Measurements by Temperature Sensitive Paint on Flexible and Deforming Model in Hypersonic Flow

By Masato Taguchi,1) Ryo Maruyama,1) Takuma Sato1) and Koichi Mori1)

1) Department of Aerospace Engineering, Nagoya University, Nagoya, Japan

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Temperature measurement on deforming aeroshell model was performed in hypersonic test flow. Temperature Sensitive Paint (TSP) was used to measure surface temperature on the model. Generally, TSP is not available on flexible surface due to a problem in normalization procedure of images. Present paper describes the improved methodology of TSP which is able to apply to flexible and deforming model surface. For the improved TSP, two different kinds of luminophore, namely Ruphen and Fluorescein, are employed to observe reference image and test image simultaneously. An optical system is produced to detect the luminescence from Ruphen and Fluorescein separately. Results indicate that temperature rise caused by aerodynamic heating is observed, and the temperature distribution measured by the improved TSP method on flexible model shows qualitative agreement with the one obtained by conventional TSP measurement on rigid model which simulates deformed model configuration. Furthermore, the temperature measurement by this method shows good capability to follow model deformation.

Key Words: TSP, Inflatable Aerodynamic Decelerator, Wind Tunnel Test, Aerodynamic Heating, Hypersonic Flow

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>D</td>
<td>diameter</td>
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<tr>
<td>L</td>
<td>model length</td>
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<tr>
<td>d</td>
<td>thickness of torus</td>
</tr>
<tr>
<td>R</td>
<td>radius of nose</td>
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<tr>
<td>Re</td>
<td>Reynolds number</td>
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<tr>
<td>p</td>
<td>pressure</td>
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<td>T</td>
<td>temperature</td>
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<td>Mach number</td>
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<td>α</td>
<td>angle of attack</td>
</tr>
<tr>
<td>λ</td>
<td>wave length of light</td>
</tr>
<tr>
<td>I</td>
<td>luminance of TSP luminescence</td>
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<tr>
<td>Ą</td>
<td>heat transfer rate</td>
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<tr>
<td>TSP</td>
<td>Temperature Sensitive Paint</td>
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<tr>
<td>SNR</td>
<td>Signal to Noise ratio</td>
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Subscripts

<table>
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<td>tor</td>
<td>torus</td>
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<tr>
<td>∞</td>
<td>static value</td>
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<tr>
<td>0</td>
<td>total value</td>
</tr>
<tr>
<td>i</td>
<td>initial value</td>
</tr>
<tr>
<td>s</td>
<td>surface value</td>
</tr>
<tr>
<td>nylon</td>
<td>value on nylon fabric model</td>
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<tr>
<td>rigid</td>
<td>value on rigid model</td>
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1. Introduction

Inflatable aerodynamic decelerator (IAD)1-3) is a device for deceleration process in Entry, Descent and Landing (EDL) process5 of planetary exploration mission. For instance, in Mars exploration mission, supersonic parachute which is a kind of IAD is used to achieve adequate deceleration for the landing. IADs have flexible and inflatable structure which is inflated during vehicle flying. Because such inflatable structure yields low ballistic coefficient5 to entry vehicle, lower surface heat transfer by aerodynamic heating is expected than cases of entry without IAD devices. Several concepts of hypersonic inflatable aerodynamic decelerators (HIADs)5,6) are also proposed. NASA conducted Inflatable Re-entry Vehicle Experiment (IRVE) -3 mission to demonstrate durability for aerodynamic heating, system performance and controllability in atmosphere.7) The IAD device of IRVE-3 has a blunted cone configuration such as reentry capsule. JAXA also develops a concept of HIAD called flare-typed membrane aeroshell concept.8-10) The unique point of this concept is its simple structure. The body of aeroshell is composed of thin fabric membrane which is supported by an inflatable torus located at trailing edge of the body.

The most concerned effect in all of atmospheric entry is aerodynamic heating. This effect induces extremely high heating load to entry vehicle, and it becomes primal risk that has to be controlled. Generally, effects of aerodynamic heating to vehicle surface are estimated by measurements with conventional thermal sensors such as thermocouples under wind tunnel testing. However, these conventional sensors are not available for IAD models because sensors cannot be fixed on flexible structure that can easily deform and move in hypersonic test flow during wind tunnel operation. Accordingly, non-intrusive measurement technique is required on IAD wind tunnel tests. Temperature Sensitive Paint (TSP) is one of the
most powerful tools for non-intrusive surface temperature measurement. This method has been frequently employed for surface temperature measurements on wind tunnel tests. However, typical TSP is not valid for flexible test model owing to normalization procedure that is necessary to cancel unevenness of the paint distribution and luminous flux of excitation light.

Present paper shows an improved TSP method that can be applied to deforming surface. As is mentioned above, the key factor is normalization procedure of TSP image analysis. The improved TSP method surmounts the problem by using two different kinds of luminophore. This method is applied to wind tunnel testing, and temperature distributions on deforming surface of JAXA type IAD concept model are measured.

2. Improved method of Temperature Sensitive Paint

2.1 General description

TSP is a temperature measurement technique based on thermal quenching of a luminescence from luminophore in the paint. TSP is excited by excitation light, and a luminescence is emitted. In the observation, emission from TSP is detected by image sensor such as CCD, hence temperature information is detected as an image of measurement surface. As is mentioned above, normalization process is required to extract temperature information from the TSP images. Two kinds of image are used for the normalization process. One is reference image that is taken on OFF WIND condition, and the other one is test image which is taken on ON WIND, i.e. condition under test flow. If flexible model is employed, a problem on normalization process becomes remarkable. That is, model deformation during test flow causes incongruence of model configuration between reference image and test image, and it designates failure of the normalization scheme.

An improved normalization scheme is now presented to make TSP available on flexible model. In this normalization process, no reference image taken on OFF WIND condition is used but reference image taken on “ON WIND” condition. If reference and test image can be observed simultaneously, model configuration between reference image and test image may also be same, namely normalization becomes possible. In this study, another luminophore is installed to capture the simultaneous reference image. Two kinds of luminophore, one for reference image and the other one for test image, are mixed into single solvent, and sprayed to model surface. These two luminophores are excited by single excitation light, and respective luminescence is emitted from each luminophore. The luminescence is separated by an optical system (explained later), and the individual luminescence is detected simultaneously by single CCD image sensor. Consequently, simultaneous reference image and test image are observed and the normalization procedure becomes possible. Although some previous works also used molecular sensor with two kinds of luminophore, applications to the deforming surface has never been reported.

2.2 Compositions of the paint

Typical TSP consists of luminophore, binder and solvent. Luminophore is the critical part for temperature molecular sensing because it indicates temperature sensitivity. Binder is used to enconce the TSP film to test model surface. In the case of the improved TSP, two different kinds of luminophore are used. In present paper, Fluorescein is employed to obtain reference image and Ruphen is used for test image observation. Ruphen is a kind of Ruthenium complex, and one of typical luminophore of TSP. Polyacrylic acid and ethanol is used as binder and solvent of TSP, respectively. Thickness of TSP coating film is controlled to be about 1 \( \mu \)m.

2.3 Emission spectrum

Emission spectrum of the improved TSP is investigated to estimate suitable optical filters. The emission spectrum is shown in Fig. 1. Two different peaks can be observed. A peak around 505 [nm] indicates the emission of Fluorescein, and the other peak around 570 [nm] denotes the emission of Ruphen. From this investigation, band pass filter (520 ± 18 [nm]) for Fluorescein and long pass filter (580 [nm]) for Ruphen are elected to extract respective emission from luminescence of the improved TSP.
2.4 Calibration and thermal sensitivity
TSP calibration is previously performed to obtain a calibration curve which denotes relation between normalized luminance of TSP luminescence and temperature, namely, thermal sensitivity of TSP. The calibration system is described in Fig. 2. This system consists of chamber, Peltier device, heat sink, spectrometer and the excitation light. A calibration specimen is fixed on surface of the Peltier device, which is made of aluminum plate and its surface is coated by thin white urethane layer. Luminescence of the paint is detected by the spectrometer and respective luminance of Ruphen and Fluorescein are calculated by means of integration of luminance over the wavelength range of each optical filter. Normalized luminance is defined as ratio of the luminance of Ruphen and Fluorescein. The thermal sensitivity of the improved TSP is written as a function of the normalized luminance as shown in eq. (1). Calibration curve obtained in this study is shown in Fig. 3. The improved TSP indicates a thermal sensitivity of approximately 0.8 [%/K].

\[
T = f\left(\frac{I_{\text{Ruphen}}}{I_{\text{Fluorescein}}}\right)
\]  

(1)

2.5 Optical system
The TSP is excited by single blue LED (450±50 [nm]). Emission from TSP is detected by an optical system shown in Fig. 4. Incident light passes Lens 1 at first, and the beam is divided into two orthogonal paths by a beam splitter. After passing through individual optical filter, each beam is reflected by individual mirrors and finally two different beams reach single CCD sensor, i.e. a photograph is obtained that the reference image and test image are horizontally arranged. Thus, the simultaneous information of reference and test image can be observed by use of this system. The exposure time and sampling rate are controlled by high speed camera. In present study, improved TSP images are captured under the conditions of 125 [fps] frame rate and 8.0 [ms] exposure time.

3. Experimental Setup

3.1. Shock tunnel facility
All tests in present study were conducted in the reflected shock tunnel of Nagoya University, which consists of a high pressure (4.0MPa) driver tube, two aluminum diaphragms, a driven tube with atmospheric pressure and damp tank as shown in Fig. 5. All driven and driver gases are air. The diameter of nozzle exit in the test section is 350 [mm] and the core diameter of the test flow is approximately 260 [mm] at 137 [mm] downstream from the nozzle exit. The shock tunnel of Nagoya University can generate a test flow with Mach number 8.1, \(M_\infty = 4.0 \text{ [MPa]}\), \(T_\infty = 900 \text{ [K]}\), \(Re = 6.5 \times 10^6 \text{ [m}^{-1}\)) and a duration 30[ms]. Test flow parameters are shown in Table 1. Reproducibility of the test flow indicates 2.8% dispersion as a standard deviation of total pressure. A trigger signal which is synchronized with the shock tunnel starting, namely rupture of the diaphragms, is generated and inputted to measurement systems.

3.2. Wind tunnel model
Dimensions of the wind tunnel model are shown in Fig. 6. JAXA’s flare-typed membrane aeroshell concept is employed as the wind tunnel test model in present study. The test model consists of hemispheric nose (aluminum, \(R = 5 \text{ [mm]}\)), nylon fabric membrane (60 degree cone) and plastic torus (\(D_{\text{tor}}=80 \text{ mm}, d = 5 \text{ mm}\)). Thickness of the nylon fabric is about 420 [μm]. Fabric membrane consists of eight gores, and these gores are stitched up each other to form the corn. The top of fabric cone is crimped at nose part, and torus is fixed at bottom of cone by sewing on the fabric. On the JAXA’s concept, ZYLON fabric is employed as the membrane to
achieve a thermal tolerance. However, in the present study, the thermal tolerance is not necessary due to short duration of test flow. Therefore, nylon fabric which provides high durability against tear and lower cost than ZYLON is selected. The aluminum nose is coated by white urethane paint to enhance the luminescence reflection from model surface which provides higher SNR on TSP measurements.

Rigid model is also tested to understand surface heat transfer distribution by the effect of aerodynamic heating. Configuration of the rigid model is traced from deformed flexible model which is observed by Schlieren visualization. The rigid model is made of plastic, and coated by white urethane paint. The measurement of surface heat transfer is performed by using conventional TSP, and compared with temperature distribution measured on flexible test model. All of tests are conducted under $\alpha = 0$ [deg] condition.

### 3.3. Conventional Temperature Sensitive Paint

Conventional TSP measurement is conducted to measure surface heat transfer on rigid test model. The conventional TSP consists of Ruphen, polyacrylic acid and ethanol. It is sprayed to model surface by air blush, and thickness of TSP coating film is controlled to be about 1 [μm]. Conventional TSP images are captured with 1000 fps frame rate and 1.0 [ms] exposure time. Surface heat transfer is evaluated as heat flux on the model surface. The heat flux is calculated from surface temperature history by using eq. (2) which is based on the one dimensional heat conduction equation in a semi-infinite medium including a linear approximation proposed by Cook and Felderman. The derivation of eq. (2) is described in Ref. 15.

$$q(t_n) = 2 \sqrt{\frac{pc\kappa}{\pi}} \sum_{i=1}^{n} \frac{T(t_{i-1}) - T(t_{i+1})}{(t_n - t_{i-1})^{1/2} + (t_n - t_{i+1})^{1/2}}$$  (2)

where $\rho$, $c$ and $\kappa$ are the values of material of model surface.

### 3.4. Schlieren visualization

Schlieren visualization is conducted to understand flow topology around test model and model deformation. Schlieren photographs are observed by high speed camera at 3000 [fps] and 50 [μs] exposure.

### 4. Result and Discussion

#### 4.1. Flow field and model deformation

Time evolution of flow field is shown in Fig. 7. Strong bow shock arise upstream test model immediately due to initiation of test flow, and overpressure is caused by bow shock in
region behind the shock. Flexible model is deformed by aerodynamic force and position of torus get to move to further downstream. Fabric membrane on the model is stretched by the aerodynamic effect. Although, after approximately 8 [ms], the deformation is settled, model slightly continues to move.

4.2. Temperature distribution on flexible model

Temperature distributions on flexible surface measured by improved TSP are shown in Fig. 7(a) – (d). The figures of temperature distribution correspond to Schlieren photographs on each time. Figure 7(a) indicates image on OFF WIND condition, and $t = 0$ [ms] is defined at this moment. Photographs of luminescence of TSP emission are taken in every 8.0 [ms]. In comparison of surface temperature, it is clearly distinguished that TSP measurement reflects model deformation. This result indicates that the improved TSP provides a capability to capture the time evolution of model deformation as surface temperature is measured. The configuration of model deformation is consistent with data which are observed by Schlieren visualization.

On the other hand, images of surface temperature distribution show somewhat noisy. Even on the image at $t = 0$ [ms] (at off-wind condition), temperature distribution shows unevenness. This un-uniformity of temperature distribution is based on low SNR on TSP measurement system and chromatic aberration resulted by the optical system. The chromatic aberration leads inadequate congruence of model configuration between reference and test image and it may cause deterioration of measurement accuracy. However, comparing these four temperature data, it can be obviously observed that surface temperature is globally rising in time evolution in terms of qualitative assessment. Furthermore, several patterns of temperature rise are shown on fabric membrane surface in Fig. 8(a).

4.3. Validation of heating patterns

Distribution of surface heat transfer on a rigid model is used to validate the temperature data measured by the improved TSP method. As is mentioned above, the rigid model is configured based on the configuration of deforming model observed by Schlieren visualization. Hence, surface heating patterns between flexible and rigid model should agree qualitatively. Heat transfer rate on rigid model is calculated with thermal properties of polyurethane resin (PUR) 17), i.e. $\rho = 1.3\times10^3$ [kg m$^{-3}$], $c = 1.65\times10^3$ [J kg$^{-1}$ K$^{-1}$] and $k = 0.21$ [W m$^{-1}$ K$^{-1}$]. The distribution is described in Fig. 8(c). This result suggests that heating patterns on this configuration can be distinguished three regions, namely Region A, B, and C. Region A lies immediate downstream the nose part with drastically high heat transfer rate. This is assumed to be induced by impingement of a stream separated at nose part. Farther downstream, heat transfer is reduced in Region B. Subsequently, heat transfer increases again in Region C that locates in the vicinity of the trailing edge. The enhanced surface heating in Region C is consistent with published data that is obtained from investigations on similar configuration model.16)

In terms of temperature distribution by the improved TSP, it indicates two types of temperature pattern, namely, the pattern influenced by seams and the one by real temperature rise. The former is revealed in comparison with raw test image, i.e. the distribution of seams on fabric membrane is consistent with some patterns on the temperature rise (see Fig. 8 (a) and (b)). It seems that the overestimation of temperature at the seams is caused by an error due to low SNR on the optical measurement. The gores are stitched up on the backside of the membrane. Thus, trough structures appear on the measurement surface at the seams and the luminescence of TSP is reduced at this site because reflection of TSP luminescence from the trough is less than flat surface. On the trough regions, SNR is reduced by 85% comparing to it on flat fabric surface. By contrast, the latter is induced by real temperature rise. This is validated in the comparison with heat transfer distribution on the rigid model, that is, temperature pattern near the torus in Fig. 8 (a) shows

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**Fig. 8.** Comparison between temperature rise on flexible model and surface heat transfer rate on rigid model.
similar distribution to heat transfer pattern on Region C on the rigid model shown in Fig. 8 (c). From this comparison, it is confirmed that the improved TSP method provides good capability to measure qualitative temperature distribution on flexible and deforming surface.

4.4. Quantitativity of the temperature measurement

Temperature rise on nylon fabric surface is roughly estimated from the heat transfer rate measured on rigid model to evaluate the validity of the improved TSP measurement. The estimation is performed in the region marked with a circle in Fig. 8 (a) and (c). Although surface heat transfer on isothermal wall does not depend on the wall material, in reality, it is affected by thermal property of the wall material, namely thermal effusivity $\sqrt{\frac{ck}{\rho}}$. Surface temperature change under a boundary condition of constant surface heat flux on semi-infinite wall can be given by eq. (3).18)

$$T_s(t) = T_i + \frac{2q_i\sqrt{\frac{\rho}{\pi}}}{\sqrt{\pi} \sqrt{\frac{ck}{\rho}}}$$

Surface temperature on nylon fabric is estimated by eq. (3) under the three assumptions shown below.

Assumptions
i) 6-Nylon resin is assumed in terms of temperature calculation, though actual test model is made of nylon fabric.
ii) Initial temperature $T_i$ is assumed $T_i = 20.0 \ [^\circ C]$ at $t = 0 \ [ms]$.
iii) Surface heat transfer rate on nylon fabric is assumed as $\dot{q}_\text{nylon} = \dot{q}_\text{rigid} = 13.6 \ [W/cm^2]$ which is measured in the circled region on the rigid model.

Thermal properties of 6-Nylon resin are provided by NIMS database ‘PolyInfo’19). Median values in the database are employed in this study, i.e. $\rho = 1140 \ [kg/m^3]$, $c = 1716 \ [J/kg^\circ K]$ and $k = 0.26 \ [W/m^\circ K]$. A result of the estimation is shown in Fig. 9. The estimated surface temperature on nylon fabric is $T = 56.8 \ [^\circ C]$ at $t = 30 \ [ms]$. This value indicates that temperature measurement by the improved TSP is quantitatively reasonable.

5. Conclusion

Temperature measurement on flexible and deforming aero-shell model was performed by using an improved Temperature Sensitive Paint. Two kinds of luminophore, which are used to obtain a test image and a reference image simultaneously, were employed to make TSP possible to apply to flexible and deforming surface. Temperature distribution captured by the TSP on the flexible model indicated local temperature rise due to aerodynamic heating by hypersonic test flow, and the distribution is qualitatively consistent with the result which is measured on rigid model by conventional TSP. Furthermore, the improved TSP method successfully showed a good capability to follow the model deformation on measurement of temperature distribution. The achievement of capability for simultaneous observation of temperature distribution and model deformation is a great advance in the development of this method. Further improvement aiming to accurate assessment of temperature distribution on deforming model is expected to be achieved by reducing the effect of chromatic aberration and enhancing SNR of the measurement system.

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References