Research on Free Jet Test Technology

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Abstract. Aerodynamic thermal ground test can not completely simulate flight conditions, and there is no simple and clear similarity criterion as aerodynamic test. In practical application, it is often to grasp the local flow characteristics of materials or structures and use ground test equipment to simulate their main thermal environment parameters. Therefore, according to the thermal environment characteristics of different parts of the aircraft, a variety of arc heating test techniques have been developed. For example, free jet test technology has been developed for material test of simplified model and assessment test of small-scale components. It effectively solves some problems of thermal protection test examination.

1. Introduction
When the airflow flows out of the pipe, it is not restricted by the solid boundary. The free-expanding jet flow in a certain space is called free jet [1]. Arc heating free jet test technology refers to the high temperature and high pressure air flow (usually air) heated by arc heater, flowing through the mixed stabilization chamber, after accelerated injection by nozzle, forming high temperature and high speed free jet flow field in the test section, and examining the thermal performance of the test model placed in the uniform zone of the jet [2]. The test technology can simulate the inflow environment of different parts of the aircraft more truthfully. Because there is no restriction of solid boundary, it can also simulate the disturbance heating flow field of aircraft local structure such as bulge, pit and slot [3]. The size of uniform zone of jet flow field and the numerical value of model surface parameters are determined by the characteristics of arc heating equipment (mainly arc heaters, nozzles, etc.). They are generally used for screening and testing of small-scale heat-proof materials or structures [4]. The model (heat-proof material) is tested by measuring the parameters of model surface/back surface temperature, linear ablation rate, mass ablation rate, effective ablation heat and ablation morphology. The thermal protection performance of material or structure is evaluated [5].

2. Plate test technology
For simplified flat-plate test models, such as flat-plate or blunt wedge, flat-plate free jet can be used for test. The simulation parameters include recovery enthalpy, surface cold wall heat flux, surface pressure, surface shear force and so on. Plate model is widely used as a simplification of large area of aircraft. Some protrusions or gaps can be set on the surface of the model to study the ablation of window steps, control wings, sensors and other local structures [6].

The principle of flat free jet test is shown in Fig. 1. The supersonic rectangular or semi-elliptical shape of nozzle is generally chosen. A flat plate model is placed at the exit of nozzle to make the two joints smooth and seamless. The airflow boundary layer on the model is the natural extension of the
boundary layer on the wall of nozzle. The model can also be placed at a certain angle with the airflow, and the range of parameters on the model can be improved by the inverse pressure gradient caused by the oblique shock wave at the front of the plate. When the parameters of the arc heater and the Mach number of the nozzle are fixed, the surface pressure and heat flux of the model can be increased by increasing the angle between the model and the air flow. However, in order to avoid the separation of the compressed corner of the air flow, the angle generally does not exceed 20 degrees.

![Fig.1 Principle diagram of flat plate free jet test](image)

The aerodynamic heating rate of the plate surface can be calculated by the following mature engineering formulas: laminar flow aerodynamic heating of the plate:

$$q_x = 0.332 \Pr^{-2/3} \rho_e u_e \left( \frac{\rho^* e^*}{\rho_e \mu_e} \right)^{0.5} (Re_e)^{-0.5} (h_r - h_w)$$

Flat-plate turbulent aerodynamic heating:

$$q_x = 0.0296 \Pr^{-2/3} \rho_e u_e \left( \frac{\rho^* e^*}{\rho_e \mu_e} \right)^{0.8} \left( \frac{\mu^*}{\mu_e} \right)^{0.2} (Re_e)^{-0.2} (h_r - h_w)$$

In the formula, the density and viscous coefficients corresponding to the reference enthalpy are obtained. Reference enthalpy to Eckert's formula:

$$h^* = 0.28h_e + 0.22h_r + 0.5h_w$$

When the angle of flow is increased, the pressure rise caused by oblique shock compression can be calculated according to Plante's oblique shock equation. The peak heat flow compressible force interference method can be used to estimate laminar flow $n=0.5$, turbulent flow $n=0.2$, and plate shear force can be calculated according to the following formula.

$$q_2 = \frac{q_2}{q_1} = \left( \frac{p_2}{p_1} \right)^{1-n}$$

$$\tau = \frac{\Pr^{7/3} q_{cw} u_e}{H_r - H_{cw}}$$

3. **Stationary point test technology**

For simplified stagnation point type test model, stagnation point free jet technology is used to test. The simulation parameters include total enthalpy, cold wall heat flux density, stagnation point pressure and so on. The stationary point model can be the shape of the aircraft head, the local structure of the
wing/rudder leading edge or the simplified structure, or the spherical or flat head model to study the ablation performance of materials. Usually, the supersonic axisymmetric conical nozzle is used in the experiment. The model is placed on the central axis at a certain distance from the nozzle outlet. The experimental principle is shown in Figure 2.

![Fig.2 Principle diagram of blunt wedge free jet test](image)

Free jet test with nozzle outlet static pressure equal to or higher than ambient atmospheric pressure can be carried out directly in atmospheric environment. The high temperature air heated by arc flows through the test model after acceleration by nozzle. The heat-proof performance of the test model is checked. The test gas and ablation products of the model are directly discharged into the atmosphere. The free jet test with nozzle outlet static pressure lower than ambient atmospheric pressure needs to be carried out in the vacuum environment of the wind tunnel.

The heat flux at stagnation point can be calculated by Fay-Riddell hemispheric stagnation point theory formula. The following formula can be obtained by considering air dissociation and neglecting air separation:

\[ q_{s,sh} = 0.763 \cdot Pr^{-0.667} \left( \frac{\rho_s \mu_w}{\rho_1 \mu_t} \right)^{0.1} \left( \frac{h_s}{h_t} \right)^{0.5} \left\{ 1 + \left( \frac{Le}{1 - 1} \right) \frac{h_s}{h_t} \right\} \sqrt{\left( \frac{dU}{ds} \right)_s (h_s - h_w)} \]

Sometimes, in order to estimate the surface heat flow of aircraft quickly, according to a large number of calculation results of the equation, the axisymmetric stagnation heat flow at angle of attack of 0 degrees can be approximately given by stagnation pressure, stagnation enthalpy and head radius:

\[ q_{sw} = \frac{0.115}{\sqrt{R}} \sqrt{P_s (h_s - h_w)} \]

The stationary point pressure \( P_s \) is ATM in unit and the head radius \( R \) is cm in unit. This formula is accurate enough for engineering application. According to the requirements of the simulated stagnation heat flux and the total enthalpy of the airflow, the stagnation point pressure can be calculated by the formula, and then the heater operating parameters are calculated back and the state is debugged.

4. Conclusion
From the technical realization of the test, the thermal protection test mainly involves three aspects: thermal environment simulation technology, model test technology and parameter measurement technology. It is impossible to simulate flight conditions completely in any ground test. The thermal environment simulation technology mainly refers to the selection of simulation parameters and technical realization. Model test technology refers to what kind of test model (including material, structure, shape and size), what kind of test flow field conditions should be matched, and which test parameters should be measured in order to achieve the purpose of a certain test investigation.
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