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Hypersonic Simulation of Mars Entry Atmosphere Based on Gun Tunnel

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Abstract

Hypersonic tests in the FD20 shock/gun tunnel of CAAA with the test gas of carbon dioxide(CO_2) have been conducted to validate the capability of the hypersonic Mars entry simulation. The facility operates as the gun tunnel mode, which could obtain a longer test period, so that it could be easier to measure the aerodynamic force characteristics. The CO_2 supply system and vacuum system were adjusted to suit for the test gas of CO_2 to simulate the atmosphere of Mars. The hypersonic flow with Mach number of 6 was calibrated over a range of Reynolds numbers. Based on the results, a method that combined the shock relations and numerical simulation has been developed to determine the characteristics of the flow field. This method was validated to be reasonably accurate by CFD simulations, because the computational values of the heat transfer at the stagnation point and the Pitot pressure are well agreement with the corresponding measurements.

1 Introduction

Mars exploration is a focus because of its scientific significance since 1960s. The Mars atmosphere is a mixture of approximately 96% CO_2 and 4% N_2 with a relativity low pressure, it is quite different from the Earth's atmosphere, Nerrerfield et al. (1996).In order to study the aerodynamics problems of entry into the Mars atmosphere, the experimental investigations need to be conducted in the hypersonic shock tunnel. The key of experimental study is recreation of the entry environment which means hypersonic CO_2 flow need to be produced by shock tunnels. From the previous researchers' experience, it can be established through replacing air by CO_2 as a test gas since the most of facilities were originally designed for air test, a proper method of determining reservoir conditions and free stream flow conditions should be developed.
Most of the experiments with CO_2 are conducted in the shock tunnels so far. Such as, Netterfield et al. (1996) have studied a blunt body in the high enthalpy shock tunnel HEG with CO_2/N_2 gas mixtures, Matthew MacLean et al. (2005) have investigated blunt bodies with CO_2 test gas in LENS I facility. For these shock tunnels, the reservoir conditions and free stream conditions could be assessed by shock tube relations and CFD simulations respectively. Different from previous studies, experimental study in this paper is based on gun tunnel which means that a different method is needed for determining flow conditions.

The purpose of this paper is to produce hypersonic CO_2 flow at conditions of Mach 6 over a range of Reynolds numbers in the FD20 shock/gun tunnel for Mars entry vehicles tests. In order to achieve this goal, modification works of facility are required, a method based on gun tunnel was developed to determine the flow conditions, numerical simulations were performed to validate this method.

2 Analysis of Nozzle Flow in Carbon Dioxide

In this section, thermodynamic properties and nozzle flow of CO_2 are analyzed. In present study chemical reactions are not considered since the maximum total temperature of FD20 tunnel is lower than 1200K when CO_2 is used as a test gas, CO_2 molecules don't dissociate until temperature above 1300K at 0.1atm for pure CO_2 flow ,Rini et al. (2004),so that it is reasonable to neglect chemical effects in this study.

A. Thermodynamic Properties of CO_2

CO_2 gas consists of triatomic molecules, its thermodynamics properties are quite different from diatomic gases. Unlike diatomic gas molecule, the vibrational internal energy mode of the CO_2 molecule is much more significant at moderate temperatures, this is not a chemical reaction, but it does have some impact on the properties of the gas. The vibrational energy cause the gas to show more significant “real-gas effects” than is typically seen in air at similar energy levels. The theoretical variation of specific heat ratio for CO_2 and air as a function of temperature is shown in Fig.1,calculated by the NASA CEA package described by Mcbride and Gordon (2004). The specific heat ratio(Gamma) of CO_2 varies with temperature obviously, and can't be regarded as constant at moderate temperatures anymore.

In present study, the CO_2 gas is assumed as a thermally perfect gas where specific heat ratio is variable and specifically is function of temperature only, all numerical simulations results were obtain under the assumption of thermally perfect gas.

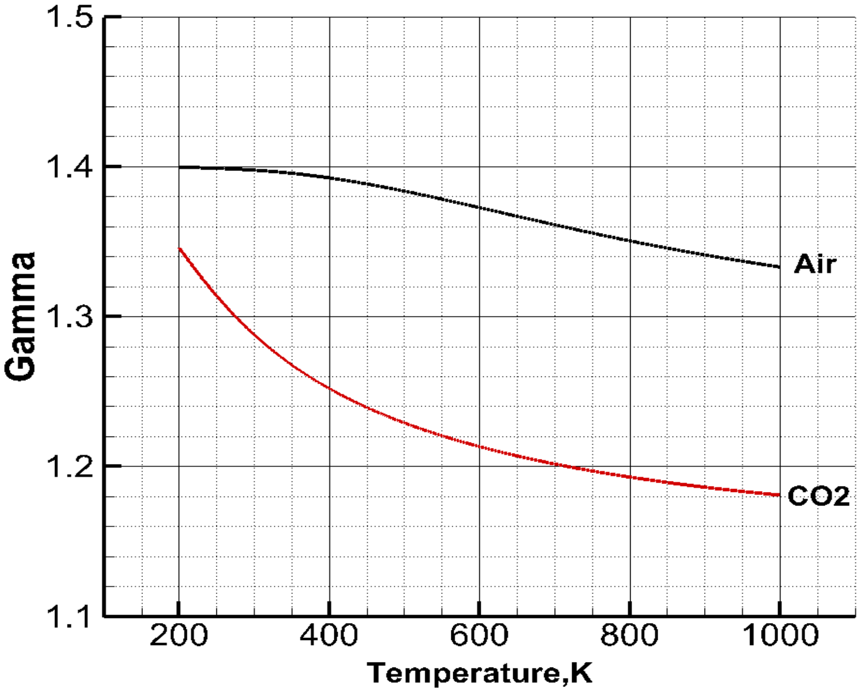

Figure 1: Schematic of the Temperature Variation of Specific Heat Ratio

B. CO_2 Nozzle Flow Analysis

Mach number of free stream flow at nozzle exit is the most important parameter in present study, the mach number at nozzle exit maybe strongly dependent on reservoir conditions since the specific heat ratio of CO_2 is variable. In order to obtain flows with desired mach number, the influence of reservoir conditions to mach number need to be figured out. A Ma8-Air nozzle(exit diameter of 1m) flow of CO_2 is simulated by a CFD code based on N-S equations,Blazek(2005), this nozzle can produce a Ma8 flow at nozzle exit when using air as a test gas.CO_2 gas is assumed as a thermally perfect gas, and the properties of gas are calculated by the NASA CEA package.

A serial test cases are simulated to figure out the influence of reservoir conditions,the influences of T0 and P0 are analysed separately. 1) Simulating the nozzle flow at conditions of same total pressure(P0=5.8MPa) over a range of total temperature(T0 varies from 500K to 1500K); 2) Simulating the nozzle flow at conditions of same total temperature(T0=756K) over a range of total pressure(P0 varies from 4MPa to

18MPa).The Mach number variations with T0 and P0 for simulations in CO_2 are plotted in Fig. 2and Fig. 3 espectively. The results indicate that the Mach number is significantly influenced by T0 , the mach number is decreasing while increasing, the influence of P0 can be neglected. T0 is a critical parameter to obtain desired mach number at the nozzle exit, and it must be set at 756K to produce CO_2 flow of Mach 6 for this nozzle. It also indicate that nozzles which were designed for air can be used to produce CO_2 flow with lower mach number by setting a specific value of total temperature, and the uniformity of core flow is pretty good as shown in Fig.4.

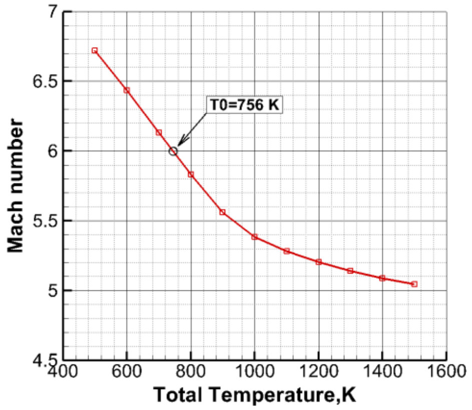

Figure 2: Mach Number Variations with T_0 for Simulations in CO_2

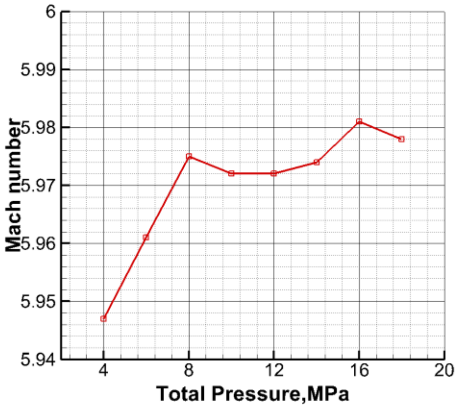

Figure 3: Mach Number Variations with P_0 for Simulations in CO_2

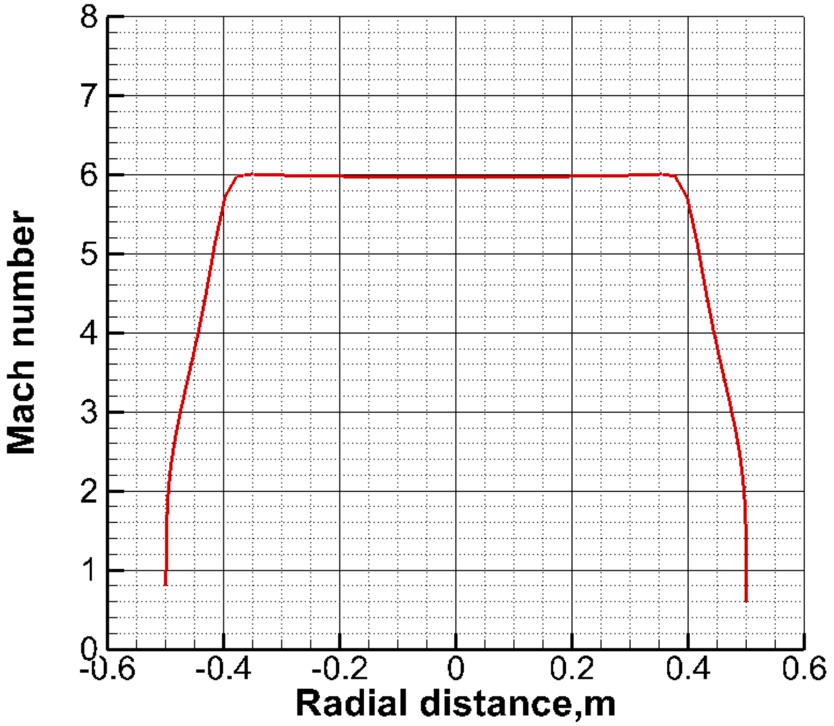

Figure 4: Mach Number Profile at Nozzle Exit(P0=5.8MPa,T0=756K)

3 Experimental Setup

A. Facility Description and Modification

All experiments were conducted in the FD20 shock/gun tunnel at China Academy of aerospace aerodynamic(CAAA), a schematic of the facility is shown in Fig.5,photography is given in Fig.6.The driver section consists of a tube 10m long with an inside diameter of 16cm,the driven section consists of a tube 20m long with an inside diameter of 13cm.The contoured nozzle has an exit diameter of 0.5m,changeable throat sections are used to vary mach number(from Mach 4 to 14) at nozzle exit. The facility can operate in two modes, reflected shock tunnel mode and gun tunnel mode respectively. For the previous mode, the reservoir conditions of stagnant gas at the end of the driven tube is created by the passing of the incident shock which then reflects off the end wall. For the gun tunnel mode, a light piston is put into the driven tube with the exception that the higher reservoir conditions levels and longer test period are created by the passing of shock and piston compression. The typical test period varies from 10ms to 60ms and total pressure from 1MPa to 30MPa, the maximum total temperature is about 1700K.
In order to produce hypersonic CO_2 flow at nozzle exit, some modification works need to be done since the FD20 tunnel was original designed for air test. A new capability of employing CO_2 as test gas in place of air was developed by setting CO_2 supply system and vacuum system, these two systems work together to control CO_2 partial pressure (or mass fraction).The light piston is still driven by high pressure air, and reservoir conditions are controlled by adjusting the ratio of the driver pressure to the driven pressure.

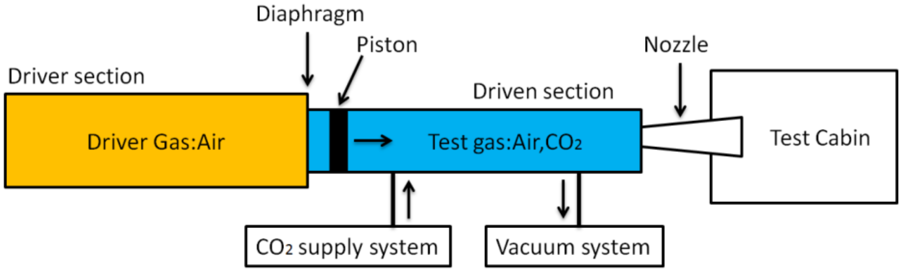

Figure 5: Schematic of the CAAA FD20 Shock/gun Tunnel

Figure 6: Photography of the CAAA FD20 Shock/gun Tunnel

B. Calibration of the FD20 Facility for CO_2 Test

A series of experiments were conducted to measure total pressure(P0), pitot pressure (Pt) and stagnation point heat flux(Qs) at nozzle exit, a contoured Ma8-Air nozzle(exit diameter of 0.5m,different from the previous one) is used to produce hypersonic CO_2 flow. The FD20 tunnel operates as the gun tunnel mode for obtaining longer test period and higher reservoir conditions, it also can avoid driver gas contamination which would shorten the test period in reflected shock tunnel mode. The driver tube and driven tube fill with air and CO_2 respectively, initial test gas temperatures(T1) and driver gas temperatures(T4) are set to 290K for all cases. The total pressure is measured by a pressure sensor at the end of driven tube, flow conditions at nozzle exit are measured in the test cabin using a 24 probe pitot rake, probes are located at 4cm intervals, and provide measurement of stagnation point heat flux and impact pressure. Stagnation point heat flux was measured by thin-film transducers with diameter of 2mm which was installed in a hemisphere with diameter of 60mm.

In order to produce hypersonic CO_2 flow with the same mach number over a range of Reynolds number at nozzle exit, three operating conditions with same ratio of the driver pressure to the driven pressure were selected. The ratio was set at 100 for all tests to make sure that the total temperature could reach 900K, free stream flow with Mach 6 will be produced at this conditions. The operating conditions and measured data are given in Table 1,these parameters are critical for determining free stream conditions. Total pressure was measured by pressure sensor at the end of driven tube, pitot pressure and stagnation point heat flux are average of values in the core flow. The pitot pressure profile at nozzle exit is shown in Fig.7,it indicates that the uniformity of core flow at nozzle exit is good enough for the aerodynamic forces and heat flux measurements.

Table 1: FD20 Tunnel Operating Conditions and Measured data

Shots No.	Driver gas pressure P4, MPa	Test gas pressure P1, MPa	Total pressure P0, MPa	Pitot pressure Pt, kPa	Stagnation point heat flux Qs,kW/m^2
181	5	0.05	3.00	27.06	139.02
182	11	0.11	7.21	63.21	228.41
187	23	0.23	13.16	115.94	324.93

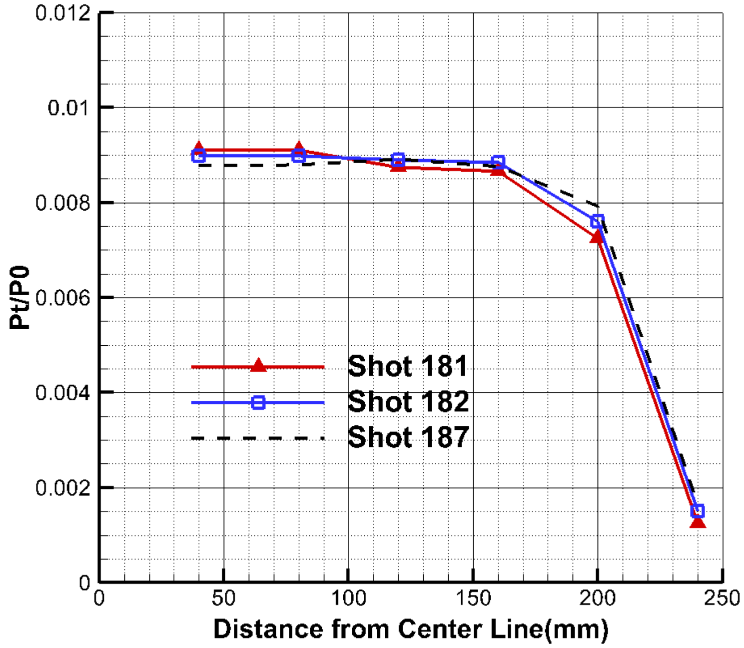

Figure 7: Pitot Pressure Profile at Nozzle Exit

4 Determination of Flow Conditions

Flow conditions need to be calculated are total temperature and free stream flow parameters at nozzle exit. According to the previous study, the critical step to determine the flow parameters is the total temperature determination. As soon as the total temperature is known, other parameters can be calculated by CFD simulations of nozzle flow.

A. Method of Flow Conditions Determination

It is difficult to introduce the method for air test to CO_2 test because of the specific heat ratio of CO_2 is variable. According to the operating type of tunnel and measured data, a combined method for CO_2 test has been established by combining shock tube relations with CFD simulations of nozzle flow.

The key of this method is the determination of T0, an unknown equivalent specific heat ratio(Gamma) need to be introduced with the assumption that specific heat ratio is the same in the flow. All initial conditions and measured data,P4,T4,P1,T1,P0,Pt,etc,are known, calculation steps for unknown parameters as follows:

1) Obtain the relation of mach number to equivalent specific heat ratio from Eq.(1).

2) With the values of a serial equivalent specific heat ratio just obtained, use P0,P4,P1 to calculate T0 through shock tube relations which include piston compression. A relation(result_1 shown in Fig.8) of mach number to T0 is obtained.

3) Because of the values of P0 and T0 are known, another relation(result_2 as shown in Fig.9) of mach number to T0 can be obtained by CFD simulations of nozzle flow,CO_2 gas is regarded as thermally perfect gas in simulations.

4) These two relations have only one intersection point as shown in Fig.1,T0 and mach number of every shot can be obtained from the coordinate of point A.

5）At this stage,T0 has been determined, other flow parameters at nozzle exit can be calculated by CFD simulations. Calculated flow parameters for all shots are shown in Table 2.

$$\frac{P_t}{P_0}=\left[\frac{(r+1)Ma_\infty^{\ 2}}{(r-1)Ma_\infty^{\ 2}+2}\right]^{\frac{r}{r-1}}\left[\frac{r+1}{2r\,Ma_\infty^{\ 2}-(r-1)}\right]^{\frac{1}{r-1}} \qquad (1)$$

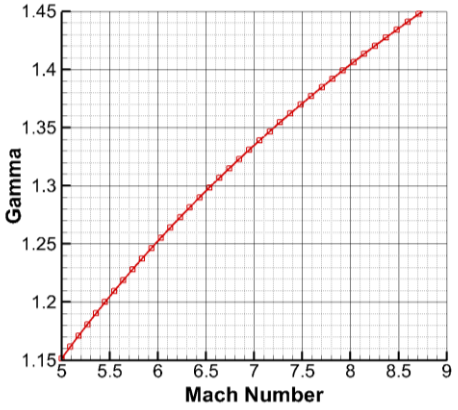

Fig.8. Relation of Mach Number to Gamma

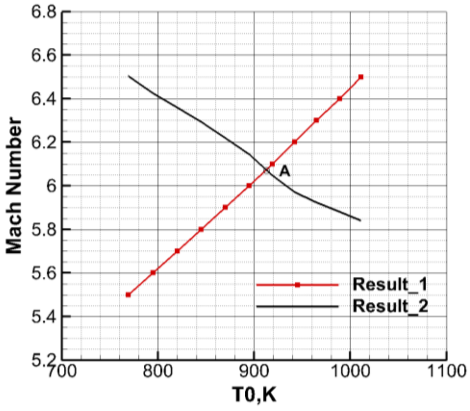

Fig.9. Intersection Point of Two Relations

Table 2: Reservoir Conditions and Free Stream Flow Conditions

Shots No.	Total pressure P0, MPa	Total temperature T0, K	Mach Number	P, kPa	T, K	Velocity m/s	Re, 1/m
181	3.0	905	6.11	0.586	158	1225	2.40E6
182	7.21	913	6.07	1.394	160	1232	5.65E6
187	13.16	893	6.16	2.486	152	1216	1.04E7

B. Method Validation

The method was validated by comparing measured values of pitot pressure and stagnation point heat flux with calculated values. The calculated values are obtained from CFD simulations of hemisphere and cylinder flows, the hemisphere has a diameter of 60mm.CFD simulations were performed at flow conditions calculated before which are given in Table 2,CO_2 gas is regarded as thermal perfect gas.
The static pressure and temperature contours of shot 181 are shown in Fig.10 and Fig.11.The compression of measured and calculated pitot pressure and stagnation point heat flux are given in Table 3. The calculated results are good agreement with the measured data, the variations of pitot pressure between the measurements and calculations compare within 4.5%, and stagnation point heat flux within 6.6% for all shots. It indicates that the method developed in present study cloud reliably calculate T0 and free stream flow conditions for gun tunnel, the calculated flow conditions are reasonably accurate.

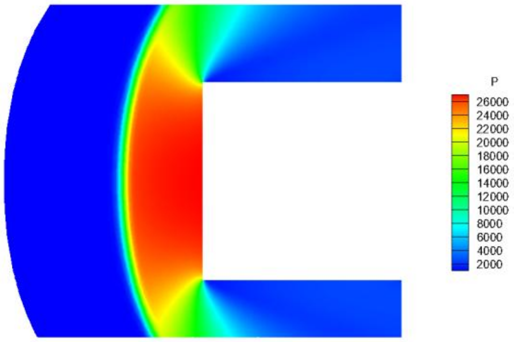

Figure 10: Cylinder Pressure Contours of Shot 181

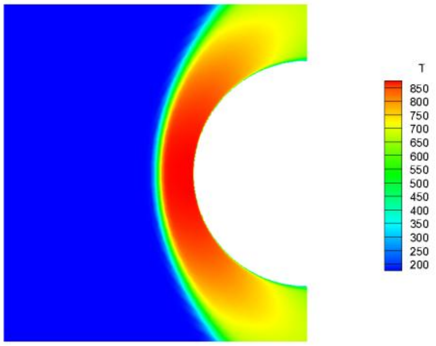

Figure 11: Hemisphere Temperature Contours of Shot 181

Table 3: Comparison of Measured and Calculated Pitot Pressure and Stagnation point Heat Flux

Shots No.	Mach Number	Pt, kPa Measured	Pt, kPa CFD	Qs,kW/m^2 Measured	Qs,KW/m^2 CFD
181	6.11	27.06	27.91	139.0	148.1
182	6.07	63.21	65.99	228.4	239.3
187	6.16	115.94	120.59	324.9	335.1

5 Conclusions

The capability to simulate flow field of Martian atmospheric entry vehicles in carbon dioxide gas has been developed for FD20 shock/gun tunnel, the facility was calibrated at conditions of Mach 6 over a range of Reynolds numbers. The combined method was developed to calculate flow conditions of FD20 shock/gun tunnel, the CFD results are reasonably accurate and showed the credibility of this method to confirm the characteristics of the flow field. Finally, the capability to test in carbon dioxide with the FD20 tunnel will support current and future missions to Mars.

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