Experimental investigation of shock stand-off distance on spheres in hypersonic nozzle flows

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Summary. In order to understand thermochemical non-equilibrium phenomena which occur during re-entry, shock stand-off distances on a simple hemi-spherical model were measured in a high enthalpy shock tunnel. Moreover, from the measurements, the unresolved question of how much influence un-recombinated oxygen atoms and vibrationally excited molecules related to the frozen phenomena of nozzle flows have on the flow was investigated. It was also discussed whether a binary scaling parameter which indicates a non-equilibrium process can accommodate the nozzle flows of a shock tunnel.

1 Introduction

During atmospheric re-entry at speeds of 7 km/s or higher, the air behind the shock wave generated around a body will be compressed and heated to 10,000 K. At these temperatures, real gas effects are dominant and lead to drastic changes in the aerothermodynamic characteristics of the flow. Therefore, the development of thermal protection system against aerodynamic heating and a detailed investigation of aerodynamic characteristics are essential topics to investigate.

Air molecules flowing around re-entry vehicles become vibrationally excited, dissociated and ionized, and the shock layer is in thermochemically non-equilibrium with flow duration times of the same order as the chemical reaction time in air. Since this effects influence aerodynamic characteristics, it is necessary to understand them, particularly for the development of space transportation systems [1].

In the hypersonic regime, a simple geometry is sensitive to real gas effects in the shock layer. In the case of a sphere, the high temperature behind a shock wave brings vibrational excitation and dissociation of air molecules, and the temperature is reduced by heat absorption due to real gas effects. As a result, shock stand-off distances are shortened. Therefore, shock stand-off distances are good reference quantites and useful for validating the results of numerical simulations [2].

As a result, a lot of papers have experimentally, numerically and theoretically investigated shock stand-off distance for high enthalpy flows. Lobb [3] experimentally measured shock wave stand-off distances with a light gas gun and clarified the relationship between flight speed and the shock stand-off distance. Nonaka [4] acquired more detailed data and arranged it according to the binary scaling parameter.

Hornung and Wen [5] measured the shock stand-off distance with a shock tunnel and explained the results by introducing a reaction rate parameter. Olivier [6] further developed this theory and obtained very good agreement with the experimental results.

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A shock tunnel is one of the ground test facilities that can generate high enthalpy uniform flows. However, the test gas remains thermally excited and chemically frozen after it becomes a plasma at the nozzle reservoir and is expanded very rapidly in the nozzle without returning to its original state.

In particular, a not negligible amount of un-recombined oxygen atoms are left in the nozzle flow and, hence, the nozzle flow does not accurately reproduce real re-entry conditions. However, the extent of such a chemically frozen state has not been well examined and this is one of the most serious criticisms made of high enthalpy shock tunnel characteristics. In particular, because of the presence of chemically frozen flow in the nozzle, non-equilibrium effects in the shock layer are weakened.

In the present study, in order to experimentally investigate the influence of the thermochemical non-equilibrium, shock stand-off distances on a hemispherical model were measured in the enthalpy range of 4 to 16 MJ/kg using the High Enthalpy Shock Tunnel (HIEST) at the Japan Aerospace Exploration Agency (JAXA). The obtained results were compared with those from a ballistic range and the effect of changes in the flow density and model radius for a fixed binary scaling parameter and flow velocity was also examined.

2 Test facility and condition

HIEST can produce a test flow with a maximum stagnation enthalpy of 25 MJ/kg and a maximum stagnation pressure of 150 MPa to reproduce the dissociation of molecules in re-entry flight [7]. Three kinds of hemispherical model were manufactured to examine thermochemical non-equilibrium effects by varying the binary scaling parameter. The radii of the models were 25, 40, and 50 mm. The shock stand-off distances were measured from the visualization results using the Schlieren method and pressure measurements were also made near the stagnation point.

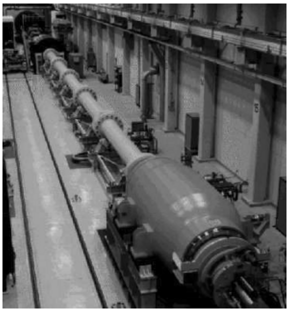

Fig. 1. High Enthalpy Shock Tunnel, HIEST

Table 1 shows the test conditions as calculated by the Nonequilibrium Nozzle Flow (NENZF) code [8]. The binary scaling parameter was set to values of 2.0, 4.0 and 8.0 $\times$ 10^{-4} kg/m^2. The nozzle flow velocities were set to 2.5 to 4.5 km/s, corresponding to enthalpies of 4 to 16 MJ/kg. The test gases were air and nitrogen. A diode pumped solid-state (DPSS) laser was used as a light source and a digital still camera as the recording medium.

Table 1. Test conditions

velocity (km/s)	P_0 (MPa)	ρ (kg/m^3)	R (mm)	ρR (kg/m^2)	test gas
2.5	14.8	0.016	25	4.0×10^{-4}	Air, N_2
3.0	13.0	0.01	40	4.0×10^{-4}	Air, N_2
3.0	38.5	0.03	25	8.0×10^{-4}	Air
3.5	16.7	0.01	40	4.0×10^{-4}	Air, N_2
3.5	35.8	0.021	40	8.0×10^{-4}	Air
3.5	57.8	0.031	25	8.0×10^{-4}	Air
4.0	17.7	0.008	25	2.0×10^{-4}	Air
4.0	17.7	0.008	50	4.0×10^{-4}	Air, N_2
4.0	33.8	0.016	25	4.0×10^{-4}	Air, N_2
4.0	33.8	0.016	50	8.0×10^{-4}	Air
4.5	28.4	0.011	40	4.0×10^{-4}	Air, N_2

3 Test results

Figure 2 shows a Schlieren photograph for an enthalpy of 16MJ/kg, flow velocity of 4.5 km/s and radius of 50 mm as a typical condition. Errors appearing in the data measured from the photographs result from the determination of the shock position and average approximately 2%. The shock stand-off distances, Δ, are normalized by the model radius, R.

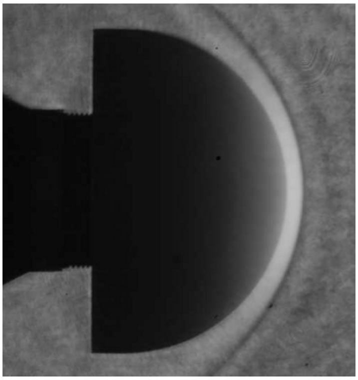

Fig. 2. Schlieren photograph over a sphere for a radius of 50 mm and enthalpy of 16 MJ/kg

Figure 3 shows the test results for ρR=4.0×10^{-4} kg/m^2 and an enthalpy of 4 to 13 MJ/kg when the test gas is nitrogen. The abscissa designates the flow velocity and the ordinate is the normalized shock stand-off distance. The upper solid line designates the analytical results for $\gamma = 1.4$ and the broken line is the prediction of the state of chemical equilibrium at a pressure of approximately 2.7 kPa. Actually, in the higher enthalpy of this range, nitrogen molecules begin to dissociate but the vibration mode is dominant in this region. In the shock tunnel experiments, the nitrogen molecules are not relaxed and reach the nozzle exit in a vibrationally non-equilibrium state due to the frozen phenomena in the nozzle mentioned previously. Therefore, since plenty of excited

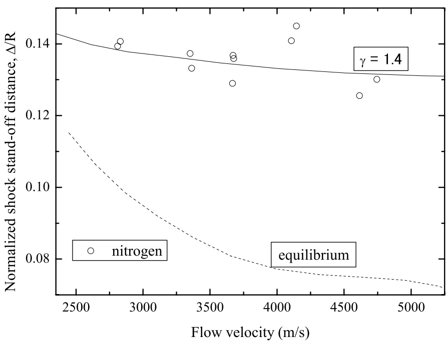

Fig. 3. The normalized shock stand-off distances for nitrogen in HIEST

molecules already exist, the contribution to the internal energy behind the shock wave becomes small and the stand-off distances become relatively long.

The shock stand-off distances measured in HIEST for a test gas of air are plotted in Fig.4 for ρR values of 2.0, 4.0 and 8.0 $\times$ 10^{-4}kg/m^2. The obtained data lie between the curves designated for an ideal gas and for chemical equilibrium. Therefore, the region between the two curves is non-equilibrium region with a finite ρR. Data taken at lower velocities is close to the ideal gas value and, as flow velocity increases, strong non-equilibrium effects clearly appear. It is noted that non-equilibrium effects are exhibited even in the region of 2.5 km/s. Moreover, as the value of ρR increases, the normalized shock stand-off distances approach the equilibrium value.

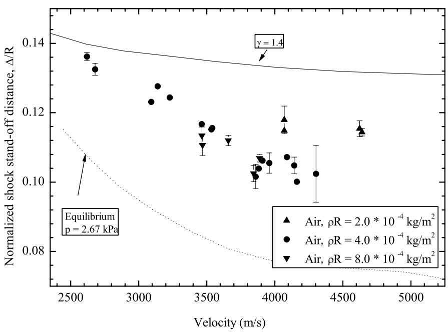

Fig. 4. The normalized shock stand-off distances for air in HIEST

Figure 5 shows a comparison of the normalized shock stand-off distances for ρR = 4.0 $\times$ 10^{-4}kg/m^2. The normalized shock stand-off distances measured in the shock tunnel

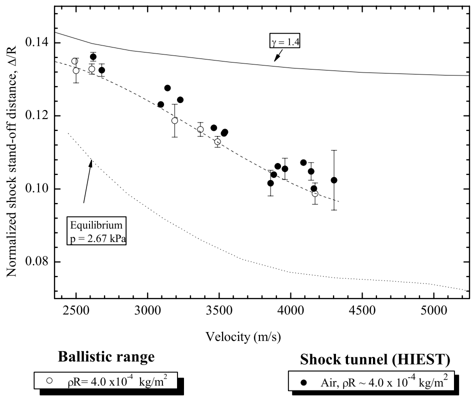

Fig. 5. The comparison of shock stand-off distances between shock tunnel and ballistic range for $\rho\text{R} = 4.0 \times 10^{-4}$ kg/m^2

are compared with those obtained in a ballistic range by Nonaka. As the velocity of the flow and the projectile goes up, it is clear that both results have the same tendency. However, the values obtained in the shock tunnel are generally larger than those of the ballistic range. As mentioned above, the shock tunnel test flows keep a higher temperature without returning to their initial state at the nozzle exit. Therefore, the Mach number of the test flows in the shock tunnel becomes lower and that is thought to be one of the causes of the increase in the normalized shock stand-off distance. However, a simple comparison like this is difficult to make due to the presence of other factors. It will be necessary to examine these effects in more detail in the future.

Three values of radius and density are combined in the velocity area of 3.8 to 4.3 km/s and the results of normalized shock stand-off distances at almost constant ρR=4.0 $\times$ 10^{-4}kg/m^2 are shown in Fig. 6. The results show good agreement and the binary scaling parameter was found to be established in the non-equilibrium flowfield in HI-EST. However, because the density and velocity are calculated from NENZF, further examination is required.

4 Conclusion

In order to experimentally investigate thermochemical nonequilibrium phenomena which occur during re-entry, shock stand-off distances on a simple hemi-spherical model were measured in a high enthalpy shock tunnel. The results summarized as follows:

- Due to the frozen phenomena in the nozzle, the stand-off distances become relatively long for a test gas of nitrogen.
- The shock stand-off distances measured in HIEST for a test gas of air were conducted for three kinds of ρR. As flow velocity increases, strong non-equilibrium effects clearly appear, and as the value of ρR increases, they approach the equilibrium value.

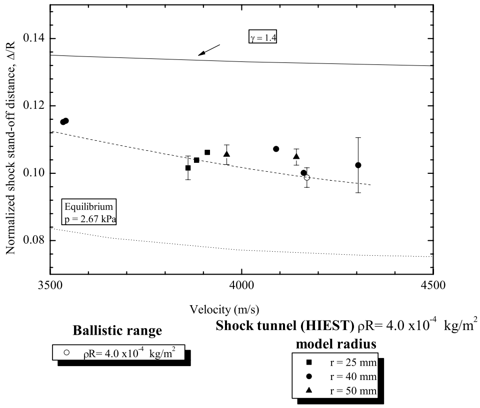

Fig. 6. The normalized shock stand-off distances for different model radius, R = 25, 40, 50 mm, at constant ρR=4.0 $\times$ 10^{-4}kg/m^2.

– The normalized shock stand-off distances measured in the shock tunnel are compared with those obtained in a ballistic range by Nonaka for $\rho\mathrm{R} = 4.0 \times 10^{-4}$kg/$m^2$, and both results have the same tendency. However, a simple comparison is difficult to make due to the presence of other factors. It will be necessary to examine these effects in more detail in the future.

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