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Experimental investigation on the boundary layer transition characteristics of the blunt body

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Abstract

An experimental investigation on the boundary layer transition characteristics of a typical large blunt body configuration of the mars lander has been conducted in the China Academy of Aerospace Aerodynamics FD-20a wind tunnel. Laminar, transitional, and turbulent heating data were obtained for different angle of attack and free stream Reynolds numbers in the air and carbon dioxide test gas. It was concluded from these data that for CO2 and air, the boundary layer transition rules was almost identical at different angle of attack. For same angle of attack and close unit Reynolds number , the boundary layer transition was achieved easier in CO2 than air. With the increase of angle of attack and unit Reynolds number, the lee side boundary layer transition was achieved more easier. Compared with air, the transition process of the lee side surface boundary layer in CO2 was more shorter.

1 Introduction

Mars is a planet which is closest to the earth in the solar system. For a long time, people have always believed that there were lives in Mars. Thus, study on evolution of Mars is of great scientific significance to understand evolution of the living environment of human beings in the earth in the future. Since 1960, the former Soviet Union and America started to launch detectors to explore the Mars. So far, the world just has 19 unmanned Marx explorations, and only 7 were successful, thus the technical difficult is obvious, especially aerodynamic heat problems. For the reasons, first, differing from earth atmosphere, Mars atmosphere is mainly constituted by CO2（making up about 95.7%）, and the density is just 1/100 of earth atmosphere. To realize rapid reduction of speed and safe landing of detectors in the thin air, aerodynamic configuration of detectors should select big blunt body, and the generated severe aerodynamic heating and influence of CO2 on aerodynamic heat should be further studied. Second, with development of large scale Marx detectors, the number of Reynolds will increase and thus makes the boundary layer on the surface of detectors transit into turbulence flow in advance to greatly increase the heat flux on the surface, and the boundary layer transition and aerodynamic heat problems of turbulence also need to be studied.
Foreign countries started the mission of Marx exploration earlier. Hollis et al studied influence of different appearances on heat flow distribution on the surface of Mars landers, and the results indicated that heat flow of stagnation point of the appearance of double curved surface is smaller, while heat flow of the appearance of radial sphere-cone in bigger shoulders is higher. Dyakonov et al studied influence of angle of attack on aerothermodynamics on the surface of Mars landers, and discovered that angle of attack could increase heat flow of shoulders in the windward side. Moreover, Liechty et al studied influence of transition/turbulence on surface of Mars detectors and aerodynamic heat of CO2 medium, obtained the test data of laminar flow, transition and aerodynamic heat of turbulence, and discovered that the predicted value of aerodynamic heat of turbulent air medium was lower than test data by 25%, while the predicted value of aerodynamic heat of turbulent CO2 medium was higher than the test data by 60%. Collier et al

used CFD to calculate aerodynamic heat of laminar flow and turbulence and compare it with the test data, and they discovered that for the transition area, the calculated data had a big difference with the test data. Compared with the dozens of years of study in foreign countries, domestic study on Mars atmosphere just started, and it mainly focuses on numerical modeling. Moreover, there is no experimental study or test data. Lv Junming et al used numerical modeling to predict aircraft entering into the airflow field of Mars and discovered that in the trail flow of detectors, there were complex flow separation phenomena like vertical motion. Meanwhile, Lv Junming et al also studied static instability of Mars landers which flied with a small angle of attack by use of numerical modeling, and they found that when they flied with an angle of attack of 2°, landers would have static instability along the track.
Based on the research status at home and abroad, in the FD-20a gun wind tunnel of CAAA, a test about aerodynamic heat of typical appearance test model of a Mars Science Laboratory (MSL) was carried out. With the two kinds of air text media, air and CO2 , it tested transition and turbulence characteristics of typical areas (windward side and lee side) of models, analyzed aerodynamic influence of transition and turbulence effects under the condition of different Reynolds number and angles of attack, and compared heat flow distribution rules on surface of test models of the two kinds of air media so as to provide test data as a reference to thermal environment prediction, calculation and thermal protective design of Mars detectors.

2 Test methods

2.1 Test equipment

The test was carried in the wind tunnel FD-20a of hypersonic speed pulse in CAAA. The driving section of FD-20a is 16m, the inner diameter is 260mm, the driven section is 24m, the inner diameter is 260mm, the cross sectional dimension of tested section is 3m×2.8m, the scope of nominal mach number which can be simulated is 4~12, and the valid time of blow in the wind tunnel is 5ms~30ms. According to different operation modes, it can be divided into the two kinds of operation modes of shock wave and piston, as shown in Fig.1. For real environment simulation of CO2, CO2 is driven by air through the operation mode of piston. The specific method is to full the drive section with air and the driven section with CO2， and separate the drive section from the driven section with a piston. According to the physical property that mach number of CO2 has fierce changes with total temperature, to obtain the state needed by the test and guarantee purity of tested CO2, the operation mode of piston is selected.

Fig. 1 Hypersonic pulse wind tunnel FD-20a

2.2 Sensor technology

Thin-film resistor is used to obtain heat flow distribution on surface of models. Thin-film electrical resistance thermometer is a kind of sensor to measure transient temperature of object surface according to the characteristic that metal thin-film electrical resistance value changes with temperature. Since platinum thin film is thin and the heat capacity is small, its thermal conductivity is very high, thus thin-film electrical resistance thermometer can reflect surface real temperature accurately. And at last, surface heat flow of the model is obtained by use of the data processing method based on the principle of one-dimensional semi-infinite assumption, as shown in Fig.2.

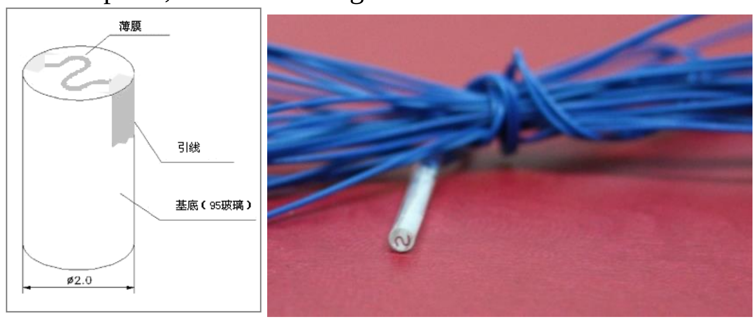

Fig. 2 Photo of the thinfilm

2.3 Test model

The test was carried out by selecting the typical appearance (70°sphere-cone) of MSL lander of Mars science lab as the appearance of the test model, which is as shown in Fig. 3, θ=70°, Rbase=150mm, Rcorner=0.050×Rbase, Rnose=0.500×Rbase， and 30CrMnSiA is the material of the test model. The severe thermal environment of the big blunt body test model is mainly reflected in the undersole area of the model, thus the test mainly had the measurement study on the heat flow on the model undersole. Moreover, it arranged 8 measure points along the central line on the lee side Φ=180°（1-1 to 1-8）and the central line on the windward sideΦ=0°（2-1 and 2-8）respectively, and 1 measure point in the stagnation point (0), and it had 17 measure points in total, as shown in Fig. 4.

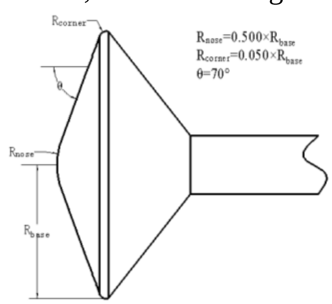

Fig. 3Sketch of the experiment model

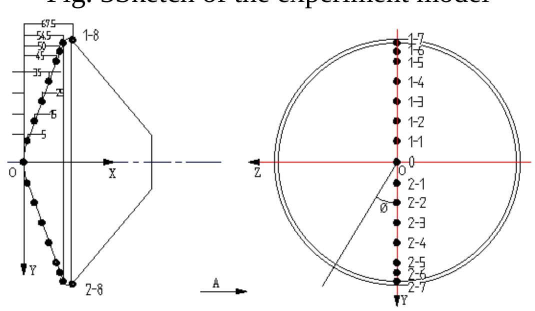

Fig. 4 Sketch of thinfilm layout

2.4 Test state

Table 1 shows the parameters of free incoming flow in FD-20a wind tunnel test. For each unit Reynolds number of free incoming flow, it corresponds to three test angles of attack, 0°、10° and 20°. Since CO2 is triatomic molecular gas, the thermodynamic property is complex, and specific heat ratio changes with temperature obviously, specific heat ratio in areas with different temperature in flow field is different, and temperature of stagnation point of CO2 cannot be calculated accurately, for the two tested air media, the heat flux q0 of the stagnation point measured under the 0°angle of attack is taken as the reference heat flux.

Table 1 FD-20a nominal operating conditions

Test gas	Re_∞ (/m)	M_∞	P_∞ (Pa)	T_∞ (K)	ρ_∞ (kg/m^3)	U_∞ (m/s)	q_0 (kW/m^2)
air	4.8×10^6	6.01	596	87	0.0239	1124	100.82
	1.4×10^7	6.05	1468	83	0.0616	1105	85.23
CO_2	3.0×10^7	6.15	751	166	0.0235	1266	101.87
	4.0×10^6	6.23	971	185	0.0321	1248	84.76

3 Test results and analysis

Heat flux in the central line of undersole of the two test sir media was obtained through test, and the test results are given in the form of nondimensionalize q/q0. According to heat flux q0， of stagnation point of 0°angle of attack under different test state, nondimensionalize dimensional heat flux density q in various measure points to obtain the vertical coordinate q/q0. According to the coordinate system defined in figure 4, the x-coordinate r/R=-y/R, then -1≤r/R≤0 corresponds to the central line on the windward side of the test model, and 0≤r/R≤1 corresponds to the central line on the leeside of the test model.

3.1 Influence of angle of attack

Fig.5 – Fig.8 showed changing curves of heat flow in the central line of undersole when the angle of attack was 0°、10°、20° under different unit Reynolds numbers. According to fig.5 – fig.6, we can see that for test air media, when unit Reynolds number is low, with increase of angle of attack, heat flow on the surface on the leeside of the test model would decrease (increase from 0°to 10°), and the heat flow on the surface of the windward side of the model would increase （increase from 0°to 20°）. And it is known that the boundary layer on the leeside under the angles of attack of 0° and 10° and the boundary layer of the windward side under the angles of attack of 0°, 10°and 20°are at the laminar conditions. When the angle of attack increased to 20°, the boundary layer on the leeside of the test model had transition between the measure points from 1-1 to 1-2. Under the condition of high unit Reynolds number, the boundary layer on the leeside of the test model had transition under the angles of attack of 0°, 10°and 20°, and the layer transition would develop into reduction of turbulence time with the angle of attack increasing from 0°to 20°. Meanwhile, under the angle of attack of 10°, the boundary layer of the windward side of the test model also had transition. From fig.7-fig.8, we can see that for test air medium CO2，under low unit Reynolds number, it was consistent with the changing rules of heat flow when the test air medium was air, and the boundary line on the leeside under the angels of attack of 0°and 10° and the boundary layer of the windward side under the angles of attack of 0°, 10° and 20°were on the laminar conditions, and the boundary layer on the leeside of the test model had transition under the angle of attack

of 20°.Under the condition of high unit Reynolds number, the boundary layer on the leeside of the model had transition under the angle of attack of 10°, while the boundary layer of the windward side was on laminar conditions under the three angles of attack.

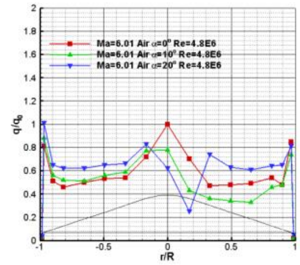

Fig. 5 Air、Re=4.8×10^6/m, different angle of attack heat flux curves

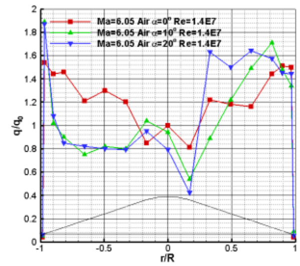

Fig. 6 Air、Re=1.4×10^7/m, different angle of attack heat flux curves

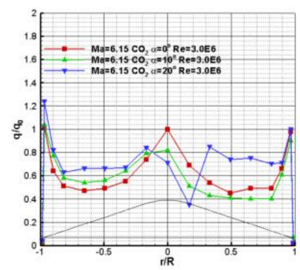

Fig. 7 CO2、Re=3.0×10^6/m, different angle of attack heat flux curves

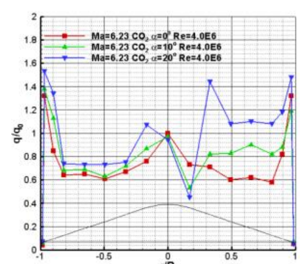

Fig. 8 CO2、Re=4.0×10^6/m, different angle of attack heat flux curves

3.2 Influence of air medium

Fig.9-Fig.11 showed the correlation curve of heat flow of different test air media under the angles of attack of 0°, 10° and 20°. Moreover, it compared under the state when the two unit Reynolds numbers were basically the same by selecting test CO2 medium when Re=4.0×106/m, and test air medium when Re=4.0×106/m. According to the figures, we can see that for the two unit Reynolds numbers that were basically the same, the influence rules of the two kinds of test air media on surface boundary layer transition of the whole test model was basically the same. Under the angle of attack of 0°, influence of test CO2 medium on the neighboring area of the shoulders of the model was stronger than that of test air medium; while under the angle of attack of 10°, the surface boundary layer on the leeside of the test model had transition in the test CO2 medium, but the test air medium still maintained the laminar conditions, indicating that for big blunt body, compared with air, CO2 is easier to realize boundary layer transition.

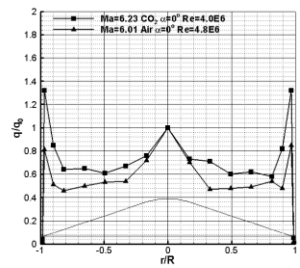

Fig. 9 0° angle of attack, different test gas heat flux curves

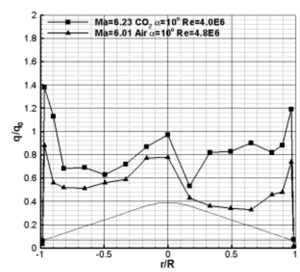

Fig. 10 10° angle of attack, different test gas heat flux curves

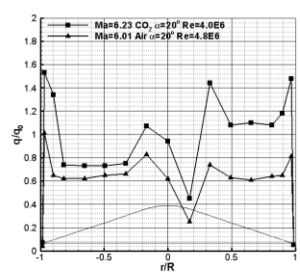

Fig. 11 20° angle of attack, different test gas heat flux curves

4 Conclusion

A test study on transition and turbulence of different test air media was carried out in the FD-20a wind tunnel according to the typical big blunt body of a Mars lander. By use of thin-film electrical resistance thermometer, the nominal mach number 6 was obtained, and test data of laminar flow, transition and turbulence under the condition of different angles of attack and unit Reynolds numbers. The test results indicated:

1. For the blunt body of Mars landers, compared with air medium, under the condition of same angle of attack and close unit Reynolds number, CO_2 medium is easier to realize boundary layer transition.
2. Under different angles of attack, for air and CO_2, surface boundary layer transition rules of the test model are basically the same. Under the state when angle of attack is 0° and Reynolds number is low, the boundary layer motion is on the laminar conditions. With increase of angle of attack (increase from 0°to 20°), the boundary layer on the leesideof the test model first starts the transition and the time from laminar transition to turbulence get shorter. At the same time, under the angle of attack of 10°, the boundary layer of air on the windward side of the model with high Reynolds number also has transition.
3. With increase of unit Reynolds number, surface boundary layer transition on the leeside of the test model is easier to be realized; and compared with air, in CO_2,the surface boundary layer transition on the leeside of the model would continue for a shorter time.

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