Aeroheating Test of Double Cone Configurations in Shock Tunnel

Jiasui Zhou, Tao Jiang, Xiaowei Ma, Rongzong Kong, Kouli Zhang, and Runyu Tian

Introduction

Double cone is a commonly used axial symmetric configuration in numerical and experimental studies to simulate complex flow with shock/shock and shock/boundary layer interactions [1–4]. For hypersonic vehicle thermal protection system design, interactions between the bow shock with the shock waves generated by the wing or control surface and between shock wave and boundary layer must be considered of primary concern because it may cause severe local heating load. Double cones with different cone corners become a good choice for aerothermodynamic researchers to investigate the complex heating distribution caused by different kinds of shock interactions. It is critical to accurately determine the spatially continuous heat flux distributions on double cone model surface for understanding of complex flow mechanisms and for comparison with computational fluid dynamics (CFD) predictions, but it is difficult to get the detailed aerodynamic heating data with traditional point measurement techniques, which use separately located thin film gauges or coaxial thermocouples to get the heat flux value on the point. Temperature-sensitive paint (TSP) technique, a global heating measurement technique, makes acquiring such data possible. In this work, a new developed fast-responding TSP system [5] is used to measure the global heat flux distributions on two double cone models in shock tunnel, and the results are compared with the data from thin film gauges and CFD predictions. The main objective of this experiment is to develop experience in the application of TSP in the shock tunnel testing environment and to evaluate the effectiveness of the different measurement and computation techniques in the complex flow field.

J. Zhou (✉) • T. Jiang • X. Ma • R. Kong • K. Zhang • R. Tian
China Aerodynamics Research and Development Center,
Hypervelocity Aerodynamics Institute, Mianyang 621000, China
e-mail: js.zhou@cardc.cn

Test Model

The models employed in this test are 25°/35° and 25°/55° half-angle double cone that were designed and fabricated for surface heat flux measurement in hypersonic shock tunnel facility. The nose radius of each model is 2 mm. The length of the first cone and the second cone and the total model length were given in Fig. 1.

The models were made of fibreglass. A commercially available white acrylic paint was firstly applied on the model surface to enlarge the reflected TSP emission intensity. The TSP layer was then painted on it.

For the purpose of comparison and in situ correction, five rows of heat flux sensors were installed on the back surface of the model (relative to the camera). There are three rows of orifices that have the same coordinates for data comparison on symmetric locations. Heat flux sensors used Φ 2 mm cylindrical thin film gauges.

Test Facility and Flow Condition

All the experiments were performed in the FD-14 shock tunnel (FD14ST) of China Aerodynamics Research and Development Center (CARDC). A diagram of the facility is shown in Fig. 2.

FD14ST is a reflective shock wind tunnel. It started by rupturing a double diaphragm, which permits the high-pressure driver gas (hydrogen or hydrogen mixing with nitrogen) to expand into the driven tube. A normal shock develops and propagates through the low-pressure-driven gas (nitrogen or air). When the normal shock strikes the end of the driven section, it is reflected back towards the driver section, compressing the driven gas repeatedly, leaving a region of near stationary high-pressure, high-temperature-driven gas, eventually causing the second diaphragm rupture. The driven gas is then expanded through a nozzle and into the test section. The nozzle exit diameter of

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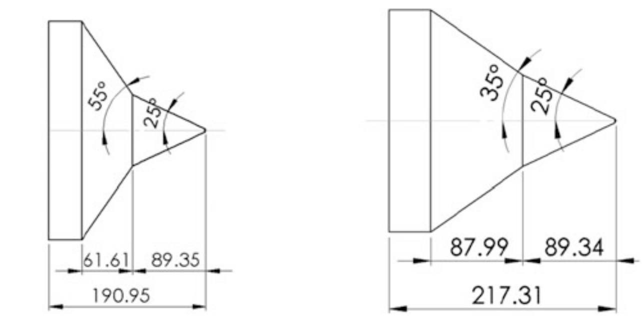


a. 25°-55° double cone b. 25°-35° double cone

Fig. 1 Two double cone model. (**a**) 25°–55° double cone. (**b**) 25°–35° double cone

FD14ST is 0.6 m. FD14ST is capable of simulating a wide range of flow conditions, but as an impulsive facility, is limited in terms of test duration. The tunnel's effective run times range between 2 and 14 ms depending on initial conditions (driver gas pressure, driven gas pressure, type of gases, etc.); it is thus critical that any measurement technique employed has a response time short enough to be able to resolve such time scales.

Flow conditions for the tests discussed in this paper are listed in Table 1.

TSP Technique

TSP is an optical diagnostic technique capable of recovering global surface temperature on test models. The technique exploits luminescent materials with thermal quenching effect that dispersed in polymer binders or paints. In wind tunnel applications, the TSP is applied to the model by conventional paint spraying techniques. Light sources with appropriate wavelength are mounted external to the test section to illuminate the painted model to emit light with wavelength different from (usually longer than) the light source. Scientific cameras with appropriate filters are used to collect the paint emission which responds to a change in temperature. Then, the model surface temperature distribution can be derived from the prior or in situ calibration for the relation between temperature and the emission intensity (or ratio of emission intensity). The heat flux can subsequently be determined from heat transfer analysis for the certain experimental condition.

For shock tunnel experiment, the analysis of TSP data usually follows that of thin film gauges and other conventional sensors for heat flux measurement, as introduced in reference [6–8]. With this analysis method, the TSP layer thickness should be kept smaller than a finite value (0.5 μm, e.g., depends on the relative thermal properties of the base and TSP layer) to assure the accuracy [8], and the entire temperature history is needed to derive the heat flux at a given time. Those two requirements could not be satisfied in FD14ST test. Accordingly, to get enough signal-noise ratio (SNR), TSP layer thickness on the double cone model is about 10 μm, and the exposure time of the camera was set to several milliseconds, causing only one picture to be caught during the whole test duration. Therefore, we need to find other data processing method suitable for FD14ST TSP test.

Simulating a three-layer model for heat transfer analysis is shown in Fig. 3. Assuming that the heat flux was constant during the test, the relation between the surface temperature at a given time and the heat flux was numerically calculated, as shown in Fig. 4. It seems that on the conditions previously described, the surface temperature is almost linear to the heat flux. Using this relation, we could use at least two sensors' data to calculate the model surface heat flux distribution from TSP temperature distribution at the given time.

Experimental Result and Discussion

All the experiments were conducted for the angle of attack, $\alpha = 0°$.

25°–35° Double Cone

Figure 5 shows the TSP measurement results on 25°–35° double cone.

Heat flux on the model is symmetrically distributed. As the Reynolds number increased, the model surface heat flux increased, while the basic pattern of heat flux distribution are almost identical. There is a narrow valley region which corresponds to the flow separation at the corner of the cones caused by the adverse pressure gradient, and a broad peak region on the second cone caused by the flow downstream of the reattachment shock. This is consonant with the Type VI shock/shock interaction pattern defined by Edney and the schlieren image (Fig. 6a).

The TSP and the thin film gauge measurement result are compared with CFD prediction in Fig. 7. It is found that the three results meet well on the first cone, while on the second cone, the thin film gauge measurement value is higher than the TSP results, and the difference became bigger as the Reynolds number increased. From primary analysis, we considered the phenomena might be caused by the different boundary layer conditions for the TSP surface and the thin film gauge surface due to their different surface roughness. For TSP technique, the model surface is relatively smooth, and continuity may help to keep the surface flow conditions laminar. For the thin film gauge measurement on the other side, the model surface smoothness may be critically affected by the sensor orifices, especially when the white

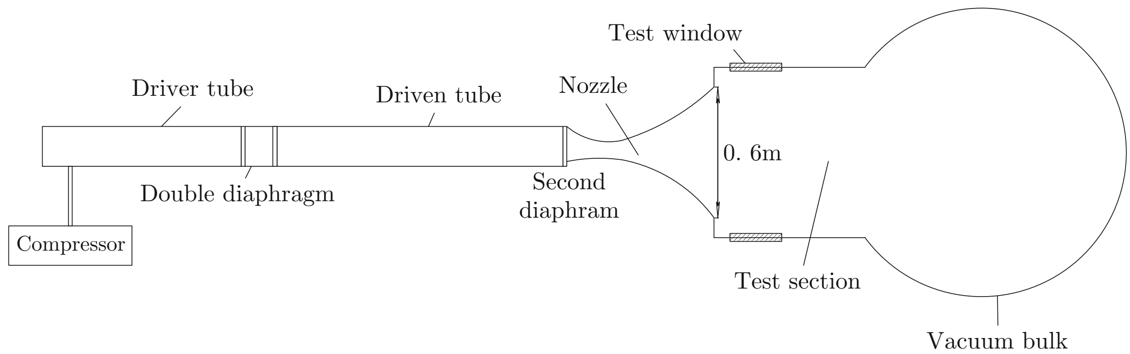


Fig. 2 Schematic of FD14ST

Table 1 Flow condition for the FD14ST double cone model tests

		M_∞	Re_∞ (1/*m*)
Conditions	A	12.11	8.14E + 05
	B	11.8	1.46E + 06
	C	12.12	2.83E + 06

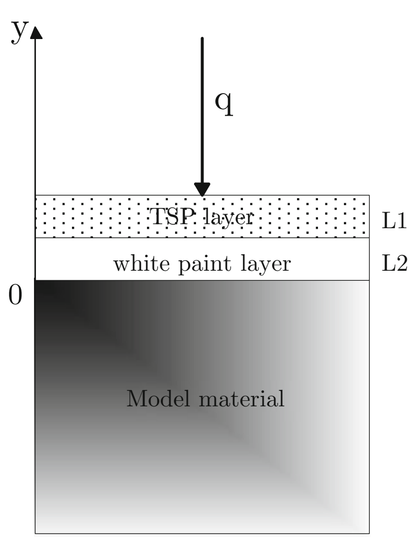


Fig. 3 Three-layer model

paint layers were partially dropped off as the sensors were installed. It may cause the surface flow transition with Reynolds number increase, and the heat flux rise.

25°–55° Double Cone

Figure 8 shows the TSP measurement results on 25°–55° double cone. The experimentally observed flow exhibited a slight unsteadiness in the shock structure. Figure 6b gives typical schlieren image (condition C), in which a curved bow shock appears, that is, consonant with the Type V shock/shock interaction. The separation zone is much larger than

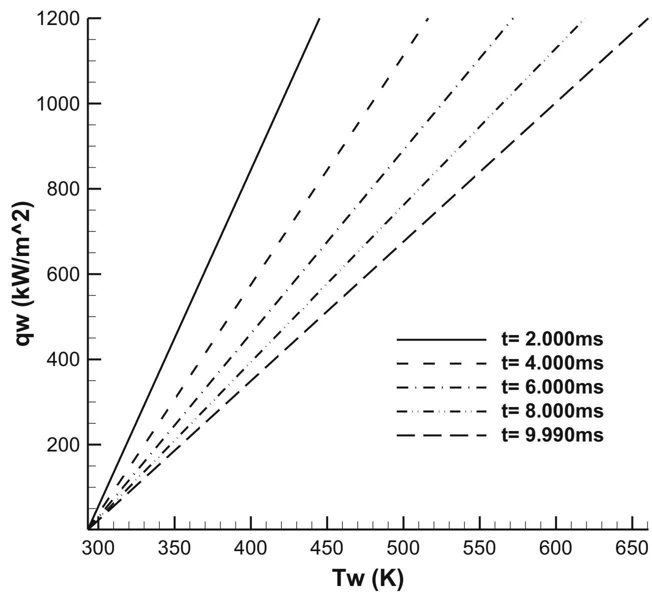


Fig. 4 Simulating result of T_w–q_w relation

that for the 25°–35° double cone, and for the higher Reynolds number, the separation zone is smaller. It may be caused by flow transition, because it is well known that the presence of turbulence reduces the size of separation region.

In conditions B and C, temperature on the high heat flux regions on the second cone is over the TSP calibration range (80 °C); thus the measured value is not correct any more. Figure 9 gives the comparison of results from TSP and sensors measurement and CFD. Just as for 25°–35° double cone test, the results from sensors are in good agreement with that from TSP on the first cone but do not fit very well in the second cone. We also found that the sensors results itself are not repeated very well for the two tests with the same test condition, especially in the interaction zone. There is no peak heat flux region measured by sensors or TSP technique as predicted by CFD in the second cone for condition A; the reason for this is not clear yet.

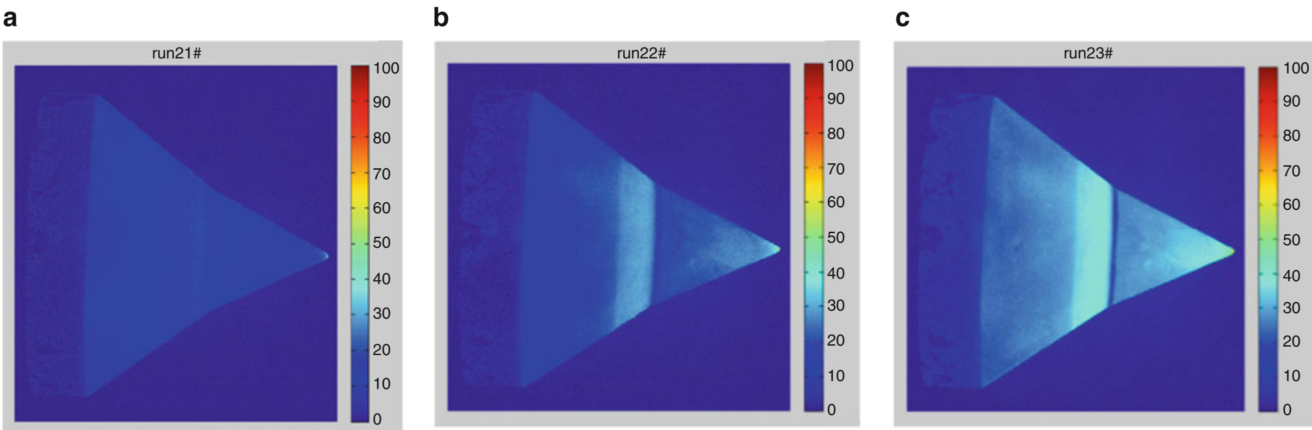
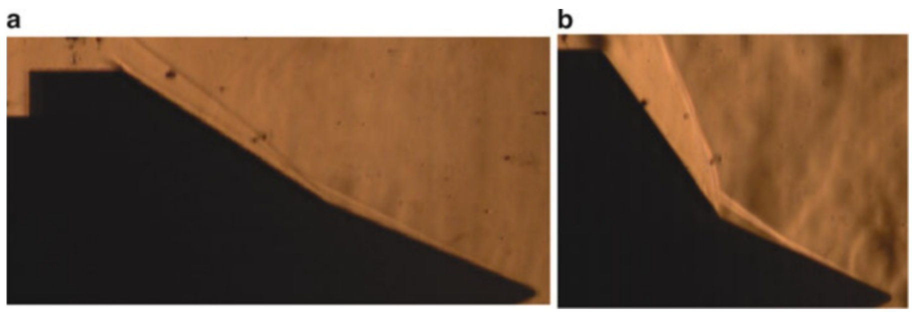


Fig. 5 TSP results of 25°–35° double cone model. (**a**) Condition A. (**b**) Condition B. (**c**) Condition C

Fig. 6 Double cone schlieren image. (**a**) 25°–35° double cone schlieren image. (**b**) 25°–55° double cone schlieren image



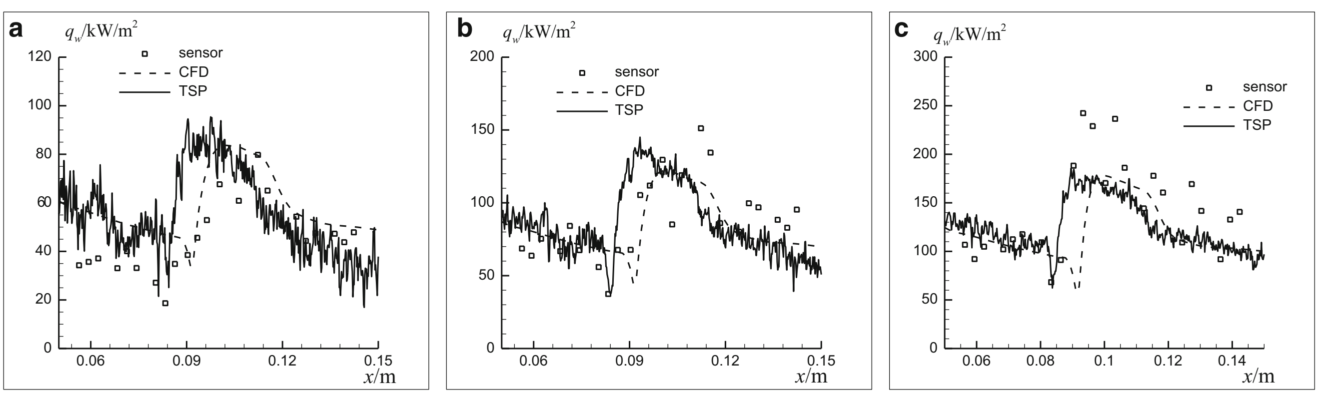


Fig. 7 Comparison of results from TSP and sensors measurement and CFD for 25°–35° double cone. (**a**) Condition A. (**b**) Condition B. (**c**) Condition C

Conclusions

We have conducted a serious of experiments in FD14ST to study the heat flux distribution on double cone geometries. Both thin film gauges and TSP are used in the measurement. Also, schlieren has been taken as an auxiliary approach. Although the test time for the shock tunnel is less than 10 ms, the fast response TSP technique could still get quantified results that show clearly the change of the aeroheating on the double cone model with different cone angles and in the different test conditions. The temperature distribution is calculated from the pre-calibrated relation between luminescent intensity and temperature. One-dimensional heat transfer theory is applied to a three-layer heat transfer model with assumption that the aeroheating is step rised to a constant value during the test time; relation between heat flux and temperature rise at a given time could then be calculated numerically, and the heat flux distribution could be calculated from the temperature distribution. TSP results are qualitatively agreed with the schlieren images. Of the first cone, the thin film gauge results also well agree with the TSP results. But on the second cone, the thin film gauge results are much higher than the TSP results in almost all test

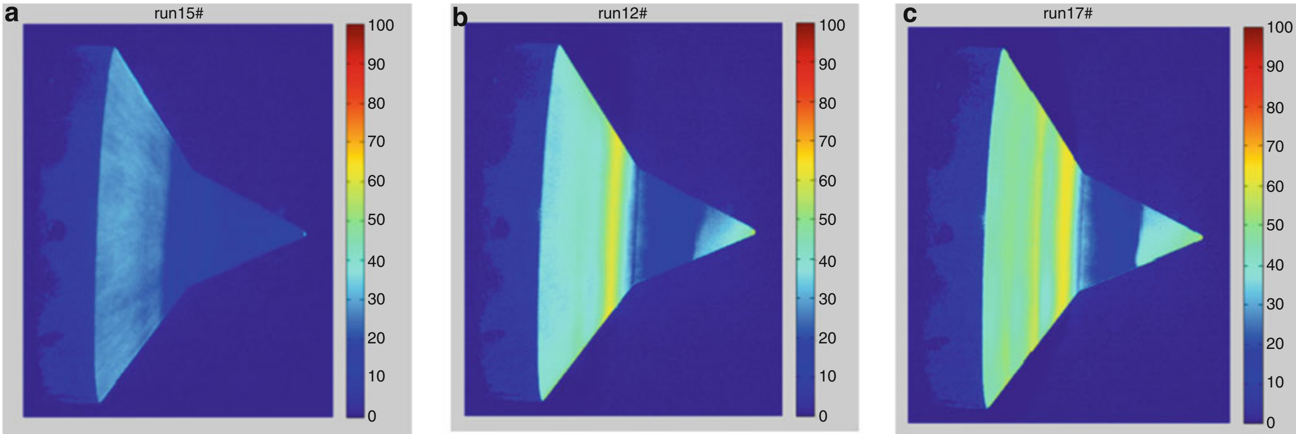


Fig. 8 TSP results of 25°–55° double cone model. (**a**) Condition A. (**b**) Condition B. (**c**) Condition C

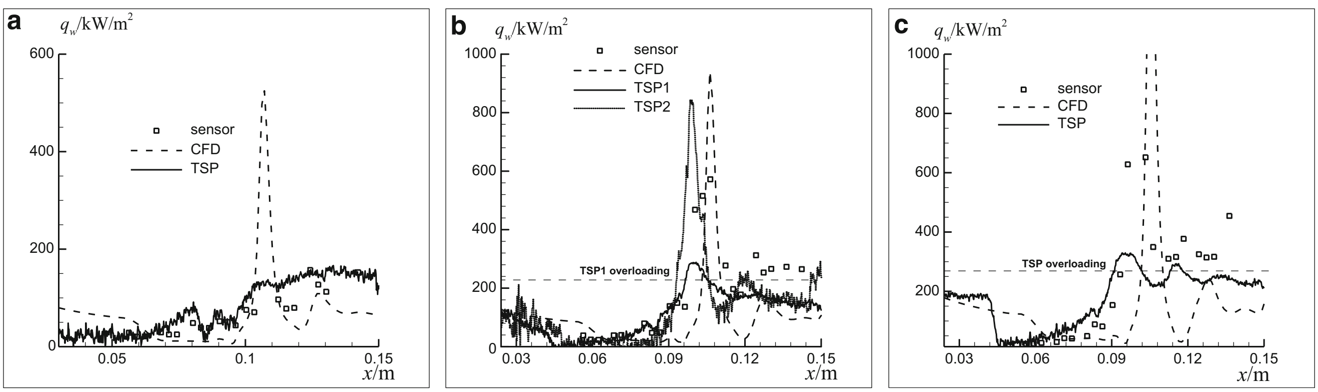


Fig. 9 Comparison of results from TSP and sensors measurement and CFD for 25°–55° double cone. (**a**) Condition A. (**b**) Condition B. (**c**) Condition C

conditions. Several possible factors may induce such phenomena. For example, on the location of the shock wave reattachment on the second cone, the model surface temperature may be higher than the measurement limit of the TSP technique. This would make the TSP results incorrect. Also, the TSP model surface is always smoother than the thin film gauge model surface. This may develop two different boundary layer states on the two kinds of models, especially in the complicated flow field, and then cause the different heat transfer rate.

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