicinity. This evidences an intensive heat release in the electrode vicinity.

In the course of an inspection of the electrodes after a series of experiments, traces of erosion of the brass surface were observed which, in our opinion, evidence an arc discharge. Such a discharge regime, as Schlieren flow pattern shows, results in a destruction of the shock wave structure over the whole flow field, which excludes carrying out the experiments using the model chosen in the frame of the objective of the present investigation.

As a result of the investigation of the current passage through the channel it was ascertained:

1. The flow structure in the compression corner vicinity in a situation with no external influences corresponds to the theoretically expected pattern. In a case when the flow is deflected through 30°, a local separation zone emerges in the corner vicinity.
2. Minimum magnitudes of the voltage of the external source has been determined at that the current passage starts. In the given configuration of the channel with 15° flow deflection this voltage is roughly 120 V, whereas with 30° flow deflection it reaches 240 V.
3. At a certain strength of the current passed through the channel the transition occurs from a flow with no separation to a separated flow. This transition is accompanied by a characteristic change in the current pulse shape which evidences a more intensive heat release in a separated flow.

4. When flowing the current through the channel with 30° flow deflection a destruction of the shock wave pattern is observed. For this reason a more particular investigation of the given flow model was not carried out.

Measurements of magnetically induced electromotive force (e.m.f)

For implementation of an MHD interaction in the BST a magnetic system is applied which provides a discharge of a capacitor bank with the capacity 30 mF through two coils (see Fig. 3). The discharge current in such a circuit varies aperiodically with a considerable damping. For this reason, the experimental measurements are carried out during the first half-cycle when the discharge current is maximum. When this takes place, the duration of the magnetic pulse amounts 4.5 ms which is two times as large than the duration of the steady-state plasma flow through the nozzle. At such a duration and shape of the magnetic field, on the one hand, and the plasma flow duration, on the other hand, the time shift between development of these processes can be of great importance. Primarily, this may results in magnitudes of the magnetically induced e.m.f. arising between the electrodes in the MHD channel. Figure 12. shows variation of the induction of the external magnetic field with time and three dependences of the magnetically induced e.m.f. corresponding to different moments of the plasma flow onset through the nozzle with respect to the establishing the magnetic field.

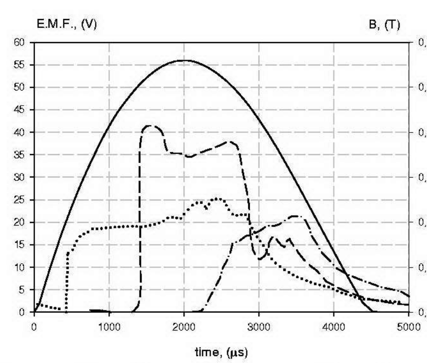

Fig. 12. Variations of the electromotive force between the channel electrodes with time (chopped lines) corresponding to different time instants of the flow initiation with respect to the variable magnetic field (solid line).

Variation of the magnetic field induction was calculated on the basis of measurements of voltages induced in a standard coil positioned in the interaction region. The magnetically induced e.m.f. in the channel was measured between the electrodes embedded in the channel when flowing the plasma in the operational regime.

In Fig. 12 it is seen that the magnitude and pulse shape of the magnetically induced e.m.f depend essentially on both the magnetic field induction at the initial moment of the plasma flow initiation and on its derivative with respect to time. Besides, the character of variation of the magnetically induced e.m.f. may be associated with the flow formation inside the compression corner accompanied by changing gasdynamic parameters including the flow velocity and conductance. It is obvious that the nature of the processes observed is sufficiently complicated and demands the further investigations.

For a continuation of the experiments we chose a regime in which the middle of time interval of the flow existence coincided approximately with the time instant corresponding to the peek value of the magnetic field induction (in Fig.12. this regime is shown by a dashed line). Here and below as a parameter characterizing MHD interaction we use the maximum value of the magnetic induction.

<u>Measurements with the use of the first pair of electrodes in the presence of the magnetic field</u>

Measurements with the use of the first pair of electrodes were carried out at the constant initial voltages of the capacitor bank and external current source. Fig. 13. demonstrates pulses of the current passed through the channel at various limiting resistors and a maximum magnitude of the magnetic field induction $B = 0.56$ T.

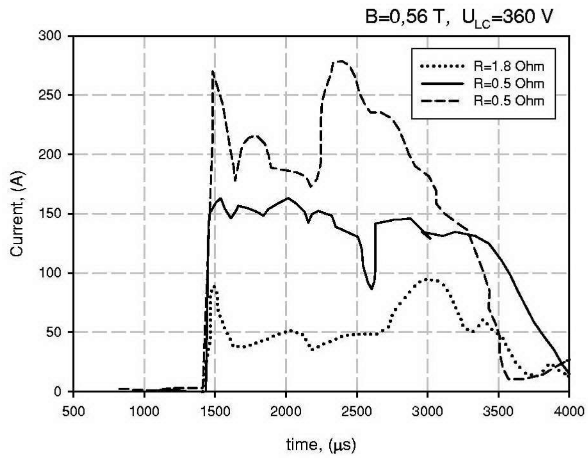

Fig.13. Pulses of the current flowing through the first pair of electrodes at various load resistors. The upper curve corresponds to a separated flow, two others – a flow without separation.

The upper curve in Fig.13 corresponds to a regime close to the transition to a separated flow, and two lower curves – to flows with no separation. In the plot it is seen that the current pulse shapes undergo oscillations with amplitudes increasing with growth of the current. Noticeably, that the transition to a separated flow, in this case, occurs at a considerably slower current (~ 200 A) than with no magnetic field. In Fig. 14 there is a flow pattern close to the transitional regime. One should pay attention to the bifurcate image of the shock wave, which, probably, is a consequence of either deformation of its surface or a slope of its surface with respect to the illumination direction. In the vicinity of the first electrode a radiation region is seen which occupies areas both upstream and downstream from the electrode.

The experimental results obtained allows us to conclude that, in flow regimes with no separation, there are no noticeable changes in the shock wave position and shape. A range of the determinative parameters of the MHD interaction in which the the shock wave remains to be attached is rather narrow.

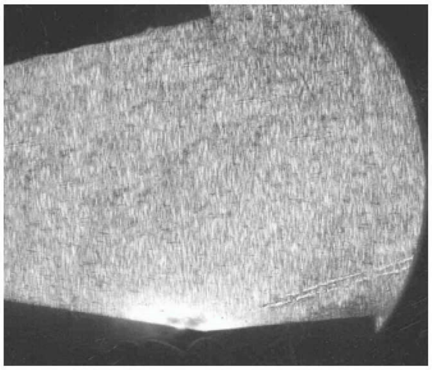

Fig. 14. Flow pattern observed when flowing the current through the first pair of electrodes with the presence of the magnetic field.

This allows us to draw a conclusion on inefficiency of the control of a supersonic plasma flow by an MHD impact on the flow upstream from the attached shock wave.

Measurements with the use of the second pair of electrodes in the presence of the magnetic field

We think that a more advantages way for the flow control is an MHD impact on the flow region immediately behind the attached shock wave, that is, the use of the second pairs of electrodes. Because of an MHD effect is a result of the joint action of an electric current passed through the plasma and magnetic field applied, we carried out measurements aimed at elucidating what a role is played by each of these parameters.

The first series of the measurements was performed at an invariable maximum magnitudes of the magnetic field induction. The strength of the current through the channel was varied by means of changing resistor R_{lim} in the discharge circuit at a constant voltage of the external source. The characteristic view of oscillograms of the current through a plasma with no flow separation in the compression corner is shown in Fig. 15. In the plot it is seen that as the limiting resistor decreases, along with increasing the current, irregular current oscillations increase too. Probably, this is a consequence of the interference between the heightening MHD impact and changes in the plasma flow parameters.

The second series of the measurements was carried out at constant parameters of the discharge circuit and variable induction of the magnetic field. Influence of changing the magnetic field induction on the character of the current passage through the plasma flow with no separation is shown in Fig. 16.

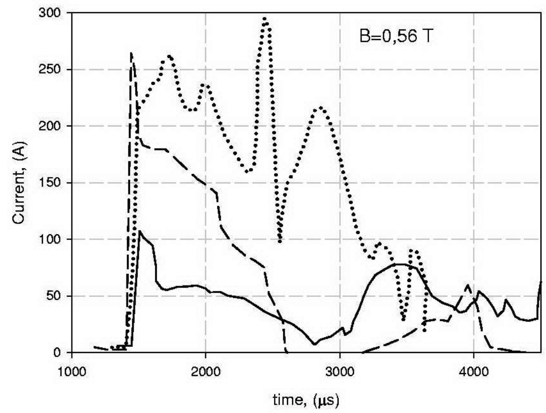

Fig. 15. Pulses of the current flowing through the second pair of electrodes at different limiting resistors without flow separation.

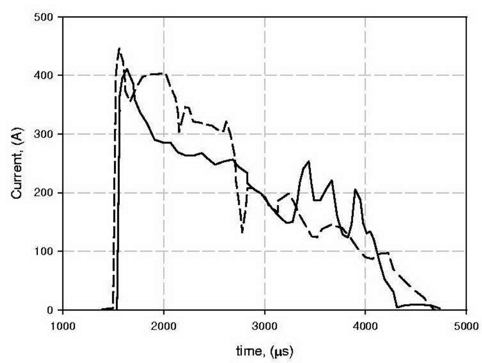

Fig.16. Pulses of the current flowing through the second pair of electrodes without flow separation at maximum magnitudes of the magnetic field induction 0.38 T (dashed line) and 0.76 T (solid line)

In this case, the initial voltage applied to the electrodes in MHD channel and the limiting resistance remained invariable. The initial voltages applied to the capacitor bank of the magnetic system differed in magnitude by a factor of 2. In the plot is seen that as the magnetic induction increases the current through the channel decreases to some extent. Irregular oscillations of the current have approximately the same character as in the previous plot.

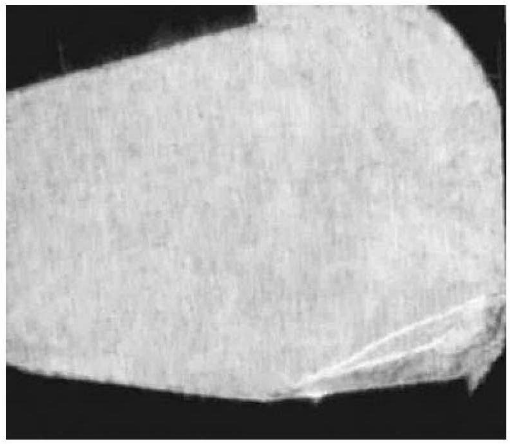

Fig. 17. Flow pattern observed when flowing the current through the second pair of electrodes with the presence of the magnetic field.

In Fig. 17 there is a Schlieren pattern of the supersonic plasma flow inside the compression corner affected by an MHD impact. The shock wave projection onto the frame plane is depicted by to light lines radiating from the compression corner vertex. One may suppose that because of the current has a maximum density near the electrodes, the MHD impact in these regions turns out to be the strongest. Fig. 18 displays a photo recording of the plasma radiation from a region adjacent to the electrodes.

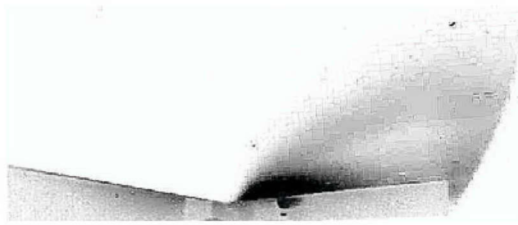

Fig. 18. Radiation of the plasma heated by the current passed through the second pair of electrodes.

An attention is attracted by that the radiating region being heated by the current passed through the plasma occupies the areas on both sides from the attached shock wave. The maximum current density is realized in a comparatively narrow flow region abutting on the electrodes (darker part of the pattern because it is negative image).

The higher gas pressure near the lateral channel walls causes deformation of the front of the attached shock wave and results in local changes in its slope angle. The shock wave surface shape arising in this case is hypothetically presented in Fig. 19.

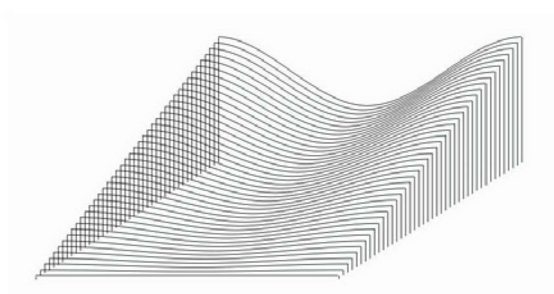

Fig. 19. Hypothetical shape of the attached shock wave

The upper light line in the Schlieren pattern (Fig. 17) is the trace of the shock wave on the channel glass window, and the lower line is the projection of the meridial generatrix of the shock wave surface. The slope angles of these lines with respect to a wall of the compression corner allow one to judge the MHD interaction efficiency.

Results of measurements of the slope angles of the shock wave images are presented in Fig. 20. On the abscissa a dimensionless parameter characterizing the MHD interaction efficiency is plotted. As such a parameter we use Stuart number calculated as follows

$$St = \frac{IB}{\rho u^2 h}$$

where I is the strength of the current passed through the MHD channel, B is the of magnetic field induction, ρ and u are the gas density and velocity, respectively, and h is a length characterizing the linear size of the region of the current passage. As a parameter h we take the product of the length of the deflecting plate by sine of the flow deflection angle. Note that h corresponds approximately to the height of the flow region with higher plasma temperature in the vicinity of the electrodes (see Fig.18.). The points in Fig. 20. are the measurement results, and the curves are approximations of them. It is seen that as Stuart number increases (more than 0.3) the MHD efficiency increases to such an extent that it causes deflections of the central parts of the shock wave.

Observations showed that at Stuart numbers more than 0.6, conditions for flow separation emergence are formed in the compression corner. In Fig. 21. there is a pattern of a developed separated flow. The separation zone is a flow region with low subsonic velocities, therefore an MHD control of such a flow seems to be of low efficiency.

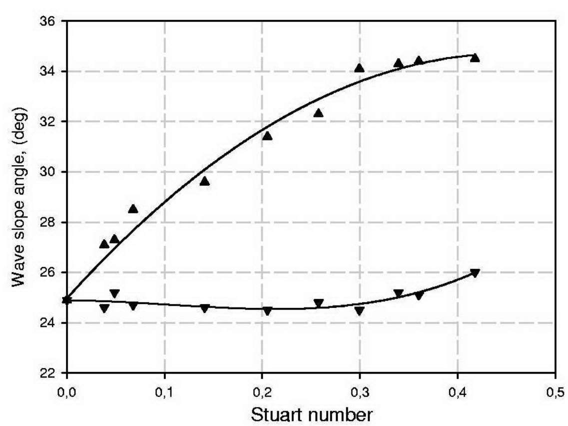

Fig. 1.2.20. Variation of the slope angles of the attached shock wave with the MHD interaction efficiency characterized by Stuart number.

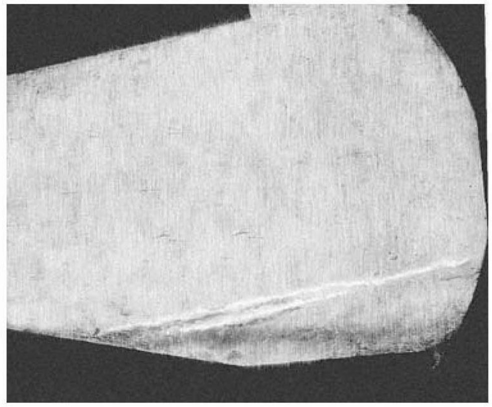

Fig. 1.2.21. Pattern of a separated flow observed when flowing the current through the second pair of electrodes with the presence of magnetic field.

As a result of the investigations of the passage of an electric current through the supersonic plasma flow exposed to a magnetic field we can draw the following conclusions.

1. Electrophysical state of the plasma exposed to a variable external magnetic field depends not only magnitude of the magnetic induction but also on its variation with time.
2. It has been ascertained that a region of the current passage through the plasma occupies flow zones both in front of the attached shock wave and behind it independently on the positions of the electrodes with respect to the attached shock wave.
3. An irregular oscillating character of the current passage through the plasma evidences possible initiation of unsteady processes capable of simulating a flow separation.
4. The presence of a local separation zone near the electrodes changes significantly the electrophysical plasma state. An MHD impact on such a flow may expedite development of a separated flow of a larger scale.
5. The MHD impact efficiency in a region of developed separated flow reduces due to low flow velocities in the separation zone.

CONCLUSIONS

On basis of the Big Shock Tube at the Ioffe Institute an experimental research equipment has been developed and are functioning. This equipment allows the researcher to model MHD effects in pulsed supersonic plasma flows with a duration of 2ms. The magnetic system provides establishing a pulsed magnetic field (with a duration of 4.5ms) with the peek magnetic induction up to 1.5 T. The equipment includes an optical device of high quality for the flow visualization, systems for piesoelectric, photometric, and electric measurements parameters of high-speed processes.

Investigation has been carried out of processes taking place under MHD impact on the xenon plasma flow through a plane supersonic nozzle with Mach number 5. At the nozzle outlet the flow was deflected by a plane through an angle of 15 or 30°. Such a flow model is well studied and may serve as a simple means for detecting changes in the flow state caused by an external influence on the flow. In particular, the position of an attached shock wave emerging due to the flow deflection is readily visualized by the Schlieren method and allows one to judge the MHD interaction efficiency. An MHD impact is implemented by means of passing an electric current from an external source across the plasma flow through electrodes embedded in the channel wall upstream from the attached shock wave and downstream of it. It has been found that an impact on a region behind the wave (downstream) is more efficient.

In the course of the investigations, measurements were performed of the magnetically induced electromotive force (e.m.f.) arising between electrodes due to the separation of the electric charges in the moving plasma under the action of the external magnetic field. It has been found that the e.m.f magnitude depends essentially not only on the magnitude of the magnetic induction, but on the character of its variation with time. Due to that in these measurements there was no current through the plasma, and, consequently, the gasdynamic flow parameters remained invariable, the difference between e.m.f. magnitudes (in the case considered they differ by a factor of 2) should be explained, probably, by nonconstancy of the magnetic field. In spite of the complexity of the phenomenon observed we think that it is possible to use such simple measurements for diagnostics of plasmas in experimental supersonic plasmadynamics.

When changing the MHD impact efficiency one can provoke a flow separation at which the impact itself becomes less efficient. In flows with no separation we succeeded in controlling the position of the attached shock wave in a region of Stuart numbers up to 0.5.

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