Aeroheating test of re-entry capsule in Hypersonic high-Reynolds number flow

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Abstract

An aero-heating test campaign under Hypersonic high Reynolds number condition was conducted in the high-enthalpy shock tunnel JAXA-HIEST. A Hayabusa SRC (sample return capsule) 70% scale model, which diameter was 250mm, was applied in the test. The model had forty-eight fast-response coaxial thermocouples on the heatshield side and the back-shell side to measure the heat flux distribution. Eight piezo-resistive pressure transducers were also mounted on the back-shell to determine flow establishment around the model. To onset the boundary layer transition, high Reynolds number test condition was selected, which stagnation enthalpy and pressure were H_0=13MJ/kg and P_0=81MPa, respectively. The unit Reynolds number under the condition was Re=2.3 million/m. Measured surface heat-flux under the above condition showed an unexpected augmentation at the shoulder of the model. A single beam Schlieren interferometer implied that the compression wave vicinity of the shoulder was a cause of the heat flux augmentation.

Keywords: Aeroheating, Reentry, Hypersonics, Boundary layer transition

Nomenclature :

P_0 = Stagnation pressure
H_0 = Stagnation enthalpy

Introduction

For the optimum design of TPS (thermal protection system) of reentry or planet-entry capsules, numerical codes to predict accurate aeroheating load is crucial. Recently, the size of the capsule tends to be larger [1, 2] resulting risk of the boundary layer transition which causes aeroheating augmentation accordingly. However, the precise numerical prediction at high Reynolds number still remains as a significant technical issue due to the lack of high-quality experimental data as a benchmark for validations. Although many turbulent aeroheating experiments in cold hypersonic wind tunnels have been reported, the experimental data in the hot hypersonic flow is quite limited due a few number of ground test facilities.

In the free-piston high-enthalpy shock tunnel HIEST (Fig.1 top) [3], test campaigns have been conducting to provide benchmark data to validate numerical codes for the aeroheating of capsule-shaped reentry vehicles. The tunnel produces stagnation pressures up to 150 MPa and stagnation temperature up to 10000 K. At the maximum stagnation condition, the test duration is 2 ms or longer. With the HIEST contoured nozzle (exit diameter of 800 mm), test models with diameters up to 300 mm are available. As shown in the HIEST operation envelope (Fig.1 bottom), the unit Re number easily exceeds 4x10^6 at H_0 = 15 MJ/kg, which Re number is sufficient for boundary layer transition.

In this script, aeroheating test results with 70%-scaled Hayabusa SRC model under high-enthalpy condition (H_0=13MJ/kg) in HIEST were reported. At the maximum stagnation pressure (P_0=81MPa), the free-stream unit Reynolds number Re=2.3×10^6/m was obtained, which Reynolds number is expected to onset boundary layer transition on the model windward surface. Forty-eight miniature coaxial thermocouples flush-surface-mounted on the model surface enabled heat flux distribution to observe boundary layer. Moreover, single-beam Schlieren interferometer was tried to measure density in the shock layer. The preliminary visualization results showed a disturbance vicinity of the shoulder of the SRC test model.

Shock tunnel test

Free-piston shock tunnel HIEST

The free-piston shock tunnel HIEST has been used for aerothermodynamic studies since 1998, and over 2700 shots have been successfully conducted so far. The tunnel can be

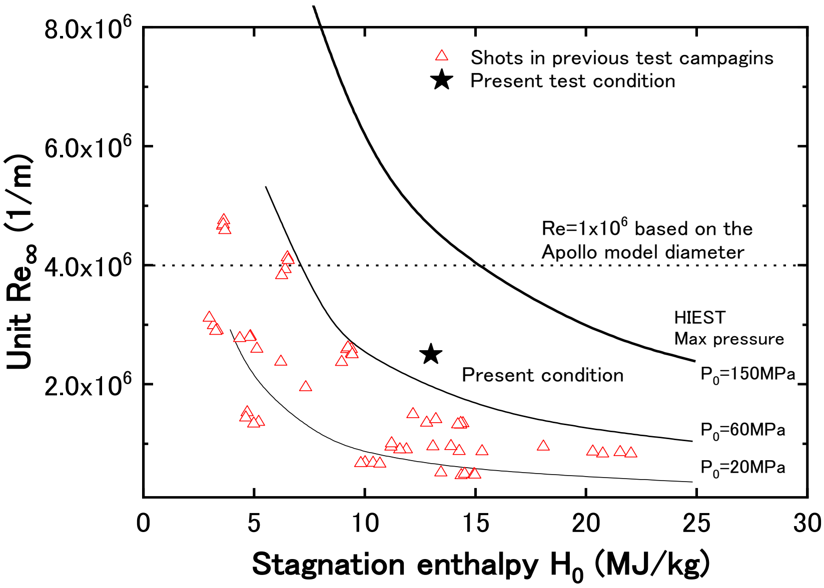


Fig.1: (Top)The free-piston shock tunnel HIEST. (Bottom) Operation envelope of the HIEST

Table 1: HIEST free-stream condition of the present test

Condition	P_0 (MPa)	H_0 (MJ/kg)	T_0 (K)	T_∞ (K)	P_∞ (kPa)	ρ_∞ (kg/m^3)	u_∞ (m/s)	M_∞	Re/l (1/m)
A	4.7×10	1.4×10	7.5×10^3	1.5×10^3	7.1	1.6×10^{-2}	4.7×10^3	6.1	1.3×10^6
	±8.7%	±8.1%	±5.2%	±8.0%	±10%	±1.9%	±3.7%	±0.8%	±1.1%
B	8.1×10	1.3×10	7.4×10^3	1.5×10^3	1.2×10	2.8×10^{-2}	4.6×10^3	6.0	2.3×10^6
	±1.6%	±4.4%	±2.8%	±4.5%	±2.7%	±2.3%	±1.9%	±0.5%	±3.3%

operated at stagnation pressures up to 150MPa and stagnation enthalpies up to 25MJ/kg with test times of 2ms or longer. In the present test campaign, the HIEST contoured nozzle of 2.8m length, 800mm exit diameter was adopted. The characteristics of the free-stream were discussed in previous report [4]. The previous report showed that a steady test core flow diameter was maintained up to 400mm, in which the deviation of the free-stream Pitot pressure was less than 6%. Since the test duration depends on the stagnation condition, a quasi-steady Pitot pressure (defined as the test time) of 7ms or longer can be attained for low-enthalpy conditions (H_0 = 3.5MJ/kg or lower).

Stagnation conditions in the nozzle reservoir (shock tube end) were calculated for each shot conducted in HIEST with an equilibrium computation code[5] using the measured shock speed in shock tube and the measured nozzle reservoir pressure (pressure at the shock tube end). The free-stream conditions were calculated for the present stagnation conditions with an axis-symmetrical JAXA in-house nozzle flow code[6]. Table 1 shows the two free-stream conditions (Low pressure condition A and High pressure condition B) for the present test campaign calculated by this procedure. In the present test campaign, the dry air was selected as the test gas.

Hayabusa test model

The Hayabusa capsule model (Fig. 2) used in this test campaign was made of SUS 303, which is 70% scaled (diameter 282.8 mm) with respect to the actual flight vehicle. On the front (heat shield side) surface of the model, 32 co-axial miniature thermocouples were flush-mounted, and 16 co-axial miniature thermocouples and eight Kulite XCS-093 Piezoresistive pressure transducers were instrumented on the back shell surface (Fig.2 left). The right picture in Fig.2

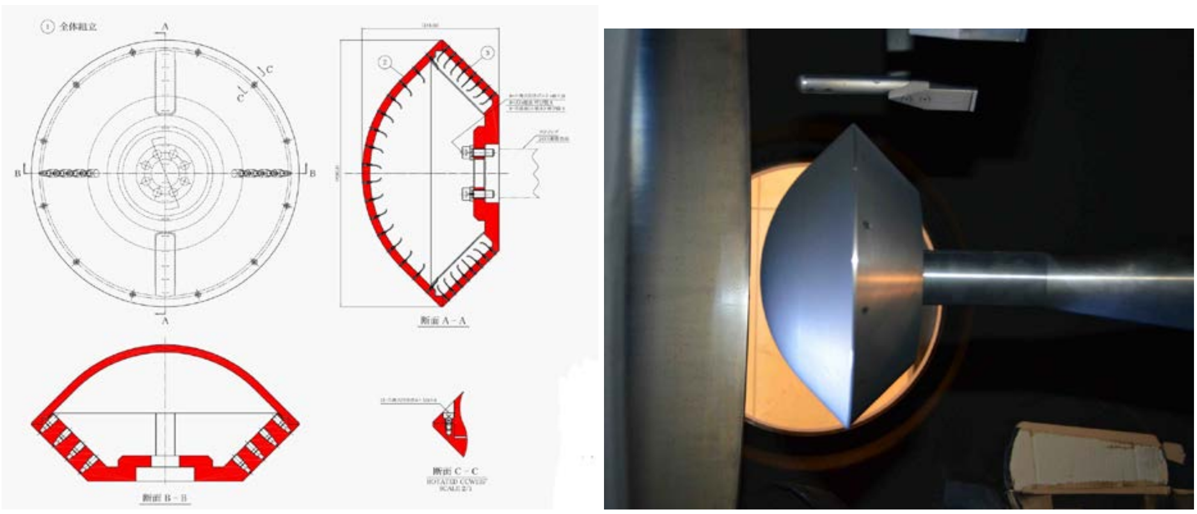


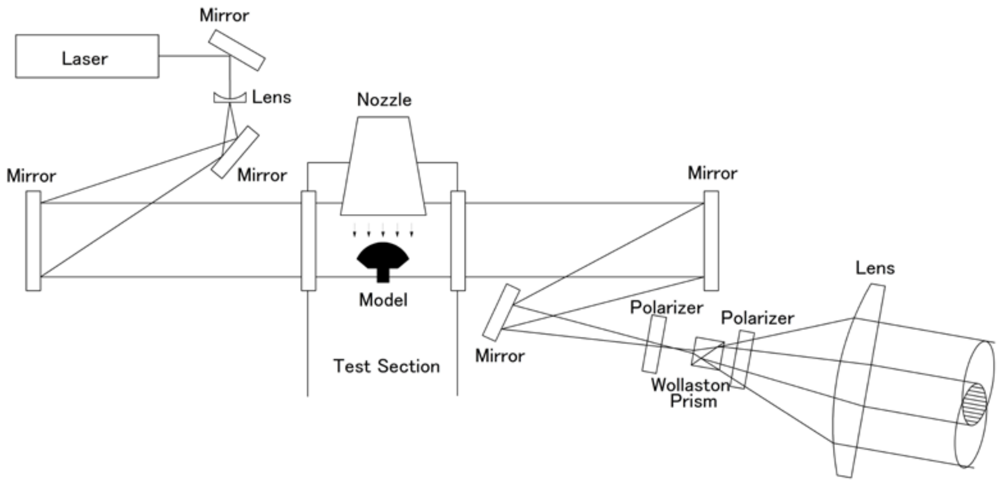
Fig. 2: (Left) A schematic drawing of Hayabusa SRC 70% scaled model. (Right) The Hayabusa SRC model installed in the HIEST test section.

showed the model installed in the HIEST test section. Whole the present test campaign, the angle of attack of the model was fixed at 0 degrees. To monitor the test free-stream, there are two permanent probes (Pitot pressure probe and heat flux probe) in the HIEST test section. Both of the two permanent probes were located 250 mm from the nozzle centre.

Coaxial thermocouples

Thermocouples used in this study were Type-E Chromel-Constantan thermocouples with miniature co-axial configuration. The thermocouples were originally developed at California Institute of Technology [7,8] for heat-flux measurement in the free-piston shock tunnel T5. With its microsecond response and good durability, this thermocouple is suitable for heat flux measurement in HIEST. The noteworthy feature of this thermocouple is its coaxial contact line between Chromel and Constantan, which provides the required durability in the harsh environment of the test flow, in which soot and micro debris strike its surface at extremely high speed. In the whole of the present test campaign, all of the thermocouples survived the entire campaign, including high-enthalpy high-pressure shots. The heat-flux data reduction procedure in the present test was described in a reference [9]. In the Stanton number, the wall enthalpy of the model surface was hence ignored because of quite high stagnation enthalpy.

Before the present test campaign, the measurement precision of the coaxial thermocouples was evaluated. Through the several former aeroheating tests performed in HIEST, the standard



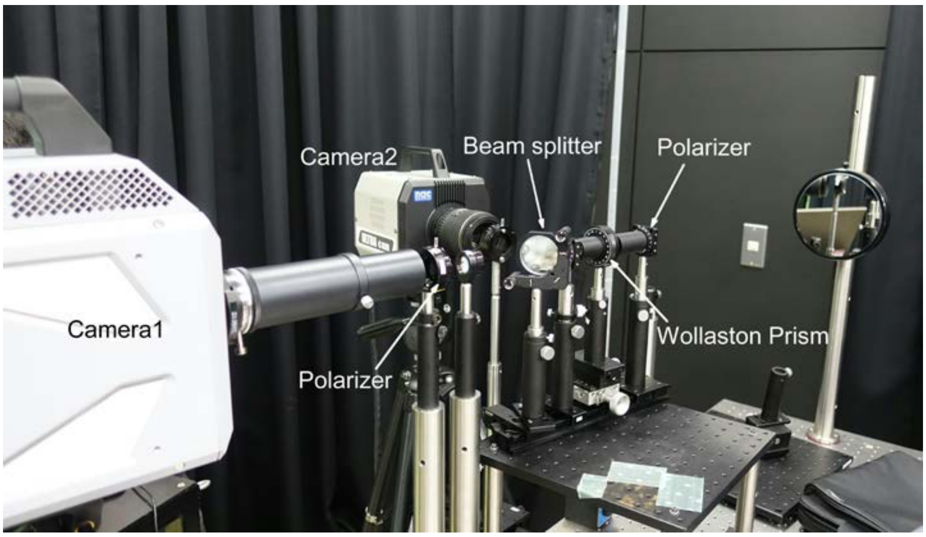


Fig. 3: (Top) Optical diagram of the single beam Schlieren interferometer. (Bottom)Photograph of the optics instrumented in the HIEST test section.

deviation σ of the Stanton number with a thermocouple was found to be 3.1%. Since measurement uncertainty in wind tunnel testing is generally defined as double the standard deviation, 2σ, measurement uncertainty was ±6.2%.

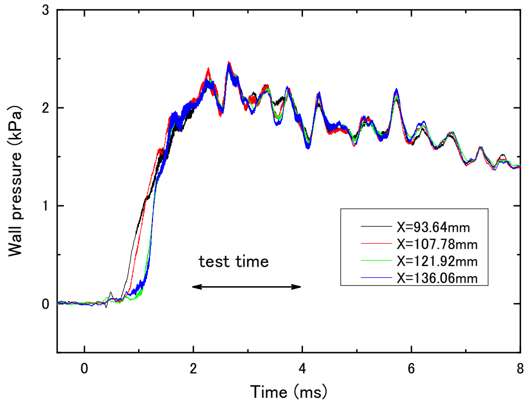


Fig. 4: An example of the measured surface pressure at the back shell of the Hayabusa capsule model.

A single beam Schlieren interferometer

For the quantitative observation of the flow around the test model, a single beam Schlieren interferometer with a polarizer-Wollaston prism [10] was implemented. Although it's observation area is narrower than those of other interferometers such as Mach-Zehnder, it has a special feature that it can be easily converted from conventional Schlieren optical systems by replacing the knife edge with a polarizer-Wollaston prism. Fig.3 (top) is the optical diagram of the present optical setup of the interferometer. Fig.3(bottom) showed a photograph of the present optics, which were instrumented in the HIEST test section.

Results

Heat flux measurement

Fig.4 showed an example of pressure traces on the back shell of the model under condition A. From the traces, at least 1ms after the test flow arrival seemed to require for the flow establishment around the model. Under the condition, quasi-steady state pressure was maintained for approximately 2msec, which was defined as the test time.

Fig.5 showed the normalized heat flux (Products of Stanton number and square root Reynolds number) profiles around the model. The left figure showed the profiles around the whole model, and the right figure indicated the magnified image vicinity the model shoulder.

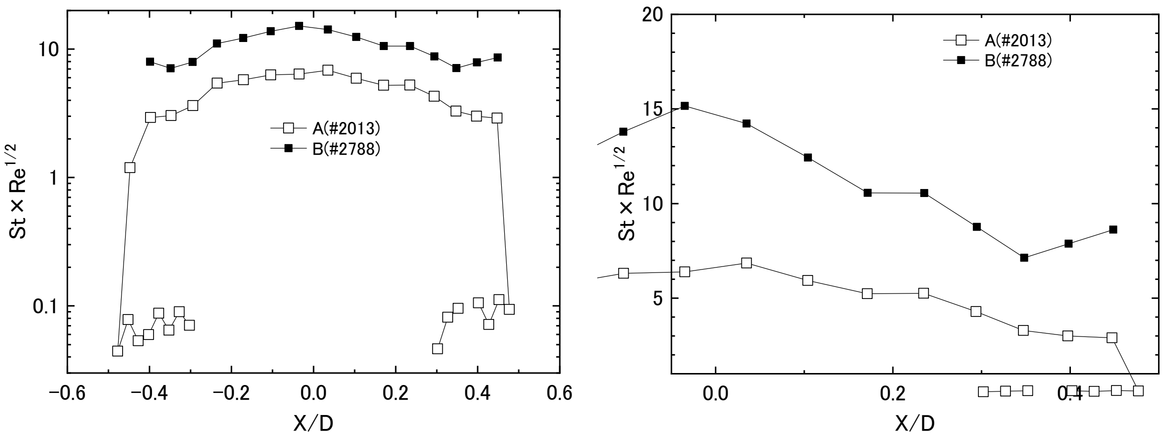


Fig.5: (Left)Measured heat flux distribution of the windward (heat shield side) of the model. Heat flux was normalized as a product of Stanton number and square root Reynolds number. (Right) Magnified heat flux distribution vicinity of the capsule shoulder.

In the figure, the test results of the low-pressure (condition A) and high-pressure (condition B) under the almost identical stagnation enthalpy. Due to the heat flux anomaly caused by radiation from impurities in the test flow [11], a quantitative heat flux was not discussed in the paper. Under the condition A, a simple heat flux profile, which monotonously decreased from the stagnation point to the shoulder, was observed. However, a heat flux augmentation was observed at the model shoulder.

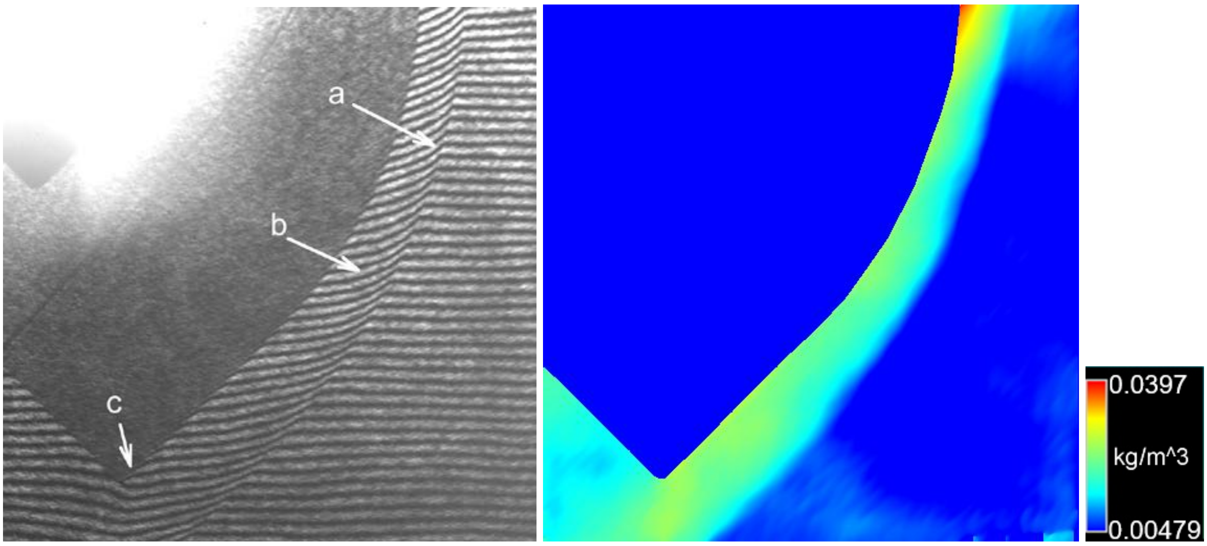


Fig.6: (Left)An example of the interferometry fringe image around the Hayabusa SRC in HIEST test flow(under condition B) taken with the present single beam Schlieren interferometer. In the figure, a:bow shock, b:shock layer, c:disturbance. (Right) (b)Density contour obtained from the left image.

Optical observation

To analyse the details of the flow field around the Hayabusa SRC in particular the heat flux augmentation at the shoulder mentioned in the previous section, quantitative optical visualization was tried under the condition B. Fig.6 showed an example of the interferometry results obtained with the single beam Schlieren interferometer. The left figure was the image of the interferometry fringe, while the right figure was digitally processed density contour [12]. It should be noted that the interferometry images clearly indicated that the HIEST test free-stream uniformity ahead of the bow-shock. The figure showed that there seemed compression waves appeared vicinity of the shoulder, which was suspected as the cause of the heat flux augmentation observed with the thermocouple measurements. The resolution of the image was still insufficient, the additional discussion is hence required to analyse the detail flow structure around the shoulder.

Summary

In order to obtain a benchmark for numerical codes validation, the heat flux of a 70%-scaled Hayabusa SRC (Sample Return Capsule) model was measured in HIEST under high-enthalpy and high Reynolds number condition (H_0=13 MJ/kg, P_0=81MPa and unit Reynolds number 2.3×10^6 / m). Heat flux was measured at a 0 degrees angle of attack, and the measured heat flux was normalized to the products of Stanton number and the square root of Reynolds number. It was found that the heat flux augmentation was observed at the test model shoulder. Through the optical observation with a single beam Schlieren interferometer, it was implied that the compression wave vicinity of the shoulder was the cause of the heat flux augmentation.

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