Numerical and experimental investigation of plasma plume deflection with MHD flow control

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Abstract
This paper presents a composite magneto hydrodynamics (MHD) method to control the low-temperature micro-ionized plasma flow generated by injecting alkali salt into the combustion gas to realize the thrust vector of an aeroengine. The principle of plasma flow with MHD control is analyzed. The feasibility of plasma jet deflection is investigated using numerical simulation with MHD control by loading the User-Defined Function model. A test rig with plasma flow controlled by MHD is established. An alkali salt compound with a low ionization energy is injected into combustion gas to obtain the low-temperature plasma flow. Finally, plasma plume deflection is obtained in different working conditions. The results demonstrate that plasma plume deflection with MHD control can be realized via numerical simulation. A low-temperature plasma flow can be obtained by injecting an alkali metal salt compound with low ionization energy into a combustion gas at 1800–2500 K. The vector angle of plasma plume deflection increases with the increase of gas temperature and the magnetic field intensity. It is feasible to realize the aim of the thrust vector of aeroengine by using MHD to control plasma flow deflection.

Keywords: MHD, plasma, ionization degree, thrust vector, aero engine

(Some figures may appear in colour only in the online journal)

1. Introduction

With the rapid development of modern military technology, the future air combat environment requires that fighters have high maneuverability in all types of flight states. Thrust-vector technology is considered as the key technology to realize this requirement; thus, thrust-vector technology is of great importance in worldwide military technology, and scholars have performed much relevant research [1–5]. At present, the thrust vector control of international advanced fighters mainly involves mechanical control and pneumatic control. However, the mechanical hydraulic control system is heavy and complex. The pneumatic control consumes much compressed air and reduces the engine efficiency. With the development of magneto hydrodynamic (MHD), magnetic fluid technology has been widely used in power, aviation, navigation and other fields. The research on magnetic fluids in aviation engineering is mainly focused on magnetic fluid flow control [6, 7], magnetic fluid acceleration [8], magnetic fluid power generation [9] and the magnetic fluid combined engine [10, 11]. Compared with the mechanical flow control method, the MHD flow control method allows the control device to be inside the engine block and avoids the influence of the control mode on the engine flow passage design. Compared with the pneumatic flow control method, the MHD flow control mode does not require additional configuration of air bleed/exhaust.
device, making it beneficial to the compact design of the aircraft/engine. Therefore, MHD control technology has prospects for further development in the future [12, 13]. A scheme using the MHD control technology to deflect the low-temperature and micro-ionized plasma flow in the combustion gas and realize the thrust vector of an aeroengine is proposed in this paper.

In this paper, the MHD control theory is introduced, and the plasma flow deflection using MHD control is realized by numerical simulation. The plasma plume deflection is verified by experiments on the MHD control test rig, and the results are analyzed and discussed.

2. MHD control theory

2.1. Principle of plasma flow with MHD control

Thrust vector control with MHD control is a technology that combines electromagnetic control and MHD to realize active flow control. When the airflow is fully ionized and reaches the near plasma state, the electromagnetic energy is injected into the jet flow field through the electromagnetic field. The charged particles are subjected to the Lorentz force to do the cyclotron motion, as shown in figure 1. Because positive ions and molecules are the main body of fluid mass, the positive ion will dominate the fluid when the cation concentration is high enough, and the macro airflow state is determined by the positive ion motion state. The coupling force of between the Lorenz force and the interaction force between particles leads to the deflection induced force and deflection moment, which causes the jet to deviate from the axis direction, thereby forming the jet deflection angle and producing the thrust vector effect.

2.2. Electrical properties of magnetic fluids

Gas is ionized at a high temperature to form charged particles. The ionization rate can be used to assess the ionization capacity of a gas. The parameter to evaluate the ability of gas ionization is the ionization degree. Ionization degree \( \alpha \) is determined by the Saha equation, given as

\[
\alpha = \frac{n_i}{n_n + n_i} \approx \frac{n_i}{n_n} = 3 \times 10^5 \frac{Z^3/2}{n_i} \exp(-E_i/T). \tag{1}
\]

In the equation, \( n_i \) is the number of electrons per unit volume; \( e \) is the electron charge; \( m_e \) is the electron mass; \( m_i \) is the neutron mass; \( \nu_{ei} \) is the average collision frequency for electrons and neutrons; \( \varepsilon_0 \) is the dielectric constant; \( T_e \) is the electron temperature (unit eV); \( Z_i \) is the ionic charge; and \( \Lambda \) is the plasma parameter.

2.3. Realization of low-temperature gas plasma

The gas at 2500 K has an ionization degree of \( 10^{-9} \) and has no electrical conductivity. To convert the gas in this temperature range into a magnetic fluid, by adding chemicals with low-ionization energy to the ionized gas, the overall ionization degree and charged ion concentration of the gas are increased.

As shown in figure 2, the ionization energy of alkali metal is the minimum in the periodic table; therefore, we pay more attention to its electrochemical properties. As shown in table 1, the standard electrode potential of the alkali metal is approximately \(-3.000\, \text{V} \), which indicates that its elemental substance very easily loses electrons. The ionization energy and the electron affinity decrease continuously as the number

![Image of charged particles moving in a magnetic field.](image1)

**Figure 1.** Charged particles moving in a magnetic field.

![Image of ionization energy cyclical change rules.](image2)

**Figure 2.** Ionization energy cyclical change rules.

In the equation, \( E_i \) is the ionization energy, and \( T \) is the total temperature. When the atmospheric temperature is 300 K, the ionization degree of air is only \( 10^{-122} \). When the temperature reaches 11 600 K, the ionization degree of air reaches \( 10^{-3} \), which is similar to that of plasma. Moreover, gas can exhibit the electromagnetic characteristics of plasma states, and its electrical conductivity can be expressed by the formula of conductivity given below

\[
\sigma = \frac{n_e e^2 (m_e + m_i)}{m_e m_i \nu_{ei}} \approx \frac{n_e e^2}{m_e \nu_{ei}} \tag{2}
\]

\[
\nu_{ei} = \frac{1}{(4\pi\varepsilon_0)^2 \frac{4\sqrt{2\pi n_e Z_i e^4 \ln \Lambda}}{3 m_e^{1/2} T_e^{3/2}}}
\]

\[
\ln \Lambda = \ln \left( \frac{4\pi (\varepsilon_0 T_e)^{3/2}}{e^4 n_i^{3/2}} \right). \tag{4}
\]
of nuclear charges increases, i.e., the ability to lose electrons is constantly increasing. Although the alkali metal element is ionized (the conversion temperature is above 10 000 K), the temperature is still far greater than that under hypersonic flow conditions. The energy of the particles is shown in figure 3; the energy distribution is described by the Maxwell–Boltzmann distribution function. Thus, the energy of a fraction of alkali metal salt particles is greater than its own ionization potential. As a result, a small amount of alkali metal salt ionizes and releases free electrons; macroscopically, the gas flow becomes a weakly ionized plasma. Thus, the plasma state is reached at a lower temperature. The chemical properties of alkali metal are unstable; therefore, alkali metal salt Cs₂CO₃ is selected as a seed additive for catalytic ionization. In high-temperature gas, the Cs₂CO₃ reaction process is as follows:

\[ \text{Cs}_2\text{CO}_3 \rightarrow \text{Cs} + \text{CO}_2 \]  
\[ \text{Cs} \rightarrow \text{Cs}^+ + \text{e}^- \]  

### 3. Numerical simulation of plasma flow with MHD control

#### 3.1. Control equations

Under the effect of MHD, the plasma obeys both the electromagnetic equation and the fluid dynamics equation, and the complete MHD equation [14] is given by:

- **Continuity equation:**
  \[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0. \]  

- **Momentum equation:**
  \[ \rho \frac{d\mathbf{u}}{dt} = \nabla \cdot \mathbf{P} + \mathbf{J} \times \mathbf{B}. \]  

- **Energy equation:**
  \[ \rho \frac{d}{dt} \left( e + \frac{u^2}{2} \right) = \nabla \cdot (\mathbf{P} \cdot \mathbf{u}) + \mathbf{E} \cdot \mathbf{J} - \nabla \cdot \mathbf{q}. \]  

- **State equation:**
  \[ p = p(\rho, T). \]  

- **Maxwell equation:**
  \[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  
  \[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \]  
  \[ \nabla \cdot \mathbf{B} = 0. \]
Ohm’s law:

\[ J = \sigma (E + u \times B). \]  

Equations (7)–(14) comprise the MHD equations set. Different from the conventional equation of N–S, the source term of electromagnetic force is added to the equation. \( \rho \) is the mass density, \( t \) is time, \( u \) is the velocity vector, \( P \) is the stress tensor, \( J \) is the current density, \( \varepsilon \) is the dielectric constant, \( B \) is the magnetic field intensity, \( E \) is the induction electric field strength, \( p \) is the pressure, \( q \) is the heat loss, \( \sigma \) is the conductivity, and \( \mu_0 \) is the magnetic conductivity.

Once the Lorenz force of ions is the only force taken into account in the fluid, all the ions subjected to Lorenz force can be regarded as the volume force \( F \) produced by the magnetic field acting on the fluid, and the volume force \( F \) can be taken as the source force in the flow field.

\[ F = J \times B. \]  

### 3.2. Computational domains and grids

The calculation model uses the conventional two element nozzle; its structure is shown in figure 4. The length of the nozzle is 75 mm, the minimum cross-sectional area is 27 mm \( \times \) 22 mm, the nozzle convergence angle is 8°, and the outlet expansion angle is 4°. The computational domain mesh is shown in figure 5; the domain includes the nozzle, the test section and the far field. Considering the influence of the surface layer on the wall of the nozzle, the boundary layer is divided on the near wall surface. In the region where the velocity gradient of the nozzle is larger, the grid is properly encrypted. After the analysis of mesh independence, the computational domain is all hexahedral orthogonal mesh, and the total number of grids is 1.3 million.

### 3.3. Boundary conditions and flow model

CFD software FLUENT is used to simulate complex flow phenomena. In the numerical calculation, it is assumed that the fluid is an ideal high temperature fluid, the magnetic field strength is constant, the ionization material is evenly distributed, and the ionization degree is ideal and effective. The MHD model is applied to solve the three-dimensional N–S equation by User-Defined Function (UDF). The standard \( k \)-epsilon model is used to simulate the turbulent phenomena, and the two-order upwind scheme is used to discretize the partial differential equations. The gas is considered as an incompressible fluid, the inlet is set as the velocity inlet and the outlet and sidewall are set as far field pressure, the ambient temperature is 300 K, the pressure is 101 325 Pa, the magnetic field width is 30 mm, the strength of the magnetic field along the X axis covers the area from the throat to the export expansion section, and the magnetic field strength near the wall is loaded by UDF. The calculation parameters are shown in table 2.

### 3.4. Results and analysis

The shape and direction of the gas plume under all calculation conditions are shown in figure 6. According to figure 6(a), the velocity distribution of flow field is symmetrical on the plane, and the plume does not deflect. At 1800 K, it is shown that the ionization of gas is low, the magnetic field force is small, and the deflection motion cannot be formed. Figures 6(b)–(d) show that the deflection angle of gas plume increases gradually as the gas temperature increases. The gas forms a critical plasma state with the magnetic properties of the magnetic fluid when the temperature is above 2000 K. Under the action of the MHD control system, the fluid is subjected to the centripetal force, and the deflections will occur when it is
Figure 6. (a)–(d) Plume shape and direction at 1800 K, at 2000 K, at 2200 K and at 2400 K, units: m s\(^{-1}\).

Figure 7. (a) and (b) YZ plane total pressure distribution and YZ plane static pressure distribution for case 4, units: Pa.

Figure 8. MHD control thrust-vector test rig.

Figure 9. Schematic of the magnetic control thrust-vector experiment.
force in the plasma.

Static pressure distribution shown in blocking zone to form the air throat and throat slope. From the extends to the throat of the nozzle, creating a low velocity hydrostatic pressure near the lower wall of the nozzle exit of MHD simulating with the simulation results.

Velocity inertial action, the jet the lower wall pressure increases. In the magnetic symmetric. Next, the upper wall static pressure decreases while pressure at the upper and lower wall of the nozzle is initially de.

Formulas 2 and 3 indicate that the increase of the Lorenz motion of the fluid, forming complete, uniformly distributed tilted tail jets from the high velocity zone at nozzle exit to the lower wall low velocity region, and the deflection occurs. The total pressure distribution of figure 5 shows that the high hydrostatic pressure near the lower wall of the nozzle exit extends to the throat of the nozzle, creating a low velocity blocking zone to form the air throat and throat slope. From the static pressure distribution shown in figure 6(b), the static pressure at the upper and lower wall of the nozzle is initially symmetric. Next, the upper wall static pressure decreases while the lower wall pressure increases. In the magnetic field force and velocity inertial action, the jet flow moves around the obstruction flow zone and then flows backward to the flow resistance zone, gradually producing jet deflection. Thus, the MHD control can realize the thrust vector of a critical plasma jet.

4. Experimental investigation of plasma jet deflection

The gas temperature of an aeroengine is generally below 2500 K. At this temperature, the gas cannot be completely ionized and has no electrical conductivity. To convert the gas into a magnetic fluid in the range of temperature, the airflow motion in the electromagnetic field is changed. A test rig of the engine combustion chamber was designed to form a magnetic thrust vector control system that forced the gas to be ionized artificially. Because the thermal ionization energy of alkali metal elements is relatively small, the metal cesium salt is chosen as the catalyst additive, and the gas ionization degree and charged ion concentration are increased to realize the jet flow state of the magnetic fluid gas.

4.1. Experimental device

As shown in figure 8, the MHD thrust-vector test system consists mainly of high temperature combustion chambers, nozzles, and electromagnetic control components. The nozzle dimensions are shown in figure 4. The magnetic field is supplied by a high-strength Nd–Fe–B permanent magnet around the nozzle, and the distance between the two magnetic pole plates is 110 mm. A temperature measurement system based on a water-cooled thermocouple and an electrical signal acquisition system are installed on the sidewall of the test section. The fuel supply is controlled by monitoring the temperature, and the wall voltage signals are observed. The inlet speed is 105–115 m s⁻¹, the environmental pressure is 1.04 × 10⁵ Pa, the mass fraction of cesium in the gas is 5%, and the outlet temperature is between 1800 and 2500 K. The schematic diagram of the experiment system is shown in figure 9, and the parameters of the experiment are shown in table 3.

4.2. Experimental method

During the experiment, the gas is supplied by an air compressor at a flow rate of 0.25 kg s⁻¹ and a maximum pressure of 2 atm. The airflow flows into the combustion chamber head pressure stabilizing cavity through the pipe and enters the combustion chamber through each airflow hole. The four flame guns can be used as the ignition source of the fuel at the same time to produce a high-temperature zone (after the fuel is added, the maximum temperature in this region exceeds 2500 K). Ionized seeds are blown into the combustion chamber and vaporized rapidly in the region to form the magnetic fluid that is ejected from the nozzle. The test process mainly involves the following steps:

<table>
<thead>
<tr>
<th>Case</th>
<th>Temperature (K)</th>
<th>Magnetic field Intensity (T)</th>
<th>Ionization Degree</th>
<th>Conductivity (S m⁻¹)</th>
<th>Vector angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1800</td>
<td>0.45</td>
<td>10⁻⁷</td>
<td>10.1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
<td>0.45</td>
<td>10⁻⁶</td>
<td>32.5</td>
<td>3.7</td>
</tr>
<tr>
<td>3</td>
<td>2200</td>
<td>0.45</td>
<td>10⁻⁵</td>
<td>111.9</td>
<td>6.8</td>
</tr>
<tr>
<td>4</td>
<td>2400</td>
<td>0.45</td>
<td>10⁻⁴</td>
<td>204.7</td>
<td>11.1</td>
</tr>
<tr>
<td>5</td>
<td>2200</td>
<td>0.6</td>
<td>10⁻⁵</td>
<td>111.9</td>
<td>7.9</td>
</tr>
<tr>
<td>6</td>
<td>2400</td>
<td>0.6</td>
<td>10⁻⁴</td>
<td>204.7</td>
<td>12.1</td>
</tr>
</tbody>
</table>
1. Open the oxygen-acylene valve, start the ignition power, ignite the acetylene high temperature separate gun, and adjust the acetylene and oxygen flow rate to make the flame reach the best high temperature state;

2. After four high temperature flame guns are ignited, start the air compressor, input air into the combustion chamber, and then start the air compressor and adjust the flow of the compressor to ensure the temperature is stable in the range of 1400–1500 K;

3. Open the fuel valve, inject fuel into the combustion chamber, adjust the fuel supply, according to different test conditions, and keep the exit temperature between 1800 and 2500 K;

Figure 11. (a)–(f) Plume shape and direction with 5% additive for case 1, for case 2, for case 3, for case 4, for case 5 and for case 6.
(4) open the air source of the seeds powder test bottle, blow the powder into the combustion chamber, decompose the ionization reaction, and control the supply of Cs$_2$CO$_3$ powder.

4.3. Results and analysis

4.3.1. Influence of ionized seeds on jet state. Comparing figures 10 and 11, it can be seen that in the magnetic field, the jet extends flat along the axis of the export after being injected, and the jet flame ionization state is basically stable when not adding ionization seeds; the jet nozzle deviates from the central axis under the action of magnetic field to form a certain angle of the jet deflection when adding seeds. Thus, the ionization characteristics of the gas are strengthened when the Cs$_2$CO$_3$ ionized seeds are injected into the high-temperature combustion chamber. At the same time, the low-temperature plasma composed of neutral ions, electrons and ions has been produced, and the ionization degree of gas reaches a considerable magnitude of $10^{-4}$–$10^{-3}$. The MHD flow control effect is displayed under the magnetic field when the gas plasma flows through the test section.

From the point of view of particle electrical property, the positive ion number density is greater than the electron number. From the point of view of particle quality, the mass of positive ion and negative ion is much higher than that of electron. This finding suggests that cations mainly assume the function of momentum transport, and electrons play a major role in the transport of electricity. The former mainly shows the phenomenon of jet deflection under the action of MHD, and the latter can be explained by the voltage signals captured during the MHD energy extraction process.

Because positive ions and neutrons of the magnetic field are the main fluid quality, the positive ion movement play the leading role of the fluid movement when the positive ion concentration is high enough. Macroscopic air movement is mainly determined by the state of positive ion motion. A positive ion deflects under the action of Lorenz force and collides with the neutral particles in the forward motion to transport energy and momentum. The positive ion after the collision continues to deflect under the action of the magnetic field, while the neutral particle obtains momentum in the deflection direction and moves along the deflection direction, as shown in figure 12(a). Because the mass of an electron is far less than the positive ion mass, and the rotation radius of an electron is far less than that of the positive ion. This dynamic causes electrons to accumulate in the near upper electrode plate and positive ions to accumulate in the downstream near the lower electrode plate (most of the...
positive ions are entrained by other high mass ions); thus, an induced electric field will be formed, changing the voltage signal, as shown in figure 12(b). The induced electric field will restrain the rotation of the positive ion; however, the electric field is weaker without the applied electric field.

4.3.2. Influence of gas temperature on jet flow. The gas plume is symmetrically distributed along the central axis when the gas temperature is lower than 1800 K, and there is no obvious deflection motion, as shown in figure 11(a). The flame surface becomes smooth, the flame is gradually compressed, the gas plume gradually deviated from the central axis of the nozzle under the action of the magnetic field and moved closer to the mainstream, forming a deflected jet with a certain angle, as shown in figure 11(b). Combined with the relationship between the test parameters in table 3, it can be seen that when the temperature increases, the ionization characteristics of gas plasma are enhanced, the ion concentration in the gas is increasing, and the conductivity magnitude increased significantly. The effect of the magnetic force on the plasma increases, leading to the increase of the deflection angle of the jet. The higher temperature of the gas, the greater change of the angle of jet will be. This dynamic indicates that the effect of temperature change on the vector angle is very significant.

4.3.3. Influence of the magnetic field intensity on the jet flow. Under the condition of the outlet gas temperature of 2200 and 2400 K, with the magnetic field intensity changed from $B = 0.45$ T to $B = 0.6$ T, keeping the other parameters unchanged, by comparing the shape of the flames figures 11(c), (e) and (d), (f), the flame deflection angle is found to increase with the increase of magnetic induction intensity. As the magnetic induction increases, the centripetal force required by the Lorenz force to provide magnetic fluid deflection increases and changes accordingly.

From the angle of vector shown in table 3, the jet vectoring angle is greater when the magnetic induction $B = 0.6$ T than in the first group under the same temperature at $B = 0.45$ T, which shows that the magnetic induction intensity increases the effect of jet deflection torque of the magnetic fluid, making it much more effective to achieve the deflection and the thrust vector. Under the condition of the same temperature and content of the ionized substance, as the magnetic field intensity increases, the vector angle increases. However, the amplitude of the change is not significant.

In conclusion, the effect of temperature on the change of vector angle is the most significant. In the application of the actual aircraft, it is more feasible to choose the method of increasing the temperature.

5. Conclusion

A new method of MHD plasma thrust-vector control was proposed to achieve plasma plume deflection under the condition of temperature lower than 2500 K. The theoretical basis of the MHD involved was analyzed, and the numerical simulation and experimental research on the plasma plume deflection were conducted. The main conclusions drawn are as follows:

a. Under the low-temperature condition of 2500 K, the ionization degree of gas is very low, and the gas has no electromagnetic properties. The catalytic seeds with low ionization energy are added into the gas, and the ionization degree of gas reaches a considerable magnitude of $10^{-2}$–$10^{-3}$. Thus, the gas is close to the state of plasma and exhibits electromagnetic properties.

b. The Cs₂CO₃ induced gas plasma gradually exhibits ionization characteristics when the temperature is higher than 1800 K; the higher the gas temperature is, the more obvious the ionization characteristics are, and the greater the deflection angle of the jet is.

c. When the gas temperature at outlet is 2200 and 2400 K, as the magnetic field intensity is changed from 0.45 to 0.6 T, the deflection angle of the plasma plume increases with the increase of magnetic field intensity, indicating that the Lorenz force acting on the plasma is increasing.

d. The experimental results and numerical simulation results of the plasma plume deflection are in accordance with the theoretical analysis, demonstrating that the MHD flow control has a certain credibility.

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