Design of a small plasma multi-phase flow simulated ablation system based on automatic control

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Abstract. During the development of thermal protection materials for hypersonic vehicles, the simulated ablation test based on thermal plasma has been widely used. In this paper, a small plasma multi-phase flow simulation ablation test system is designed based on the automatic control technology. After the overall design, hardware processing and software development are completed. Then the system parameters are calculated and tested by numerical calculation methods and heat flow densitometers as well as other test instruments. The results show that the system has high enthalpy, high temperature and high heat flux, and solid particles can be injected in it to simulate particle erosion effects. The system can generate plasma jet with continuously adjustable parameters. The stagnation point temperature is 11651 K and the central speed is 1222 m•s⁻¹. The particle addition rate is continuously and adjustable. The maximum speed in the experiment is 280 m•s⁻¹, and the surface temperature is about 2650°C. The work in this paper provides an important way for more inexpensive and efficient ablation tests of thermal protection material. The results provide a useful reference for the selection of the relevant material’s ablation test parameters.

1. Introduction
When hypersonic aircraft flys, the air heating environment is bad, and the stagnation temperature can reach tens of thousands of degrees [1]. Air heating can cause material ablation, destroy the aerodynamic performance of the aircraft, and even lead to the failure of the mission [2][3]. In addition, during the flight, the hypersonic vehicle will also suffer from the erosion of tiny particles such as space dust, ice crystals, and raindrops, which will increase the ablation and destruction of the aircraft. Therefore, the thermal protection of the aircraft must also consider the resistance to particle erosion [4].

In the characterization and evaluation test of the thermal protection performance of aircraft materials, the ground simulation test has been widely used for its short cycle time, low cost and highlights key factors [5]. In particular, the ablation experimental equipment using the arc thermal plasma source as a heat source has the characteristics of high temperature and high enthalpy [6][7]. The domestic and foreign simulated ablation tests are mainly as follows: arc wind tunnel test technology, arc furnace free jet experimental technology and arc heater ablation/erosion coupling experimental technique [8][9][10]. The system power of common arc wind tunnels is large, which is close to the actual situation. However, the equipment is huge and the cost is high, so it is difficult to complete a large number of experiments [11]. The main simulation parameters of arc furnace free jet experimental technology are stagnation point and heat flux density, but most devices are difficult to add particles to the flame to simulate the erosion effect of particles[12]. In the arc heater ablation/erosion coupling experimental technique, both the ablation and particle erosion factors of the
reheating environment can be taken into consideration. The experiment is generally based on the stagnation point [13].

In this paper, a small plasma multi-phase flow simulation ablation test system was designed based on the automatic control technology for the needs of plasma simulation ablation test for hypersonic vehicle’s thermal protection materials. Then the system parameters were tested. System parameters’ adjustment is convenient, and the actual thermal environment of the hypersonic vehicle can be simulated in terms of heat flux and particle erosion and other key factors. It provides a more economical and effective means for the simulation of thermal ablation experiments.

2. Overall design and system development

2.1. Calculation of hypersonic flight thermal parameters

According to the requirements, we determine the operating conditions of the system, especially the peak heat flux and the total heat. The formula for the heat flux density at the stagnation point based on the boundary conditions of Fay-Riddell equilibrium is as follows [14]:

\[
q_{ws} = 0.763 \Pr^{-0.6} \left( \frac{\rho_s \mu_s}{\rho_\infty \mu_\infty} \right)^{0.1} \sqrt{\rho_\infty \mu_\infty \frac{d\mu_\infty}{dx} \left[ 1 + \left( \Le^{0.52} - 1 \right) \frac{h_0}{h_s} \right] (h_s - h_\infty)}
\]

In the calculation, the dimensionless parameters related to the thermodynamic properties and transport properties of the gas are assumed to be a series of constants. \( \Pr = 0.71, \Le = 1.0 - 2.0, \rho_s \mu_s / \rho_\infty \mu_\infty = 0.17 - 1.0 \). Taking the reentry of strategic missile warheads as an example, the data shows that during the flight, the site with the most severe heat is the tip, the maximum heat flux density is 400MW/m² and the maximum total enthalpy is 30MJ/kg [15].

On the other hand, although the density of particles in the atmosphere is not large, the speed of the aircraft is fast. So the number of particles hitting per unit area per unit time is very large. The data shows that in the more severe cases, 1 cm² area is impacted by about \( 10^4 \) particles per second. In calculations, erosion resistance is often used to represent the amount of incident kinetic energy required to erode the target mass per unit of time [16].

\[
C_x = \frac{E_p}{\tau} = \frac{m v_p \cos \varphi}{\tau}
\]

Among them, the kinetic energy flux is \( E_p = 0.5 \rho_p v_p^3 \cos \varphi \), where \( v_p \) is the particle velocity and \( \rho_p \) is the particle density. So, the main parameter of interest is the particle kinetic energy flux when using a method of adding particles in a plasma jet to perform a multi-phase flow simulation test. Since the particle speed is difficult to achieve at high speed in ground test, it can be achieved by increasing the particle density to achieve the desired target. By controlling the heat flux, total enthalpy, total pressure, and particle erosion coefficient of multiphase flow, the system can achieve effective equivalent simulated ablation tests.

2.2. Hardware design

The composition of the small plasma multi-phase flow simulation ablation test system mainly includes a plasma generator, a control system, a test bench, an air source, a DC power supply, a water and electricity transfer box, a particle delivery system, a cooling system, and an on-line monitoring system, etc. Figure 1 shows the system hardware design.

When the system is working, the working gas (argon or nitrogen) is ionized by the plasma generator and accelerated by the nozzle to form a high-temperature high-speed plasma jet. In order to simulate the gas composition in the actual flight effectively, the main gas can be switched to air when the plasma generator is operating normally. The system can add particles whose size greater than 10
\( \mu m \) as erosion particles. By adjusting the parameters of the working gas and particles, an ablative/erosion plasma jet can be formed, which is similar to the actual thermal environment.

![Fig. 1. Schematic diagram of test system](image1)

Figure 2 shows the plasma generator schematic. Figure 3 shows the flow controller schematic. The console adopts Siemens S7-1200 series PLC combined with high-precision mass flow controllers and sensors to monitor and control various operating parameters such as water, electricity, gas, and particles in the entire test system. The system has designed the human-machine interface (HMI) to facilitate the experimental operation. One of the important flow sensors uses capillary heat transfer temperature differential calorimetry principle to measure the mass flow of gas. The thermocouple output voltage signal reflects the change in mass flow of the gas accurately. At the same time, the gas flow is controlled by a piezoelectric control valve, and the gas flow rate is changed by changing the valve opening.

![Fig. 2. Plasma generator schematic](image2)

![Fig. 3. Flow controller schematic](image3)

As shown in Figure 4, the test bench can perform longitudinal and lateral movements and deflections. The position and angle of the sample in the ablation jet can be controlled, then the temperature and heat flux of the sample’s surface can be adjusted dynamically. System components include control cabinets, test benches, motor control cables, and measurement transmission cables. The plasma generator is bolted to the heat source mount, the monitoring instrument is mounted on the instrument mount, and the sample is mounted in the sample holder.

Figure 5 shows the DC power, which supply power to the plasma generator. It uses SCR three-phase full-bridge control, with a no-load voltage up to 125V, and a 1000A operating current. The current can be stabilized at 100-800A, and the current accuracy can be 1%. The DC power output has a small pulsation and a steep dropout characteristic.
The water and the current are mixed into a channel in the transfer box and then connected to the ablation gun through the water cable. At the same time, arc-arranging device was installed in the transfer box to realize the ignition of the system.

![Fig. 4. Test bench structure schematic](image1)

![Fig. 5. Test bench structure schematic](image2)

The main components of the particle conveyor are the motor, the grain tank and the turntable, and the working principle is similar to the scraper. The particles leak from the hole in the bottom of the particle tank to the groove of the turntable. The rotation of the turntable transports the particles to the outlet of the turntable. Then the particles are sent along the hose to the plasma generator under the driving of the carrier gas. The water cooling system protects the cathode and anode that work under high temperature conditions. It consists of a chiller unit and a cooling water circuit. Its working condition is controlled by a smart temperature controller.

2.3. Software design
According to the ablation test process, the control process shown in Figure 6 is designed, and the LAD program is created under the TIA Portal software platform. The program mainly includes functions such as startup check, power start, ignition, operation, powder feeding, and status detection.

The configured touch screen in this system is WEINVIEW MT8101IE. It communicates with the SIEMENS S7-1200 CPU through Industrial Ethernet. A human-machine interface is built on the Easy Builder Pro platform. By loading variable tags created under the Portal project, the HMI can directly read or modify the variable value of the address in the corresponding buffer area in the PLC[17]. Figure 6 is the software system schematic.

![Fig.6. Software system schematic.](image3)

3. Simulation and test of flow field parameters
The objective of the design is to simulate conditions of hypersonic thermal protection. In this paper, the energy conservation principle was used to estimate the enthalpy at the outlet of the generator, and then the outlet temperature and velocity parameters were calculated. Based on the estimation, the numerical simulation software was used to simulate the plasma jet flow field. Finally, the heat flux of
the system was measured by a water-cooled calorimeter. The parameters of solid-phase particles in the plasma jet was measured by the Spray Watch.

3.1. Estimation of plasma generator’s outlet airflow parameters

Irrespective of plasma radiation, according to the law of conservation of energy, the difference between the energy input by the plasma generator and the amount of heat removed by the circulating cooling water can be basically regarded as the energy gained by the working gas [18].

Average enthalpy at the outlet of the plasma generator:

$$H_g = \Delta H + H_{in}$$  \hspace{1cm} (3)$$

Among them, $H_g$ is the enthalpy value of the outlet air flow, $\Delta H$ is the enthalpy change of the air flow, and $H_{in}$ is the enthalpy value of the inlet air flow. Its calculation formulas are as follows:

$$\Delta H = (EI - W_{H_{2}O}C_{H_{2}O}(\Delta T_{0} - \Delta T_{1}))W_{g}^{-1}$$  \hspace{1cm} (4)$$

$$H_{in} = \sum_{i=1}^{n} W_{g_{i}}H_{in_{i}}W_{g_{i}}^{-1}$$  \hspace{1cm} (5)$$

Where $E$ is the arc voltage, $I$ is the arc current; $W_{H_{2}O}$ and $W_{g}$ are the mass flow rates of water and gas respectively; $C_{H_{2}O}$ is the specific heat of the water; $\Delta T_{0}$ and $\Delta T_{1}$ are the temperature rises of the water before and after the arc start. In equation (5), $W_{g_{i}}$ and $H_{in_{i}}$ are the mass flow rate and enthalpy value of the third gas. The corresponding parameters of the working gas and the cooling water can be obtained through the PLC integrated control system. According to the above formula, the average enthalpy of the jet at the outlet of the generator under different conditions can be calculated. The velocity distribution of the exit of the plasma jet can be calculated by the following exponential function:

$$V(r) = V_{c}[1-(r/R)^{n}]$$  \hspace{1cm} (6)$$

$V_{c}$ is the velocity of the center of flame. In the actual calculation process, the average outlet speed will be obtained firstly, and then the speed at any point can be calculated according to the speed distribution relation (6). The average speed is:

$$V_{g} = W_{out} / \rho_{g}S_{out}$$  \hspace{1cm} (7)$$

In the above formula $W_{out}$ is the mass flow of the generator outlet, $\rho_{g}$ is the density of the plasma, and $S_{out}$ is the outlet cross-sectional area. Selected a condition: the argon pressure is 0.8 MPa, and the other operating parameters and calculation results are shown in Table 1. The results show that the center temperature is 11651 K and the center speed is 1222 m·s⁻¹. At the outlet of the generator, the radial distribution of temperature and velocity of the plasma jet is parabolic. The temperature and velocity of the plasma jet near the center of the jet are significantly higher than those of the surroundings.

Table 1. Operating parameters and results of experiment system

| Ar (L·min⁻¹) | Water (m³·h⁻¹) | Temperature rise /°C | Voltage /V | Current /A | Center temperature /K | center speed /m·s⁻¹ |
|--------------|----------------|----------------------|-----------|-----------|-----------------------|-------------------|
| 45           | 1.02           | 8.6                  | 41.2      | 452       | 11651                 | 1 222             |

3.2. Simulation of plasma generator jet

As only a simple empirical formula is taken into consideration, ignoring the influence of more actual physical parameters, as well as the limitations of the instrument and equipment performance in practice, it is difficult to conduct a comprehensive measurement of the flow field. Therefore, in order to understand the characteristics of the full flow field, simulation based on the finite element numerical method is particularly important [19][20]. Since no current passes through the plasma jet, only the
conservation of mass, conservation of momentum, conservation of energy, conservation of the components, the turbulent kinetic energy equation and the energy dissipation rate equation of the turbulent flow need be solved in the numerical simulation [21].

Figure 7 shows the distribution of velocity and temperature in the flow field. The white part of the figure is the carrier gas pipe and the nozzle. Because the carrier gas outlet is symmetrically distributed above and below and the carrier gas at the download hole is at the same speed, the plasma jet does not have a significant three-dimensional effect. From the temperature distribution along the axis, it can be seen that the jet temperature decreases rapidly along the axis and decreases to a minimum of 1100 K. But the temperature rises slightly before the sample. This is because the jet impinges on the sample and the velocity decreases or even stagnates. The kinetic energy is converted into internal energy and the temperature rises.

![Fig.7. (a) Axial velocity distribution](image1)
![Fig.7. (b) Velocity distribution along the axis](image2)
![Fig.7. (c) Temperature distribution](image3)
![Fig.7. (d) Temperature distribution along the axis](image4)

### 3.3. Particle characteristics test of multi-phase plasma

Particles are subjected to various forces in the jet, especially dragging forces. In addition, there are additional forces and gravitational forces acting on the particles due to the non-uniformity of the jet. Under normal circumstances, the drag force that the particle receives in the airflow dominates is the main force. Other forces, due to its secondary location and complexity, are ignored in engineering calculations [22]. Drag force can be expressed as (8)

$$ F_d = \frac{1}{2} C_D \rho_g |V_g - V_p| (V_g - V_p) S $$

(8)

$F_d$ is the drag force, $C_D$ is the drag coefficient, $\rho_g$ is Jet density, $V_g$ is the jet speed, $V_p$ is the particle velocity, $S$ is the windward area. According to Newton's second law, assuming that the particle is spherical, the acceleration of the particle can be expressed by the following formula (9):

$$ \frac{dV_p}{dt} = \left[ 4\pi \left( \frac{d}{2} \right)^3 C_D \rho_g |V_g - V_p| (V_g - V_p) \right] \left[ \frac{32}{3} \pi \left( \frac{d}{2} \right)^3 \rho_d \right]^{-1} = 3C_D \rho_g |V_g - V_p| (V_g - V_p)(4d \rho_d)^{-1} $$

(9)

Equation (9) shows that, on the one hand, the acceleration of particles is inversely proportional to the diameter of particles, on the other hand, the acceleration of particles is proportional to the relative
velocity between jets. The velocity of particles of different particle sizes at different distances from the exit is calculated by the standard Runge-Kutta method in MATLAB, as shown in Figure 8.

Then, the temperature and velocity of the particles in the plasma jet were measured on-line using the SprayWatch-2i system developed by Oseir, Finland. The effect of particle mass ratio, arc current, and ablative distance on particle velocity and temperature was studied. The test results are shown in Figure 9.

![Fig. 8. Distribution of velocity of different particles at different distances](image1)

![Fig. 9. Particle temperature measurement and velocity measurement system](image2)

For imaging and measurement, the velocity of the jet is calibrated by 50-70μm Al₂O₃ particles. The calibration position is 40mm from the generator outlet (this position is the default ablation position). The powder feeder’s voltage is set at a minimum value of 4V. Test results are shown in Figure 10, the corresponding multiphase flow heat flux value change chart is also given in it.

The relationship between the argon flow rate, the powder carrier gas (nitrogen) flow rate, and the alumina flow rate is shown in Figure 11, which shows the particle velocity at different mass ratios. With the decrease of current, the velocity of erosion particles generally decreases. There is a sudden change at 440A. With the decrease of current, the effect of powder feeding on particle velocity is weakened. At low current, the speed of different amount of powder is similar.

![Fig. 10. Plasma Jet Heat Flow and Particle Velocity](image3)

![Fig. 11. The particle velocity at different mass ratios](image4)

4. Conclusions
This dissertation aims at the need of failure characterization and performance evaluation of thermal protection materials for hypersonic vehicles. A miniature plasma multiphase flow simulation ablation system is designed based on the principle of automatic control. The system is stable and reliable, with a wide range of adjustment of the flow field parameters, reaching the expected target.
The engineering calculation based on numerical method neglects many secondary factors and still has certain deviations from the actual working conditions of the system. Therefore, it needs to be combined with instrument testing.

The study of the characteristics of the flow field by a combination of numerical calculations and test characterizations provides a theoretical basis for the selection and optimization of test parameters.

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