Flow Characterization of CO₂-N₂-Ar Plasma in a Hollow Electrode Arc Heater*

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The purpose of the present study is to characterize the flow of CO₂-N₂-Ar plasma in a hollow electrode arc heater using optical diagnostics. Spectroscopic measurements are conducted in the region of the arc-heated part. The rotational and vibrational temperatures are determined from the measured spectra of CN Violet $\Delta v=0$ and C₂ Swan $\Delta v=0$ using a spectrum fitting technique. It is found that the rotational and vibrational temperatures are almost same, showing that the plasma in the arc heater is close to thermal equilibrium. The chemical composition of the plasma is calculated using the NASA-CEA program. The result shows that Ar, CO, and O are dominant species in the plasma investigated in this study. Although the mole fractions of CN and C₂ are extremely low, they are strong radiators in the CO₂-N₂-Ar plasma. The numerical spectrum in the wide wavelength range is calculated using the chemical composition deduced by the NASA-CEA program and compared with the measured one. The result shows that the numerical spectrum does not agree with the measured one due to contamination caused by carbon. Spectrum calculations are conducted parametrically by changing the chemical composition to investigate the influence of carbon contamination. The numerical spectrum becomes close to the measured one when the mole fractions of CN and C₂ decrease, showing that carbon contamination has a significant influence on the reaction processes of the plasma in the arc heater.

Key Words: CO₂-N₂-Ar Plasma, Arc Heater Flow, Thermal Equilibrium, Chemical Composition, NASA-CEA

Nomenclature

I	: arc current, A
M	: unspecified third body
$\dot{m}$	: mass flow rate, g/s
T_r	: rotational temperature, K
T_v	: vibrational temperature, K
p	: pressure in the arc heater, MPa
V	: arc voltage, V

1. Introduction

Recent space missions are paying much attention to Mars exploration. In missions proposed, challenging new technologies such as a Mars airplane and Mars Aeroflyby Sample Collection (MASC) are being planned. For the success of these missions, entry into the Martian atmosphere is a main concern. Space vehicles receive a severe heat load during atmospheric entry flight. Therefore, thermal protection systems (TPS) are required to protect space vehicles from the heat load. The materials development for TPS is carried out through heat tests using an arcjet facility which generates high enthalpy plasma flows corresponding to entry flight conditions. It has been pointed out that the flow properties have a significant influence on the test results. However, the flow properties of the test flows have not yet been fully clarified, degrading the accuracy of the

heat tests. To improve the accuracy of the heat tests, characterization of the test flows is necessary.

In previous studies, experimental investigations of arc plasma flows were conducted using a test gas of 96% CO₂-4%N₂, simulating the Martian atmosphere. Schöemann et al.¹⁾ obtained the axial distribution of chemical components in CO₂-N₂ plasma flows using mass spectrometry and emission spectroscopy. Lago et al.²⁾ investigated the thermochemical states of CO₂-N₂ arc plasma flows for various CO₂ and N₂ concentrations, and clarified the influence of concentrations on the vibrational state of CN. The authors have conducted optical diagnoses of CO₂-N₂ plasma flows in an arc-heated wind tunnel and deduced temperature distribution along the stagnation streamline around a blunt body.³⁾ In addition, the authors have investigated the thermal nonequilibrium state of CO₂-N₂-Ar and CO₂-Ar plasma flows.^{4,5)} In these studies, the area intensity method that uses the molecular band spectra of CN and C₂ was newly applied to accurately evaluate the thermal nonequilibrium state of the plasma flows. The result showed that the thermochemical state of the plasma flows was in the vibrational nonequilibrium state along the stagnation streamline around a blunt body. These studies give us useful information to characterize the test flow. In a typical arcjet facility, the test gas is first excited and changed into plasma by arc discharge. Then, the plasma in the arc heater expands through a nozzle into a vacuum chamber, generating freestream flows at hypersonic speeds. For complete characterization, both freestream and arc heater flows should be investigated. Rob et al.⁶⁾ investigated radiation characteristics in the plenum of the arcjet facility at NASA

Johnson Space Center using an optical fiber. The temperatures were deduced from the measured spectra. The electronic excitation temperatures based on atomic lines are much different from those based on molecular spectra. The difference may be due to the fact that the atomic upper energy states are closely coupled with free electrons. Although this study successfully obtained the temperatures in the plenum using spectroscopic measurements, the characteristics of plasmas in the plenum were still unknown. Further investigation is required to characterize the plasma in the plenum, where plasma is first generated. There is little research about arc heater flows. This is due to the limitation of the space for spectroscopic measurements. In this study, we have newly made an observation port in an arc heater to conduct spectroscopic measurements. The purpose of the present study is to characterize $\text{CO}_2\text{-N}_2\text{-Ar}$ plasma in the arc heater.

2. Experimental Setup

2.1. Arcjet facility

In the present study, a hollow-electrode type arcjet facility is used to generate an arc-heated plasma. An illustration of the arcjet facility is shown in Fig. 1. The facility is composed of a hollow-electrode type arc heater, a test section, a vacuum tank, and a vacuum pumping system. A schematic drawing of the arc heater is shown in Fig. 2. The arc heater consists of hollow-type cathode and anode electrodes connected to a convergent-divergent nozzle. Each component of the electrodes and nozzle is independently water-cooled. The inner diameters of the cathode and anode are 12 mm, while the outer diameters are 18 mm. The nozzle is conically expanded with a half-angle of 10 degrees and its exit diameter is 22 mm. The throat of the nozzle is 23 mm in length and 3 mm in diameter. The designed Mach number is 5 for CO_2 on the assumption of isentropic flow. The cathode and anode are electrically insulated by a Teflon insulator. The working gases are supplied tangentially with swirling motion into the arc heater, producing a stable uniform flow. A magnetic coil system is attached to the outside of the cathode to reduce damage to the inner surface of electrodes by undesirable discharges. A bourdon gauge is attached to the outer case of the anode to monitor the pressure in the arc heater. The test section, which has four BK7 optical windows with diameters of 90 mm, is placed between the arc heater and the vacuum tank (not shown in Fig. 2). In the test section, freestream flows at hypersonic speeds are generated by nozzle expansion. Shock layer flows can be obtained by putting a blunt body model in the freestream flows. The vacuum tank, with a volume of 2 m^3 , is evacuated to a vacuum by a root pump (Edwards, QMB500) backed up by an oil rotary pump (Edwards, E2M80).

2.2. Optical measurement system

The anode electrode and outer case have circular holes with a diameter of 6 mm for spectroscopic measurements in the arc heater. A quartz window is located between the anode electrode and outer case with a sealing aperture. Figure 3 shows the observation section in the arc heater.

The optical measurement system is arranged so that radiation from the downstream end of the anode electrode can be measured through the quartz window, as shown in Fig. 2. The optical measurement system consists of a quartz convex lens, a fiber alley, a spectrometer (Andor, SR303i), and a CCD camera (Andor, DU920OP-OE). The wavelength dependency of the optical measurement system is calibrated using a quartz tungsten halogen lamp (Newport, 63355) which is a National Institute of Standards and Technology (NIST) traceable light source. In addition, the optical measurement system is calibrated using a mercury argon calibration light source (Ocean Optics, HG-1) to improve the wavelength accuracy of the measured spectra.

Fig. 1. Illustration of the arcjet facility.

Fig. 2. Schematic of the hollow electrode arc heater.

Fig. 3. Picture of the observation port in the arc heater.

Table 1. Experimental conditions.

Parameters	Values
I	60
V	150
p	0.35
$\dot{m}$	CO ₂ : 0.131
	N ₂ : 0.0042
	Ar : 0.743

Fig. 4. Overall spectrum in the arc heater.

2.3. Experimental conditions

The experimental conditions are listed in Table 1. In the present measurement, the arc heater is operated with a plenum chamber pressure of 0.35 MPa, an arc current of 60 A, and a voltage of 150 V. For the simulation of entry into the Martian atmosphere, a mixture of 95.7% CO₂, 2.7% N₂, and 1.6% Ar should be used as a test gas. However, it is found that the arc plasma flow generated is unstable using the actual composition as a test gas. Increasing the amount of Ar enables us to observe a stable arc plasma flow. Therefore, in this study, a mixture of CO₂-N₂ diluted in Ar is used as a test gas, with the respective mass flow rates of 0.131 g/s, 0.0042 g/s, and 0.743 g/s. Under these conditions, the specific enthalpy of the arc plasma flow is about 7.2 MJ/kg at the nozzle exit.

3. Results and Discussion

3.1. Emission spectra

Figure 4 shows the overall spectrum of emission intensity in the arc heater. CN Violet and C₂ Swan bands are prominent in the overall spectrum. The most intense emission is seen to originate from CN Violet $\Delta v = 0$. Atomic lines of oxygen, argon, and carbon are seen in the long wavelength range above 700 nm. Atomic carbon is considered to come from the contaminated electrode surface because the water-cooled electrodes are polluted with a black layer of carbon or carbonic compounds. Atomic lines of copper are seen in the near-ultraviolet region due to the erosion of electrodes by arc heating. A continuum emission is seen in the wide wavelength range. Although the features

(a) CN violet $\Delta v = 0$ (b) C₂ Swan $\Delta v = 0$

Fig. 5. High-resolution spectra.

of band systems are not well recognized, the continuum spectrum is considered to be mainly composed of many overlapped bands of CO, NO, and CN.

3.2. Temperature evaluation

Figures 5(a) and (b) show the high-resolution spectrum of CN Violet $\Delta v = 0$ and C₂ Swan $\Delta v = 0$ observed using 1200-line/mm grating, respectively. In Fig. 5(a), five bandheads are seen to be clearly identified by referring to standard tables of molecular spectra.⁷⁾ In Fig. 5(b), two bandheads are clearly seen separated from the atomic lines of copper. These band structures depend on the rotational and vibrational temperatures of the plasma. In this study, a spectrum fitting method using SPRADIAN 2⁸⁾ is applied for the temperature evaluation. In this calculation, the numerical spectra of CN and C₂ are computed by SPRADIAN 2 for the rotational and vibrational temperatures from 5000 K to 10000 K at every 250 K interval and stored in spectrum databases. Then, a least square method is applied to find the numerical spectrum that minimizes the root mean square of difference between the numerical and measured spectra from the spectrum databases. Finally, the

Fig. 6. Spectrum fitting results

spectrum obtained gives the rotational and vibrational temperatures of the measured spectrum. The spectrum fitting results for CN and C₂ are shown in Figs. 6(a) and (b), respectively. A good agreement between the measured and computed spectra is obtained in both cases. In Fig. 6(a), the rotational and vibrational temperatures of CN are deduced to be 6500 K, respectively. In Fig. 6(b), the rotational and vibrational temperatures of C₂ are deduced to be 6000 K, respectively. The error analysis of these temperatures is conducted by considering the uncertainty of the spectroscopic constants used in SPRADIAN 2. According to the result, the error in these temperatures is 500 K at most. In both cases, the rotational and vibrational temperatures are considered to be almost same values within 500K, showing that the plasma in the arc heater is close to thermal equilibrium. The freestream flow in the test section was characterized to be vibrational nonequilibrium in our past study. This is because the gas expands through the nozzle into the test section where the pressure is on the order of 100 Pa and the flow velocity is extremely high. On the contrary,

the pressure in the arc heater is on the order of a few hundred kPa, which is much higher than that in the test section. In addition, the flow velocity in the arc heater is relatively low. Therefore, the time of the energy exchanges among internal modes is much shorter than that of the flow characteristics. Therefore, the flow in the arc heater is considered to have thermal equilibrium. The temperature difference between CN and C₂ is considered to be caused by the contamination of plasma flows. This is because the measured spectrum of C₂ Swan is contaminated with two atomic lines of copper seen near the bandheads. On the other hand, the measured spectrum of CN violet is not contaminated with any atomic lines. Therefore, the rotational and vibrational temperatures of CN are seen to be more reliable.

3.3. Chemical composition in the arc heater

The spectrum fitting results show that CO₂-N₂-Ar arc plasma in the arc heater is close to thermal equilibrium and the equilibrium temperature is estimated to be 6500 K. Based on this result, the chemical composition of the CO₂-N₂-Ar gas mixture in the arc heater is deduced using the NASA computer program Chemical Equilibrium with Applications (CEA)⁹⁾ under the assumption of thermochemical equilibrium. The input parameters are listed in Table 2. The initial pressure is 0.35 MPa, corresponding to the pressure in the arc heater. The mixture ratio is given as mass fractions corresponding to the mass flows rates in the experiment. Figure 6 shows the chemical composition of the CO₂-N₂-Ar gas mixture at temperatures from 2000 to 10000 K. The chemical composition varies as a function of temperature. In the temperature range between 2000 and 4000 K, the mole fraction of CO₂ rapidly decreases as the temperature increases. In contrast, the mole fractions of CO, O and O₂ increase and become higher than that of CO₂. In the temperature range, CO and O are produced from CO₂ by the dissociation reaction shown in the following equation.

The dissociation reaction is aided by the following exchange reaction.

CO and O₂ are produced by the exchange reaction. At a temperature around 4000 K, the mole fraction of N starts to increase due to the N₂ dissociation shown in the following equation.

The mole fraction of C increases rapidly at about 4500 K due to the dissociation and exchange reactions shown in Eqs. (4) and (5), respectively.

On the other hand, the increase in CO is suppressed by these reactions. At a temperature around 5000 K, it can be seen that the CN mole fraction increases. CN is produced

Table 2. Input parameters for NASA-CEA.

Parameters	Values
Chemical species	CO ₂ , N ₂ , Ar
Initial pressure, MPa	0.35
Temperature, K	2000~10000
Mass fraction, %	CO ₂ : 14.9
	N ₂ : 0.48
	Ar: 84.6

Fig. 7. Chemical composition of CO₂-N₂-Ar plasma.

Table 3. Chemical composition at 6500 K.

Species	Mole fraction, %
Ar	68.8685
C	2.1535
CN	0.012
CO	11.7335
CO ₂	0.0025
C ₂	0.0025
N	0.9885
NO	0.0315
N ₂	0.173
O	16.0225
O ₂	0.0105

mostly by the following exchange reactions.

At a temperature around 6,000 K, the mole fraction of C₂ increases due to the following exchange reactions.

The mole fraction of CN is relatively low in the chemical composition. However, the CN radiation is most intense, as seen in Fig. 4. The result shows that the temperature evaluation using the CN emission spectrum is effective in the high-temperature range between 5000 and 10000 K. In the entire temperature range, the mole fraction of Ar is high

and almost unchanged. Table 3 shows the chemical composition of CO₂-N₂-Ar plasma at the estimated temperature of 6500 K. It is found that Ar, CO, and O are dominant species in the plasma. Since the mole fractions of CN and C₂ are extremely low, they are found to be strong radiators in the CO₂-N₂-Ar plasma.

3.4. Influence of contamination

The numerical spectrum for the chemical composition in Table 3 is calculated and compared with the measured overall spectrum. The result is shown in Fig. 8. It is found that the numerical spectrum does not agree with the measured one. In the near UV region, the effect of continuum radiation seems significant. The result shows that continuum radiation is underestimated in the calculation. This is attributed to the fact that plasma in the arc heater is contaminated with carbon. The inner surfaces of the anode and cathode are polluted with a black layer of carbon because they are water-cooled. The pollution of the anode and cathode results in an unstable discharge of the arc, which may affect the chemical reaction processes in the plasma.

To investigate the influence of carbon on the spectrum, numerical spectra are calculated by only changing the mole fraction of carbon, and compared with the measured one. The results are shown in Fig. 9. In the figure, the red line shows the numerical spectrum with a tenfold mole fraction of C and the green line shows the numerical spectrum with a one-tenth mole fraction of C. The difference in the mole fraction of C shows the change in the spectrum intensity of the carbon atom in the near infrared region. On the contrary, in the ultraviolet and visible regions, the numerical spectra are the almost same and disagree with the measured one. This result indicates that the influence of carbon on the spectrum is limited in the infrared region.

The formation reactions of CN and C₂ are considered to be affected by the unstable discharge. To investigate the influence of unstable discharge, numerical spectra are calculated by reducing the mole fractions of CN and C₂, and compared with the measured one. The results are shown in Fig. 10. In the figure, the red line shows the numerical spectrum with one-tenth mole fractions of CN and C₂. The green line shows the numerical spectrum with one-hundredth mole fractions of CN and C₂. The numerical spectrum becomes close to the measured one as the mole fractions of CN and C₂ decrease. Especially, good agreement can be seen in the ultraviolet and visible regions. The present result indicates that carbon contamination has a significant influence on the reaction processes of the plasma in the arc heater.

4. Conclusion

In the present study, characteristics of CO₂-N₂-Ar plasma in a hollow electrode arc heater were investigated using optical diagnostics. Temperatures of the plasma were evaluated using spectrum fitting to the CN Violet $\Delta v=0$ and C₂ Swan $\Delta v=0$ measured. The rotational and vibrational temperatures were evaluated to be 6500 K for CN and 6000 K for C₂, showing that the plasma is close to thermal equilibrium in the arc heater. The chemical composition is de-

duced using the NASA-CEA program. It is found that Ar, CO, and O are dominant species in the plasma. Although the mole fractions of CN and C₂ are extremely low, they are strong radiators in the CO₂-N₂-Ar plasma. The numerical spectrum was calculated using the chemical composition deduced by the NASA-CEA program and compared to the measured one. The result shows that the numerical spectrum does not agree with the measured one due to carbon contamination. To investigate the influence of carbon contamination, spectrum calculations were conducted by changing the mole fractions of carbon, CN, and C₂. A good agreement between calculated and measured spectra was obtained when the mole fractions of CN and C₂ decreased, showing that carbon contamination has a significant influence on the reaction processes of the plasma in the arc heater.

Fig. 8. Comparison between numerical and measured spectra.

Fig. 9. Influence of C.

Fig. 10. Influence of CN and C₂.

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