東京大学大学院新領域創成科学研究科
基盤科学研究系　先端エネルギー工学専攻
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Spectroscopic Diagnostics of Thermochemical Nonequilibrium Hydrogen Plasma Flow

－ 熱化学非平衡水素プラズマ流の分光診断－

46026　高間良樹
（指導教員　鈴木宏二郎　助教授）

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1. Introduction

Continuous explorations of outer planets are expected in the future, since missions in the past such as Galileo and Cassini have given us a lot of knowledge and discoveries of planetary science. In those atomospheric entries, the entry velocity is so high that a strong shock wave is formed in front of them. With extremely high temperature behind the shock wave, the gas, whose main component is hydrogen, is dissociated and ionized into plasma, which surronds the spacecrafts and gives them significant aerodynamic heating. Therefore, the exact prediction of aerodynamic heating caused by the plasma flow is one of the most important issues in order to make those missions feasible.

In such a flow whose velocity is extremely high, both temperature and chemical composition of the flow don't reach their equilibrium states. It is called thermochemical nonequilibrium flow. For nonequilibrium flow of hydrogen, it has been still difficult to create an appropriate model of relaxation and chemical reaction and to predict the nonequilibrium flow properties accurately. This is because of the lack of ground test data on thermochemical nonequilibrium effect. In the present study, a experimental facility utilizing inductive heating at low pressure has been developed to generate a strong thermochemical nonequilibrium flow.

Another motivation of this work is the establishment of hydrogen emission spectroscopy technique as a method of flow diagnostics, which hasn’t been investigated enough. In this work, plasma temperatures and the degree of dissociation have been measured by line intensity fitting of Fulcher-α band of molecular hydrogen and by actinometry, respectively.

2. Experimental Setup

An experimental facility and an optical system are shown in Fig.1. The greatest characteristic is a single-piece transparent quartz tube which includes plasma generation part, nozzle, and test section, and enables the observation and the measurement of the whole plasma flow. The flow is accelerated through the nozzle. The diameters of the nozzle throat and the nozzle exit are 10mm and 30mm, respectively.

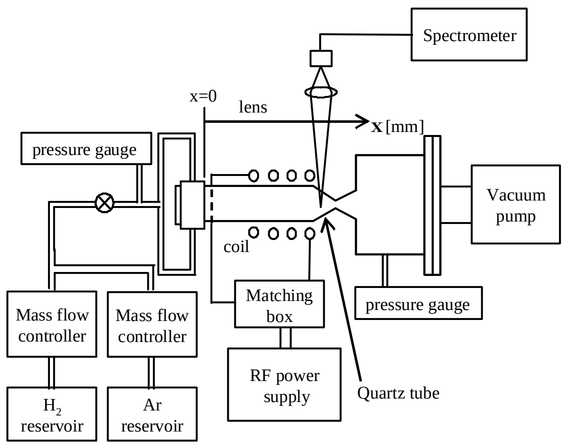

Figure 1: Experimental facility

3. Emission spectroscopy

The Spectroscopic method is shown in Fig.2.

3.1 Fulcher-α band line intensity fitting

In hydrogen plasma, the molecular band called Fulcher-α exist in the visible part of 590-640nm. It is convenient to analyze beause they are relatively free from the interference by other emission lines. Theoretical intensities of their lines are calculated as a function of rotaional, vibrational, and electron temperature. Therefore, those three temperatures can be determined so that the calculated spectra can reproduce the experimental data with the best accuracy.

3.2 Actinometry

Actinometry is the spectroscopic method for obtaining the degree of dissociation by seeding the test gas with a small amount of a noble gas. It is calculated from the intensity ratio of a line of the dissociated molecule to that of the admixed gas. In this work, argon is admixed, and Balmer H_α line(656.3nm) and Ar 750.4nm line are used.

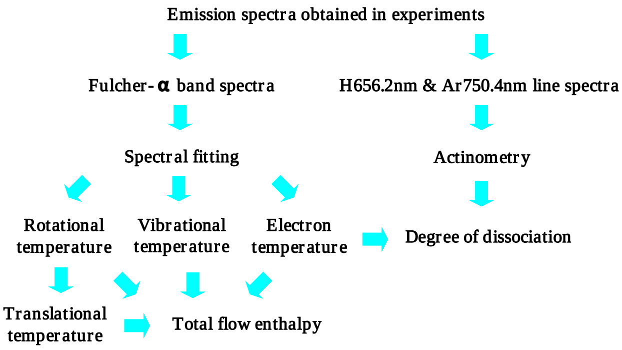

Figure 2: Diagnostic method by emission spectroscopy

4. Experimental results

The temperature distribution in the case of H_2 1SLM and Ar 0.1SLM is shown in Fig.3. It shows:

- the flow is in thermal nonequilibrium.
- the plasma is heated significantly in the upstream region of the nozzle throat.
- the input energy is first given to translational mode of electron, second to vibrational mode of hydrogen molecule, and last to rotational mode of it.
- the rotational energy is converted to kinetic energy in the nozzle region, however the vibrational and the electron energy not.
- the relaxation process between the rotational and the vibrational mode is very slow.

The degrees of dissociation obtained by actinometry and by equilibrium calculation are shown in Fig.4. It shows chemical nonequilibrium.

The measurements have been carried out in changing the mass flow rate of H_2(1.5, 2SLM).The results show the same tendency as Figs. 3 and 4. The degree of dissociation increases as the mass flow rate decreases because the energy given per hydrogen molecule increases. The calculated total enthalpy of hydrogen molecule also increases, however the increment of the enthalpy is consumed mainly for dissociation reaction. Therefore, the sum of internal and kinetic energy of the plasma is nearly constant, which is around 25-30MJ/kg. Knudsen number is around 0.001-0.005, which shows the flow is in the transitional or rarefied flow region.

The measurement errors of the temperatures are estimated with the fitting error within 5%. The counterpart of the degree of dissociation is estimated by taking into account the effects from the instability of the emission, the excitation cross sections, and the deexciation by collisional quenching of the excited atoms.

5. Concluding remarks

In order to investigate thermochemical nonequilibrium of hydrogen plasma flow, we developed a experimental facility using inductive heating at low pressure. Then, the flow diagnostics by emission pectroscopy of line intensity fitting and actinometry has been carried out, and the rotational, vibrational, and electron temperature and the degree of dissociation have been obtained. From the results, the basic characteristics of ICP flow through the nozzle are clarified. The calculated total enthalpy and Knudsen number show that our experimental facility has a capability of a high enthalpy wind tunnel in the transitional or rarefied flow region.

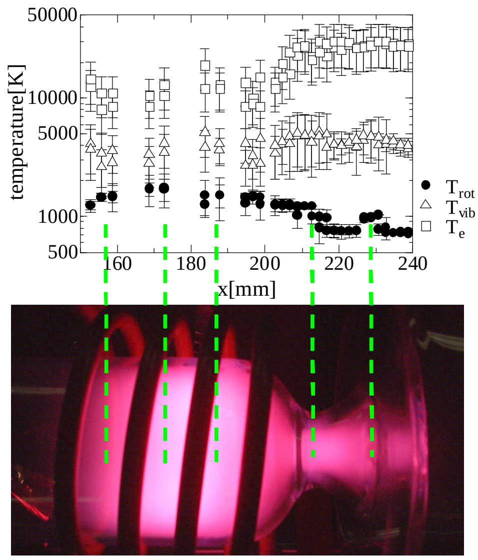

Figure 3: Plasma temperatures

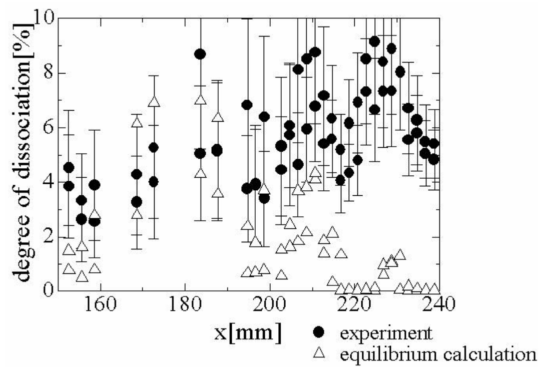

Figure 4: Degree of dissociation