Research on Shock-Induced Aerothermodynamics for Future Planetary Explorations

K. Fujita, T. Suzuki, H. Takayanagi, T. Ozawa, S. Nomura, N. Takizawa, S. Matsuyama, A. Lemal, and M. Mizuno

Abstract Researches on shock-induced aerothermodynamics are conducted at Chofu Aerospace Center (CAC) of Japan Aerospace Exploration Agency (JAXA) for future planetary explorations currently entertained in JAXA. The hyper-velocity shock tube (HVST) simulates the thermochemical properties in the shock layer of hypersonic systems in flight, while the hyper-velocity expansion tube (HVET) reproduces those in the wake region of the test model. The hypersonic rarefied wind tunnel (HRWT) enables us to directly measure the rarefied aerodynamics of hypersonic systems in transition flows. The light-gas gun (LGG) allows us to clearly understand the wake flow structure of capsules in supersonic flight, from which the parachute ejection conditions are determined. Numerical investigations of shock-induced aerothermodynamics are overviewed as well.

1 Introduction

Thermal protection of atmospheric entry systems for planetary explorations and manned/unmanned reentry missions is a big concern from a viewpoint of flight safety as well as design optimization to maximize mass and volume of mission instruments transportable to the planetary ground. Accurate predictions of the flight environments around the atmospheric entry system, which can be only brought about through a detailed understanding of aerothermodynamics in flows behind the strong shock wave, are required for satisfactory design of the thermal protection system (TPS) and mission success. In addition to this, accurate predictions of the hypersonic aerodynamics of the planetary entry system, which are key to the guided flight toward the target landing point, are only obtained through accurate understandings of the thermochemical properties behind the strong shock wave. Based on these backgrounds, both experimental and numerical researches on

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the shock-induced aerothermodynamics have been conducted at Chofu Aerospace Center (CAC) of Japan Aerospace Exploration Agency (JAXA) to support future planetary missions currently entertained in JAXA. In this article, an overview of the aerothermodynamic researches at CAC is presented.

2 Experimental Aerothermodynamics

Aerothermodynamic researches are conducted by using major five facilities at CAC. The appearance of the aerothermodynamics test facilities at CAC is presented in Fig. 1. The hyper-velocity shock tube (HVST), shown in the middle of Fig. 1, is a two-stage double-diaphragm shock tube driven by a free piston, having a 70×70 mm square test section. HVST can generate shock waves at a velocity higher than 12 km/s in the simulated Earth atmosphere at 30 Pa, so that it can cover all the flight conditions for the Jupiter Trojan sample return capsule under consideration in JAXA [1–3]. Other test gases, such as the simulated Martian atmosphere, can be also used for aerothermodynamic researches toward future planetary missions. Instantaneous spectroscopy system, which allows us to acquire emission spectra from vacuum ultraviolet (VUV) to infrared (IR) wavelengths with high spatial and temporal resolution, is equipped with HVST to measure variation of the thermochemical properties along with the distance from the shock wave. Absolute intensity of radiation is measured as well to assess radiative heat transfer rate for the atmospheric entry system. By using these diagnostic instruments, HVST

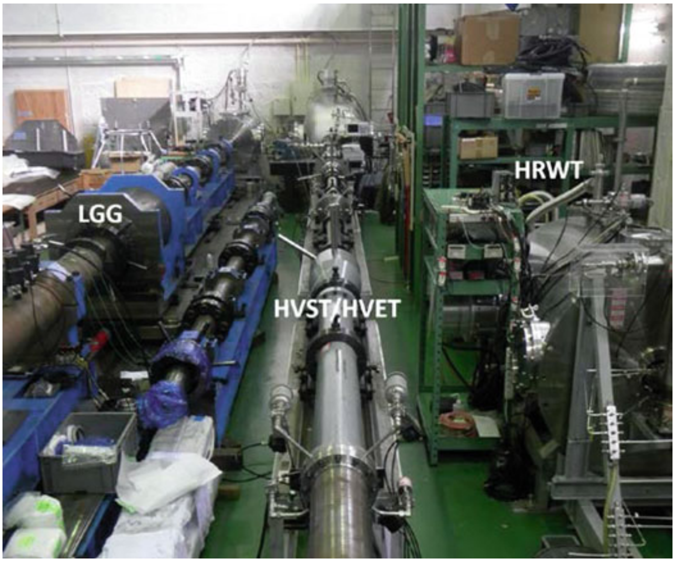

Fig. 1 Appearance of aerothermodynamics test facilities at CAC

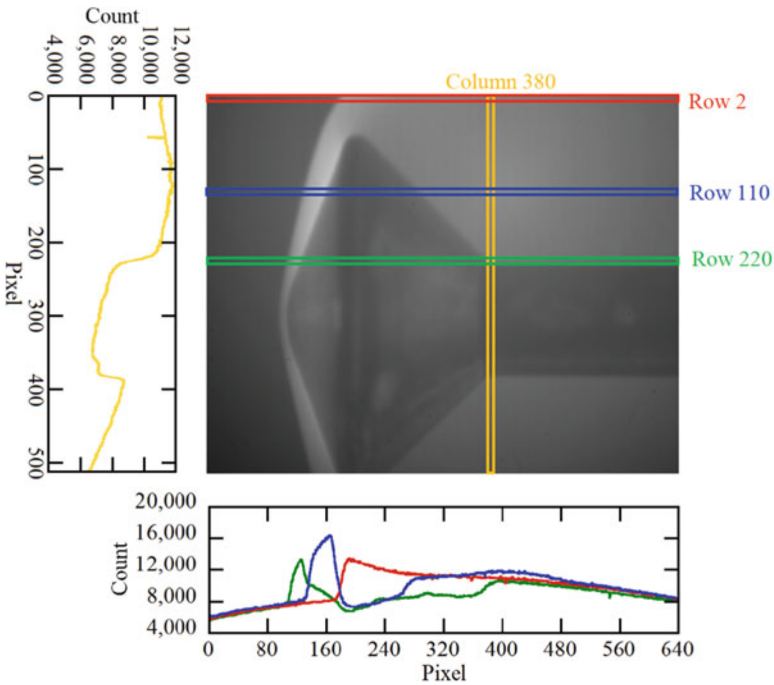

Fig. 2 Distribution of IR radiation around Martian capsule in Martian atmosphere

is used to investigate thermochemical kinetics and radiation in high-temperature gases. Recent researches are focused at assessment of the radiative heat transfer rate for very high speed reentry such as the Jupiter Trojan sample return capsule whose reentry velocity is higher than 14 km/s [2]. Influences of precursor ionization on aerothermodynamic processes behind the shock wave are also investigated [4].

The hyper-velocity expansion tube (HVET) is an expansion tube where HVST is operated in the expansion mode by using a thin polyester film as the second diaphragm. The effective core flow available for testing has a 50 × 50 mm cross section in the test section, and the typical test time is 100 μs. HVET is mainly used to measure pressure and heat transfer rate distribution around the test model exposed in the test flow. Recent researches are focused at assessment of the radiative heat transfer rate of Martian entry capsules, where the major portion of aftbody heating is due to IR radiative heating from high-temperature CO_2 and CO in the wake region [5]. Figure 2 is a representative result of IR radiation integrated from 2 to 6 μm around a Martian entry capsule model, which is taken by an InSb array camera with simulated Martian atmosphere as the test gas [6]. It is seen that IR radiation emanates not only in the shock layer but also in the wake region. Although not shown here, IR spectra are obtained as well at representative points around the capsule model. The IR spectra suggest that vibrational excitation is frozen in the expanding wake flow, which brings about intense IR radiative heating on the aftbody of the Martian capsule.

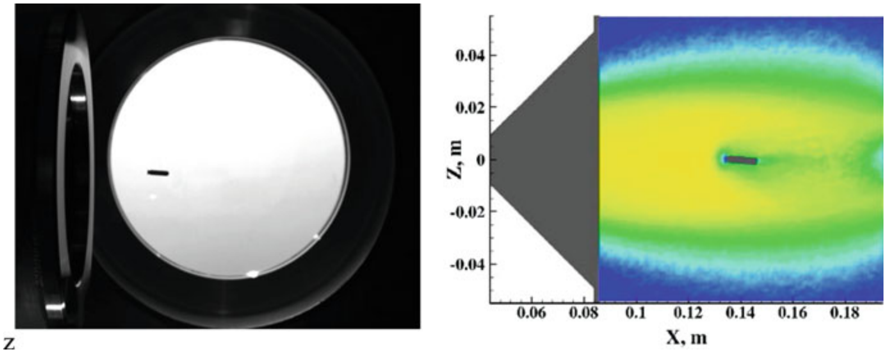

Fig. 3 Appearance of rarefied aerodynamic coefficient measurement in HRWT with the aid of DSMC calculations by MOTIF (angle of attack = 5°, $Kn \sim 0.3$, simulated air)

The hypersonic rarefied wind tunnel (HRWT) is a blowdown continuum wind tunnel which can produce test flows at Mach numbers higher than 10 and Knudsen numbers greater than 0.1 [7]. A gas preheater is equipped with HRWT to avoid condensation of the test gas during nozzle expansion. The half cone angle and the exit diameter of the nozzle are 45° and 100 mm, respectively, while the core flow diameter is typically 25 mm at a 17 mm distance from the nozzle exit. HRWT is mainly used to directly measure the rarefied aerodynamic coefficients in the transition regime and to determine the thermal accommodation factor of the material [8]. In these measurements, the test model is suspended in the test flow by thin nichrome wires of 15 μm in diameter, and the aerodynamic force and the momentum acting on the model are deduced from changes in model position and attitude from the pendulous equilibrium state with the aid of direct simulation Monte Carlo (DSMC) calculations of the test flow with the test model. A typical example of rarefied aerodynamic coefficient measurement is shown in Fig. 3. Recent researches are focused at development of the hypersonic rarefied aerodynamic database of a Super Low Altitude Test Satellite (SLATS) to be launched in 2017 [9]. Applications to a future Mars mission and an air breathing ion engine (ABIE) satellite are currently undertaken by improving HRWT test capabilities [10, 11].

The light-gas gun (LGG) is a free-flight test facility, which can let test models of 18 mm in diameter fly at a velocity higher than 1.7 km/s [12]. LGG is originally developed to obtain detailed understandings of the flow structure around Martian entry capsules, from which the supersonic parachute ejection conditions can be quantitatively determined with the aid of computational fluid dynamic analysis. Figure 4 is a typical result of flow visualization around the Martian capsule model of 16 mm in diameter flying at Mach number of 1.9 in the simulated Martian atmosphere (upper), compared with the numerical result computed by a computational fluid dynamic (CFD) code, JONATHAN, which is described in the next section [13]. LGG is currently under modification to enhance its projectile shooting performance up to Martian entry velocity to assess the real-gas effects

Fig. 4 Flow visualization around a Martian capsule model in free flight at Mach number 1.9 (upper) and comparison with numerical result by JONATHAN (lower)

of a CO_2-N_2 mixture on the hypersonic aerodynamic coefficients of Martian entry capsules. In this research, evolution of attitude and velocity of the test model in free flight is observed by high-speed cameras, from which the aerodynamic coefficients are deduced as an inverse problem with the aid of numerical analysis.

The last facility is the 750 kW arc heated high enthalpy wind tunnel (HEWT), which enables us to evaluate test specimens whose diameter is 50 mm [14]. HEWT is mainly used to develop TPS for hypersonic vehicles; however, it is also used for aerothermodynamic researches such as development and assessment of diagnostic tools and numerical tools which are used in high-speed facilities [15, 16].

3 Numerical Aerothermodynamics

In addition to the experimental aerothermodynamic researches described above, a variety of numerical investigations are conducted at CAC. One of the most fundamental researches is quasi-classical trajectory (QCT) analysis, in which binary collisions among the gases of interest are numerically simulated in the Monte Carlo manner [17]. A huge number of QCT calculations are performed, from which macroscopic models of thermal relaxation and chemical reaction are deduced in a statistical manner. The thermochemical models so developed and improved are experimentally evaluated by using the aerothermodynamic test facilities described above, and finally introduced into the aerothermodynamic tools, such as JONATHAN [18, 19], a direct simulation Monte Carlo code MOTIF [20], a radiation analysis code SPRADIAN2 [21], and an ablator TPS analysis code SCMA2 [22]. These numerical tools are used to assess the flight environments around the atmospheric entry systems as well as to predict and reconstruct TPS performance in the test facility and along the flight trajectory.

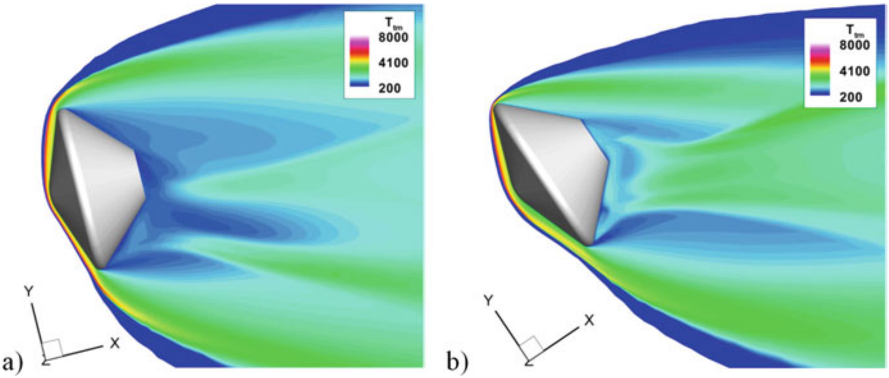

Fig. 5 Flow fields around a Martian entry capsule at (**a**) $\alpha = -14°$ and (**b**) $\alpha = -34°$ (computed by JONATHAN with $V = 5.39$ km/s, $T = 169.5$ K, and $P = 18.27$ Pa)

Figure 5 illustrates typical results of the flow filed around a Martian entry capsule computed by JONATHAN at different angles of attack (α) [18]. The aerodynamic coefficients of the capsule and the heat transfer rate distributions are obtained as well through such computations. When rarefication of the flow has considerable influences on the aerodynamic coefficients and the transport properties, MOTIF is used instead. A typical result of the nozzle flow computation with a test model is already shown in Fig. 3. MOTIF is also used in development of the rarefied aerodynamic coefficient database of SLATS. Very recently, MOTIF is applied to prediction of precursor photo-ionization for high-speed shock waves, where strong VUV radiation transfer from behind the shock wave plays a considerable role in thermochemical processes across the shock wave [20]. The latest advancement of SPRADIAN2 is improvement in accuracy in VUV and IR wavelengths, which are presented in [23, 24], respectively. These results are introduced to designing the Jupiter Trojan sample return capsule and the Martian entry capsule under consideration in JAXA.

4 Conclusion

Five aerothermodynamic test facilities, HVST, HVET, HRWT, LGG, and HEWT, are located at JAXA CAC to conduct aerothermodynamic researches required for future planetary explorations. Finite rate thermochemistry and radiation models are developed and evaluated with HVST, while distribution of pressure and heat transfer rate on the test model surface is assess with HVET. Recent IR diagnostics suggest frozen thermochemistry of CO_2 in the wake region, which brings about considerable IR radiative heating on the aftbody of Martian entry capsules. The hypersonic rarefied aerodynamic coefficients in the transition flow can be directly measured with HRWT. Flow visualization around a Martian capsule model in free flight at Mach number 1.9 is successfully obtained with LGG, from which the Martian supersonic parachute ejection conditions can be deduced. A variety of numerical aerothermodynamic researches are conducted as well to obtain better understandings of aerothermodynamic processes behind the shock wave and to support JAXA's future atmospheric entry missions.

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