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The Measurement Method Research of the Aerodynamic Heating Test for the Micro-Ablative Materials

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Abstract. This paper introduces the test of the ablation resistance of different micro-ablative materials in high pressure low enthalpy and high heat flux conditions. In order to meet the thermal environment of the future near space vehicle, using pipe arc heater to do the ablation resistance tests for different micro-ablative materials. Due to the low redundancy design of the thermal protective structure, the thermal parameters in ground simulation test need to be high accuracy and repeatability. Use the improved reusable block type heat meter to measuring heat flux, and check the status by using the calibration sheet steel. The results show that this heat meter has good measuring precision accuracy and commendable repeatability. In the end, it shows the analysis of the ablation resistance of the different micro-ablative material models.

1. Introduction

Hypersonic vehicles encounter a significant aerodynamic heating problem in the atmosphere, which requires appropriate measures to be taken to provide thermal protection to the aircraft in order to ensure its flight safety [1].

In recent years, near-space vehicle with high lift-resistance aerodynamic shape will do the maneuver flight within the atmosphere for a long time. Its structure has a thin layer of lightweight features, which makes stringent requirements for the heat-resistant structure design [2]. Micro-ablative heat-resistant materials are generally composed of anti-erosion panels and heat-insulating materials, which have certain anti-ablation and heat-insulating properties and have good application prospects for near-space high-speed aircraft.

In order to improve dynamic performance and control accuracy for the hypersonic vehicle, and reduce the manufacturing cost of emission, a low redundancy and more accurate thermal design is urgently needed. Thereby it requires arc heating ground tests can be more realistic and repeatability to the real aircraft heating environment to evaluate the thermal insulation performance of heat-resistant materials and structures. Uncertainties in heating values lead to demands for increased thickness in heat shield designs for the near-space vehicle. Imelda [3] examined the measurements of heat transfer used in shear in arc jet flows. Nawaz [4] accomplished the investigation of slug calorimeter gap influence for plasma stream characterization, the results indicates that the gap does not play a major role for heat flux measurement.

In this paper, the anti-ablation tests of the 100mm plus 100mm slab models composed of micro-ablative materials of different panel materials were carried out in an arc tunnel using the supersonic flat-panel test technique. The heat flux density was measured by an improved reusable block calorimeter, and the use of calibration of the thin plate for the state check. The results show that this

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heat meter has good measuring precision accuracy and commendable repeatability. Finally, the ablation resistance of micro-ablative material models of different panel materials are compared and analyzed.

2. Test methods and equipment

2.1. Test method

Arc wind tunnel ground ablation test is an effective means to assess the performance of heat-resistant materials; supersonic flat-panel test technology is one of the most commonly used techniques [5]. The parameters of the experiment simulation are total enthalpy of air flow, heat flux density of cold wall of model surface and surface pressure of model.

The basic experimental layout of the supersonic flat panel test technology is shown in Figure 1. The flat panel model holder is placed close to the exit of the two-dimensional rectangular nozzle at a certain angle of attack with the air flow. The model is installed inside the bracket. The boundary layer on the model is a natural extension of the boundary layer on the nozzle wall.

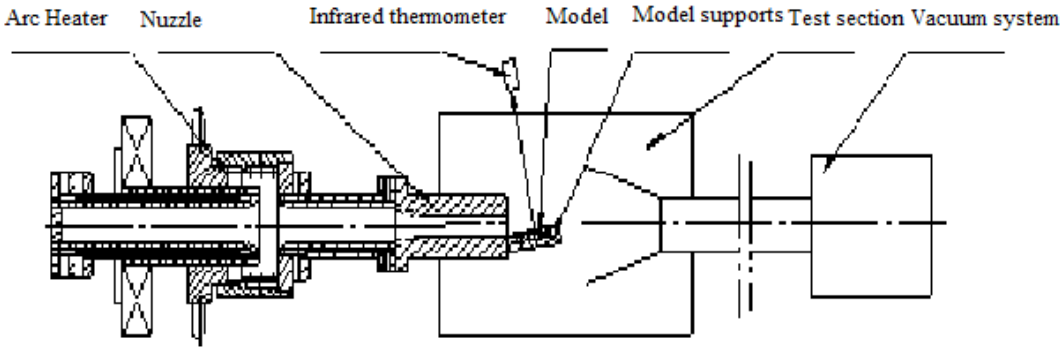


Figure 1. Supersonic flat free jet test schematic in arc wind tunnel.

2.2. Test equipment

The experimental study is carried out in the supersonic arc wind tunnel of the high temperature aerodynamic laboratory of China Academy of Aerospace Aerodynamics. The wind tunnel is a pressure-vacuum supersonic arc wind tunnel, which is mainly composed of arc heater, mixing chamber, nozzle, test section, diffuser section, cooler and vacuum system.

The working principle of the wind tunnel is that the electric arc heater is used to heat the high-pressure air [6]. Then the high-temperature and high-pressure air is accelerated and expanded by the supersonic nozzle, and a high temperature and supersonic flow field is formed in the test section for pneumatic thermal protective ground simulation test. The test gas undergoes deceleration within diffusion section, and then cooled into the vacuum tank after the cooler group.

For different structures and test models of different sizes and with reference to the thermal environment parameters to be simulated, different types of heaters, mixing plenums and nozzles are required. The test uses tubular arc heater, which is characterized by working in high current, and suitable for experimental study of large-scale models under high heat flux. This test uses a rectangular nozzle with its outlet size 120mm plus 60mm. The high temperature and pressure gas is accelerated within the nozzle into the test section to form the required flow field to access the aerodynamic heating tests for the models.

3. Flow field calibration and parameter measurement

The ground thermal test need to measure the state parameters generally include the total enthalpy of air flow H_0, the total flow pressure P_0, the model surface cold wall heat flux density q_{cw} and model surface pressure p. Besides, the formal model test needs to monitor the model surface temperature T_w and back surface temperature T_b. Also it needs to measure the quality of the model *m and* thickness L before and after the test and so on.

The total airflow enthalpy is measured by the equilibration velocity method [7]. This method assumes that the airflow above the nozzle throat is in equilibrium, isentropic and steady state, and calculates the enthalpy from the thermodynamic formula based on the gas continuity equation, the energy equation and the thermodynamic properties of the high temperature gas. The gas flow rate is measured by the sound velocity flow method. The principle is to measure the mass flow of gas by the mechanism of reaching the speed of sound at the street section of the sound jet.

Model surface pressure through the test model to open Φ1.0mm pressure hole, welded behind the fine brass and pressure sensors can be measured. The cold wall heat flow on the model surface was measured using a transient plug-block calorimeter mounted on a flat panel test model.

The surface temperature of the model is measured by a non-contact infrared thermometer through a quartz glass observation window. The monochromatic infrared thermometer used has a measurement range of 450 ° C to 2250 ° C, a response wavelength of 1.6 μm, a response time of 2 ms, ± 0.3% of full scale. Model backside temperature is measured by welding or pasting K-type thermocouple. This type of thermocouple has high sensitivity, good reproducibility and high anti-oxidation ability under high temperature. It is a type of thermocouple widely used in the laboratory.

4. Heat flow measurement improvement and status check

In the simulated parameters, the heat flux density of the model surface is an important basis for determining the ablation state and total heating of the surface of the model. In the case of the low redundancy design of the heat-protection structure, the accuracy and repeatability of the heat flow measurement directly affects the anti-ablation performance and thermal insulation performance of the micro-ablative material, and also directly determines the selection of anti-ablation panel materials and the determination of the thickness of the insulation panel in the micro-ablative material. Therefore, how to debug the heat flow that meets the test accuracy requirements in the test and commissioning is particularly important.

4.1. Traditional plug calorimeter and problems

Traditional block calorimeter structure is shown in Figure 2. It is consist of the heat flow plate, block, protective cover, thermocouple and other components. According to the principle of energy conservation, a good thermal conductivity of the plug block with the side and the bottom of the insulation. The heat introduced into the surface of the plug block is absorbed by the plug itself and lead to block temperature rise. By measuring the temperature rise of the block-time curve, the temperature gradient of the plug block can be calculated to get the heat flux density of the incoming plug block[8]:

$$q = C_p \cdot \frac{m}{A} \cdot \frac{dT}{dt} \tag{1}$$

Where q represents the heat flux density [kW/m^2], C_P represents the specific heat capacity of the plug [kJ/(kg·K)], m is the mass of the plug [kg], A is the heating area of the plug [m^2], dT/dt represents the temperature rise rate of the plug [K/s].

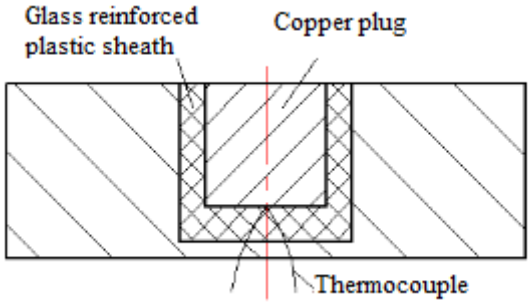


Figure 2. Traditional plug calorimeter structure diagram.

As the glass reinforced plastic sheath exposures to the high heat flow, the surface will appear ablation, forming a depression, causing larger error of the heat flow measurement parameters, and after the ablation can not be reused. The three-dimensional structure and temperature distribution of the traditional plug calorimeter after 2 seconds can be seen in Figure 3. We can see the temperature of glass fiber reinforced plastic up to more than two thousand degrees Celsius, has long exceeded its critical ablation temperature, so in this micro-ablative material of the anti-erosion test state debugging, you need to improve the traditional plug-type calorimeter to ensure that in the debugging process, the measured heat flux density accuracy and repeatability.

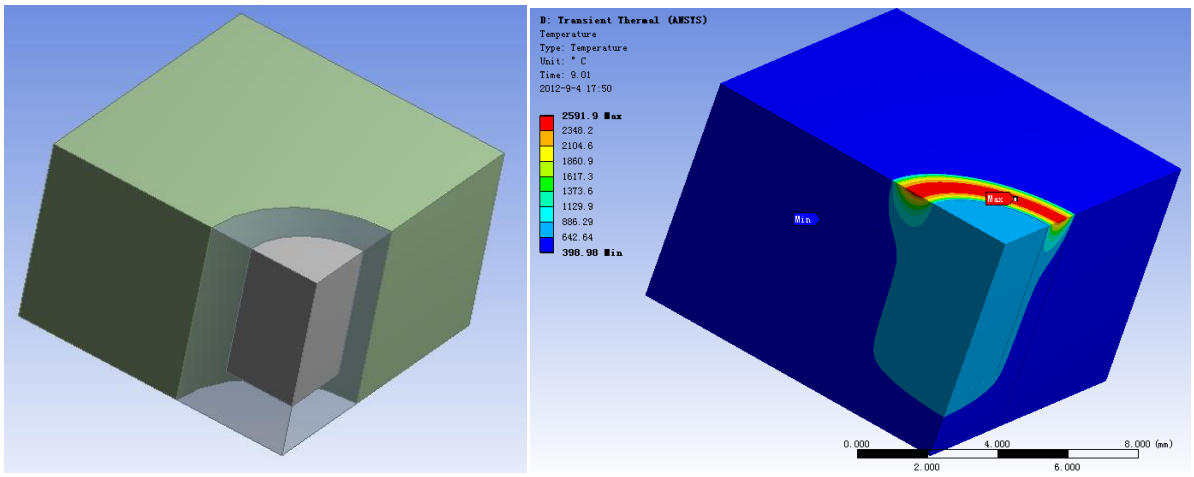


Figure 3. The three-dimensional structure and temperature distribution of the traditional plug calorimeter.

4.2. Improved block calorimeter

In order to ensure the accuracy and repeatability of the block calorimeter, it is required that the protective thermal insulation sleeve should not ablate, fall off or be deformed during prolonged use of high heat flux, and should have good side and bottom thermal insulation. To this end, this paper presents an improved plug-type calorimeter shown in Figure 4.

The surface of the calorimeter in contact with the hot air is all metal. After 2 seconds of heating, the temperature profile of the entire calorimeter is shown in Figure 4. It can be seen that the entire surface of the gauge has a low surface temperature and can be reused. In the process of test and commissioning, the improved block calorimeter has good surface finish and good reusability. However, the conventional calorimeter ablates after being repeatedly used many times by high heat flux.

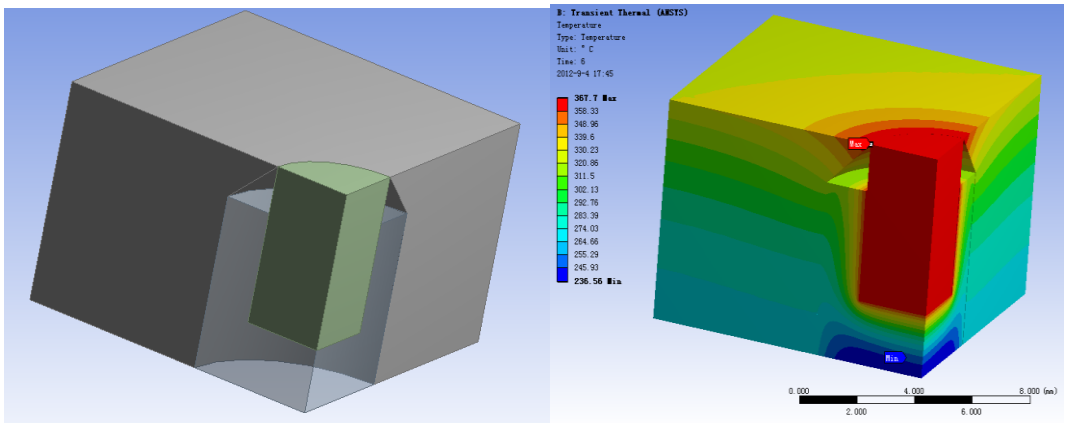


Figure 4. The three-dimensional structure and temperature distribution of the improved plug calorimeter.

4.3. Status check

After commissioning the required state, the temperature response test was conducted in this experiment using 2mm thin steel plate with physical parameters calibrated. According to the calibrated physical parameters, the one-dimensional transient thermal response of the steel sheet is calculated based on the measured thermal parameters as the boundary output value. The temperature responses of 0-18s of the steel sheet are calculated considering the effect of the thermal wall heat flux and the surface radiation. The control equation [9] is:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{2}$$

$$\text{x=0} \quad q = q_{test}(H_r - H_e)/(H_r - H_w) - \varepsilon\sigma T^4 \tag{3}$$

$$\text{x=h} \quad \partial T/\partial t = 0 \tag{4}$$

Where T is the temperature of the sheet, x is the distance from the surface of the steel sheet, t is the time of the test, α is the thermal diffusivity of the steel sheet, q_{test} is the cold wall heat flow value obtained from the test, H_r is the recovery enthalpy of the high temperature airflow, H_e is the local wall enthalpy; H_w is initial wall enthalpy; ε is the emissivity of the steel plate.

Figure 5 shows the comparison of the calculated results and experimental values of the temperature at the back of the steel sheet. It can be seen from Figure 5 that the calculated temperature response is in good agreement with the actual measurement point within 0-12s, which proves the validity and accuracy of the heat flux density measured by the improved block calorimeter. In the figure, the measured value after 12s deviates from the calculated value because the temperature of the steel plate is very high at this time, and the physical property parameter changes with temperature, and the assumption of one-dimensional heat conduction is not established either.

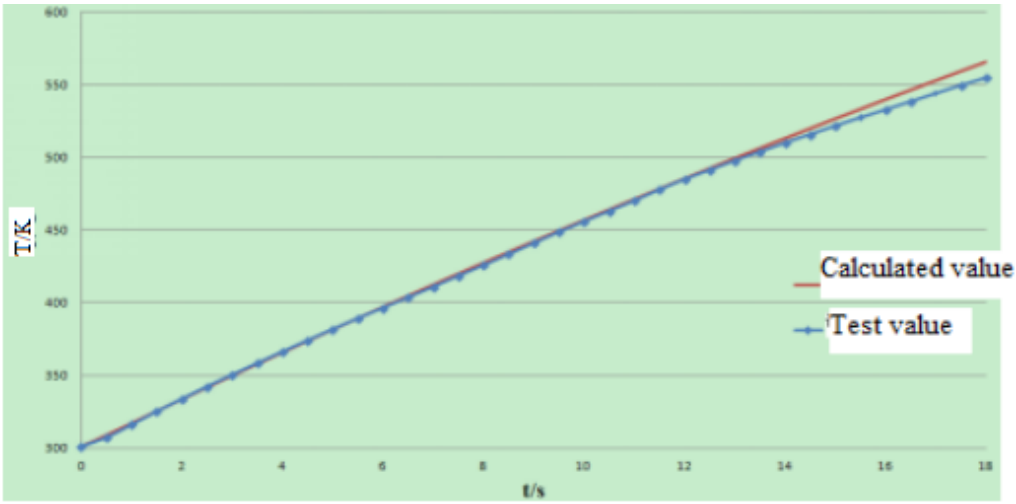


Figure 5. Comparison of calculation results of temperature response on the back of thin steel plate and experimental measurement value.

5. Results and discussions

In the two groups of tests, the ablation resistance of four different micro-ablated material models of panel materials was tested. At low conditions, each panel material remained intact during the test without ablation or flaking. In the high state, in addition to a slight spalling of the surface of the panel, no ablation of the other panel materials has been ablated by the micro-ablation heat-resistant model, and the surface is intact, as shown in figure 6. In addition, the temperature rise on the back of the model is also consistent with the expected test unit, with good thermal insulation effect.



(a)model a (b)model b

Figure 6. Different panel model photos after the same state tests.

It can be seen from the test results that the state of the test has a great influence on the ablation resistance of the micro-ablative materials, and each of the panel materials has a certain use range of the thermal environment. Therefore, the accuracy and repeatability of the thermal evaluation state have a decisive influence on the evaluation of the micro-ablative and heat-protection materials with low redundancy design.

6. Conclusions

The anti-ablation test of the micro-ablation heat-proof material is carried out by the electric arc wind tunnel, the low-redundancy status debugging is realized, and the accuracy and repeatability of the debugging status are guaranteed. The improved plug-type calorimeter used in this test has good measurement accuracy and reusability. Micro-ablation heat-resistant materials have good resistance to ablation and thermal insulation properties, and will gain considerable application prospect of hypersonic vehicles.

7. Acknowledgments

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