

THERMAL AND CHEMICAL NON-EQUILIBRIUM FLOWFIELDS IN AN ARCJET EXPANSION NOZZLE FOR LOW PRESSURE PLASMA PROCESSING

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Abstract

10-kW-class water-cooled nitrogen-arcjet flowfields were studied by means of spectroscopic diagnostics. The atomic excitation temperature and electron density on the center line in the constrictor increased from 10,000 to 12,500 K and from 1×10^{15} to 2×10^{16} cm⁻³, respectively, with input power levels of 7–11 kW. In the expansion nozzle, the pressure and electron density drastically decreased downstream, and therefore the plasma was expected to be in high non-equilibrium. The vibrational temperature was axially kept about 8,000–9,000 K in the nozzle, and the rotational temperature was expected to drastically decrease downstream, resulting in about 2,000 K near the exit.

I. INTRODUCTION

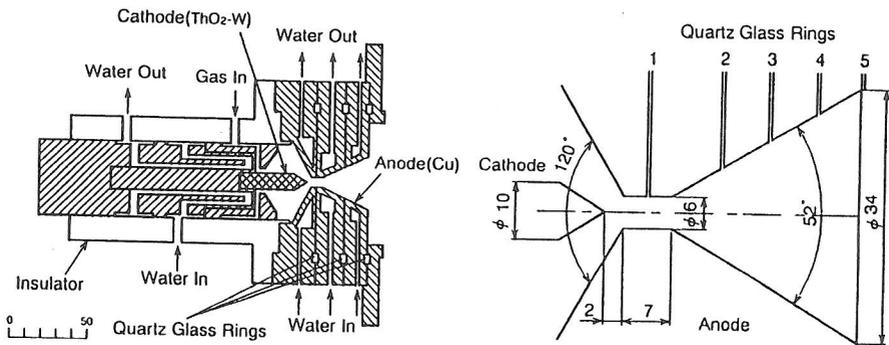
The direct-current arcjet generator is a promising plasma source suitable for economically assisting material processing in which a high through-put of material is desired. When an arcjet generator with an expansion nozzle operates in a low pressure environment, a supersonic exhaust plasma is expanded radially and axially. Various large-area processings can be conducted using the arcjet generator. For example, ceramic coatings, ceramic-metal composite coatings such as SiC-Co, TiC-Co(Ni), Al₂O₃-Cu and ZrO₂-Cu systems, reactive coatings such as TiN and AlN, related to reaction processes using Ti and Al and other metals with a N₂ working gas or in a N₂ atmosphere as well as TiO₂ and Al₂O₃, formation of advanced-function inter-metallic compound coating films, and surface modification have been successfully demonstrated by means of thermal plasma spraying. The plasma characteristics in the arcjet generator, such as several temperatures and densities of particle species and their spatial profiles, influence the properties of films deposited or modified. However, inner plasma properties are not clear because of the complicated flowfield including the interaction between arc and gas flow, and internal energy excitations of atoms and molecules etc [1]–[6].

The purpose of the present research is to understand plasma features in an arcjet generator with an expansion nozzle for low pressure plasma processing, particularly non-equilibrium flowfields in the expansion nozzle, by

means of optical diagnostics and numerical analysis. Nitrogen is used as the working gas. The discharge voltages, local pressures and current fractions on the anode are measured. Spectroscopic measurement is carried out, and several plasma properties are examined from the data. Atomic electron excitation, molecular vibrational and rotational temperatures are determined, and electron densities are also estimated using hydrogen $H\beta$ line Stark broadening. Furthermore, arcjet flowfields are numerically analyzed using a quasi-one dimensional core-flow model, in which radial mass transfer, and dissociation and ionization processes in chemical and thermal non-equilibrium (partially-LTE) condition are considered [3][4][6]. The analyzed results are compared with the experimental ones.

II. EXPERIMENTAL APPARATUS

Figure 1 shows the cross section of the 10-kW-class dc arcjet used for this study. A constrictor has a diameter of 6 mm and a length of 7 mm. A divergent nozzle has an exit diameter of 34 mm and an angle of 52 deg. The ratio of the cross sectional area of the nozzle exit to that of the constrictor is 32.1. The convergent-divergent anode made of copper is divided into the expansion nozzle part and the constrictor-plenum-chamber part, and both anode parts are electrically insulated from each other with a silicon sheet; thus, the current entering each anode part can be measured. As shown in Fig. 1(b), the anode is provided with quartz glass rings for arc observation and optical diagnostics. A cylindrical cathode made of 2%-thoriated tungsten has a diameter of 9.8 mm. The gap between the electrodes, which is defined as the axial distance between the cathode tip and the constrictor upstream exit, is set to 2 mm. Nitrogen is used as working gas. The arcjet is operated with input power levels of 3–12 kW at discharge currents of 70–150 A. The arcjet is set on a flange of a vacuum tank, into which the heated gas is exhausted. The vacuum tank 0.8 m in diameter and 1.5 m long is evacuated to 1–10 Pa during operations.



(a) Configuration of dc arcjet.

(b) Arrangement of electrodes and quartz glass rings.

Fig. 1 Cross section of 10-kW-class water-cooled direct-current (dc) arcjet.

Emission spectroscopic measurement is conducted as reliable plasma diagnostics in arcjet chambers. Light comes from the plasma through a quartz glass slit of 0.5 mm in width, as shown in Fig. 1(b). The emission is collected by a lens of 80 mm in focal length and is introduced into a 0.5-m monochrometer. The monochrometer of diffraction-grating-type HAMAMATSU C5095 is provided with a 2,400 grooves/mm grating plate and a 1024-channel diode array detector, achieving spectral resolutions of 0.05 nm per detector channel. Electron number densities and several plasma temperatures of an atomic excitation temperature for N^+ and molecular vibrational and rotational temperatures for N_2 and N_2^+ are determined using the spectral data. The electron density is estimated from the Stark width of hydrogen $H\beta$ line 486.1 nm, in which a mixture of nitrogen and a few percent seed hydrogen is used. The spectral intensities measured in this experiment are line-of-sight values, measured by looking through the arc from the side perpendicular to the center line of the arcjet. For line-of-sight measurements, the intensity values correspond to integrated values of intensity as a function of position, and average physical properties can be calculated simply from them. Also, Abel transformations are performed to determine the radial-dependent emission coefficient, i.e., radial profiles of several temperatures.

The atomic-ion excitation temperature is determined using a relative intensity method of spectral lines, i.e., by means of Boltzmann plotting with NII spectral lines of 417.6, 444.7, 453.0, 460.7, 461.4, 462.1, 463.1, 566.7, 567.6 and 568.0 nm. The molecular vibrational temperature is also determined from an intensity ratio of two lower energy transitions under the assumption of partial LTE. Spectral band heads of 380.4 and 375.4 nm (second positive band $C^3\Pi_u - B^3\Pi_g$) for N_2 and of 427.8 and 423.6 nm (first negative band $B^2\Sigma_u^+ - X^2\Sigma_g^+$) for N_2^+ are used. The relative intensity method can not be used to determine rotational temperatures because the rotational lines are too close together and overlapped. Therefore, the theoretical intensity distribution for a band is calculated with an assumed rotational temperature and compared to the measured spectrum. The rotational temperature is found iteratively by varying the temperature of the theoretical distribution. The N_2 $C^3\Pi_u - B^3\Pi_g$ and N_2^+ $B^2\Sigma_u^+ - X^2\Sigma_g^+$ transition bands at 380.4 and 427.8 nm, respectively are used.

III. RESULTS AND DISCUSSION

OPERATING CHARACTERISTICS AND ARC PLASMAS IN CONSTRICTOR

Figure 2 shows the discharge voltage vs discharge current characteristics. The discharge voltage gradually decreases with the discharge current at a constant mass flow rate, and it is approaching a constant value for high current levels above 120 A. An increase in the mass flow rate raises the voltage with a constant current. Thus, the electrical input power ranges from 3 to 11 kW. The pressure in the constrictor increased linearly with the input power at each mass flow rate and ranged from 10 to 30 kPa. Also, the

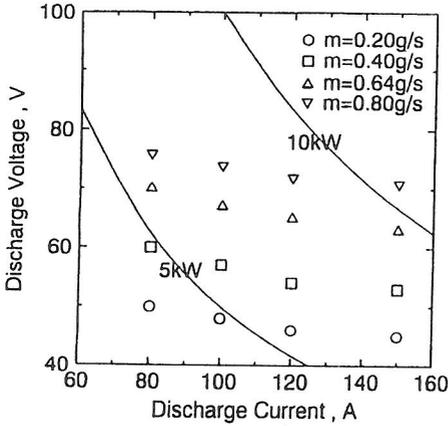


Fig. 2 Voltage vs current characteristics.

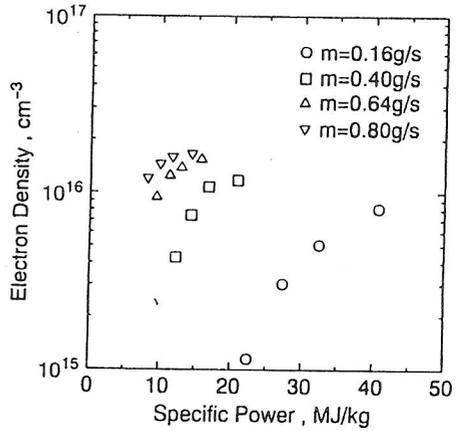


Fig. 3 Dependence of specific power vs electron density in constrictor.

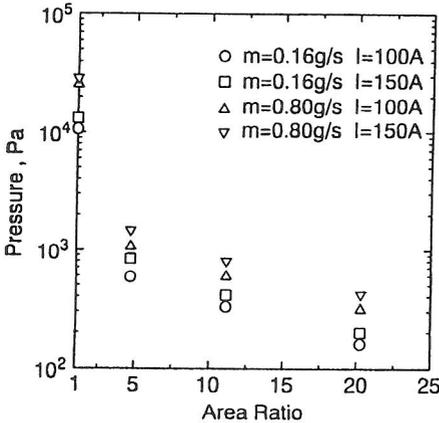


Fig. 4 Axial variations of pressure in nozzle.

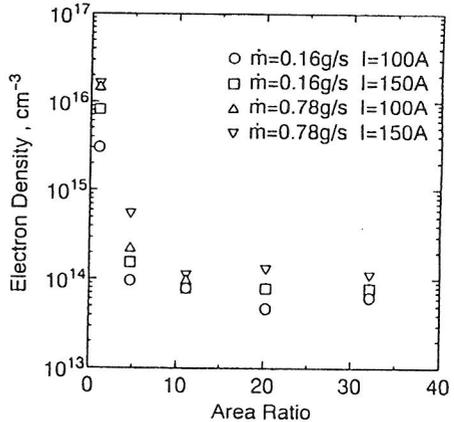


Fig. 5 Axial variations of electron density in nozzle.

thermal efficiency evaluated was 50 to 70 % for all operations. The measured current fraction on the anode showed that most of the discharge current entered the expansion nozzle part regardless of operational conditions. It is expected that the arc passes through the constrictor and attaches to the expansion nozzle, which is called a constricted arc.

For the spectra emitted from the plasma in the constrictor, the bands for N_2 and N_2^+ were observed at a low discharge current of 100 A or at a small mass flow rate of 0.16 g/s. On the other hand, the atomic ion spectra

NII were observed at a high discharge current of 150 A or at a large mass flow rate of 0.78 g/s.

Figure 3 shows the dependence of the specific power on the electron density on the center line in the constrictor. The electron density increases with the input power at a constant mass flow rate. Also, the N^+ excitation temperature increased linearly, and the characteristic line was independent of the mass flow rate. The excitation temperature and electron density ranged from 10,000 to 12,500 K and from 1×10^{15} to $2 \times 10^{16} \text{ cm}^{-3}$, respectively, in an input power range of 7–11 kW. An increase in the mass flow rate raises the electron density with a constant specific power. This is expected because an increase in the mass flow rate enhances the thermal pinch effect, by which Joule heating occurs efficiently in the constricted arc column. This agrees with the variation of spectral species observed.

NON-EQUILIBRIUM PLASMAS IN EXPANSION NOZZLE

Figure 4 shows the axial variations of the pressure on the center line in the expansion nozzle. The pressure decreases drastically from 10–30 kPa in the constrictor to an order of 10^2 Pa downstream in the nozzle because of supersonic expansion. This feature agrees with that of the electron density as shown in Fig. 5; that is, the electron density reaches an order of 10^{13} cm^{-3} at the nozzle exit. As a result, no atomic ion spectrum was observed in the expansion nozzle, and the bands of N_2 and N_2^+ were mainly observed. This is expected because excitation collisions between atomic ions and electrons hardly occur under the low pressure and small electron density environment in the nozzle. Hence, the heated gas is expected to be in high non-equilibrium throughout the nozzle.

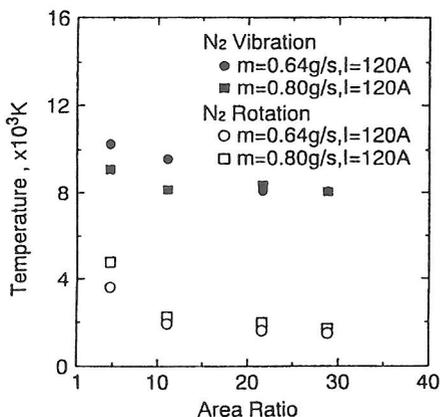


Fig. 6 Axial variations of vibrational and rotational temperatures for N_2 in nozzle.

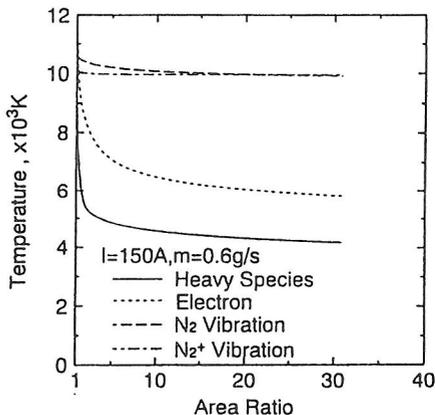


Fig. 7 Axial variations of several temperatures calculated in partially-LTE.

Figure 6 shows the axial variations of the vibrational and rotational temperatures of N_2 on the center line in the expansion nozzle. The vibrational temperature is almost kept a constant value of about 8,000–9,000 K. This is because of much slower relaxation of vibrational modes than the characteristic flow time. On the other hand, the rotational temperature was expected to drastically decrease from about 10,000 K to 2,000 K downstream in the nozzle by supersonic expansion, since the condition in the constrictor is considered to be near thermal equilibrium. This is also reasonable compared with the analytical results, as shown in Fig. 7.

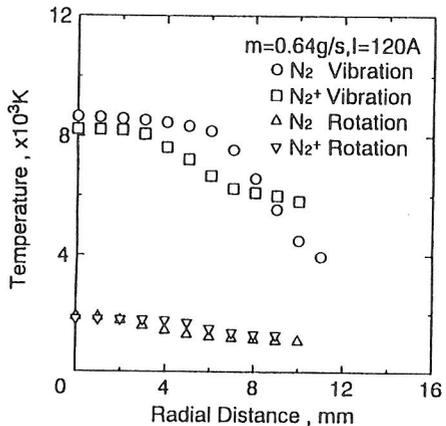


Fig. 8 Radial profiles of several temperatures at nozzle exit.

In the radial profiles as shown in Fig. 8, the vibrational temperatures of N_2 and N_2^+ have peaks of about 8,500 K on the centerline at the nozzle exit, and they extremely decrease radial-outward, although the profiles of both rotational temperatures are almost flat with 1,500–2,000 K.

IV. CONCLUSIONS

10-kW-class water-cooled nitrogen-arcjet flowfields were studied by means of spectroscopic diagnostics and numerical analysis. The atomic excitation temperature and electron density in the constrictor increased from 10,000 to 12,500 K and from 1×10^{15} to 2×10^{16} cm^{-16} , respectively, with the input power level of 7–11 kW. In the expansion nozzle, the pressure and electron density drastically decreased downstream, and therefore the plasma was expected to be in high non-equilibrium. The vibrational temperature was kept about 8,000–9,000 K in the nozzle, and the rotational temperature was expected to drastically decrease downstream, resulting in about 2,000 K near the exit.

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