Nonequilibrium shock layer in large-scale arc-heated wind tunnel

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Received 10 December 2021, revised 6 February 2022
Accepted for publication 1 March 2022
Published 14 March 2022

Abstract
An arc-heated wind tunnel is one of the most important facilities to reproduce the high-temperature environment during atmospheric entry for plasma studies and spacecraft development. However, the properties of the plasma flow cannot be determined easily, because of the complex physical phenomena, such as arc discharge and supersonic expansion, occurring inside the tunnel. The shock-layer structure should be clarified to evaluate the aerodynamic characteristics, communication conditions, and thermal-protection performance in a high-temperature environment. In this study, shock-layer spectroscopic measurements of a plasma flow in a 1 MW-class arc-heated wind tunnel were performed. The $\gamma$-band system spectra of nitric oxide (NO) molecules in the ultraviolet region were measured, and the rotational temperature was determined via spectral fitting through comparison with numerical spectra. The rotational temperature of the NO molecules in the shock layer was 6620 ± 350 K, whereas that in the free jet was much lower at 770 ± 60 K. This difference is attributed to the increase in translational temperature by flow stagnation across the shock wave, followed by the increase in rotational temperature owing to energy relaxation. A computational science approach revealed the detailed structure of the flow through comparisons with the spectroscopic measurement data. The wind tunnel flow became hypersonic with high temperature and low pressure due to the expansion and acceleration at the nozzle and test chamber. Although the temperature increased across the shock wave, the chemical reaction progressed slowly owing to the low-pressure environment. The rotational temperature in the shock layer increased with the translational temperature; this agrees with the trend of the measurement results. The arc-heated flow was found to be in strong thermochemical nonequilibrium in the shock layer. Through this study, a detailed structure of arc-heated flow was revealed and its methodology was also proposed.

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Keywords: aerodynamic heating, reentry plasma, thermochemical nonequilibrium, spectroscopic measurement, computational science approach

(Some figures may appear in colour only in the online journal)

**Nomenclature**

- \( D \): effective diffusion coefficient, \( \text{m}^2\text{s}^{-1} \)
- \( E \): internal energy, \( \text{J m}^{-3} \)
- \( F \): flux vector
- \( h \): enthalpy, \( \text{J kg}^{-1} \)
- \( \Delta h^0 \): enthalpy of formation, \( \text{J kg}^{-1} \)
- \( H \): enthalpy flux transported by diffusion, \( \text{J (m}^2\text{s})^{-1} \)
- \( J \): diffusion flux, \( \text{kg (m}^2\text{s})^{-1} \)
- \( n_m \): number of molecules
- \( n_s \): number of chemical species
- \( p \): pressure, \( \text{Pa} \)
- \( q \): heat flux, \( \text{W m}^{-2} \)
- \( Q \): conservative variable vector
- \( R \): gas constant, \( \text{J (kg K)}^{-1} \)
- \( S \): area, \( \text{m}^2 \)
- \( S_{\text{int}} \): internal energy exchange rate, \( \text{W m}^{-2} \)
- \( t \): time, \( \text{s} \)
- \( T \): temperature, \( \text{K} \)
- \( u \): velocity, \( \text{m s}^{-1} \)
- \( V \): volume, \( \text{m}^3 \)
- \( W \): source term vector
- \( x \): coordinate, \( \text{m} \)
- \( \chi \): mole fraction
- \( \dot{\psi} \): mass production rate, \( \text{kg (m}^3\text{s})^{-1} \)
- \( \delta_{ij} \): Kronecker delta
- \( \Theta_{\text{vib}} \): vibrational characteristic temperature, \( \text{K} \)
- \( \lambda \): thermal conductivity, \( \text{W (K m)}^{-1} \)
- \( \mu \): molecular viscosity, \( \text{N s m}^{-2} \)
- \( \rho \): density, \( \text{kg m}^{-3} \)
- \( \tau_{ij} \): viscous stress tensor, \( \text{N m}^{-2} \)

**Subscripts**

- \( \text{ele} \): electron
- \( \text{free} \): free jet
- \( \text{rot} \): rotation
- \( s \): species
- \( \text{shock} \): shock layer
- \( \text{trs} \): translation
- \( \nu \): viscous
- \( \text{vib} \): vibration

1. **Introduction**

Atmospheric entry vehicles face various risks when entering the atmosphere at orbital velocities. A strong shock wave is formed in front of the vehicle, and a high-temperature plasma is produced; this results in aerodynamic heating [1–3] behind the shock wave, which causes thermal damage to the vehicle as well as a communication blackout [4–6]. This aerodynamic heating is a critical factor in the design and development of atmospheric entry vehicles. A suitable thermal protection system (TPS) should be designed to protect the vehicle from heating and enable successful atmospheric entry. Examples of TPSs include ablators, heat-resistant tiles, ballutes, flexible structural aeroshells, and electromagnetic shields.

For the design and development of a TPS, the atmospheric entry environment should be reproduced on the ground. One method for accomplishing this is to use an arc-heated wind tunnel, a high-enthalpy wind tunnel in which an arc discharge heats the input gas to produce a supersonic plasma flow through a de Laval nozzle (i.e. convergence-divergence nozzle). Arc-heated wind tunnels with different discharge styles, operating conditions, and power inputs are available. Such tunnels can be used to perform tests lasting from several minutes to several hours.

Complex phenomena, such as arc discharge and supersonic expansion, occur inside arc-heated wind tunnels. The physics of the processes can be easily comprehended; however, the details vary significantly from one facility to another. In particular, high-enthalpy flow through a nozzle results in thermochemical nonequilibrium, whereby measurements of the arc-heated flow become difficult. In light of this, various studies have been conducted to determine the characteristics of arc-heated flows.

The impact pressure and heat flux of arc-heated flows have been measured using Pitot probes and Gardon gauges [7], respectively. Several approaches have been proposed for determining the flow enthalpy [8, 9]. Emission spectroscopy [10], laser-induced fluorescence (LIF) [11, 12], and cavity-enhanced absorption spectroscopy [13] have been used to investigate such flows. In some studies, spectroscopic measurements of heated areas have been performed [14, 15]. Zander et al [16] used the Fabry–Perot spectroscopic technique to measure the translational temperature and velocity. Gülhan et al [17] used various measurement methods, such as coherent anti-Stokes Raman scattering, LIF, and microwave interferometry, at the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR) plasma wind tunnels. Steffens et al [18] used a Langmuir probe, microwave interferometry, and microwave plasma transmission spectroscopy to determine the electron number density. Löhle et al [19] developed a new probe for performing enthalpy measurements. Hermann et al [20] used spectroscopic methods to determine the local enthalpy of a plasma flow.

Studies have also reproduced arc-heated flow through numerical analyses [21]. For example, numerical simulations of a 20 MW aerodynamic heating facility and 60 MW interaction heating facility have been conducted [22–24]. Sahai et al [25] numerically investigated a three-dimensional unsteady arc-heated flow. Takahashi et al [26–29] conducted plasma flow analyses of a 20 kW constrictor-type Japan Aerospace Exploration Agency (JAXA) arc-heated wind tunnel and a
DLR arc-heated wind tunnel. These studies revealed the importance of turbulence and radiative heat transport in the heating section, as well as of thermochemical nonequilibrium in the nozzle and test chamber regions. Katsurayama and Abe [30] and Yu et al [31] validated a highly accurate model of transport coefficients. Heat-transfer coupling analysis in the arc-discharge field and inside electrodes [32] have been performed as well.

The characteristics of the arc-heated flow have been investigated using various measurement methods. However, although the plasma flow is affected by many parameters, such as temperature, velocity, and species mole fractions, only a few parameters can be investigated in a single experiment owing to the difficulty of the measurement. The numerical-analysis approach can obtain comprehensive flow parameters by solving the governing equations, whereas the prediction performance is always subject to the model uncertainty. In particular, the nonequilibrium of arc-heated flows and atmospheric-entry plasmas makes these trends more pronounced. Therefore, it is essential to formulate, validate, and discuss the measurement and evaluation approaches for nonequilibrium.

An arc-heated flow that expands and accelerates through a de Laval nozzle generates a shock wave in front of the test model. The flow varies drastically across the shock wave, and a complicated flow field appears, comprising a nonequilibrium region behind the shock wave and an equilibrium region near the model surface. The same conditions occur during the atmospheric entry of a vehicle. To properly evaluate the aerodynamic heating caused by the arc-heated flow, the plasma flow parameters in the shock layer should be clarified.

The JAXA 1 MW arc-heated wind tunnel is one of the largest wind tunnels in the world, and it has been used for TPS research and development for the Hayabusa sample return capsule [33, 34]. Takahashi et al [35] determined the enthalpy of a 1 MW arc-heated free jet using spectroscopic tests and a computational science approach. However, the shock layer of the arc-heated flow has not yet been clarified. Hence, the present study was conducted to clarify the shock layer flow based on the flow enthalpy distribution. Further, the rotational temperature of NO molecules in the shock layer was determined through emission spectroscopy, and the plasma flow structure in the shock layer was investigated through comparisons with computational results.

The remainder of this paper is organized as follows. Section 2 describes the arc-heated wind tunnel used in this study. Section 3 discusses the numerical method for simulating arc-heated flow. Section 4 presents the results obtained through measurements and simulations. Finally, section 5 presents the conclusions of this study.

2. Arc heating facility

2.1. Specifications

The JAXA 1 MW arc-heated wind tunnel [36] used in this study was composed of an arc heater and test chamber. The arc heater shown in figure 1 was segmented type, consisting of anode and cathode chambers; inlet and constrictor sections (i.e. heating section); and throat and nozzle sections (i.e. expansion section). Between the electrode chambers, a segment pack consisting of 14 water-cooled segmented disks that are electrically insulated from each other was placed, which determines the arc length. The arc heater had this segmented heating system and was operated with up to four segment packs. The inside of the segment packs consisted of a cylindrical constrictor, 520 mm in length and 25 mm in diameter. The throat diameter was 10 mm. The nozzle with a conical shape was 100 mm in length, and its exit diameter was 25 mm.

The test gas was supplied to each segmented disk and heated by the arc discharge in the constrictor section. The heated gas choked at the throat and expanded in the nozzle section. Mach number at the nozzle exit was approximately 3.4. The arc-heated flow emitted from the nozzle exit was formed in the test chamber. The test gas was air; its mass flow rate could be varied between 10 and 30 g s$^{-1}$. Further, the input arc current could be varied between 300 and 700 A, and the input power was approximately 1 MW. In the present study, however, the operating conditions were set as a mass flow rate of 18 g s$^{-1}$ and an input arc current of 450 A. This supersonic plasma flow was used for aerodynamic heating tests.

The shock wave of the arc-heated flow in the test chamber was generated in front of a flat-face probe with a diameter of 50 mm. The front was set to 150 mm downstream of the nozzle exit, and the central axis of the probe corresponded to that of the nozzle.

2.2. Arc-heated flow

In the 1 MW arc-heated wind tunnel, the pitot pressure and heat flux of the arc-heated flow were measured using a Pitot tube and a Gardon gauge, respectively [37]. For the given operating conditions, namely a mass flow rate of 18 g s$^{-1}$ and an input arc current of 450 A, the heat flux was 16 MW m$^{-2}$, and...
the pitot pressure was 80 kPa for flat face probes with diameters of 25 and 50 mm, 25 mm downstream of the nozzle exit. These conditions corresponded to the aerodynamic heating of the Hayabusa sample return capsule during its superorbital atmospheric entry, and a high-heating environment was reproduced. The properties of the arc-heated flow should be properly evaluated at the nozzle exit (i.e. test chamber inlet). In this study, we used the computational results reported by Takahashi et al [35], which numerically reproduced the arc discharge and supersonic expansion in the arc-heated wind tunnel. The results were validated on comparison with the experimental data. Figure 2 shows the computed enthalpy distribution at the nozzle exit. A high-velocity, high-temperature, and low-density plasma region was formed at the core, and a low-velocity, low-temperature, high-density cold gas region was formed around the core.

2.3. Band spectra measurement

The emission spectra of nitric oxide (NO) in the shock layer in front of a test model exposed to the arc-heated flow were measured using a spectrometer (MS2004i, SOL Instruments) with a CCD camera (iStar DH340T-AY, ANDOR). The spectrograph grating was set to 2400 1/mm, corresponding to a center wavelength of 225 nm, with a slit width of 30 \( \mu \)m and an exposure time of 0.5 ms. The spectrometer with the CCD camera was placed at the outside of the test chamber, which focused on the plasma through a convex lens and the test-chamber window. Because the window was composed of quartz glass, the ultraviolet light could penetrate it.

2.4. Rotational temperature estimation

The NO band spectra distributed in the ultraviolet region are strongly dependent on the rotational temperature of molecules. Few other band spectra appear in the ultraviolet region in high-temperature air. Therefore, it is easy to identify the rotational temperature from the NO band spectra obtained by spectroscopic measurement by comparing them with the numerically reproduced spectra.

The spectra of NO bands were numerically reproduced using SPRADIAN [38]. Only NO molecules were considered as chemical species in the reconstruction of the numerical spectra. In this calculation, we assumed a Lorentzian shape with a full width at half maximum of 0.1 nm. The resolution of the spectra in the wavelength direction was set to 0.1 nm. In this case, each band spectral shape of NO molecule based on bound-bound transitions was affected by the rotational temperature, while these were not highly affected by the other temperatures. The heavy-particle translational temperature, vibrational temperature, electronic excitation temperature, and electron translation temperature were all fixed at 8000 K because they do not significantly affect the formation of the NO band spectra. The NO band spectra were generated by varying the rotational temperature in the range of 300–8000 K in 100 K increments and compared with those obtained using spectroscopy. The area of both spectra was compared by integrating them over a certain region in the wavelength direction. Subsequently, the calculated area was used to determine the rotational temperature.

3. Computational science approach

The flow field around the test model in the test chamber was simulated and compared with the spectroscopic measurement results of the shock layer. These computations revealed the plasma flow properties in the shock layer in detail.

3.1. Governing equations

The arc-heated flow in the test chamber was assumed to be a continuum, laminar, steady flow that was in thermochemical nonequilibrium. The temperature was assumed to be separated into translational, rotational, vibrational, and electron temperatures. In this study, the rotation and vibration energy modes were assumed to have single rotational and vibrational temperatures, respectively. The flow field was expressed using the Navier–Stokes equation, which was extended to a thermochemical nonequilibrium flow, and the equation of state. The equation consists of the total mass, momentum, and total energy conservation laws. To describe a thermal nonequilibrium flow, rotational, vibrational, and electron energy conservations were added. In addition, to consider chemical nonequilibrium, 11 chemical species, namely, \( N_2, O_2, NO, N_2^+, O_2^+, NO^+, N, O, N^+, O^+, e^- \), were considered. The mass conservation of these species was also taken into account. The governing equations can be expressed in integral forms as follows:

\[
\frac{d}{dt} \int_V QdV + \int_S \left( F_j - F_{vj} \right) n_j dS = \int_V WdV, \quad (1)
\]

where the conservative vector is expressed as \( Q = [\rho, \rho u_i, E, \rho_i, E_{\text{rot}}, E_{\text{vib}}, E_{\text{ele}}]^T \). In addition, \( n_j \) represents an
element of the normal vector of area \( dS \). The vectors of the advection flux \( F \), viscous flux \( F_v \), and source term \( W \) in equation (1) are expressed as:

\[
\begin{align*}
F_j &= \begin{bmatrix}
\rho \mu_{ij} \\
\rho \mu u_j + \delta_{ij} p
\end{bmatrix} \quad (E + p) u_j \\
\rho \mu u_j \\
E_{rot} u_j \\
E_{vib} u_j \\
E_{ele} u_j \\
\end{bmatrix}, \\
F_{ij} &= \begin{bmatrix}
\tau_{ij} \\
q_j + u_i \tau_{ij} + H_j \\
J_{rot,i} \\
q_{rot,i} + H_{rot,i} \\
q_{vib,i} + H_{vib,i} \\
q_{ele,i} + H_{ele,i} = p_{ele} u_j
\end{bmatrix}, \\
W &= \begin{bmatrix}
0 \\
0 \\
0 \\
S_{int,rot} \\
S_{int,vib} \\
S_{int,ele}
\end{bmatrix}
\end{align*}
\]

where \( \delta_{ij} \), \( \hat{w}_s \), and \( S_{int} \) denote the Kronecker delta, mass production rate, and internal energy exchange rate, respectively. The subscript ‘s’ in the equations represents each chemical species, and ‘M’ indicates the set of molecules considered (\( M = \text{N}_2, \text{O}_2, \text{N}_2^+, \text{O}_2^+, \text{and} \text{NO}^+ \)). The stress tensor, \( \tau_{ij} \), and heat flux, \( q_j \), in equation (2) can be expressed as follows:

\[
\tau_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{ij},
\]

\[
q_j = q_{visc,j} + q_{rot,j} + q_{vib,j} + q_{ele,j} = \lambda_{visc} \frac{\partial T_{visc}}{\partial x_j} + \lambda_{rot} \frac{\partial T_{rot}}{\partial x_j} + \lambda_{vib} \frac{\partial T_{vib}}{\partial x_j} + \lambda_{ele} \frac{\partial T_{ele}}{\partial x_j}.
\]

The diffusion flux and enthalpy fluxes transported by the diffusion are expressed as:

\[
J_{rot,j} = \rho D_{rot} \frac{\partial X_j}{\partial x_j},
\]

\[
H_{rot,j} = \rho \sum_{s=1}^{n_s} h_s D_{rot} \frac{\partial X_j}{\partial x_j},
\]

\[
H_{vib,j} = \rho \sum_{s=M}^{n_M} h_s D_{vib} \frac{\partial X_j}{\partial x_j},
\]

\[
H_{ele,j} = \rho h_{ele} D_{ele} \frac{\partial X_j}{\partial x_j},
\]

where \( D_{rot} \), \( h_{ele} \), and \( X_s \) are the effective diffusion coefficient, enthalpy, and mole fraction of species \( s \), respectively.

The equation of state is expressed as:

\[
p = \sum_{s \neq \text{ele}}^{n_s} \rho_s R_s T_{visc} + p_{ele} = \sum_{s \neq \text{ele}}^{n_s} \rho_s R_s T_{visc} + \rho_{ele} R_{ele} T_{ele}.
\]

The total internal energy can be calculated as:

\[
E = E_{visc} + E_{rot} + E_{vib} + E_{ele} + \sum_{s=1}^{n_s} \rho_s \Delta h_s + \frac{1}{2} \mu \rho u_i u_j,
\]

where \( \Delta h_s \) represents the enthalpy of formation. The translational, rotational, vibrational, and electron energies are respectively given by:

\[
E_{visc} = \sum_{s \neq \text{ele}}^{n_s} \frac{3}{2} \rho_s R_s T_{visc},
\]

\[
E_{rot} = \sum_{s=1}^{n_M} \rho_s R_s T_{rot},
\]

\[
E_{vib} = \sum_{s=M}^{n_M} \rho_s R_s \Theta_{vib,s} \exp(\Theta_{vib,s}/T_{vib}) - 1,
\]

\[
E_{ele} = \frac{3}{2} \rho_{ele} R_{ele} T_{ele},
\]

where \( \Theta_{vib,s} \) represents the vibrational characteristic temperatures.

3.2. Physical models

The transport coefficients appearing in the viscous term of the Navier–Stokes equation, namely, the viscosity, thermal conductivity, and effective diffusion coefficients, were based on the first-order Chapman–Enskog approximation [39] and were extended to a multicomponent and multitemperature gas using Yos’ formulation [40]. The effective diffusion coefficients were calculated using the Curtiss and Hirschfelder model [41] with binary diffusion coefficients. The effect of the ambipolar diffusion on ionized heavy particles was also considered. The collision cross-section required for calculating the transport coefficients was curve-fitted as a function of temperature. In this simulation model, Gupta’s model [42] was used between all pairs of chemical species except for e−–N and e−–O, and Fertig’s model [43] was used for the collision cross-section between these pairs.

The energy exchange between internal energy modes was considered to express thermal nonequilibrium flows: translation-rotation [44], translation-vibration [45, 46], translation-electron [47–49], rotation-vibration [50], rotation-electron [51, 52], and vibration-electron [53, 54]. In addition, the energy loss and release models for the vibrations and rotations associated with the chemical reactions for the dissociation energies of heavy-particle impact reactions were introduced; these were obtained using a nonpreferential dissociation model [49]. The electron energy loss and release due to the electron-impact dissociation and ionization were also considered [28]. These formulations are summarized in Takahashi’s work [55].

Next, 49 chemical reactions in high-temperature air were considered for the 11 chemical species, as listed in table 1. The forward reaction rate was given by the Arrhenius equation,
where Park’s model [56] was used to obtain the reaction-rate coefficient. The backward reaction rate was obtained using the ratio of the forward reaction rate to the equilibrium constant obtained by curve fitting using Park’s model [57] and Gupta’s model [42].

3.3. Numerical models

The governing equations were discretized using a finite volume approach. All physical properties were defined at the cell center. The SLAU2 scheme [58] was used for numerical flux calculations of the advection term. The viscous term was obtained by curve fitting using Park’s model [57] and Gupta’s model [42].

The minmod function was used as the slope limiter. Time integration was performed using the Euler implicit method, and the steady-state solution was obtained using the point implicit method [59] for the source term. The coefficient matrix was solved by the lower-upper symmetric Gauss-Seidel method [60].

3.4. Computational conditions

Figure 3 shows the computational grids and boundary conditions. The number of computational grids was 240 (axial) × 250 (radial) (i.e. 60 000). As boundary conditions for the flow-field simulation, the flow properties obtained at the nozzle exit in the arc-heated flow simulation inside the above-described arc heater were applied at the inlet (see figure 2). An axisymmetric condition was imposed on the central axis. At the outflow, the flow properties were determined under gradient-free conditions. The ambient conditions were set as follows: fixed pressure of 10 Pa, the fixed temperature of 300 K, slip, and zero pressure gradient normal to wall, and noncatalytic.

4. Results and discussion

4.1. Shock layer spectra

Figure 4 shows a photograph of the plasma flow and shock layer formed in front of the test model during the experiment. In the arc-heated wind tunnel, a high-temperature flow was generated by arc discharge, and it expanded through the nozzle to form a supersonic expansion. The emission could be seen at the nozzle exit owing to the high temperature of the free jet, and the emission intensity decreased downstream. This is because, in the low-pressure environment (approximately 10 Pa) inside the test chamber, the plasma flow temperature downstream of the nozzle exit decreased owing to expansion acceleration. The test model was set up such that the central axis of its front was located on the central axis of the nozzle and 150 mm downstream of the nozzle. In other words, when the center of the nozzle exit is at the origin, that is, \( x = 0 \) mm and \( y = 0 \) mm, the center of the test model front is at \( x = 150 \) mm and \( y = 0 \) mm. The shock layer was formed in front of the test model, and the emission intensity was higher than that of the free jet because of the high-temperature and high-pressure gas region due to the flow stagnation. By observing the emission spectra, the composition of the chemical species and the temperature of each species could be identified.

Figure 5 shows the emission spectra of the shock layer at wavelengths of 220–260 nm. The focal position was \( x = 145 \) mm and \( y = 0 \) mm. The spectra exhibited an upward trend.
trend from low to high wavelengths, and the influence of some continuous spectra was confirmed. The spectrum with a peak at approximately 237 and 247 nm was the $\gamma(0,1)$ band and $\gamma(0,2)$ band, respectively. In both cases, a characteristic double head was observed in the emission of heterogeneous molecules such as NO molecules. In this wavelength region, the $\gamma$ system appeared as a prominent band. In particular, the $\gamma(0,1)$ and $\gamma(0,2)$ spectra were clear. The rotational temperature of the arc-heated flow can be estimated using the spectral fitting method.

Figure 6 shows the measured free jet spectra for comparison with the shock layer spectra. The focal position of the free jet spectrum was also $x = 145$ mm and $y = 0$ mm. As in the shock layer spectrum, the NO molecule $\gamma$ band could be clearly seen. In addition, $\delta$ band spectra, which were hardly observed in the shock layer spectra, appeared. The width of the $\gamma$ band in the free jet spectra was much smaller than that in the shock layer spectra. In general, the lower the rotational temperature of the plasma flow, the thinner the spectrum appears. This implies that the rotational temperature in the shock layer is higher than that in the free jet. When a shock wave was generated, the translational temperature increased owing to the conversion of kinetic energy to thermal energy. Then, through energy exchange (i.e. relaxation) between internal energy modes, the temperature of each degree of freedom increased. In high-temperature air species, the energy relaxation of the translational and rotational temperatures generally occurs rapidly. Thus, the rotational temperature naturally increases in the shock layer and appears in these spectra. In the free jet spectra, the effect of the continuous spectrum as observed in the shock layer spectrum did not appear at all. This is because the electron excitation temperature and the number of electrons were low in the free jet, and the effect was small.

4.2. Measured rotational temperature

Numerical spectra were reproduced for the $\gamma(0,1)$ and $\gamma(0,2)$ spectra. The measured and the numerical spectra were compared for the wavelength region where $\gamma(0,1)$ and $\gamma(0,2)$ exist. In the present numerical spectra, only the $\gamma$-band system of the NO molecule was considered, and the continuous spectrum confirmed by shock layer spectroscopy was not reproduced. Then, to eliminate the effect of the continuous spectrum, we assumed that the $\gamma(0,1)$ and $\gamma(0,2)$ measurement spectra have a continuous spectrum that is linear with respect to the wavelength, and we subtracted that portion from the radiation intensity distribution. In this case, the radiation intensity at the edge of the wavelength region was assumed to be the same as that of the numerical spectrum. Figures 7(a) and (b) show a comparison between the measured and the
Comparison of measured and numerical spectra of NO band system in shock layer at focal position of $x = 145$ mm and $y = 0$ mm.

Table 2. Rotational temperatures of NO molecule in shock layer and free jet.

| Band system | Rotational temperature, K (shock layer) | Rotational temperature, K (free jet) |
|-------------|----------------------------------------|-------------------------------------|
| $\gamma (0, 1)$ | 6548 ± 323 | 755 ± 37 |
| $\gamma (0, 2)$ | 6692 ± 362 | 781 ± 73 |

The numerical spectra in wavelength regions of 227.0–237.7 and 237.0–248.5 nm, respectively. The numerical spectra show the results for the rotational temperatures of 6000, 7000, and 8000 K as typical cases. The numerical spectrum did not include the data set of the $\gamma (1, 3)$ band; therefore, it could not be reproduced. The measured and the numerical spectra were found to agree well at a rotational temperature of approximately 7000 K in both wavelength regions.

In both wavelength regions, the spectral shapes were strongly affected by the rotational temperature. In consideration of this characteristic, the rotational temperature was determined by comparing the intensity of the measured and the calculated spectra with the area of the wavelength in a certain wavelength region. The target wavelength ranges were 233.0–237.0 and 244.5–248.0 nm for $\gamma (0, 1)$ and $\gamma (0, 2)$, respectively. Table 2 shows the rotational temperatures of the shock layer and free jet at the focal position of $x = 145$ mm and $y = 0$ mm. In this study, three shock layer spectra were measured for $\gamma (0, 1)$ and $\gamma (0, 2)$. For each, we calculated the mean value and standard deviation from the rotational temperature result obtained by spectral fitting. The determination of the rotational temperature of the free jet spectra is described in reference [35]. The NO rotational temperature in the shock layer was 6620 ± 350 K; this is higher than the free jet rotational temperature of 770 ± 60 K. This is because the translational temperature first increases due to the flow stagnation across the shock wave, following which the rotational temperature increases owing to the energy relaxation process from the translational to the rotational degrees of freedom. The rotational temperatures calculated from $\gamma (0, 1)$ and $\gamma (0, 2)$ were similar in both cases.

4.3. Shock layer structure

The plasma flow in the shock layer was investigated using the computational science approach. Figure 8 shows the Mach number distribution near the test model. The arc-heated flow from the nozzle exit expanded and accelerated in the low-pressure test chamber with an increase in the Mach number. In front of the test model, the flow became supersonic with a Mach number of approximately 9. Therefore, the arc-heated flow stagnated in front of the test model, and a strong shock wave was generated. Specifically, a shock layer with a thickness of approximately 10 mm was formed.

Figure 9 shows the pressure distribution around the test model. The pressure near the nozzle exit was approximately...
8000 Pa, and it rapidly decreased owing to expansion in the test chamber. At the stagnation point in front of the model, the pressure was approximately 5500 Pa. In the test chamber, the flow velocity was high, and the pressure was very low. In this case, insufficient collisions occurred between the molecules and atoms in the flow to allow the internal energy relaxation and chemical reactions to proceed sufficiently. This indicated that the arc-heated flow and the shock layer generated by the wind tunnel were in strong thermochemical nonequilibrium.

Knudsen number of the arc-heated flow was evaluated based on the computed results. Because the evaluated Knudsen number was in the order of $10^{-3}$, the assumption of continuum was found to be reasonable.

Figures 10(a) and (b) show profiles of the temperatures and species mole fractions on the central axis of the nozzle obtained by the computational science approach, respectively. The test model with a diameter of 50 mm was located at $x = 150$ mm. A previous study [35] reported that strong thermal nonequilibrium is also observed inside the nozzle, where the electron temperature and vibrational temperature at the nozzle exit ($x = 0$ mm) are higher than the translational and rotational temperatures. This trend was the same as that of the free jet in the test chamber. The translational temperature increased owing to the formation of shock waves at around $x = 140$ mm. The rotational, vibrational, and electron temperatures increased in a manner that is relaxed with the translational temperature. Near the test model, the flow velocity decreased, and the flow density increased, causing the temperature to equilibrate. Thermal nonequilibrium was also observed in the shock layer, except near the surface. With
regard to the chemical species, a dissociation reaction with a slow rate was confirmed to occur in the shock layer. The dominant chemical species in the shock layer were N, N$_2$, and O. The composition of the shock layer was not greatly different from that of the free jet. Some NO production was observed, and the number of ionized species was low. Compared to the temperature change in the shock layer, the chemical reactions were inactive owing to the low pressure and low collision frequency between molecules and atoms, as mentioned above. Thus, in addition to thermal nonequilibrium, strong chemical nonequilibrium was observed in the shock layer plasma.

Table 3 lists the comparison of temperatures at $x = 145$ mm in shock layer and free-jet cases obtained in the present computations. On comparing with the measured rotational temperature listed in table 2, the computed rotational temperature agreed with the measured one well. However, the computed rotational temperature in the shock layer overestimated the measurement. The ratio of the rotational temperature in the shock layer and that in the free jet, $T_{rot, shock}/T_{rot, free}$, was approximately 12.4, which was higher than that of the measurement data. This discrepancy is mainly attributed to the thermal nonequilibrium model, i.e. Parker’s translational-rotational energy relaxation model [44] which overestimates a relaxation rate between the two energy modes.

### 4.4. Nonequilibrium in shock layer

Figure 11 shows a comparison of the rotational temperatures obtained by the spectroscopy measurements and computational science approach. The results obtained using Parker’s relaxation model in the computations, as well as those obtained using Park’s relaxation model [61] were included. The relaxation between the translation and rotation energy modes evaluated using Park’s model was generally lower than that by Parker’s model. The experimental values were determined by the measured spectra of the $\gamma (0,1)$ and $\gamma (0,2)$ band systems (see table 2). The computational results obtained using Parker’s model reproduced higher rotational temperatures in the shock layer owing to the relatively strong relaxation with the translational model. At the same time, because Park’s model evaluated the relaxation to be relatively low, a low rotational temperature was reproduced. However, in both cases, the model overpredicted the experimental values. This was mainly due to the difficulty of thermal nonequilibrium modeling in the numerical simulation. The relaxation rate between the translation and rotation modes can be lower than that evaluated using Park’s model. A reliable energy relaxation model set has been insufficiently proposed for the nonequilibrium state of arc-heated flows. In addition, the present computational model assumed that all molecules have a single rotational or vibrational temperature. However, in the measured spectrum, only the rotational temperature of the NO molecule was evaluated. Abe et al [10] introduced a multi-rotational and multi-vibrational temperature model for air species of N$_2$, O$_2$, and NO for 20 kW arc-heated flow simulation. In an environment with strong thermal nonequilibrium, the rotational temperatures of different molecules might differ. This may explain the discrepancy between the present computational and experimental data.

Evaluating both the aerodynamic heating and the aerodynamic force is important in reproducing the atmospheric entry environment using an arc-heated wind tunnel. These are strongly dependent on the temperature and pressure in the equilibrium region, which tends to be distributed near the test model. Because the physical modeling in the equilibrium region was reliable, the heating and force reproductions obtained using the arc-heated wind tunnel should not pose a major problem.

### 5. Conclusions

The plasma flow in the shock layer of a large arc-heated wind tunnel was investigated through emission spectroscopy and a computational science approach. The emission spectroscopy investigation focused on the $\gamma$-system band of NO molecules in the ultraviolet region, and we obtained the spectra in the wavelength range of 230–260 nm. In the arc-heated flow, almost no spectra other than the $\gamma$ system band existed in the aforementioned wavelength region, making it easy to identify the temperature based on the measured spectra. In general, the $\gamma (0,1)$ and $\gamma (0,2)$ band spectral shapes strongly affected the rotational temperature of the NO molecule. Specifically,
this temperature was determined via spectral fitting using the numerical spectrum for each measured spectrum. Its value was found to be $6620 \pm 350 \, K$ in the shock layer and $770 \pm 60 \, K$ in the free jet, indicating a large temperature increase because of flow stagnation across the shock wave.

The computed results indicated that the translational temperature increased to approximately $10000 \, K$ in the shock layer, following which the rotational temperature increased to approximately $9000 \, K$ owing to internal energy relaxation. In comparison, the rate of temperature increase in the shock layer, the chemical reaction rate was slow owing to the low-pressure environment. The dominant chemical species were not significantly different from those in the free jet. Thus, the shock layer was in strong thermochemical nonequilibrium.

The results indicated that the thermal nonequilibrium model used in the computational science approach overpredicted the measured rotational temperature. The relaxation between translation and rotation energy modes evaluated using the measurement was lower than those used in the present analysis model. Future studies should further investigate the internal energy relaxation model in the high-temperature region, review these models, and perform further modeling.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The authors would like to thank Mr Naoya Enoki (Hokkaido University) for his valuable cooperation. This work was supported by JSPS KAKENHI Grant Nos. 17KK0123 and 20H02360. The wind tunnel experiments were conducted in an arc wind tunnel facility at the Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency. The computations were performed using the computational facilities at the Research Institute for Information Technology, Kyushu University.

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