Hypervelocity Test with a Detonation-Driven Expansion Tube

Z. Hu, K. Zhou, J. Peng, and Z. Jiang

Abstract A shock-expansion tube/tunnel is a ground-based test facility to generate hypervelocity test flows for the study of atmospheric reentry physics. Such a high enthalpy test flow features thermochemically non-equilibrium which may lead to critical difficulties in flow diagnostics and measurements. In addition, the test time of such an impulse facility is extremely short which implies a requirement of transducers with high-frequency response capability for model tests or flow diagnostics. In the present work, computations for non-equilibrium reacting flow are conducted to diagnose the key flow parameters and evaluate the test flow for facility upgrading. A conic nozzle is appended to the original facility and to obtain a larger test section and larger Mach numbers. Further experiments are conducted to visualize the overall flow structures over the test models by self-illumination of radicals at high-energy states post strong shock waves. The heat flux at the stagnation point is measured with specially designed thermal couples.

1 Introduction

When an orbital vehicle enters an atmosphere at a hypervelocity, the flow field around it features thermochemical non-equilibrium induced by extremely high-temperature post the strong shock wave. The thermal environment and aerodynamic force performance depend on the degree of the flow non-equilibrium. One of the challenges associated with the hypervelocity entry physics lies on the simulation of such a flow condition on a ground-based test facility. The primary difficulty is due to the extremely high total enthalpy or total temperature required to generate the hypervelocity test flow. Even such a high enthalpy flow can be realized in some

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specially designed shock tunnels, e.g., a shock-expansion tube/tunnel; the pulse operation mode with an extremely short test time leads to a lot of challenges in flow diagnostics and measurements.

The first shock-expansion tunnel named X-1 was set up at Queensland University [1] and is still in operation with a series of upgrading [2]. Several shock-expansion tunnels have been set up around the world, e.g., JX-1 in Japan [3], HYPULSE at GASL [4], LENS-X at CUBRC [5], and JF-16 at LHD IMECH [6–8], among others. X-1 and JX-1 are operated in a free-piston driven mode, while LENS-X is driven by heated light gases such as hydrogen or helium. JF-16 is a detonation-driven shock-expansion tunnel which was built based on a forward-detonation-driven shock tube [9, 10]. A detonation driver is capable of generating high enthalpy flows due to the high speed of sound and pressure of the driver gas.

The test time of the shock-expansion tunnel is extremely short as compared to a reflection shock tunnel of the similar scale which leads to difficulties in measurements and flow diagnostics. Generally, the test flow properties are predicted indirectly via other available measurements, e.g., static pressure measurements, shock speed measured by ionization probes, etc. A computer-aided flow diagnostic technique was applied for the prediction of JF-16 test conditions. A series of studies indicate that high level non-equilibrium and dissociation of oxygen occur in the test flow [11–13].

In the present work, CFD techniques coupled with available experimental data are used to determine the key parameters of the test flow, especially the composition variation due to the chemical non-equilibrium, in the shock-expansion tunnel. Based on the CFD outputs, the facility was upgraded by appending a conic nozzle to obtain larger test domain and cooled test flow after the steady expansion in the nozzle. With the upgraded test facility, visualization is conducted for several test models by self-illumination of radicals. In addition, the heat flux at the stagnation point is measured with specially designed thermal couples.

2 JF-16 Upgrading

The original JF-16 facility is operated in a shock-expansion tube mode [6, 7] which is shown in Fig. 1a, b. A series of simulations have been conducted according to the experimental runs to evaluate the performance and the test flow properties of the original facility. A test flow of 8.85 km/s, which is calculated using a chemical flow simulation with detailed chemistry kinetics, in the acceleration tube as shown in Fig. 2a is obtained in JF-16. Figure 2b shows the profile of mole fraction for each species at the transient when the second shock wave arrives at the test windows.

We can find that the test gas primarily consists of molecular nitrogen and atomic oxygen, i.e., N_2 and O. The dissociation of oxygen is due to the high temperature, $T_5 = 2665$ K, of the test flow as shown in Fig. 2a. Therefore, further expansion via a diverging tube is recommended to JF-16 to cool down the test flow. The upgrade has been completed by appending a conic nozzle to the original shock-expansion

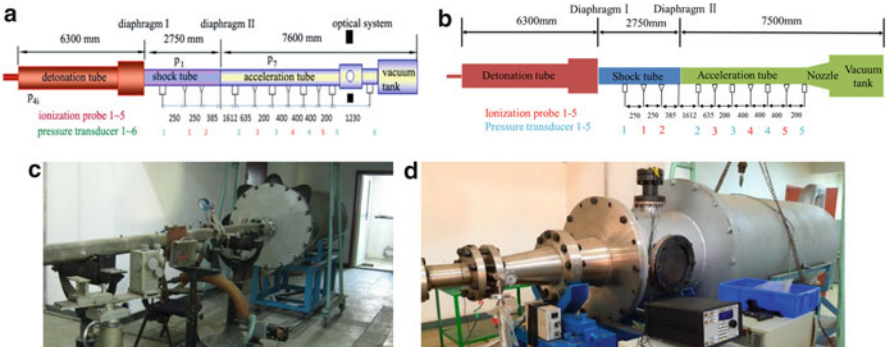

Fig. 1 Upgrading of JF-16, (**a**, **b**) Original shock-expansion tube [6, 7]; (**c**, **d**) Shock-expansion tunnel, with a conic nozzle [14, 15]

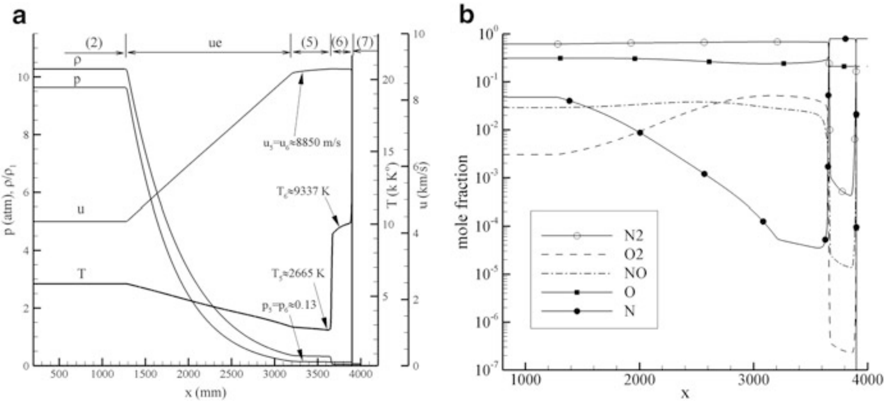

Fig. 2 The transient wave structure in the acceleration tube: (**a**) Key flow parameters; (**b**) Chemical composition of the test gas

tube [14, 15] as shown in Fig. 1c, d. Through the steady expansion in the nozzle, the test flow temperature is reduced to 950 K from 2665 K, while the Mach number is increased to 14 from 8. Simulations indicate that the oxygen atoms cannot be recombined since frozen flow maintains in the expansion nozzle. Nevertheless, the temperature of the test flow obtained in the upgraded facility is still higher than the requirement. As the total volume of the facility is insufficient, an expansion nozzle with a larger exit/entrance area ratio is not applicable. To further cool the test flow to appropriate temperature level, the facility need to be totally enlarged.

3 Flow Visualization and Model Test

The uniform test flow size reaches a diameter of 170 mm after the aforementioned upgrade of JF-16 shock-expansion tunnel. As such, test models of a larger size can be accommodated in the test section. Here, a half-sphere blunted model with a diameter of 50 mm and a half-cylinder blunted model with the same diameter are used for the flow visualization. Flow structures are captured directly from the self-illumination of radicals at high-energy states post the strong shock wave. The resolution of the camera (FASTCAM SA4) is 1024 × 1024 with a frame rate of 500 kfps.

Further experiments are conducted with the obtained hypervelocity flow over several test models of different geometries, such as wedge and double wedge, cone and double cone, cylinder, and sphere. Some transient images over the sphere and cylinder models are given in Fig. 3, where one can see the color variation which implies the variation of the degree of non-equilibrium in the high-temperature flow post the strong shock wave.

It was reported that the shock shape doesn't match in a computation-experiment integrated study from a CUBRC group [16, 17]. The uncertainty in thermochemical states of the freestream flow was supposed to be the primary, although not all, contributing factor to the mismatch. In a later study, however, a good agreement was achieved where the freestream flow condition of the test facility could be well determined [18]. Therefore, the test flow condition should be well predicted prior to the comparison study. A series of computations are conducted for comparison with the experiments. The freestream flow conditions for the simulation are determined with a computer-aided flow diagnostic technique [11–13]. The comparison is shown in Fig. 4 where the computed flow structures are superposed on the experimental photos. The agreement is acceptable which implies the well predicting of the test flow. For quantitative comparison, the standoff distances of the bow shock wave are listed in Table 1. Discrepancy can be seen obviously which may be caused by

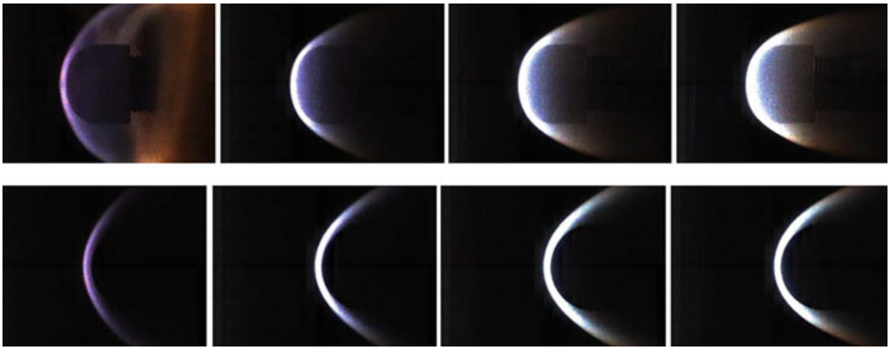

Fig. 3 Flow visualization by self-illumination of radicals post bow shock waves: upper, sphere; lower, cylinder ($V_\infty = 8$ km/s, time interval 33 μs)

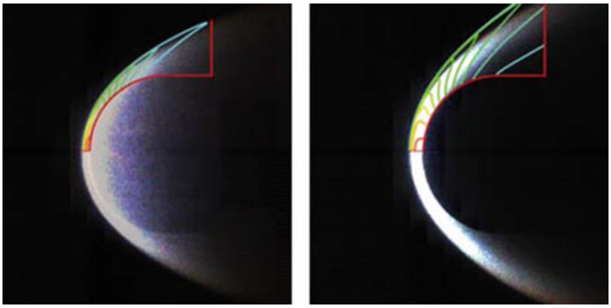

Fig. 4 Comparison between experiment and computation: (left) sphere-blunted model; (right) cylinder-blunted model

Table 1 Comparison of standoff distance

	Standoff (mm)		
Model	Experiment	Computation	Discrepancy (%)
Sphere	2.5	2.3	8
Cylinder	4.1	4.7	14.6

uncertainties in the flow diagnostics. One can also see the remarkable discrepancy in the bow shock shape within the outer region. The reason is still unclear currently, and a reasonable expectation is the uncertainty in the chemical model used for the computations especially for the flow domain where the expansion wave is predominant. Nevertheless, this problem is still open, and further studies on the uncertainties in the flow diagnostics and chemistry kinetics are required in the future.

As aforementioned, the test time of the shock-expansion tunnel is extremely short, around 100 μs. This leads to difficulties in flow measurement since the response time of a conventional transducer may exceed such a short duration. A specially designed sphere model has been applied for stagnation heat measurement [15]. As shown in Fig. 5, the sphere model of 50 mm in diameter, along with a coaxial thermal couple mounted at the stagnation point, is coated with a film of copper (averaged thickness 300 nm). Such a technique can significantly reduce the response time of the transducer. Several runs with different total enthalpies have been conducted for the measurement of stagnation heat flux, $\dot{Q}_{\mathrm{st}}$. The comparison among experiments, De Filippis-Serpico formula [19], and computations are given in Table 2. For the test condition with a total enthalpy of 27 MJ/kg, the measured data agree with the predicted data using a non-catalytic wall condition. When the total enthalpy exceeds 35 MJ/kg, the experiment and prediction agree with each other under the full-catalytic wall condition. Such a finding implies the strong chemical non-equilibrium present in the stagnation region, and recombination of atoms occurs at the cool model surface.

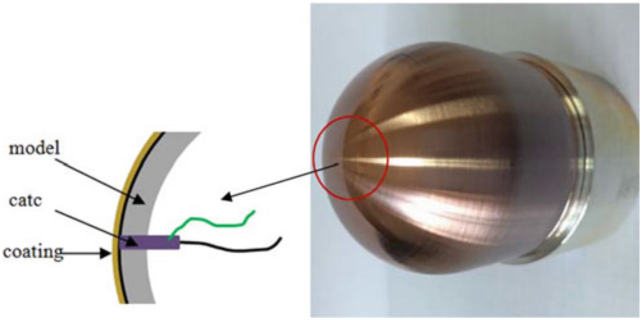

Fig. 5 Specially designed model for heat flux measurement (catc: coaxial thermal couple) [15]

Table 2 Stagnation heat $\dot{Q}_{st}$ measurement and comparison

Run no.	V_∞ (km/s)	H_0 (MJ/kg)	Experiment (MW/m^2)	De F-S (MW/m^2) [19]		CFD (MW/m^2)	
				FCW	NCW	FCW	NCW
1	7.1	27	7.9	14.5	7.2	15.1	7.1
2	7.9	35	21.5	22.2	10.7	23.2	10.1
3	8.8	45	32.5	31.3	15.9	29.6	13.3

4 Conclusions

A detonation-driven shock-expansion tunnel is set up to conduct hypervelocity flow test in the present work. With well-predicted test flow condition, acceptable agreement between experiments and computations can be achieved for the overall flow structure as well as the surface heat flux. Self-illumination images are captured in the flow visualization over several test models. Comparison with computations indicates a discrepancy within the outer region, while agreement is achieved in the stagnation region. The measurement of stagnation heat flux implies that recombination of atoms occurs along the cool model surface under the high total enthalpy condition which corresponds to a full-catalytic wall assumption.

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