Development of a Shock Tube Facility for Nonequilibrium Radiation Studies in Mars Entry Flight Conditions*

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Abstract
The purpose of the present study is to develop a shock tube facility for nonequilibrium radiation studies in Mars entry flight conditions. For the purpose, characteristic investigations and radiation measurements are conducted using the newly developed shock tube facility. In the characteristic investigations, compression process is analyzed by compression tests and numerical analysis to decide the optimum operating condition. Shock velocity at the test section is measured and compared with actual flight data to examine the performance of the facility. In radiation measurements, shock front radiation is measured using the newly developed multipoint spectroscopic measurement system. As a result, the optimum operating condition to achieve soft landing operation is obtained. From the shock velocity measurements, it is found that the shock tube can simulate typical Mars entry flight conditions. The multipoint spectroscopic measurement system enables us to observe a spatial profile of emission spectrum with high accuracy. In conclusion, the newly developed shock tube facility can be used for nonequilibrium radiation studies in Mars entry flight conditions.

Key words: Shock Tube, Mars Entry, Nonequilibrium Radiation, Spectroscopy, Piston Motion, Free Piston Driver

1. Introduction
Recently, many planetary explorations have been proposed as future space missions around the world. In these missions, Mars exploration has gained attention and extensive works have been conducted\(^{(1)-(3)}\). For example, NASA is now conducting Mars Science Laboratory (MSL) aiming at the manned flight to Mars in 2030’s\(^{(4)}\). In Japan, MELOS-1 will be planned in 2018\(^{(5)}\). In these missions, atmospheric entry flight is a key technology for the success of missions. When space vehicles enter the planetary atmosphere, a shock wave is formed around space vehicles, resulting in the severe aerodynamic heating. Therefore, a reliable thermal protection system (TPS) is required to protect space vehicles from the severe heat load. Nonequilibrium processes of thermal relaxation, dissociation and recombination reactions around space vehicles affect the heating environments. For the development of TPS, one must predict the thermochemical nonequilibrium processes accurately. The prediction of the thermochemical nonequilibrium processes has been carried out based on the computational fluid dynamics (CFD) simulation. The accuracy of the prediction highly depends on the thermochemical model used in the simulation. The validation and improvement of the model are required by the ground testing simulating
atmospheric entry flight conditions.

A shock tube has been used as a ground testing facility for the validation of thermochemical models. In recent studies, Yamada et al.\(^ {6,7}\) conducted a number of spectroscopic measurements using a shock tube to observe nonequilibrium radiation. In these studies, the thermochemical model for Earth entry flights was validated using the measured data. Park et al.\(^ {8}\) developed the thermochemical model for Mars entry flights from investigations about the thermochemical processes in Mars entry flight conditions. However, the model has not been validated adequately because there are few experimental data in Mars entry flight conditions. Furthermore, the deviation of measured data is too large in shock tube experiments, especially for the measurement of a spatial profile of emission spectra because conventional measurement systems need many numbers of measurements\(^ {9}\). Therefore, one must develop a new measurement system to observe a spatial profile of emission spectra with high accuracy.

The purpose of the present study is to develop a shock tube facility for nonequilibrium radiation studies in Mars entry flight conditions. In this study, characteristic investigations and radiation measurements are conducted using the newly developed shock tube facility. In the characteristic investigations, first, the piston motion in a free piston driver is analyzed to decide the optimum operating condition. Second, shock velocity at the test section is measured and compared with actual flight data to examine the performance of the shock tube. In radiation measurements, shock front radiation is measured using the newly developed multipoint spectroscopic measurement system to examine its validity.

In chapter 2, we describe the detail of the shock tube facility and the multipoint spectroscopic measurement system. In chapter 3, we describe the numerical method to analyze the piston motion in the free piston driver. In chapter 4, we present the results for characteristic investigations and radiation measurements. Finally, we make a conclusion of the present study.

**Nomenclature**

- \(A\) cross sectional area
- \(a\) sound speed
- \(d_c\) diameter of the compression tube
- \(d_d\) diameter of diaphragm
- \(d_r\) instantaneous internal diameter of partially opened diaphragm
- \(L_c\) length of the compression tube
- \(M_p\) piston mass
- \(m_c\) mass of the driver gas
- \(m_t\) mass of the driver gas at the moment of diaphragm rupture
- \(n_c\) polytropic index
- \(p_c\) pressure in front of a free piston
- \(p_R\) pressure behind a free piston
- \(t\) time
- \(t_d\) diaphragm thickness at the scratch
- \(t_{op}\) diaphragm opening time
- \(u_p\) piston speed
- \(u_r\) piston speed at the moment of diaphragm rupture
- \(x\) distance from the compression tube end
- \(\gamma_R\) specific heat ratio of the reservoir gas
- \(\mu\) dimensionless mass of the driver gas
- \(\rho\) density of the driver gas
- \(\xi\) dimensionless position of a free piston
- \(\tau\) dimensionless time
2. Experimental Setup

2.1 Shock tube facility

The shock tube facility developed in this study is a free-piston driven shock tube. Figure 1 shows a schematic drawing of the shock tube. Figure 2 shows a picture of the shock tube. The shock tube consists of a reservoir, compression tube, low pressure tube, vacuum tank, and a free piston driving in the compression tube. The dimensions of constituents are shown in Table 1. To protect the facility from the impact produced by the piston operation, the facility is located on movable mounts and connected to the vacuum tank by a bellows tube. The reservoir is filled with nitrogen from a high pressure bomb. The high pressure nitrogen drives the free piston by opening a quick-action valve inside the reservoir. The free piston adiabatically compresses helium gas toward high pressure and high temperature at the end of the compression tube. Figure 3 shows a picture of the free piston. Piston rings made of polytetrafluoroethylene (PTEF) are attached to reduce the friction coefficient between the surface of the piston and the inner wall of the compression tube. The steel diaphragm at the boundary between the compression tube and low pressure tube is ruptured by compressed helium. Figure 4 shows a picture of the diaphragm before and after rupture. The diaphragm has a cross-shape scratch on the surface and the rupture pressure is controlled by the diaphragm thickness and the depth of the scratch. Finally, a strong shock wave is generated in the low pressure tube. The low pressure tube with 44 mm square cross-section is made of aluminum alloy because a shock tube made of stainless steel produces a considerable amount of impurity in the test section, consisting mostly of iron which emits strong radiation\(^{(10)}\). The test section is located at the position of 2300 mm from the diaphragm. This position is determined by considering that the formation distance of the plane shock wave is about 40 times tube diameter\(^{(11)}\). Quartz windows for radiation measurements are mounted on both sides of the test section wall. The compression tube and low pressure tube are evacuated to the pressure of 3.0 Pa using a roots pump (EDWARDS, QMB500) backed up by an oil rotary pump (EDWARDS, E2M80) before filling a test gas. A pressure transducer (KYOWA, PGM-500KD) is mounted at the end of the compression tube to measure the pressure of compressed helium. The signal of the pressure transducer is monitored by a digital oscilloscope (Iwatsu, DS-8608).

| Name           | Cross-section | Size            | Material      |
|----------------|---------------|-----------------|---------------|
| Reservoir      | Round         | Volume 0.0158 m\(^3\) | SUS304        |
| Compression tube | Round          | \(\phi 50 \times 2350 \text{ mm}\) | STKM13A       |
| Low pressure tube | Square         | \(44 \times 44 \times 2500 \text{ mm}\) | A6063         |
| Vacuum tank    | Round         | Volume 2 m\(^3\) | SUS304        |
| Free piston    | Round         | \(\phi 49.7 \times 80 \text{ mm}\) | SUS304        |
Fig. 1 A schematic drawing of the shock tube facility

Fig. 2 A picture of the shock tube facility

Fig. 3 A picture of the free piston

Fig. 4 A picture of the metal diaphragm
2.2 Optical measurement system

Figure 5 shows a schematic drawing of the optical measurement system at the test section. The shock velocity at the test section is measured using two laser beams. The laser beams are aligned along the flow direction to pass through the test section perpendicularly to the axis of the shock-tube flow. The optical path is adjusted to arrive at separate avalanche photodiodes (APD) using flat mirrors. Deflection of the laser beams as a result of a density gradient at the shock front causes a change in the output signals of avalanche photodiodes. The shock velocity at the test section can be obtained from the beam distance and time difference of the output changes.

A multipoint spectroscopic measurement system with short test duration is newly developed to improve the accuracy of the measured data based on our previous work\(^{(12)}\). The measurement system consists of a quartz convex lens, a fiber alley, an imaging spectrometer (Andor, SR303i) and an image intensified CCD (ICCD) camera (Andor, DH334-18U-03). Figure 6 shows a detail of the multipoint spectroscopic measurement system. The radiation along the central axis is focused on the collecting area of the fiber alley. Ten fiber elements are aligned at 1.0 mm intervals on the collecting area. Therefore, the fiber alley enables us to measure the radiation from ten positions at 1.0 mm intervals along the central axis at a time. The radiation collected by the fiber alley is dispersed into its spectral components by the spectrometer which generates a two-dimensional image (spectrum position along the central axis in one dimension and wavelength in the other dimension) on the photosensitive surface of the ICCD camera attached to the spectrometer. The total radiation intensity is measured by the APD placed on the other side of the spectrometer and its output signal is used to trigger the ICCD camera. The outputs of the laser beams and the total radiation intensity are monitored by a digital oscilloscope (Agilent Technologies, DSOX2024A).
2.3 Determination of spectrum position from shock front

Figure 7 shows the detail position among laser beams, measurement points and shock front. Radiation measurements are conducted after shock front passes through the upstream laser beam. The arrival of the shock front can be detected by the output change of the upstream laser beam. The trigger timing of the ICCD camera is controlled by the delay time using the delay pulse generator inside the camera based on the output change. The position of the upstream laser beam from shock front, $L_1 + L_2$, can be obtained by multiplying the measured shock velocity, $V_{sh}$, by the delay time from the shock arrival, $\Delta T$ as

$$L_1 + L_2 = V_{sh} \times \Delta T \quad (1)$$

The position of the upstream measurement point from shock front, $L_1$, can be obtained by

$$L_1 = V_{sh} \times \Delta T - L_2 \quad (2)$$

Finally, ten spectrum positions from shock front can be obtained because the measurement points are equally spaced at 1.0 mm intervals.

3. Numerical analysis

In order to investigate characteristics of a free piston driver, a numerical analysis is conducted under the following assumption:

(1) flows on both sides of the piston are quasi-one-dimensional;
(2) flow ahead of the piston is polytropic and quasi-steady process $^{(13)}$;
(3) flow behind the piston is adiabatic and forms an unsteady expansion $^{(13), (14)}$. 
friction and leakage between the piston and compression tube inner-wall surface are negligible.

In this analysis, the loss in the gas behind the piston is assumed to be pressure loss at the quick-action valve in the reservoir and represented by the following equation.

$$p_{R0} = \psi p'_{R0}$$

(3)

where $p'_{R0}$ is the initial pressure in the reservoir without pressure loss. $p_{R0}$ is the initial pressure in the reservoir with pressure loss. The loss in front of the piston is represented by the polytropic process. The polytropic index depends on the magnitude of heat loss in individual facilities and can be determined from the comparison between numerical and experimental results. Figure 8 shows a numerical model of the piston motion. The piston motion is described by the following equation of motion.

$$-M_p \frac{d^2 x}{dt^2} = \frac{\pi d^2}{4} (p_R - p_c)$$

(4)

In the following sections, the piston motions before and after diaphragm rupture are separately described.

3.1 Piston motion before diaphragm rupture

Before diaphragm rupture, pressures ahead and behind of the piston are represented as

$$p_c = p_{c0} \left( \frac{L_c}{x} \right)^{n_c}$$

(5)

$$p_R = p_{R0} \left( 1 - \frac{\gamma_R - 1}{2} \frac{u_p}{a_{R0}} \right)^{\frac{2\gamma_s}{\gamma - 1}}$$

(6)

Substituting Eqs. (5) and (6) into Eq. (4) gives the following equation.

$$-M_p \frac{d^2 x}{dt^2} = \frac{\pi d^2}{4} \left[ p_{R0} \left( 1 - \frac{\gamma_R - 1}{2} \frac{u_p}{a_{R0}} \right)^{\frac{2\gamma_s}{\gamma - 1}} - p_{c0} \left( \frac{L_c}{x} \right)^{n_c} \right]$$

(7)

Initial conditions are $x = L_c$ and $du/dx = 0$ at $t = 0$. Following Hornung(15), dimensionless variables for the piston position, piston velocity and time are represented by

$$\xi(t) = \frac{x}{d_c}$$

(8)

$$\phi(t) = \frac{u_p}{a_{R0}}$$

(9)

$$\tau = t \frac{a_{R0}}{d_c}$$

(10)

Equation (7) is transformed using these dimensionless variables and represented by

$$\ddot{\xi} = -\phi$$

(11)

$$\phi' = C_1 \left[ 1 - \frac{\gamma_R - 1}{2} \phi^{\frac{2\gamma_s}{\gamma - 1}} \right] - C_2 \phi^{-n_c}$$

(12)
\[ C_1 = \frac{\pi d_c^3 p_{R0}}{4 M_\rho d_{R0}^2} \] (13)

\[ C_2 = \frac{p_{C0}}{p_{R0}} \left( \frac{L_c}{d_c} \right)^{\gamma_n} \] (14)

where \( \cdot \) denotes differentiation with respect to \( \tau \). Initial conditions are written by

\[ \xi(0) = \frac{L_c}{d_c} \] (15)

\[ \phi(0) = 0 \] (16)

### 3.2 Diaphragm opening process

Outa et al.\(^{16}\) proposed the model of diaphragm opening process. The opening process is assumed to be two-dimensional in the model. A time dependent ruptured diameter of the diaphragm is described by

\[ \frac{d_r^2}{d_d^2} = 1 - \cos \left( \frac{\pi}{2} \left( \frac{t}{t_{op}} \right)^2 \right), \quad t_r \leq t \leq t_{r} + t_{op} \] (17)

where \( t_r \) is the time when the diaphragm starts rupturing. The diaphragm opening time is estimated by parametric comparisons of numerical results with experimental ones. In this study, \( d_d \) is calculated so that the circle-shape cross-sectional area equals to the square-shape cross-sectional area because the diaphragm has a square shape.

### 3.3 Piston motion after diaphragm rupture

After diaphragm rupture the mass flow rate to downstream increases as the opening area of diaphragm increases. The gas in the compression tube has a high ratio of specific heat and the temperature is high at the moment of diaphragm rupture. As a result, the sound speed of the driver gas becomes very large compared to the piston speed. Therefore, compressed driver gas is assumed to be choked instantaneously accordance with the change of ruptured diameter of the diaphragm. The mass flow rate is described by

\[ \frac{dm_t}{dt} = -\rho_s a_s A_s \] (18)

\[ A_s = \frac{\pi}{4} d_r^2 \] (19)

where \( \rho_s, a_s \) are density and the sound speed under the sonic condition. Compressed driver gas is assumed to be expanded to the sonic condition in a polytropic process. The pressure ahead of the piston is described by

\[ \frac{p_{c}}{p_r} = \left( \frac{p_{c}}{p_r} \right)^{\gamma_n} = \left( \frac{m_s}{m_r} \right)^{\gamma_n} \left( \frac{x_s}{m_r} \right)^{\gamma_n} \] (20)

The equation of piston motion is described by
\[-M_p \frac{d^2 x}{dt^2} = \frac{\pi d^2}{4} (p_R - p_c)\]
\[= \frac{\pi d^2}{4} \left[ p_{R0} \left(1 - \frac{\gamma R - 1}{2} \frac{u_{c}}{a_{R0}} \right)^{\frac{2}{\gamma R - 1} - 1} - p_c \left( \frac{m_c}{x} \right)^{\frac{n_c}{n_c}} \right] \tag{21}\]

A dimensionless variable with respect to the mass of the driver gas is defined as
\[\mu = \frac{m_c}{m_r} \tag{22}\]

Introducing the dimensionless variables, the equation of motion is reduced to the dimensionless system of equations and given by
\[\ddot{x} = -\phi \tag{23}\]
\[\phi' = C_1 \left[1 - \frac{\gamma R - 1}{2} \phi \left( \frac{\mu}{x} \right)^{\frac{n_c}{n_c}} - C_2 \left( \frac{\mu}{x} \right)^{\frac{n_c - 1}{2}} \right] \tag{24}\]
\[\mu' = -C_3 \left( \frac{\mu}{x} \right)^{\frac{n_c - 1}{2}} \tag{25}\]
\[C_3 = \left(2^{\frac{n_c - 1}{n_c + 1}} \right) \frac{a_{c0}}{a_{R0}} \left( \frac{d_c}{d_c} \right)^{\frac{2}{n_c}} \left( L_c \right)^{\frac{n_c - 1}{2}} \tag{26}\]

Initial conditions are represented by
\[\xi(\tau_r) = \frac{x_r}{d_c} \tag{27}\]
\[\phi(\tau_r) = \frac{u_r}{a_{R0}} \tag{28}\]
\[\mu(\tau_r) = 1 \tag{29}\]

The piston motions before and after diaphragm rupture can be calculated by solving the differential systems of equations. The 4th-order Runge-Kutta method is used to solve the equations in this study.

![Fig.8 Numerical model of piston motion](image)

4. Results and Discussion

4.1 Compression characteristics in the compression tube

In order to investigate compression characteristics in the compression tube, compression tests are conducted in various operating conditions of $p_{R0}$ and $p_{c0}$. Figures 9 and 10...
show pressure profiles without and with diaphragm rupture, respectively. Operating conditions of $p_{R0}$, $p_{c0}$ and diaphragm thickness at the scratch, $t_d$ are shown in these figures. In Fig. 9, pressure increases up to the peak value and then decreases gradually. Times for the pressure increase and decrease are almost same. On the other hand, in Fig. 10, pressure increases up to the peak value and decreases rapidly at the moment of diaphragm rupture. The peak value is the rupture pressure of the diaphragm. Figure 11 shows the rupture pressure as a function of the diaphragm thickness at the scratch. The rupture pressure increases linearly with increasing the diaphragm thickness at the scratch.

Fig.9 Pressure profiles in the compression tube without diaphragm rupture

Fig.10 Pressure profiles in the compression tube with diaphragm rupture

Fig.11 Relationship between rupture pressure and diaphragm thickness at the scratch
4.2 Optimum operating condition

Figure 12 shows the comparison between measured and calculated pressure profiles without diaphragm rupture. Piston velocity is also shown as a blue dashed line. In this case, \( p_{R0} \) and \( p_{c0} \) are 800 kPa and 40 kPa, respectively. And \( t_d \) is 1.3 mm. Pressure loss and polytropic index are estimated as 0.634 and 1.40, respectively. These values are determined from parametric comparisons between measured and calculated pressure profiles. The calculated pressure profile agrees well with the measured pressure profile. The piston decelerates with increasing pressure and stops at the peak pressure. After the peak pressure, the piston accelerates with decreasing pressure and moves away from the compression tube end. From this result, the pressure and piston motion in the compression tube can be predicted by the present numerical analysis.

Figures 13 and 14 show pressure profiles with diaphragm rupture in two operating conditions. In case 1, \( p_{R0} \) and \( p_{c0} \) are 900 kPa and 35 kPa, respectively. In case 2, \( p_{R0} \) and \( p_{c0} \) are 950 kPa and 35 kPa, respectively. In both cases, \( t_d \) is 1.3 mm. Red and blue dashed lines are calculated pressure and piston velocity, respectively. Diaphragm opening time of \( t_{op} \) is determined from parametric comparisons between calculated and measured pressure profiles. As a result, good agreement can be obtained for the diaphragm opening time of \( t_{op} = 60 \mu s \), except the peak values. The difference of peak values between calculated and measured pressure profiles can be caused by the irregularity of diaphragm rupture. In case 1, a piston damper at the compression tube end is not damaged because a free piston stops softly at the piston damper after diaphragm rupture. In case 2, however, a piston damper is damaged because a free piston crashes into the piston damper after diaphragm rupture. At the moment of diaphragm rupture, the piston velocity in case 2 is higher than that in case 1. Therefore, a piston damper is damaged in case 2. To avoid the damage of the piston damper, we should use optimum operating conditions.

To find optimum operating conditions, a numerical analysis is conducted for various operating conditions of \( p_{R0} \) and \( p_{c0} \). Table 2 shows the calculation conditions. Figure 15 shows characteristics of piston motion around the compression tube end. Case 1 and case 2 are corresponding to the conditions in Figs. 13 and 14. Piston motions depending on operating conditions are classified into three regimes, which are (1) rebound impact, (2) soft landing, and (3) direct impact. In case 2, the piston impacts on the compression tube end with a high velocity over 15 m/s after diaphragm rupture, damaging the piston damper. This condition is the direct impact. In case 1, the piston impacts on the compression tube end with a low velocity under 10 m/s after diaphragm rupture, not damaging the piston damper. This condition is the nearly soft landing. In case 3, zero piston velocity can be obtained after diaphragm rupture. This condition is the soft landing. If we set a piston damper at the position with zero velocity, the soft landing operation can be achieved. In case 4, the piston rebounds and re-accelerates after diaphragm rupture. This condition is the rebound impact. In this condition, the piston velocity at the diaphragm rupture is a minimum. However, the piston impacts on the compression tube end with a high velocity, because of the piston re-acceleration after rebound. From this result, it is found that we should use the operating condition of case 3 to achieve the soft landing operation. This is the optimum operating condition for the operation using the diaphragm of \( t_d = 1.3 \) mm. The present numerical analysis enables us to find soft landing operations for each diaphragm.
Fig. 12 Comparison of pressure profiles without diaphragm rupture

Fig. 13 Comparison of pressure profiles with diaphragm rupture in case 1

Fig. 14 Comparison of pressure profiles with diaphragm rupture in case 2
Table 2. Calculation conditions

| Case | $P_{R0}$, kPa | $P_{c0}$, kPa | $t_{op}$, $\mu$s | Piston motion          |
|------|---------------|---------------|------------------|------------------------|
| 1    | 900           | 35            | 60               | Nearly soft landing    |
| 2    | 950           | 35            | 60               | Direct impact          |
| 3    | 870           | 35            | 60               | Soft landing           |
| 4    | 867           | 35            | 60               | Rebound impact         |

4.2 Shock velocity measurement

To investigate the performance of the shock tube, the shock velocity at the test section is measured using CO$_2$ as a test gas. In the measurement, $P_{R0}$ and $P_{c0}$ are 950 kPa and 50 kPa for the diaphragm of $t_d = 0.9$ mm. $P_{R0}$ and $P_{c0}$ are 750 kPa and 50 kPa for the diaphragm of $t_d = 0.7$ mm. Test gas pressure is varied ranging from 30 to 200 Pa. Figure 16 shows the measured shock velocity as a function of test gas pressure. In this figure, the flight environments of Pathfinder and Phenix are shown for comparison. When the diaphragms of $t_d = 0.9$ mm are used, the measured shock velocities are higher than the flight conditions of Pathfinder and Phenix. On the other hand, when the diaphragms of $t_d = 0.7$ mm are used, the measured shock velocities in lower test gas pressure ranges are close to the flight conditions of Pathfinder and Phenix, covering the typical Mars entry flight conditions. From the result, the shock tube can simulate Mars entry flight conditions.
4.3 Radiation measurements

Shock front radiation is measured using the newly developed multipoint spectroscopic measurement system in CO$_2$-N$_2$ test gas simulating a Martian-like atmosphere. In this measurement, test gas pressure is 100 Pa and shock velocity is 5.26 km/s. The gate time of the ICCD camera is 200 ns. The spectrometer setting with a 300 grooves/mm and 500 μm slit width is used. Figure 17 shows a spectrum image obtained by ICCD camera. The image provides intensity of the emission for a range of wavelengths with distance along the shock tube axis. Emission spectra are extracted from the image and the measured intensity is calibrated into relative intensity using a quartz tungsten halogen lamp (Newport, 63355). Figure 18 shows a spatial profile of the emission spectra correlated to the distance from shock front, $L$. In the spectra, CN violet bands are predominant and the sequence of $\Delta v = 0$ is much stronger than those of $\Delta v = -1$ and 1. Radiation intensity rapidly increases and reaches the peak value immediately behind shock front. The spatial error is ±0.53 mm in this case because the shock velocity is 5.26 km/s and the gate time of the ICCD camera is 200 ns. We have successfully obtained the time-frozen spectrum and intensity variation within the spatial error of ±0.53 mm using the multipoint spectroscopic measurement system. This data is useful to clarify the nonequilibrium radiation phenomena behind a shock wave.

![Figure 17 Spectrum image obtained by ICCD camera](image17.png)

![Figure 18 Spatial variation of emission spectra correlated with shock front](image18.png)
5. Conclusion

We have developed a shock tube facility for nonequilibrium radiation studies in Mars entry flight conditions. Characteristic investigations and radiation measurements were conducted to examine the validity of the shock tube facility. In characteristic investigations, first, the piston motion in the free piston driver was analyzed by compression tests and numerical analysis to decide optimum operating conditions to achieve soft landing operation. Second, the shock velocity at the test section was measured in various test conditions and results were compared with actual flight data. In radiation measurements, shock front radiation was measured using the newly developed multipoint spectroscopic measurement system to examine the validity of the system. As a result, the optimum operating condition to achieve soft landing operation is obtained. From the shock velocity measurements, it is found that the shock tube can simulate typical Mars entry flight conditions. The multipoint spectroscopic measurement system enables us to observe a spatial profile of emission spectrum with high accuracy.

In conclusion, the newly developed shock tube facility can be used for nonequilibrium radiation studies in Mars entry flight conditions.

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