

## 論文内容の要旨

### 論文題目 Characteristics of Rarefied Plasma Jet with Applied Magnetic Field and an Orifice

(印加磁場とオリフィスを有する希薄プラズマジェットの特徴)

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Nonequilibrium hydrogen plasma jets have been widely used in material processing such as thin film deposition, surface cleaning, and passivation. Such thermal nonequilibrium plasma exhibits high electron temperature and low heavy-particle temperatures. This is because thermal nonequilibrium plasma can be used for the processing of the materials which cannot endure high heat flux. Another important requirement is high degree of dissociation, which increases the efficiency of such processing.

Unlike the active utilization of plasmas seen in material processing, there are situations where plasmas cause serious problems. One of them is seen in aerospace engineering, and it is aerodynamic heating of spacecrafts entering planetary atmospheres. Considering the atmospheric entry flights at high altitude around the outer planets, the spacecrafts are surrounded by nonequilibrium hydrogen plasma flows behind the strong shock waves. This is because the smaller number density at high altitude leads to insufficient collisions between molecules to reach their equilibrium state. The accurate prediction of the aerodynamic heating during such entries requires the understanding of the relaxation processes of hydrogen molecules. However, the relaxation models of hydrogen molecules have not been established yet. One of the reasons is that experimental data are very scarce. Steady nonequilibrium plasma jets are appropriate for this investigation. Direct measurement of the plasma temperatures along the jet enables the experimental determinations of the relaxation collision numbers, which can contribute to the improvement of the models.

Based on the backgrounds described above, the plasma jets with the following characteristics can meet the needs both for hydrogen plasma processing and the relaxation study of hydrogen molecules: 1) Steady operation is possible. 2) Plasma flow is in strong thermal nonequilibrium. Electron temperature is very high, and heavy-particle temperatures are not high. 3) Plasma jet length, which can be determined by the emission of excited atomic hydrogen, is long. 4) Degree of dissociation is high. 5) Relaxations between translational and other internal modes occur. Especially in the present work, the translational-rotational relaxation was focused. The objective of this work is to produce the plasma jets to meet these requirements.

As a method to generate such hydrogen plasma flows, a new type of an experimental facility using the combination of applied magnetic field and an orifice was proposed in this study. This concept is the hybrid of two conventional devices of a solid nozzle and applied magnetic field. A solid nozzle enabling aerodynamic acceleration of the flows has disadvantage of large heat loss. Applied magnetic field enabling the smaller heat loss has disadvantage of insufficient acceleration of the neutral particles. A solid nozzle covers the disadvantage of applied magnetic field, and applied magnetic field covers the disadvantage of a solid nozzle. Therefore, the combination of both was expected to be advantageous. Aiming for the decrease in the heat loss, and the generation of nonequilibrium jet and flow acceleration by strong free expansion, an orifice was used instead of a solid nozzle. The schematic picture of the experimental facility is shown in Fig. 1. This facility design already met the first requirement, 1) steady operation.

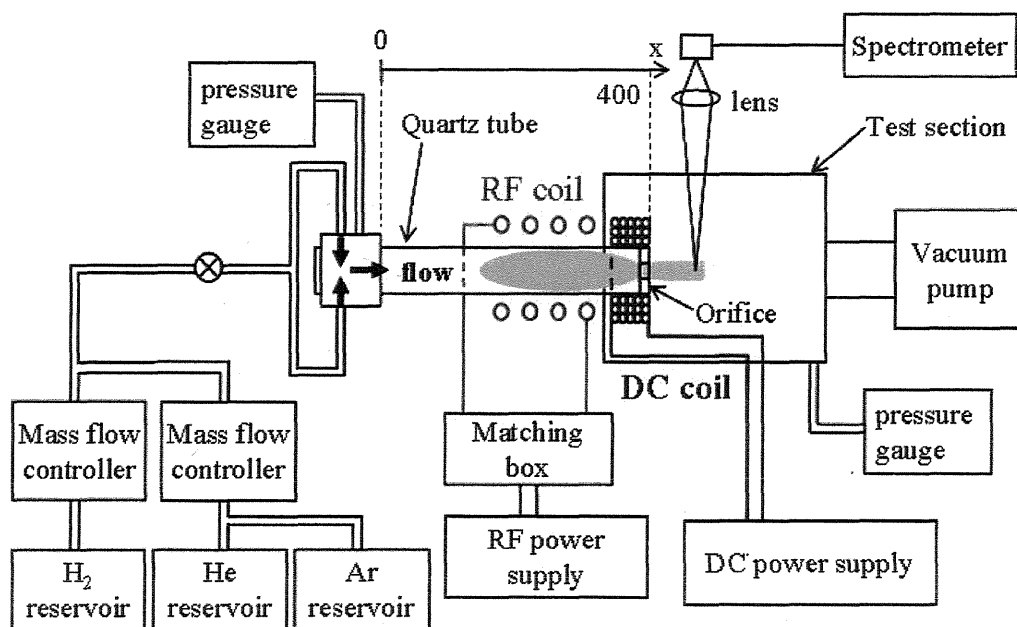


Fig. 1 Schematic picture of a new experimental facility developed in this work

The experiments were done using helium or using hydrogen admixed with a small amount of argon. Helium was used to investigate the basic dynamics of the produced jets because helium is a monatomic gas and molecular weight of helium is similar to that of hydrogen. For both gases, emission spectroscopic methods to diagnose the plasma jets were developed in this work. In helium operation, the electron temperature and the degree of

ionization were determined by the intensity fitting of the selected helium emission lines, based on the master equations. In hydrogen operation, the rotational, vibrational, and electron temperatures were determined by the line intensity fitting of Fulcher- $\alpha$  band of hydrogen molecule, the translational temperature was determined by the profile fitting of Balmer  $H_{\beta}$  line, and the degree of dissociation was determined by actinometry. These emission spectroscopic methods developed in this work were used to investigate the characteristics of the produced jets.

The usefulness of the combination of applied magnetic field and an orifice was shown in Fig. 2. There are four types of the produced plasma jets: 1) applied magnetic field and an orifice, 2) only applied magnetic field, 3) only an orifice, and 4) no applied magnetic field and no orifices. The mass flow rate of hydrogen is 0.6 SLM, and the input power is 1 kW. The orifice diameter is 6 mm. The applied DC current is 50 A, which corresponds to 42 mT of axial magnetic flux density at the center of the coil. As shown in Fig. 2, the hydrogen plasma jets produced by the combination of applied magnetic field and an orifice exhibited the longest jet length and the strongest emission. The axial distribution of the degree of dissociation obtained by the spectroscopic measurement along the centerline is shown in Fig. 3. The remarkable difference was found downstream of the orifice at  $x < 400$  mm. Though only applied magnetic field or only an orifice could increase the degree of dissociation of the produced jets, the combination of both increased the degree of dissociation much more remarkably. This combination successfully exhibited the largest degree of dissociation. The degree of dissociation in this combination was about 2 times of that in only applied magnetic field, about 5 times of that in only an orifice, and about 9 times of that in no applied magnetic field and no orifices. Higher value of the degree of dissociation is considered to be due to the increase in the electron number density, which is caused by both the increase in the static pressure by the orifice installment and the decrease in the heat loss by the applied magnetic field. Therefore, two of the requirements, 3) long jet length and 4) high degree of dissociation were met by the combination of applied magnetic field and an orifice.

Emission spectroscopic measurements revealed that the produced plasma jets have strong thermal nonequilibrium. Only the electron temperature was of the order of 1 eV, and other temperatures are low. Nonequilibrium between translational, rotational, vibrational, and electron temperatures were successfully produced, too. Therefore, the second requirement, 2) strong thermal nonequilibrium was met.

Regarding the fifth requirement, 5) relaxed flow, the translational-rotational relaxation could be spectroscopically observed by selecting the appropriate experimental condition, as shown in Fig. 4. This is due to the strong free expansion at the orifice, and the longer jet length realized by this combination. The rotational relaxation collision numbers were estimated using their temperature profiles, which supported two of the latest theoretical results.

As conclusions, the achievement of this work is that the combination of applied magnetic field and an orifice was much superior to any of only applied magnetic field, only an orifice, or no applied magnetic field and no orifices, for the production of nonequilibrium plasma jets desirable both in hydrogen plasma processing and in the relaxation study of

hydrogen molecules.

As the contents of this thesis, chapter 1 gives the introduction. Chapter 2 gives the description of the developed experimental facility. Chapter 3 describes the experiments using helium. Chapter 4 describes the experiments using hydrogen. Finally in chapter 5, conclusions are stated.

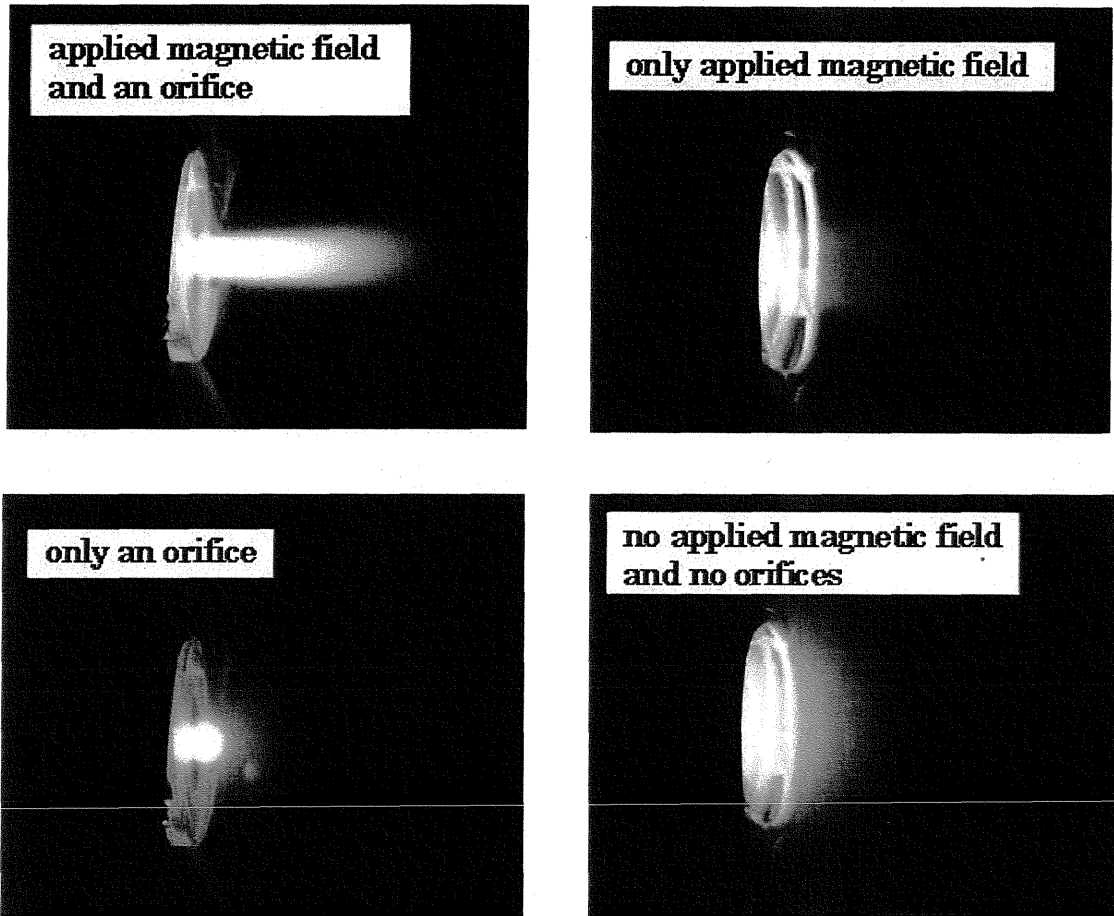


Fig. 2 Usefulness of the combination of applied magnetic field and an orifice

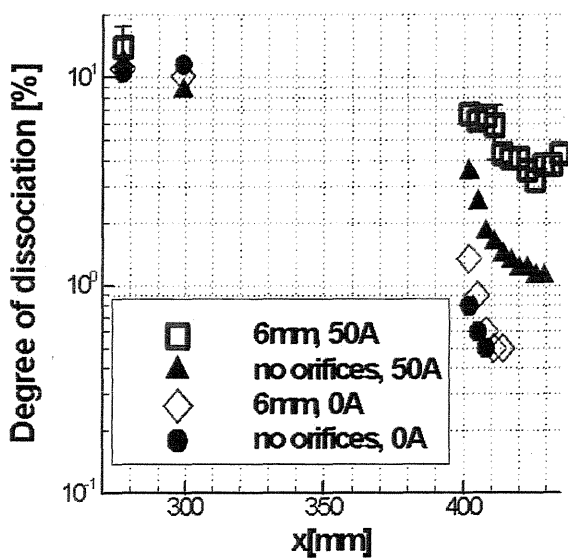


Fig. 3 Axial distribution of degree of dissociation

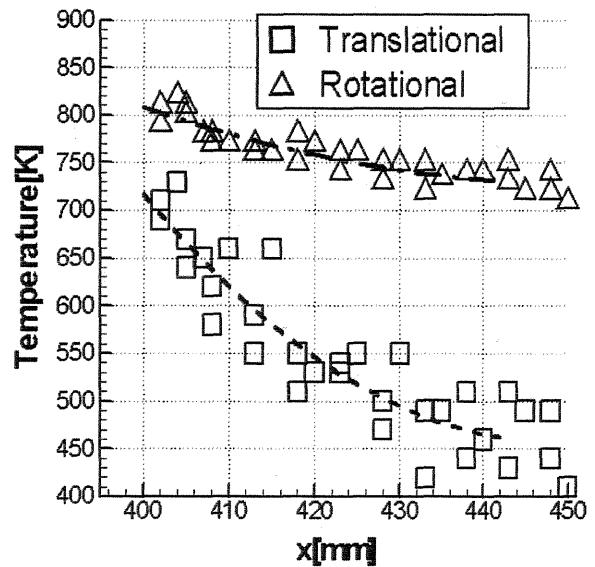


Fig. 4 Spectroscopic observation of translational-rotational relaxation