Wing Leading Edge Ablation Tests in Arc Tunnel

Zhang Youhua　　Chen Lianzhong
(China Academy of Aerospace Aerodynamics, Beijing　100074　China)

Abstract　This paper reports the results of ablation tests conducted in FD04 arc tunnel of China Academy of Aerospace Aerodynamics (CAAA) for the development of wing leading edge thermal protection materials. The models were made of high temperature ceramic (HTC), with swept angle 53°, height 75 mm, long 55 mm, leading edge radius 2 mm and symmetric cross section made up of a 5° wedge on each side. The test facility included 20 MW arc heater, mixing chamber, rectangular supersonic nozzle, test box, trajectory simulation and vacuum system etc. The rectangular supersonic nozzle with Mach number 3.6 was used in tests. The aero-heating conditions of the wing leading edge were simulated by a test trajectory with flow field parameters of three steps. The test duration was 77.0 s. The results show that HTC has well ablation performance, and two models had no breakage during the tests. The inner temperature responses are attained in tests.

Key words　Wing leading edge, High temperature ceramic, Ablation test, Arc tunnel

电弧风洞上的翼前缘烧蚀试验

张友华　　陈连忠
(中国航天空气动力技术研究院,中国北京　100074)

文　摘　介绍在CAAA的FD04电弧风洞上进行的翼前缘防热材料烧蚀试验结果。试验模型由高温陶瓷制成,后掠角53°,高75 mm,长55 mm,前缘半径2 mm,对称截面半锥角为5°。试验设备包括20 MW电弧加热器、混合室、矩形超声速喷管、试验段、轨道模拟系统及真空系统等。使用的矩形超声速喷管的马赫数为3.6,以3个台阶的轨道模拟翼前缘热环境,试验时间为77.0 s。试验结果表明高温陶瓷具有优良的抗烧蚀性能,两件试验模型在试验过程中均未出现破损现象,试验还得到了翼前缘模型试验过程中的内部温度响应。

关键词　翼前缘,高温陶瓷,烧蚀试验,电弧风洞

0　Introduction

It is very important to evaluate the ablation/insulation performance of the thermal protection materials on hypersonic vehicles. The nose and leading edge areas are more difficult than other parts to protect because they withstand more serious aero-heating[1-3]. Relatively inexpensive, arc heater facility tests are suitable for material screening[4-7].

High temperature ceramic (HTC) is one kind of thermal protection material of spacecraft. In the future design, it will be applied to the wing leading edge of hypersonic vehicles, especially when the leading edge radius is 2 mm. As we all know, in the same flight condition the sharp leading edge will endure more serious aero heating than the blunt leading edge. In order to evaluate the thermal protection performance and inner temperature response of HTC, the ground tests have been conducted in FD04 arc tunnel of CAAA. The experimental approach and results are described in this paper.

1　Experimental approach

The experimental facility including equipment, instrumentation and calibration of flow field used during the tests are presented below.

1.1　Experimental facility

The wing leading ablation tests were conducted in FD04 arc tunnel of CAAA, Fig. 1 indicates its major

收稿日期:2010-12-15
作者简介:张友华,1974年出生,硕士,高级工程师,主要从事航天飞行器气动热试验研究工作。

components.

The test facility included 20 MW arc heater, mixing chamber, rectangular supersonic nozzle, test box, trajectory simulation and system vacuum system etc.

The arc heater used is 20 MW linde-type arc heater, which comprised of a long tube-like front electrode, a long tube-like rear electrode, a magnetic coil, and a vortex chamber. By the bypass punch-through effect, airflow is injected tangentially into the heater, which induces a swirling flow to stabilize the arc and rotate the arc attachment positions. Therefore, the arc length is not fixed, but the arc itself is fixed at a relative stationary location with a nearly periodic manner. For the purpose of the ablation experiment, its efficiency is over 20% higher than the first generation of the magnetic rotation type vertical flow arc heater, and it is applied widely, for example, AFFDL50MW linde-type arc heater[8].

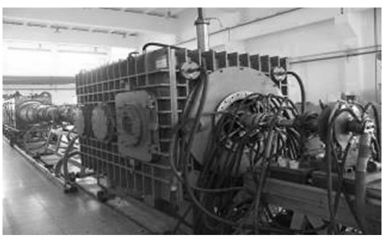


Fig. 1 Photo of test facility

The mixing chamber is located between arc heater and rectangular supersonic nozzle. The air heated by arc heater in here mixes with cold air injected. Mixing chamber will change and control arc jet temperature, and make the arc jet more steady.

The rectangular supersonic nozzle with exit cross section 50 mm×120 mm, long 300 mm, Mach number 3.6 was used in tests. The arc jet flow from the rectangular supersonic nozzle to test box.

The test box is 1.5 m×1.5 m×52.0 m. Each side has three quartz windows to observe the test models. The test models were located in test box and closed the exit cross section of rectangular supersonic nozzle.

The wing leading edge models are made of High Temperature Ceramic (HTC), with swept angle 53°, height 75 mm, long 55 mm, leading edge radius 2 mm and symmetric cross section made up of a 5° wedge on each side. Each model has a 27 mm deep groove in order to support model and install thermocouples to measure the inner temperature response. The sketch of the wing leading model is presented in Fig. 2.

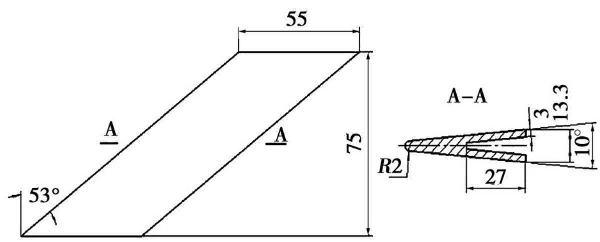


Fig. 2 Sketch of wing leading model

The trajectory simulation system includes airflow control system and current control system. The trajectory simulation system can control the magnitudes of airflow and current into the arc heater and finally simulate flight thermal condition with steps in one test.

1.2 Calibration of flow field

One calibration model was used to measure the arc jet flow field. The fore part size of calibration model is the same with the wing leading edge model. The rear part is flat plate in order to install. The measured flow field parameters include pressure, temperature of leading edge and cold-wall heat flux of one side surface locating 40 mm from the leading edge. The cold-wall heat flux of leading edge was computed owing to the leading edge radius is too small to install heat flux meters. The sketch of calibration model and installation are presented in Fig. 3.

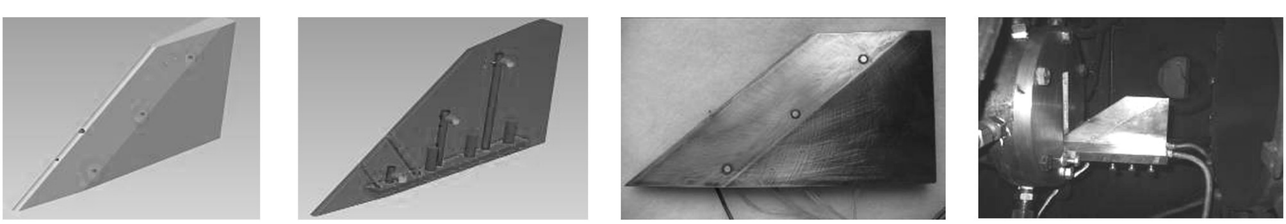


Fig. 3 Sketch of calibration model and installation

The pressure of leading edge was sensed by using 1.5 mm diam port (the small blue port in Fig. 3) and pressure transducer. The port was normal to the leading edge of calibration model. The pressure transducer has the measuring range from 0 to 0.5 MPa with accuracy of ±1 percent.

The temperature of leading edge was measured by using "B" thermocouples. The thermocouples has the measuring range from 600 to 1 700℃ with accuracy of ± 0.25 percent. The thermocouples were supported by a cylinder ceramic. The cylinder ceramic with 3.0 mm diam has two holes with 0.5 mm diam. The thermocouples and cylinder ceramic were inserted in the calibration model (the big blue port in Fig. 3).

Three calorimeters are installed in the calibration model to measure the cold-wall heat flux of one side surface locating 40 mm from the leading edge. Three pink ports in Fig. 3 indicate the three calorimeters location. Every calorimeter includes one cylinder slug made of oxygen-free copper which has very high thermal conductivity and "K" thermocouples. Because the response of the calorimeter is only related with the geometric size and the physical properties of the slug, therefore, if the insulation and adiabatic condition between the slug and its neighbor protection plate are guaranteed, and the heat conduction of thermocouples and the convective heat transfer at the rear surface of the slug are neglected, the expression of the heat flux may be written as follows:

$$q_{\mathrm{ecw}}=C_{\mathrm{P,av}}\times(m/A)\times(\mathrm{d}T/\mathrm{d}t) \tag{1}$$

The cold-wall heat flux of leading edge was computed owing to the leading edge radius is too small to install heat flux meters. The formula is following:

$$q_x=\alpha(T_{\mathrm{aw}}-T_{\mathrm{w}}) \tag{2}$$

$$T_{\mathrm{aw}}=Pr^{0.5}(T_{\infty\mathrm{o}}-T_{no})+T_{no} \tag{3}$$

$$T_{\infty\mathrm{o}}=T_{\infty}\left(1+\frac{\gamma-1}{2}M_{\infty}^2\right) \tag{4}$$

$$T_{no}=T_{\infty}\left(1+\frac{\gamma-1}{2}M_{\infty}^2\cos^2\lambda\right) \tag{5}$$

$$\alpha=\theta'_{\mathrm{w}}Pr^{-0.54}(\rho\mu)_{\mathrm{w}\lambda}^{0.5}c_p\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right)_{\mathrm{sl}}^{0.5} \tag{6}$$

$$\theta'_{\mathrm{w}}=[1+1.5(\theta'_{\mathrm{wo}})^{3.5}T_{\mathrm{w}}/T_{\infty\mathrm{o}}]\theta'_{\mathrm{wo}} \tag{7}$$

$$\theta'_{\mathrm{wo}}=\left[0.0014\left(\frac{T_{\infty\mathrm{o}}}{T_{no}}\right)^{2.113}-0.0109\left(\frac{T_{\infty\mathrm{o}}}{T_{no}}\right)^{1.113}+0.516\left(\frac{T_{\infty\mathrm{o}}}{T_{no}}\right)^{0.113}\right] \tag{8}$$

$$\mu_{\mathrm{w}\lambda}=1.69\times10^{-5}\left(\frac{T_{\mathrm{w}}}{261}\right)^{1.5}\left(\frac{375}{T_{\mathrm{w}}+114}\right) \tag{9}$$

$$\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right)_{\mathrm{sl}}=\begin{cases}\dfrac{1}{R_0}\sqrt{\dfrac{2(P_{\mathrm{wsl}\lambda}-P_{\infty})}{\rho_{no}}} & Ma_{n\infty}>1.5\\[2ex] \dfrac{2u_{\lambda\infty}}{R_0}(1-0.416Ma_{n\infty}^2-0.164Ma_{n\infty}^4) & Ma_{n\infty}<0.8\\[2ex] \dfrac{A_0-B_0}{0.7}Ma_{n\infty}-\dfrac{0.8A_0-1.5B_0}{0.7} & 0.8<Ma_{n\infty}<1.5\end{cases} \tag{10}$$

$$A_0=\left[\frac{1}{R_0}\sqrt{\frac{2(P_{\mathrm{wsl}\lambda}-P_{\infty})}{\rho_{no}}}\right]_{Ma_{n\infty}=1.5} \tag{11}$$

$$B_0=\left[\frac{2u_{\lambda\infty}}{R_0}(1-0.416Ma_{n\infty}^2-0.164Ma_{n\infty}^4)\right]_{Ma_{n\infty}=0.8} \tag{12}$$

$$P_{\mathrm{wsl}\lambda}=P_{\infty}\left(\frac{\gamma+1}{2}Ma_{\infty}^2\right)^{\frac{\gamma}{(\gamma-1)}}\left[\frac{1+\gamma}{2\gamma Ma_{n\infty}-(\gamma-1)}\right]^{\frac{1}{(\gamma-1)}} \quad Ma_{n\infty}>1 \tag{13}$$

$$P_{\mathrm{wsl}\lambda}=P_{\infty}\left(1+\frac{\gamma-1}{2}Ma_{n\infty}^2\right)^{\frac{\gamma}{(\gamma-1)}} \quad Ma_{n\infty}<1 \tag{14}$$

The formula above were well used in ablation-thermal-structure test of large scale air vane in supersonic flow in FD04 arc tunnel[9]. In that test the calculation results of cold-wall heat flux of leading edge compared well with those measured. Great details of the calculation approach can be found in reference 9.

According to the flight condition, the results of calibration of flow field are listed in Tab. 1.

Tab. 1 Measured and calculated parameters of flow field

step	P_{L} /10^5 Pa	T_{L} /K	q_{cwL} /kW·m^{-2}	q_{cwf} /kW·m^{-2}	t /s
I	3.3	933	1973	253	5.0
II	3.9	1897	6319	912	7.0
III	1.0	1223	1704	229	65.0

2 Ablation tests and results

In order to support the leading edge models and measure the inner temperatures in tests, one water cooled model support was designed. The model support and model installation are presented in Fig. 4.

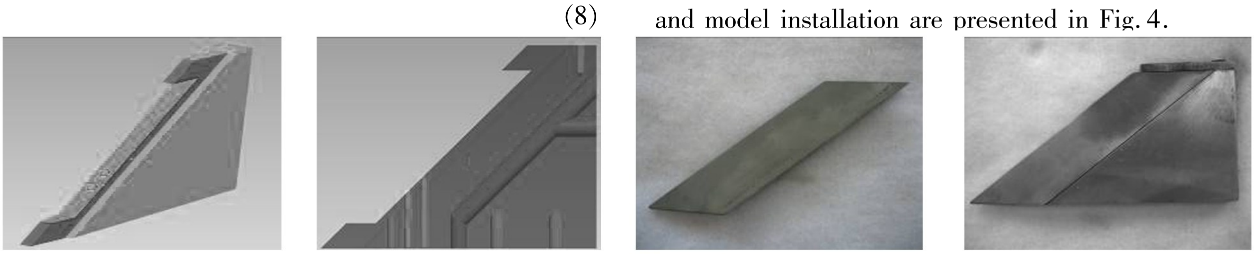


Fig. 4 Sketch of model support and model installation

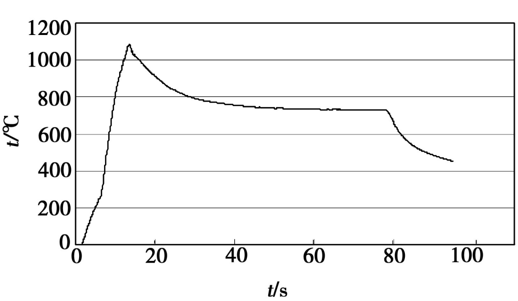
The aero-heating conditions of the wing leading edge were simulated by a test trajectory with flow field parameters of three steps listed in Tab. 1. Two wing leading edge models were tested. The total test duration is 77.0 s, with respect to every step is 5.0 to 7.0 s to 65.0 s. The inner temperature response of wing leading edge models were instrumented with "K" thermocouples in tests. The mass ablation rates of models were obtained with mass loss divided by test duration. The results show that the HTC has well ablation performance. The mass ablation rates of two models are less than 7.6 mg/s, and the two models have not breakage during the tests.

The inner temperatures increased in step I and step II, then decreased in step III. The maximum inner temperatures of models were 1 097 and 1 011℃, corresponding test times were 13.5 s and 14.7 s. The final inner temperatures were 740 and 710℃.

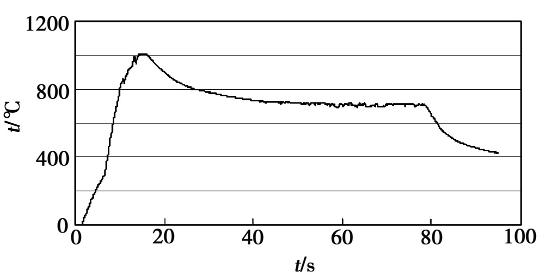
The results of ablation tests and inner temperature-time curves of models are presented in Tab. 2 and Fig. 5.

Tab. 2 Results of ablation test

model	V_m /mg·s^{-1}	T /℃	T_{max} /℃	t_{max} /s	t /s
1#	7.56	740	1097	13.5	77.0
2#	7.31	710	1011	14.7	77.0



(a) 1# model



(b) 2# model

Fig. 5 Inner temperature-time curves of models

3 Conclusions

The ablation tests of wing leading edge models made of HTC were conducted in FD04 arc tunnel of CAAA. The aero-heating condition of the wing leading edge was simulated by a test trajectory with flow field parameters of three steps. The mass ablation rate and inner temperature response were attained in tests. The results show that the HTC has well ablation performance and no breakage during the tests. In the given condition HTC can be used as the thermal protection material of the sharp wing leading edge. The next study will be the thermal structure match performance of HTC with other materials used in the wing.

References

[1] Grant P, Susan P. A heating analysis of the nosecap and leading edge of the X-34 vehicle[R]. AIAA, 1998:878

[2] Pramote D P, Wieting A L. Flow-thermal-structural study of aerodynamically heating leading edge[J]. Journal of Spacecraft and Rockets, 1989, 26(4):201-209

[3] Walker S D, Sullivan B R. Sharp refractory composite leading edges on hypersonic vehicles[R]. AIAA, 2003:6915

[4] Smith D M, Younker Lt T. Comparative ablation testing of carbon phenolic TPS materials in the AEDC-H1 arc jet[R]. AIAA, 2005:3263

[5] Peterson A B, Nichols F, Mifsud B. Arc jet testing in NASA ames research center thermophysics facilities[R]. AIAA, 1992:5041

[6] Tran H, Tauber M, Henline W. Ames research center shear tests of sla-561v heat shield material for mars-pathfinder [R]. NASA TM 110402, 1996

[7] Goken T, Stewart D A. Computational analysis of semi-elliptical nozzle arc-jet experiments: calibration plate and wing leading edge[R]. AIAA, 2005:4887

[8] James L, Richard T. Calibration of the AFFDL 50 megawatt arc heated hypersonic wind tunnel with a two-foot nozzle [R]. AD 694516, 1969

[9] Zhang Youhua, Dong Yonghui, Chen Lianzhong. Ablation-thernal-structure test of large scale air vane in supersonic flow [J]. Journal of Aerospace Materials and Technology, 2008, 38 (5):78-80

（编辑　任涛）