

Experiment of gas plasma plume deflection by magnetic control

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Abstract: To investigate the deflection effect of gas plasma plume controlled by magnetic field, a novel experimental scheme was presented. The Cs_2CO_3 catalytic ionization seeds were injected into the combustion chamber to obtain gas plasma on a high temperature magneto hydrodynamic (MHD) experiment rig. The plasma jet was deflected under the action of an external magnetic field, resulting in a thrust-vector effect. Particle image velocimetry (PIV) collected two-dimensional images of jet flow field. Through image processing and velocity vector analysis, the jet deflection angle can be obtained quantitatively. At 1800—2500 K, the jet deflection was verified experimentally under the condition of 0.45 T magnetic field strength. The results indicate that the jet deflection angle increases gradually with the increase of gas temperature, and above 2200 K, the jet deflection angle increase obviously. In the process of gas plasma jet, it is feasible to realize the jet deflection controlled by MHD by adding an external magnetic field.

Key words: gas plasma; plume deflection; magnetic fluid; thrust vector; particle image velocimetry

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Thrust-vector technology is considered as the key technology of future fighter aircraft, which has attracted great attention of military forces all over the world. At present, the main control methods of thrust vector are mechanical control, pneumatic control and electromagnetic control. The mechanical hydraulic control mode has the disadvantages of complex structure and heavy accessories, which reduces the reliability and maintainability of the system. In addition, the pneumatic control mode consumes a lot of

compressed air, which reduces the efficiency of the engine and increases the cost.

The principle of plasma thrust vector controlled by electromagnetism includes two types: electrohydrodynamics (EHD) and magneto-hydrodynamics (MHD). According to the principle of EHD, plasma generated by dielectric barrier discharge (DBD) is accelerated by high-voltage electric field to reduce fluid resistance and prevent fluid separation^[1-4]. Most of the researches focus on boundary layer flow con-

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tro[⁵⁻⁷]. Electron beam induced ionization (EBI) enhances and maintains the ionization characteristics of working substances in the irradiated region of high-energy electron beam, which is equivalent to “local” plasma, which is not conducive to for aero engine to generate thrust-vector effect.

The research of magneto hydrodynamic technology in aeronautical engineering mainly focuses on magneto hydrodynamic flow control[⁸⁻¹¹], magneto hydrodynamic acceleration[¹²], magneto hydrodynamic power generation[¹³⁻¹⁴], and magneto hydrodynamic combined engine[¹⁵⁻¹⁶]. Sun, et al. carried out numerical simulation of plasma flow field under MHD condition[¹⁷⁻¹⁸]. The results show that the jet plume under plasma condition can deflect with MHD. Zhao, et al. completed the study of jet deflection in gas plasma under external magnetic field[¹⁹]. Lineberry, et al. carried out experimental studies on extracting electrical energy from high-temperature gas plasma under the coupling effect of electric field and magnetic field[²⁰]. The Hypersonic Vehicle Electric Power System (HVEPS) project has obtained gas plasma by injecting ionization seeds during combustion[²¹].

In contrast, the effect of adding ionization seeds depends on the spatial distribution of ionization seeds, which stimulates a wider range of plasma, equivalent to the “whole” plasma. The area of magnetron action is also wider. MHD flow control mode enables the control device to be designed inside the body, avoiding the influence on the design of the engine runner. No additional air intake/exhaust devices are needed, which is conducive to the compact design of aircraft and engine structures. Therefore, it has great application prospect to introduce MHD technology into the field of engine flow control and carry out flow control research.

This paper presents a scheme of deflection of gas plasma jet controlled by MHD. Firstly, the experimental device and method are introduced. Secondly, the deflection mechanism of gas plasma jet controlled by MHD is described. Finally, the experimental results are analyzed, and the

conclusions are drawn.

1 Experimental device and method

1.1 Experimental device

The experiments were carried out on the thrust-vector experiment rig controlled by MHD. The experiment rig is mainly composed of gas source platform, flow control platform and measurement system. The experimental system is shown in Fig. 1. Gas source platform provides high temperature gas plasma as experimental working fluid. A compressor with a flow rate of 0.25 kg/s and a maximum pressure of 200 kPa provides compressed air. The combustor combusts with swirling air intake and centrifugal atomizing nozzle. The injection interfaces of ionization seeds are installed on the left and right walls of the combustion chamber respectively. The igniter is mounted on the upper wall of the combustion chamber. Temperature measurement points are distributed near the exit of combustion chamber.

The contraction section of Laval nozzle is changed from square to rectangle, which ensures the symmetrical distribution of combustion chamber outlet and weakens the three-dimensional swirling flow characteristics at the nozzle inlet. The expansion section of Laval nozzle adopts the scheme of equal width and variable height to enhance the two-dimensional characteristics of the airflow at the nozzle outlet.

The flow control platform is composed of ionization seeds fluidization device and magnetic control device. The ionization seeds fluidization device uses high-pressure air to fluidize the ionization seeds Cs_2CO_3 from the initial powder state and inject it into the combustion chamber. In the experimental section of MHD control, the equal cross-section rectangular channel length $\times$ width $\times$ height = 220 mm $\times$ 30 mm $\times$ 60 mm is selected. Copper electrode plates are installed on the inner and outer walls of the channel, and ceramic insulation planes are installed on the left and right walls. Two pairs of strong magnetic permanent magnets, which are mounted on the front and rear sides of the experimental section by a brack-

et, generate the magnetic field required for MHD flow control.

A two-dimensional particle image velocimetry (PIV) is used to measure the jet flow field. The PIV lamp light source laser projects a plane beam of light from the optical arm lens on the central section of the jet, so that the tracer particles of this section are highlighted under laser

irradiation. Then a high-speed camera (charge couple device camera, CCD camera) is used to record the images of particles at different times, which are processed by computer software. The ambient pressure is 104 kPa and the outlet gas temperature is between 1800 K and 2500 K. The schematic diagram of the experimental system is shown in Fig. 2.

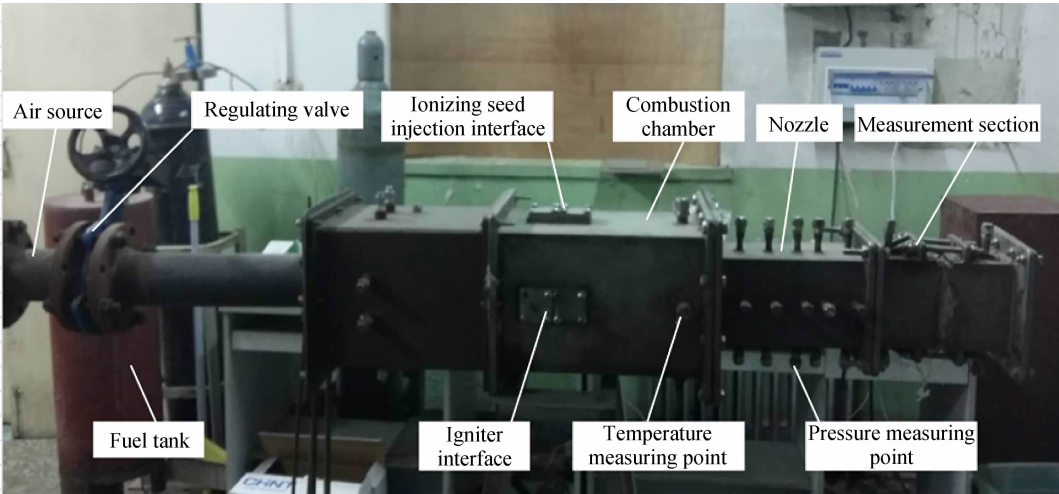


Fig. 1 Experimental system

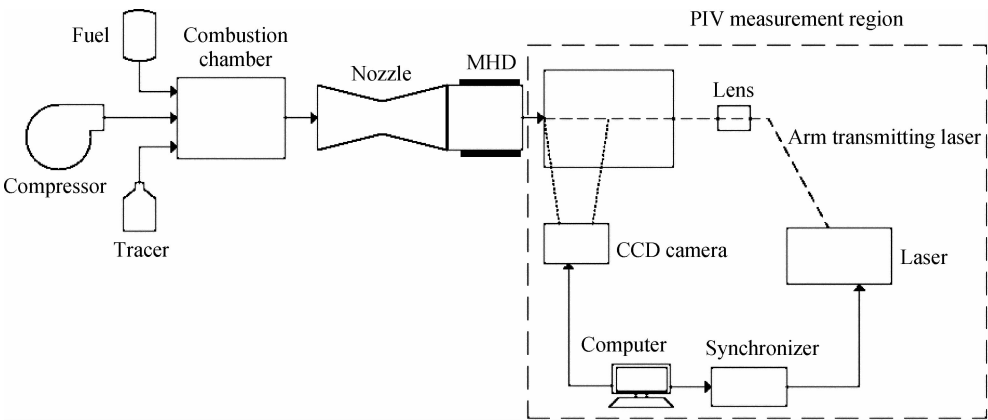


Fig. 2 Schematic diagram of the MHD thrust-vector system

1.2 PIV system parameters

PIV system has a high spatial and temporal resolution, which can fully meet the measurement requirements of flow field velocity. The equipment parameters of PIV system are as follows: (1) laser source: Nd: YAG laser with excitation energy of 200 mJ, excitation frequency of 1—15 Hz, laser wave length of 532nm, thickness of lamp light source of 0.5 mm. (2) Power View 4M model CCD

camera resolution of 2048×2048 pixels. (3) Filter lens with wave length of 532 nm.

1.3 Experimental method

During the experiment, the main processes are as follows: (1) open the high-pressure cylinder valve, increase the driving pressure of the fuel tank, slightly open the fuel supply valve, start the igniter power supply and ignite the fuel. (2) Start the compressor, supply air to the

combustion chamber, adjust the intake valve and fuel supply valve, so that the air flow rate and temperature of the combustion chamber can meet the requirements of the experimental conditions, and record the initial thermal experimental data. (3) Turn on the switch of Cs_2CO_3 ionization seeds fluidization device, add ionization seeds to combustion chamber. (4) During the experiment, according to different experimental conditions, adjust the amount of ionization seeds and record the experimental data. (5) Close the ionization seed fluidization device, fuel supply valve and compressor intake valve in turn, end the experimental process and sort out the experimental data.

2 Principle of plasma flow with MHD control

Gas was ionized at high-temperature to form charged particles. The index of evaluating gas ionization ability is ionization degree, which is given by Saha equation.

alpha = (n_i / (n_n + n_i)) approx 3 * 10^15 * (T^(3/2) / n_i) * exp(-E_i / T)

(1)

Where n_n is number of neutral particle per unit volume, n_i is number of ion particle per unit volume, E_i is the ionization energy, T is temperature. When the temperature of atmosphere is 300 K, the ionization degree of air is only 10^{-16} ; when the temperature reaches 11 600 K, the ionization degree of air reaches 10^{-3} , which is similar to that of plasma, and can show the electromagnetic characteristics of plasma. Its conductivity can be expressed by conductivity σ

sigma = (n_e * e^2 * (m_e + m_i) / (m_e * m_i * v_ei)) approx (n_e * e^2 / (m_e * v_ei))

(2)

v_ei = (1 / (4 * pi * epsilon_0)^2) * (4 * sqrt(2 * pi * n_e * Z_e^4 * ln Delta) / (3 * m_e^(1/2) * T_e^(3/2)))

(3)

ln Delta = ln [(4 * pi * (epsilon_0 * T)^(3/2)) / (e^3 * n_e^(1/2))]

(4)

Where n_e represents the number of electrons per unit volume, e represents the charged quantity of electrons, m_e is electron mass, m_i is ion mass, and v_{ei} is the average collision frequency of electrons and ion, Z_e is ionic charge, ϵ_0 is dielectric constant, T_e is electron temperature (eV), Δ is

plasma parameter.

Considering only the Lorentz force, this force on all ions may be regarded as the volume force F produced by the fluid with MHD. Under the action of MHD, Ohm's law and magnetic force are expressed as Ref. [22]

J = sigma * (E + V x B)

(5)

F = J x B

(6)

J stands for current density, V for velocity vector, B for composite magnetic field strength, E for induction electric field strength.

MHD control of plasma flow is an active flow control technology, which combines electromagnetic control with magneto hydrodynamics. The gas is ionized to a near plasma state, and the magnetic energy is loaded into the jet flow field. The charged particles in the plasma jet are rotated by Lorentz force. Because the positive ion and molecule are the main body of the fluid mass, when the positive ion concentration is high enough, the movement of the positive ion will play a leading role in the fluid, and the macroscopic airflow state is mainly determined by the movement state of the positive ion. The jet deflects from the axis and forms the jet deflection angle, which produces the thrust vector effect. The motion of plasma under magnetic field is shown in Fig. 3. In Fig. 3, q represents charge quantily of particle.

The ionization seeds are injected into the combustion chamber, which strengthens the gas ionization characteristics and forms a gas plasma composed of neutral particles, electrons and ions. When a positive ion enters the magnetic field, it rotates clockwise under Lorentz force. If the ion collides with a neutral particle moving horizontally, its momentum in the direction of the pointer will be transferred to the neutral particle, which will deflect the neutral particle downward. The positive particle after collision will continue to be affected by the magnetic field. Still doing clockwise rotation, so repeatedly. Positive ions continuously rotate and collide to transfer momentum in the forward process, which makes the neutral particles pres-

ent the flow characteristics of downward deflection as a whole, as shown in Fig. 3(a).

When electrons enter the magnetic field, they rotate counterclockwise under Lorentz force. Because the mass of electrons is much

smaller than that of positive ions, the radius of rotation of electrons is much smaller than that of positive ions. Electrons will accumulate near the upstream of the upper electrode plate, as shown in Fig. 3(b).

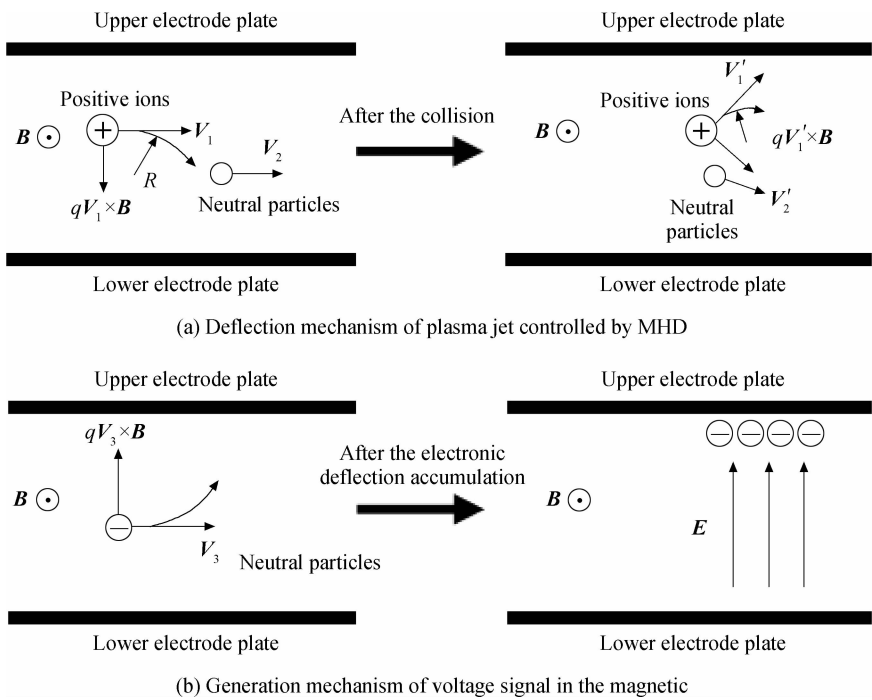


Fig. 3 Deflection mechanism of plasma jet controlled by magnetic fluid

3 Results and analysis

At 1 800—2 500 K, the experiment verifies that the gas plasma jet deflects under the control of external magnetic field and produces thrust vector effect by adding Cs_2CO_3 to enhance the gas ionization characteristics. The experimental parameters are shown in Table 1. The effect of plasma plume deflection is shown in Fig. 4. In Table 1, T_g is the gas temperature, $\dot{m}_a$ is the air flow rate, $\dot{m}_f$ is the fuel flow rate, $\dot{m}_i$ is the ioni-

zation seeds flow rate, B represents the magnetic field intensity, u_t and v_t are the instantaneous radial and axial velocities, respectively.

3.1 Evaluation of plume deflection angle

Figure 5 illustrates the process of particle image data processing captured by PIV system.

Under the experimental conditions, the statistical average value of the flow field is equal to the time average value, and the radial average velocity and the axial average velocity of the flow field can be obtained.

Table 1 Experimental parameters

Case	T_g/K	$\dot{m}_a/(\text{g/s})$	$\dot{m}_f/(\text{g/s})$	$\dot{m}_i/(\text{g/s})$	B/T	$u_t/(\text{m/s})$	$v_t/(\text{m/s})$	$\theta/(^{\circ})$
1	1800	71.2	2.19	8.9		101	0	0
2	1800	71.2	2.19	8.9	0.45	101	0.1	0.05
3	2000	71.2	3.11	8.9	0.45	102	0.6	0.33
4	2200	71.2	3.98	8.9	0.45	105	2.1	1.15
5	2350	71.2	4.65	8.9	0.45	108	13.2	6.96
6	2450	71.2	4.89	8.9	0.45	114	17.5	8.72

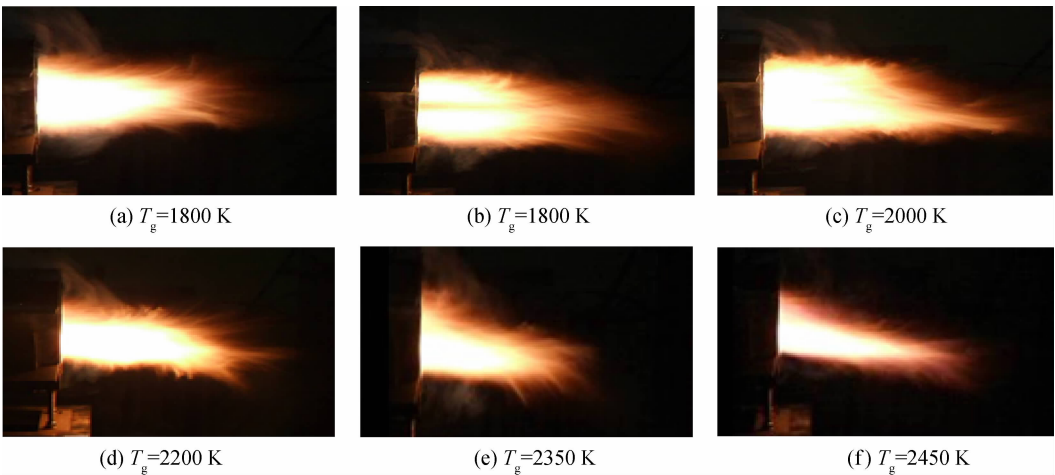


Fig. 4 Effect of plasma plume deflection under different working cases

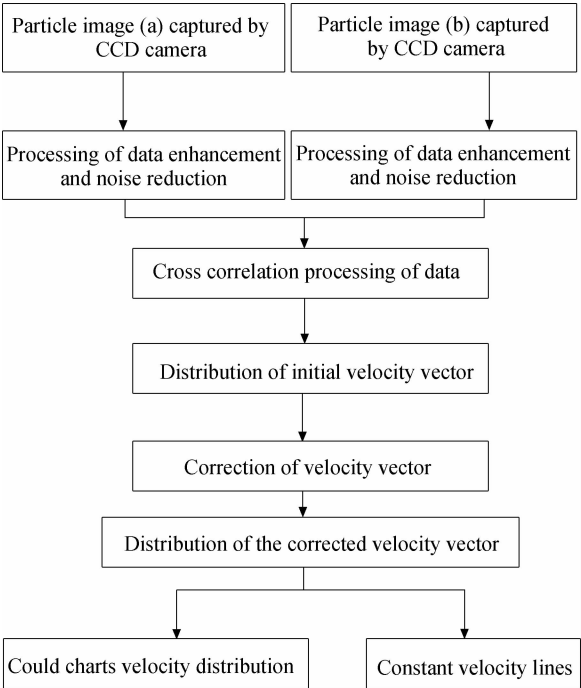


Fig. 5 Flow chart of PIV capture particle velocity

$$U(x,y,z) = \frac{1}{N} \sum_{t=1}^N u_t(x,y,z) \tag{7}$$

$$V(x,y,z) = \frac{1}{N} \sum_{t=1}^N v_t(x,y,z) \tag{8}$$

$$\theta = \arctan \frac{U(x,y,z)}{V(x,y,z)} \tag{9}$$

In the formula, t is the instantaneous number of flow field statistics, $t=1,2,3,\cdots,N$; θ is the jet deflection angle.

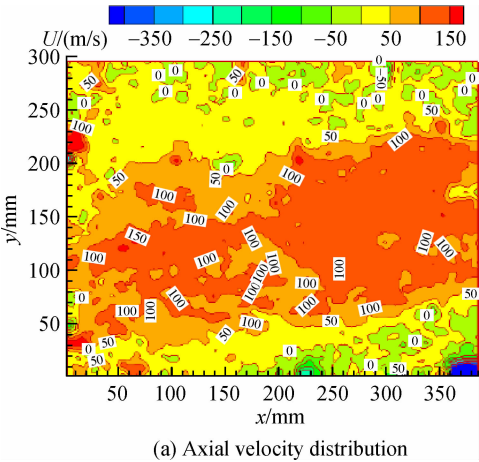
In the experiment, the PIV measurement range is selected as the rectangular region with the length multiplied by the width of $385\text{ mm} \times 295\text{ mm}$ starting from the nozzle outlet. The corresponding coordinate system is established in

PIV flow field image processing. The flow direction along the lower wall of the nozzle is defined as the positive direction of the X -axis, the direction perpendicular to the X -axis and upward is the positive direction of the Y -axis, and the intersection of the two coordinate axes is the coordinate origin.

Taking the experimental case 5 as an example, the flow field images captured by PIV were processed by dynamic studio software, and the axial velocity, normal velocity contour and velocity vector of the flow field were obtained, as shown in Fig. 6. The axial velocity is close to 100 m/s , the normal velocity is close to 10 m/s , and the velocity vector of the flow field deviates from the nozzle axis with a large obliquity.

3.2 Effect of gas temperature on plume deflection

The influence of gas temperature on MHD flow control was studied experimentally at $1800\text{--}2\,500\text{ K}$. Fig. 4 shows the plume state



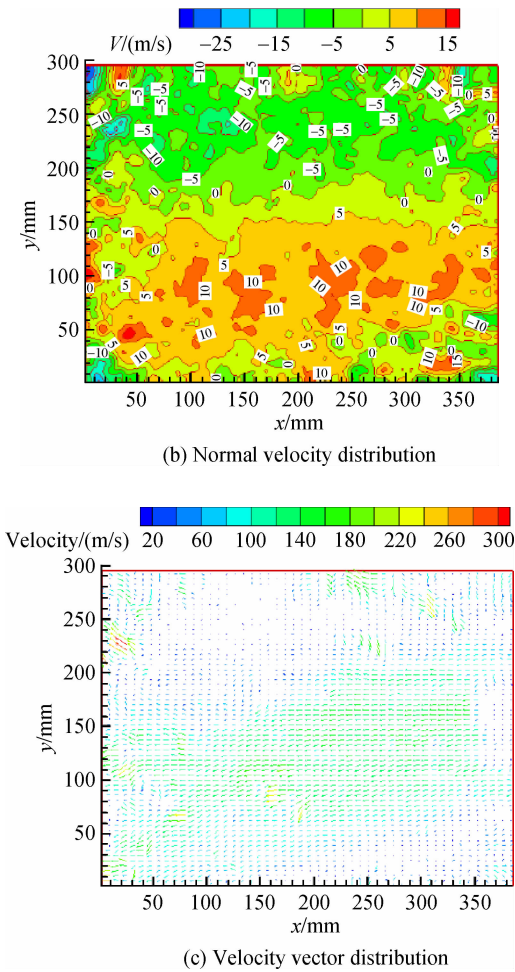


Fig. 6 Equivalent velocity and velocity vector map of jet flow field

under various operating conditions. Fig. 4 illustrates that with the increase of gas temperature, the jet deflection angle increases gradually. Combining with the experimental data in Table 1, it can be seen that the jet deflection angle increases gradually from 0° to 8.72°.

Comparing Fig. 4(a) and Fig. 4(b), it can be seen that at 1800K, when ionization seeds are added and no magnetic field is applied, the gas plume extends along the outlet axis after ejection, and the flame state of the jet is basically stable. The gas plume deviates slightly from the central axis of nozzle under the action of magnetic field, but the change of jet deflection is not obvious. This indicates that the Cs_2CO_3 seeds have been ionized at 1800 K, but the concentration of ions in the gas was very low. The plasma can not deflect under the action of external magnetic field.

At 2 000 K, the gas plume still shows a slight deviation from the central axis, and there is no obvious deviation movement. However, there are obvious flutter and rupture phenomena on the flame surface.

Above 2 200 K, the gas plume is gradually compressed. Under the action of magnetic field, the gas plume gradually deviates from the central axis of the nozzle and approaches the mainstream, forming a deflected jet at a certain angle.

According to Eq. (1)–Eq. (6), with the increase of gas temperature, the ionization of ionized seed is intensified, and a large number of ions are released. With the increase of ion concentration in gas, the ionization degree of gas is increased, and the conductivity of gas is increased, that is to say, the conductivity is increased. Under the action of the magnetic field, the Lorentz force on the plasma increases, which leads to the increase of the deflection effect of the jet.

4 Conclusions

A new method of MHD controlling gas plasma jet to realize thrust vector is presented in this paper. Based on theoretical analysis, experimental study of plasma jet deflection is carried out, and the following conclusions are drawn:

1) Gas plasma can be obtained by injecting Cs_2CO_3 ionization seeds into combustion chamber gas at 1800–2500 K by artificial forced ionization. The plasma jet deflects under the action of 0.45 T external magnetic field, resulting in thrust vector effect.

2) At 1800–2200 K, the plasma plume deflection is small. After 2 200 K, the plasma plume deflection increases significantly with the increase of gas temperature, which indicates that temperature has an important influence on jet deflection.

3) By combining PIV measurement technology with image processing, the deflection effect of plasma jet controlled by MHD can be quantitatively evaluated.

The effects of ionization seeds mass content

and magnetic field intensity on jet deflection will be studied in the future.

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