MHD Flow Control of Oblique Shock Waves Around Ramps in Low-temperature Supersonic Flows

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Abstract

This article is devoted to experimental study on the control of the oblique shock wave around the ramp in a low-temperature supersonic flow by means of the magnetohydrodynamic (MHD) flow control technique. The purpose of the experiments is to take advantage of MHD interaction to weaken the oblique shock wave strength by changing the boundary flow characteristics around the ramp. Plasma columns are generated by pulsed direct current (DC) discharge, the magnetic fields are generated by Nd-Fe-B rare-earth permanent magnets and the oblique shock waves in supersonic flow are generated by the ramp. The Lorentz body force effect of MHD interaction on the plasma-induced airflow velocity is verified through particle image velocimetry (PIV) measurements. The experimental results from the supersonic wind tunnel indicate that the MHD flow control can drastically change the flow characteristics of the airflow around the ramp and decrease the ratio of the Pitot pressure after shock wave to that before it by up to 19.66%, which leads to the decline in oblique shock wave strength. The oblique shock waves in front of the ramp move upstream by the action of the Lorentz body force. The discharge characteristics are analyzed and the MHD interaction time and consumed energy are determined with the help of the pulsed DC discharge images. The interaction parameter corresponding to the boundary layer velocity can reach 1.3 from the momentum conservation equation. The velocity of the plasma column in the magnetic field is much faster than that in the absence of magnetic field force. The plasma can strike the neutral gas molecules to transfer momentum and accelerate the flow around the ramp.

Keywords: aerospace propulsion system; magnetohydrodynamic; flow control; plasma; shock wave

1. Introduction

As an active flow control technique, magnetohydrodynamic (MHD) flow control can be used to improve the overall performance of supersonic and hypersonic vehicles, especially, by controlling external airflows on aircraft and internal airflows in engines\(^\text{[1]}\). As for the external airflow, the temperature and the aerodynamic drags around the blunt forehead and the leading edge will increase drastically because of the friction between the vehicle and the external airflow in a high-speed flow, which poses a number of challenges to vehicle designers in deciding on vehicle geometry, structure, material and otherwise\(^\text{[2-3]}\). As for the internal airflow, the primary goal of any scramjet inlet system is to assure the geometry providing an efficient compression process, generate low drags, produce needed uniform flow entering the combustor, and thus ensure satisfactory characteristics over a wide range of flight under different engine operation conditions. For conventional approaches, there must be a series of compromises that must be made between the factors, such as weight, cost and complexity of a variable geometry\(^\text{[4-5]}\).

MHD flow control technique to be discussed in following would potentially offer better approaches to meet the challenges to the aircraft external airflow and the engine internal airflow. The MHD flow control in high-speed flows has been fruitfully studied by a number of researchers\(^\text{[6-12]}\). The Lorentz body force effect has been thought to be promising for separating flows and experimentally shown to be capable of modifying turbulence.

V. A. Bityurin, et al. investigated large-scale MHD flow control and MHD power extraction in a high...
frequency plasmatron (HFP) wind tunnel in Russia. Their results showed that the MHD technique is full of future promise in aerospace applications. It could redistribute the pressure and heat fluxes over the vehicle surface, optimize the ramjet/scramjet operation efficiency, control ignition and ameliorate combustion in ramjet/scramjet combustors, generate on-board electrical power, and control boundary layers. However, it is energy-consuming for the HFP wind tunnel to generate high density plasma (200 kW). The present study uses the pulsed direct current (DC) discharge to generate the high density plasma and slim down the consumed-energy to 2 kW according to the voltage-current charts. S. O. Macheret, et al. performed theoretical and experimental studies on snowplow surface discharge in magnetic field for high-speed boundary layer control in Princeton University. Their results showed that magnetically accelerated plasma column affects the flows near the wall and might have the potential of providing a tool to accelerate the flow boundary layer and control the flow. Regrettably, they did not carry out experiments on oblique shock wave control and their DC power supply could not provide enough high frequency. In the present study, the pulsed DC discharge can achieve 500 Hz to change the flow characteristics around the ramp. K. Udagawa, et al. conducted experimental studies on the supersonic flow control with MHD interaction. Their results showed that MHD interaction could modify the upstream boundary layer flow and exert influences upon the oblique shock waves in front of a ramp. Because their experiments were carried out in a shock-tube driven supersonic wind tunnel, the test time was about 1 ms. In the present study, the low-temperature supersonic wind tunnel can run for more than 10 s steadily and thus the results are more trustworthy.

In China, a number of research groups set to work on experimental and numerical investigations in plasma aerodynamic flow control and published some important works, but they nearly all placed stress on electrohydrodynamic (EHD) interaction, which considers only electric field force rather than magnetic field force. A few of researchers now are studying the MHD flow control technique for aircraft. For instance, H. Y. Lu, et al. numerically analyzed and optimized three-dimensional MHD controlled inlets. J.F. Tang, et al. theoretically compared the performances of AJAX to the MHD-arc-scramjet combined cycle with energy-bypass system. Z. Y. Tian, et al. carried out numerical investigation in analysis of MHD oblique shock control. D. Han, et al. carried out experimental investigation in free surface MHD flow around a cylinder.

This article sets about a detailed experimental investigation into MHD flow control of oblique shock waves around a ramp in low-temperature supersonic flow. The pulsed DC discharge and the Nd-Fe-B rare-earth permanent magnets are combined to generate plasma and magnetic field instead of using only the DC discharge source and superconductive magnets. The purpose of experimental investigation is to take advantage of MHD interaction to weaken the oblique shock wave strength by changing the flow characteristics around the ramp. The effects of MHD acceleration and MHD deceleration on the flow characteristics are measured with the help of Pitot pressure and schlieren images.

2. Experimental Principles and Setup

2.1. Experimental principles

Fig.1 illustrates the experimental principles of MHD flow control. A high density plasma column, which primarily consists of ions and electrons, is generated between a pair of electrodes through pulsed DC discharge. There are three pairs of electrodes and an oblique shock wave present in front of the ramp in the low-temperature supersonic flow. The alphabets “I” and “B” mark the current and the magnetic field respectively with arrows indicating their directions.

When the magnetic field, normal to the surface, is imposed on the plasma column created in the boundary layer, it affects both the plasma and the flow, through the Lorentz body force. The direction of Lorentz body force is determined by the direction of the current and the magnetic field. In Fig.1 the alphabet “F” marks the Lorentz body force able to accelerate the flow with an arrow indicating its direction.

As the plasma column is produced by pulsed DC discharge, it would be influenced by the electric field force, the magnetic field force and the airflow inertial force with the latter two being dominant. When the direction of the magnetic field force agrees with the airflow inertial force and the velocity of plasma exceeds the neutral gas molecules, the plasma would strike the neutral gas molecules to transfer momentum and accelerate the flow in the boundary layer. Otherwise, when the direction of magnetic field force...
is oriented against the airflow inertial force, the plasma would do the same way to decelerate the flow.

2.2. Experimental setup

The MHD flow control system consists of a low-temperature supersonic wind tunnel, a plasma actuation system, an experimental ramp, a magnetic field generator, a parameter measurement system and a schlieren optical system.

The total inlet pressure of the low-temperature supersonic wind tunnel accounts to about 5-7 atm (1 atm=101.325 kPa). Atmospheric pressure and room temperature constitute the stagnation condition of the wind tunnel. The running time could be up to 60 s depending on the total inlet pressure. The experimental duct measures 115 mm (length) × 80 mm (width) with the designed Mach number of 2.2. The static pressure is 0.5-0.7 atm and the static temperature 152 K.

The plasma actuation system includes a pulsed DC power source, a plasma actuator and an insulating acrylic base. The pulsed DC power source is the critical equipment comprising a high-voltage pulsed circuit, a high-voltage DC circuit and a feedback circuit shown in Fig. 2. It can provide 0-90 kV selective high-voltage pulse and selective high-voltage direct current with 0-3 kV voltage and 0-4 kW power.

The plasma actuator contains three pairs of electrodes and an insulating dielectric. Its dimension is 60 mm (length) × 60 mm (width) × 4 mm (height). The electrodes, 10 mm in diameter, made of plumago, are flush-mounted on the top wall of the insulating dielectric of BN ceramic. Fig. 3 displays the wind tunnel experimental duct housing the plasma actuator embedded in the insulating acrylic base. There are two alternatives of arrangements for the plasma actuator to opt for according to different distances between a pair of electrodes (D=5 mm or D=8 mm).

Made of insulating acrylic material, the experimental ramp is secured on the insulating acrylic base. The ramp measures 34 mm (length) × 25 mm (width) × 6 mm (height). One angle of the ramp is A=15° and the other is A=20°. As shown in Fig. 4, ten static pressure measurement holes are drilled out in the acrylic base, the plasma actuator and the ramp. The holes, 0.5 mm in diameter, are numbered by k1-k10 from upstream to downstream. Holes k2-k8 are drilled out in the plasma actuator and k9, k10 in the ramp. In the plasma actuator, the adjacent holes are spaced by 10 mm except k2 and k3 as well as k7 and k8 by 7.5 mm. On the ramp, the distance between k9 and the edge of plasma actuator is 6 mm and that between k9 and k10 is 6 mm.

Nd-Fe-B rare-earth permanent magnets are used as the magnetic field generator located normal to the experimental duct as shown in Fig. 1. The direction of magnetic field is perpendicular to the flow and the electric field. The magnetic field strength is about 0.3 T between two magnets.

Parameter measurement system consists of sub-systems, which are for measuring electric parameters and for flow characteristics. The former includes a DPO4104 oscillograph, a P6015A high-voltage probe.
...and a TCPA300+TCP312 current probe; the latter contains ten static pressure sensors and a data collection apparatus. Because the wind tunnel runs for above 10 s in each experiment, the total inlet pressure would decrease slowly during this period. Therefore, in this study, the ratio of Pitot pressure after shock wave to that before it, labeled as $p_{k10}/p_{k7}$, is adopted to compare the flow characteristics of the airflow around the ramp.

Schlieren optical system is composed of a Optronis high-speed camera with 200 000 frames per second (FPS) as the maximum frame frequency and a storage computer. In this study, the schlieren images are taken at 8 000 FPS with the exposure time of 100 μ s and the running time of 8 s.

3. Experimental Results

Firstly, in order to verify the Lorentz body force effect, particle image velocimetry (PIV) measurement of the MHD interaction with the plasma-induced airflow velocity is studied under one atmosphere pressure at zero flow speed. Secondly, in order to study the flow characteristics with MHD interaction, two experiments are performed: The first is to measure the benchmark flow characteristics of the airflow in the absence of existence of both magnetic field and electric field. The other is to study the MHD interaction rules in the existence of both magnetic field and electric field. The flow characteristics in terms of the changes in pressure ratio and schlieren optical results are compared and analyzed as follows.

3.1. PIV measurement

As shown in Fig.5, the MHD interaction causes drastic changes in the flow field. Fig.5(a) shows the flow field structures in the existence of an electric field and in the absence of a magnetic field. From Fig.5(a), it is seen that the airflow is perpendicular to the surface, and due to the air drag force the velocity decreases from 350 mm/s to 250 mm/s. This phenomenon is caused by the Joule heating during the pulsed DC discharge. Fig.5(b) shows the flow field structures in the existence of both electric field and magnetic field. From it, the induced airflow is at 45° with respect to the surface, and for the same reason the velocity decreases from 440 mm/s to 225 mm/s. This phenomenon is caused not only by the Joule heating but also by the Lorentz body force of MHD interaction. Therefore, the body force effect of MHD interaction is obvious under one atmosphere pressure at zero flow speed.

Fig.5  PIV measurement of MHD interaction.
3.2. Flow characteristic results

A comparison is made between the four types of MHD flow control in terms of magnetic field direction, distance between electrodes, ramp angle and DC voltage and the results are analyzed as follows.

(1) Magnetic field direction
Experiments are carried out on MHD acceleration and MHD deceleration by changing the magnetic field direction. Fig.6 displays typical forms of flow characteristics. Fig.6(a) shows the time-dependent static pressure ratio \( p_{k10}/p_{k7} \) at \( D=5 \) mm and \( A=20^\circ \). The time-averaged pressure ratio is decreased by 11.64% by MHD acceleration and 8.95% by MHD deceleration. Fig.6(b) shows the same ratio at \( D=8 \) mm and \( A=15^\circ \) with the reductions of 6.04% and 5.09% respectively. Thus, it can be concluded that the MHD flow control could drastically weaken the oblique shock wave strength and improve the flow characteristics of the airflow around the ramp. Still, MHD acceleration is superior to MHD deceleration in terms of their effectiveness.

![Fig.6 Typical forms of flow characteristics.](image)

(2) Distance between electrodes
Experiments are carried out on MHD acceleration under \( A=20^\circ \) at \( D=8 \) mm and \( D=5 \) mm. Fig.7 shows the time-dependent flow characteristics varying with different distances. At \( D=8 \) mm, the time-averaged pressure ratio is cut down by 19.66% while at \( D=5 \) mm, by 11.64%. Thus, it is disclosed that increase in \( D \) would strengthen MHD acceleration ability to weaken the shock wave strength until \( D \) reaches the maximum \( D_{\text{max}} \), beyond which, the airflow could not be ionized due to its limited power source.

![Fig.7 Time-dependent flow characteristics varying with distances.](image)

(3) Ramp angle
MHD acceleration experiments are carried out at \( D=8 \) mm under \( A=15^\circ \) and \( A=20^\circ \). Fig.8 shows the flow characteristics varying with the ramp angles. At \( A=15^\circ \), it is decreased by 6.04% while at \( A=20^\circ \), by 19.66%. Thus, it is unveiled that increase in \( A \) would strengthen MHD acceleration ability to weaken the shock wave strength until \( A \) reaches the maximum \( A_{\text{max}} \), beyond which the oblique shock wave strength would be too high to be lowered.

![Fig.8 Time-dependent flow characteristics varying with ramp angles.](image)

(4) DC voltage
By letting DC voltage, \( V_{\text{DC}} \), be 2.0 kV, 2.5 kV and 3.0 kV, MHD acceleration and MHD deceleration experiments are carried out under \( A=15^\circ \) at \( D=8 \) mm. Fig.9 shows the flow characteristics varying with \( V_{\text{DC}} \). Fig.9(a) shows the varying static pressure ratios with MHD acceleration while Fig.9(b) with MHD deceleration. The time-averaged pressure ratio is decreased by 3.95%, 5.19% and 6.04% at \( V_{\text{DC}}=2.0 \) kV, 2.5 kV and 3.0 kV respectively in the former case while 3.44%, 4.26% and 5.09% in the latter case. Thus, MHD flow control is in a position to drastically weaken the oblique shock wave strength and improve the flow characteristics of the airflow around the ramp; also, the more effective MHD in-
interaction is, the higher the $V_{DC}$ is.

![Flow characteristics at different DC voltage](image)

**Fig.9** Flow characteristics at different DC voltage.

3.3. Schlieren optical results

The schlieren images are taken during flow characteristic measurements in all conditions. Fig.10 illustrates the typical schlieren pictures at $D=8$ mm, $A=20^\circ$ with MHD acceleration. Fig.10 (a) shows the benchmark flow reckoning without either electric field or magnetic field while Fig.10 (b) has both electric field and magnetic field to be reckoned with in the case of MHD acceleration. The upper two pictures of Fig.10 (a) and Fig.10 (b) are original pictures while the lower two are in terms of real dimensions. The benchmark pictures are seen to have four shock waves before the ramp, three of which are produced by the coarse interfaces between electrodes and ceramic and the lowest one by the ramp. Without MHD acceleration, the shock wave angle near the ramp is about $37.5^\circ$, and the distance between the shock wave and the ramp about 7.1 mm while with MHD acceleration, the angle is reduced to $35.0^\circ$, and the distance is increased to 10 mm, which means the shock wave has moved upstream 2.9 mm. Therefore, MHD flow control is in a position to change shock wave location, and convert a strong shock wave into many weak ones, thereby weakening the shock wave strength and improving the flow characteristics near the ramp. These results are in good agreement with Section 3.2.

![Benchmark and MHD acceleration flow in a typical condition](image)

**Fig.10** Benchmark and MHD acceleration flow in a typical condition.

4. Discussion

In this study, the plasma column is produced by pulsed DC discharge, and ions and electrons in the plasma are motivated along the direction of Lorentz body force. The heavy ions would collide with neutral molecules to transfer momentum and energy, which induces changes in the airflow characteristics. The interaction mechanism of this kind of flow control is defined as Lorentz body force effect. When the direction of Lorentz body force is in line with the flow, the interaction is called MHD acceleration\[29\], and when they are in opposition to each other, it is called MHD deceleration\[30\].

4.1. Discharge characteristics

Fig.11 shows the pulsed DC discharge voltage and current charts in the supersonic flow. The discharge is triggered by the high-voltage pulses and then retained by the high-voltage DC current. The maximum voltage of the high-voltage pulse is about 10 kV and the maximum current amplitude 15 A (Some maximum amplitudes are not collected due to poor oscillograph’s sampling collection). The pulse frequency is about 500 Hz because there exist about twenty
pulses in the period of 40 ms. Fig.12 shows the discharge photograph in the low-temperature supersonic flow. The plasma column is created between three pairs of surface electrodes, which are spaced by about 5 cm along the flow direction. The flow leads the discharge downstream and remains a localized plasma column until leaving the region between the electrodes. Upon its leaving, another plasma column would appear upstream between the electrodes and repeat the whole process. Virtually, when an orthogonal magnetic field is applied to it, the plasma column iterates by disappearing and appearing so quickly that a continuous high-frequency pulsed uniform discharging would envisage itself in the entire region between the electrodes before our eyes.

Fig.11 Pulsed DC discharge voltage and current charts.

Fig.12 Discharge photograph.

Fig.13 shows the charts of single pulsed DC discharge voltage and current from high oscillograph sampling collection. From the voltage chart, it can be determined that the interaction time of high-voltage pulse is not more than 1 μs, and the instantaneous amplitudes of voltage and current are 12 kV and 15 A respectively. With so high voltage, there must be electric surges in the power source causing negative amplitudes to appear in the charts. The purpose of the high-voltage pulse is to strike and short-circuit local airflows thus keeping the high-voltage DC to discharge. The DC voltage decreases rapidly from about 2 500 V to 400 V and the current remains between 2 A and 3 A. The consumed energy is about 2 kW. Therefore, in essence, this pulsed DC discharge is uncontinuous and ununiform. The MHD interaction time is about 75 μs which corresponds to the time for DC discharge to sustain according to the charts.

Fig.13 Charts for single pulsed DC discharge voltage and current.

4.2. Velocity calculation

In the low-temperature supersonic flow, according to S. H. Zaidi, et al. [18], the plasma column moving at a large relative velocity through the neutral gas transfers momentum and accelerates the flow. Fig.14(a) shows the results in the absence of magnetic field with the exposure time of 1, 10 and 50 μs respectively, and Fig.14(b) in the existence of a 2.0 T magnetic field with 1, 10 and 20 μs respectively. It is clear that the plasma column moves downstream much faster in the magnetic field. A direct comparison of images in the existence of magnetic field to those in the absence of it reveals that the plasma column velocity up increases to about 2 000 m/s in the latter case and about 5.7 times higher than 350 m/s in the former case. The plasma passes each element flow at an approximately six times higher velocity to transfer momentum.
The gas velocity increment in a single sweep of the plasma column can be derived from the momentum conservation equation:

\[ f \Delta t = M \Delta v_i \]  

(1)

The drag force on a molecule inside the plasma column can be estimated by [31]

\[ f = k_i n_i M' (u_p - u) \]  

(2)

where \( k_i \approx 1 \times 10^{-9} \text{ cm/s} \) is the ion-molecule momentum transfer rate constant, \( n_i \) the ion density, \( M' \) the ion-molecule reduced mass and \( u \) the gas velocity. The surviving time of a molecule inside the plasma column \( \Delta t \) is approximately

\[ \Delta t = h/(u_p - u) \]  

(3)

where \( h \) is the thickness of the plasma column. The mass of molecule \( M \) is approximately [31]

\[ M = 2M' \]  

(4)

By inserting Eqs.(2)-(4) into Eq.(1), can be derived the gas velocity increments in a single sweep of the plasma below:

\[ \Delta v_i = 0.5k_i n_i h \]  

(5)

In this study, with the estimated values \( n_i = n_e = 2 \times 10^{12} \text{ cm}^{-3}, h = 50 \text{ mm} \), the single sweep velocity increment from Eq. (5) is \( \Delta v_i \approx 55 \text{ m/s} \). However, as the gas elements in the boundary layer slowly move along the wall, they are subjected to multitude of “hits” from the consecutive high-speed plasma columns. The number of these “hits” is approximately equal to the ratio of plasma column velocity to the average gas velocity. Denoting the initial and final gas velocity, i.e. the velocity at the entrance to and the one from the interaction region, by initial velocity \( v_0 \) and final gas velocity \( v \), can be obtained

\[ v - v_0 = \frac{u_p}{2} \Delta v_i \]  

(6)

By substituting Eqs.(4) -(5) into Eq.(6), can be obtained

\[ v^2 - v_0^2 = 2u_p \Delta v_i = u_p k_i n_i h \]  

(7)

According to Ref. [17], the plasma column velocity can be simplified into

\[ u_p = \frac{E}{B} + u \]  

\[ \frac{1}{1 + \Omega \Omega_0} \]  

(8)

where \( E \) and \( B \) are the electric and the magnetic field intensity, respectively. The electron and ion Hall parameters are [31]

\[ \Omega = \frac{eB}{mv_e} \]  

\[ \Omega_0 = \frac{eB}{MV_{e}} \]  

(9)

(10)

where the electron charge \( e = 1.602 \times 10^{-19} \text{ C} \), \( m_e = 9.106 \times 10^{-31} \text{ kg} \) is the electron mass, \( MV_e = 2.4 \times 10^{-26} \text{ kg} \), \( V_{e} = 1.4 \times 10^{11} \text{ Hz} \) and \( V_{in} = 1.15 \times 10^{9} \text{ Hz} \) are the electron- and ion-molecule collision frequencies, respectively. From Eqs.(7)-(10), can be obtained the relationship between the gas square-velocity increment and plasma parameters as

\[ v^2 - v_0^2 = 2u_p \Delta v_i = u_p k_i n_i h = \frac{EB}{mv_e M' V_{in}} + u \]  

\[ 1 + \Omega \Omega_0 \]  

(11)

By substituting Eqs.(4) -(5) into Eq.(6), can be obtained

\[ v^2 - v_0^2 = 2u_p \Delta v_i = u_p k_i n_i h \]  

(7)

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where \( E \) and \( B \) are the electric and the magnetic field intensity, respectively. The electron and ion Hall parameters are [31]

\[ \Omega = \frac{eB}{mv_e} \]  

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(10)

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\[ v^2 - v_0^2 = 2u_p \Delta v_i = u_p k_i n_i h = \frac{EB}{mv_e M' V_{in}} + u \]  

\[ 1 + \Omega \Omega_0 \]  

(11)

Based on Eq.(6) and Eq.(11), two principal conclusions can be

(1) \( v \) decreases with the decline of \( v_0 \), but the velocity increment increases because the right side of Eq.(11) is constant with the determined plasma parameters. This means that the gas closer to the surface is susceptible to stronger acceleration.

(2) MHD acceleration can be strengthened by increasing the magnetic and electric field intensities. The former can be realized by using superconductive magnets while the latter by either simply reducing the ballast resistance or running a stronger current.

Under the experimental conditions: \( E = 4 \text{ kV/cm}, B = 0.3 \text{ T} \) and the initial boundary layer velocity (i.e. initial gas velocity) at about 0.5 mm from the surface according to the schlieren pictures \( v_0 = 300 \text{ m/s} \), the velocity increment is \( v - v_0 = 155 \text{ m/s} \) according to Eq.(11). The “interaction parameter” corresponding to the boundary layer velocity is \( (v^2 - v_0^2)/v_0^2 = 1.3 \), and the “interaction parameter” to the freestream velocity, \( v_0 = 544 \text{ m/s} \), would be \( (v^2 - v_0^2)/v_0^2 = 0.4 \). In this case, at the depth of the boundary layer, where \( v_0 = 50 \text{ m/s} \), the plasma-induced velocity (i.e. final gas
velocity) would become \( v = 346 \text{ m/s} \). Such a modification of the boundary layer velocity would be sure to have a significant impact on the flow.

The modification of the location and strength of shock waves results from shock wave/boundary layer interactions with MHD acceleration. On the one hand, MHD acceleration can change the flow characteristics of the boundary layer and increase kinetic energy of neutral gas. On the other hand, MHD acceleration induces high energy airflow in the main flow and introduces it into the low energy airflow in the boundary layer, thus modifying the location and strength of the shock waves.

4.3. MHD interaction

Based on Section 4.1 and Section 4.2, it can be concluded that MHD flow control of the oblique shock wave results from interaction among plasma column, boundary layer and shock waves in the existence of magnetic field.

Fig.15 renders the explanation for the upstream shift of shock waves. During the period of pulsed DC discharge, the generated high-density plasma columns would firstly change the fluid characteristics and secondly lead to instantaneous increase in the temperature and pressure because its temperature is higher than nearby airflow. The synergistic effect is to reduce the Mach number and increase the height of sound velocity line in the boundary layer, which results in increase in the boundary layer thickness. Then a new “virtual ramp” [12] can be created to obstruct airflow from flowing downstream. This will move its location upstream and weaken the oblique shock wave strength near the ramp.

In order to determine the extent of this influence, an experimental study is undertaken in the existence of electric field but in the absence of magnetic field. The flow characteristic results show a 1%-2% drop in the time-averaged pressure ratio. This is far less than what is expected with MHD interaction. In opposition to the main flow, the plasma-column-induced airflow with the interaction of MHD deceleration brings the effects of “virtual ramp” to a better play thus lowering the oblique shock wave strength more effectively. By contrast, the interaction of MHD acceleration would allow the plasma-column-induced airflow to act the same way the main flow does to increase its speed in the boundary layer thus decreasing the boundary layer thickness. Result is that strong shock waves are converted into many weak shock waves thus lowering the oblique shock wave strength more effectively.

The above discussion is validated against the continuous schlieren pictures as shown in Fig.16, where the time interval is 1/8 000 s. Fig.16(a) shows a strong shock wave generated at time of 0 s with plasma off. Fig.16(b) shows a strong shock wave having converted into many weak shock waves with the interaction of plasma column and MHD acceleration. The shock wave has moved upstream and its strength has been weakened. Fig.16(c) shows the plasma column flying to the ramp and the MHD interaction continuing to take effect. Fig.16(d) shows the plasma column flying far away from the ramp and a strong shock wave having generated again.

5. Conclusions

This article studies experimentally the boundary layer control of aircraft in low-temperature supersonic flow by means of MHD flow control. Hereafter come conclusions:

(1) The PIV measurement results show that the Lorentz body force takes an obvious effect under one atmosphere pressure at zero flow speed.

(2) The resultant flow characteristics in terms of pressure ratio change and schlieren optical images
indicate that MHD flow control can bring drastic changes to the flow characteristics near the ramp and up to 19.66% decrease in the ratio of Pitot pressure after shock wave to that before shock wave. These results allude to a reduction in the oblique shock wave strength. Moreover, the MHD acceleration takes a more active part than the MHD deceleration does in weakening the oblique shock wave strength. MHD interaction becomes more effective when electrode distance, ramp angle and DC voltage increase.

(3) The velocity of the plasma column in the existence of magnetic field is much faster than that in the absence of it because the plasma strikes the neutral gas molecules to transfer momentum and accelerates the flow near the ramp by the action of applied magnetic field.

The MHD flow control has the potentiality to be used for reducing skin friction, modifying the turbulence in boundary layers and manipulating the shock wave/boundary layer interaction in a supersonic flow. Additional efforts should be made to investigate the emission spectrum of pulsed DC discharge so as to implement correct calculation of the plasma parameters. In addition, the mechanism of plasma striking action and the shock wave/boundary layer interaction with MHD interaction (MHD acceleration and MHD deceleration) are also worthy of further investigation.

References


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