Catalytic Recombination Characteristics of Atomic Oxygen on Material Surface by Optical Emission Spectroscopy

X. Lin, S. Wang, F. Li, S. Zhang, and X. Yu

Abstract Catalytic recombination of atomic oxygen, the main species of air ionization, on heat shield material surfaces was studied in a microwave plasma flow reactor. The atomic oxygen concentration profile above material samples was nonintrusive measured by optical emission spectroscopy. The catalytic recombination coefficients on material surfaces were deduced by the diffusion equation. The catalytic recombination coefficients for the heat shield materials at high temperature obtained in the present experiment are very important parameters for thermal shield design of space vehicles.

1 Introduction

The issue of hypersonic vehicle thermal protection remains a major challenge for the field of aerospace. During the reentry phase on earth or the continued flight in the earth's atmosphere, the air around the blunt head is heated to very high temperatures because of the compression effect of the strong shock. One of the most important physical phenomena occurring on the heat shield is the recombination of atomic oxygen on the spacecraft surface. The catalytic recombination coefficients for the heat shield materials at high temperature obtained in the present experiment are very important parameters for heat shield design for future space vehicles and the development of new high-temperature materials [1, 2].

Ground test simulations under atmospheric reentry conditions are therefore necessary to characterize and select base materials for heat shields [3–8]. The most essential conditions (high-temperature, low-pressure air plasma) for simulating the reentry phase of space vehicles are reproduced through carbon dioxide laser heating

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equipment and a microwave plasma generator in the Institute of Mechanics, CAS. Although such devices cannot completely simulate the characteristics of heating surface of the environment for aircraft, it can be simulated in a small sample surface catalytic process of local thermal environment, with good control (temperature, pressure range), lower operating costs [9].

In this paper, the catalytic recombination coefficients with different temperatures by optical emission spectroscopy are proposed. This provides useful information for the future thermal protection system of the spacecraft.

2 Facilities and Experiments

2.1 Experimental Setup

Experimental investigations have been carried out in the microwave plasma generator located in the Institute of Mechanics, CAS. Figure 1 presents the experimental setup for optical emission spectroscopy measurement. It contains a microwave plasma flow reactor, auxiliary heating of the CO_2 lasers, infrared thermometers, flow controllers, and the spectrum measurement system. In addition, the vacuum system consists of vacuum pumps, vacuum gauges, and other components. The output frequency of the microwave plasma flow reactor is 2450 MHz, associating with the maximum output power of 1 kW, and it consists of a silica tube with length of 50 cm and ZnSe viewport with diameter of 5 cm. The sample (20 mm diameter and 3 mm thickness) was placed in stagnation point position at the center of the discharge. In order to change the surface temperature of the sample, we use CO_2 lasers to heat the samples and the surface temperature measured by the infrared thermometer.

Spectral information was recorded using a Princeton Instruments Acton 2300. A 300 mm focal length spectrograph with three gratings was coupled to a gated intensified charge-coupled device (ICCD). A 1200 grooves/mm grating was used in the spectrometer giving a spectral resolution of 0.1 nm/pixel. An entrance slit width of 20 μm was used throughout the experiments. Furthermore, in order to obtain the concentration distribution of the axial surface, the lens collection system can shift up and down freely.

2.2 Evaluation of the Recombination Coefficients

An actinometry technique based on optical emission spectroscopy was used to determine the spatial variation of the relative atomic oxygen concentration profiles along the discharge region. The known quantity of argon (6%) is introduced in the flow, and the evolution of the relative intensities ratio I_O/I_{Ar} of the 844.6 nm (O line)

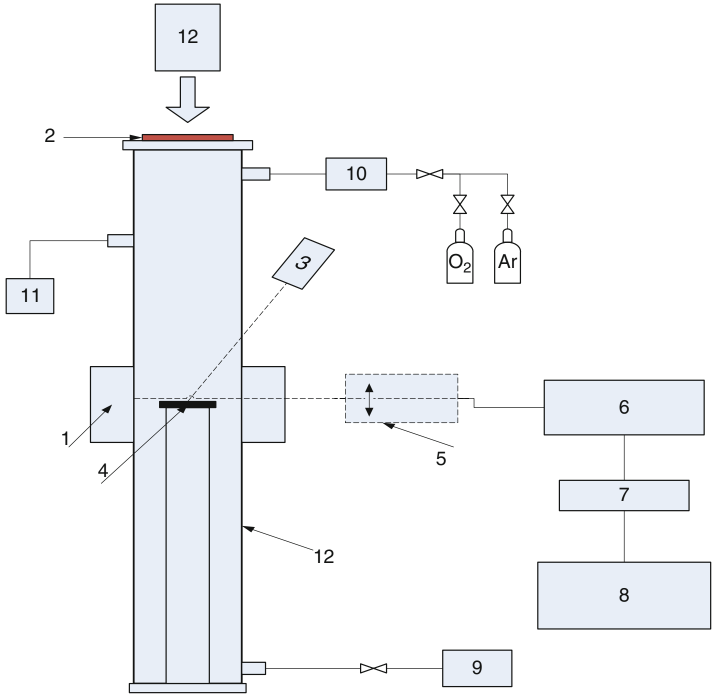

Fig. 1 Schematic of microwave plasma flow reactor and the emission spectroscopy measurement system (1. waveguide, 2. viewport, 3. infrared thermometer, 4. samples, 5. lens, 6. spectrometer, 7. ICCD, 8. computer, 9. vacuum pumps, 10. flow controllers, 11. vacuum gauges, 12. CO_2 lasers)

and 842.4 nm (Ar line) is surveyed along the discharge region through the window (diameter: 3 cm) in the waveguide. From the following equation [3]),

$$\gamma_O = \left(\frac{C_{O(x=L)}}{C_{O(x=0)}} - 1 \right) \frac{4D_{O,O_2}}{VL} \tag{1}$$

the intensity ratio profile that leads to the determination of the recombination coefficient γ is obtained, where D_{O,O_2} the binary diffusion coefficient of O in oxygen, V the mean square atomic oxygen velocity and L the thickness of the boundary layer measured from the experiment and C_O the concentration of atomic oxygen, at the entrance of the reactor ($x = L$) and at the surface of sample ($x = 0$) respectively.

Taking into account flow temperature (T_L) and surface temperature (T_S) gradient, the oxygen concentration ratio is related to the measured intensities ratio I_O/I_{Ar} by

$$\frac{C_{O(x=L)}}{C_{O(x=0)}} = \frac{\left.\frac{I_O}{I_{Ar}}\right|_{X=L}}{\left.\frac{I_O}{I_{Ar}}\right|_{X=0}} \frac{T_s}{T_L} \tag{2}$$

In this experiment, we assume that thermal equilibrium is reached, so the sample surface and gas are at the same temperature. With the assumption, the recombination coefficient γ is deduced from Eq. (3)

$$\gamma_O = \left(\frac{\left.\frac{I_O}{I_{Ar}}\right|_{X=L}}{\left.\frac{I_O}{I_{Ar}}\right|_{X=0}} - 1 \right) \frac{4D_{O,\text{air}}}{VL} \tag{3}$$

3 Results and Discussions

The relative atomic oxygen concentrations are measured in the conditions which are mentioned in the above section. In the tests, we make use of different power lasers (30, 60 W) to change the surface temperatures, which are measured by an infrared thermometer ($\lambda = 2\mu m$).

Figures 2 and 3 present the relative atomic oxygen concentrations versus the distance from the sample surface for C/SiC and low-ablation C/C respectively. The data for both figures were measured during the same experimental conditions (T $\approx$ 653 K, P = 180 Pa). Figures 2 and 3 also show good reproducibility and obvious atomic oxygen concentration gradient.

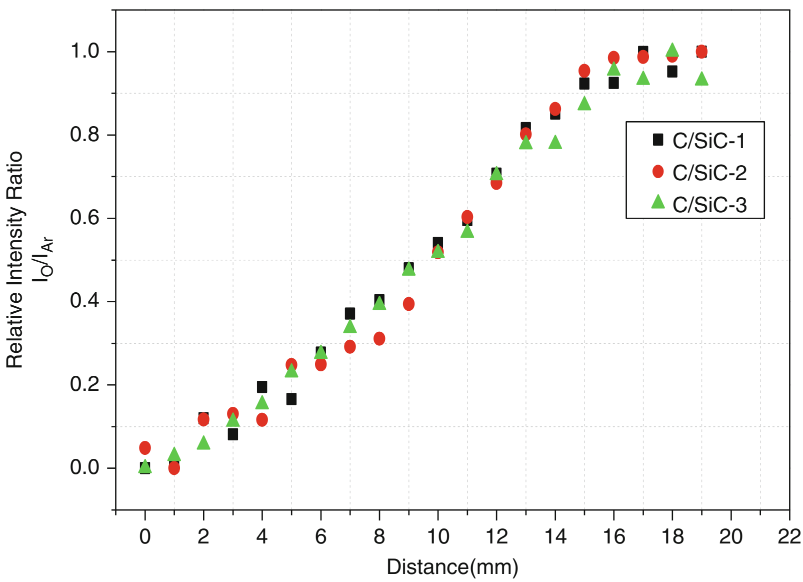

Fig. 2 The relative atomic oxygen concentration varies with the distance from the sample surface for C/SiC at 653 K and 180 Pa total air pressure

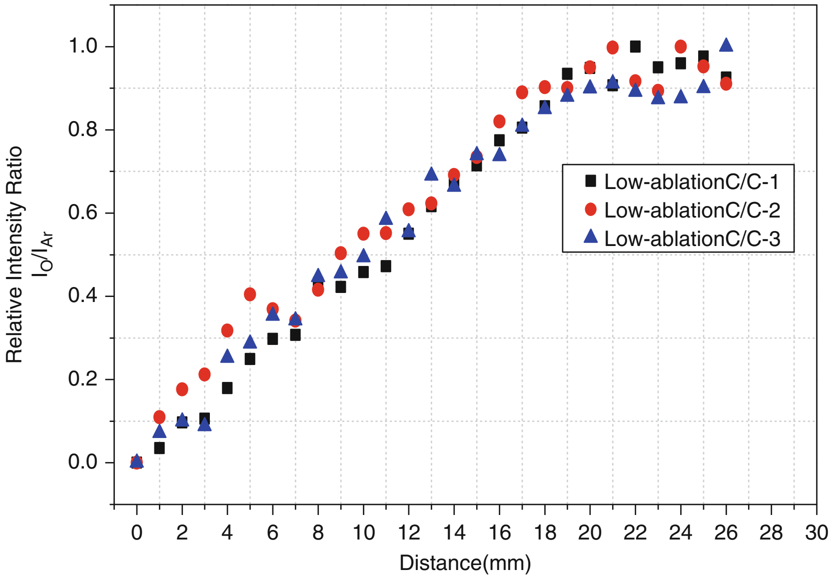

Fig. 3 The relative atomic oxygen concentration varies with the distance from the sample surface for low-ablation C/C at 623 K and 180 Pa total air pressure

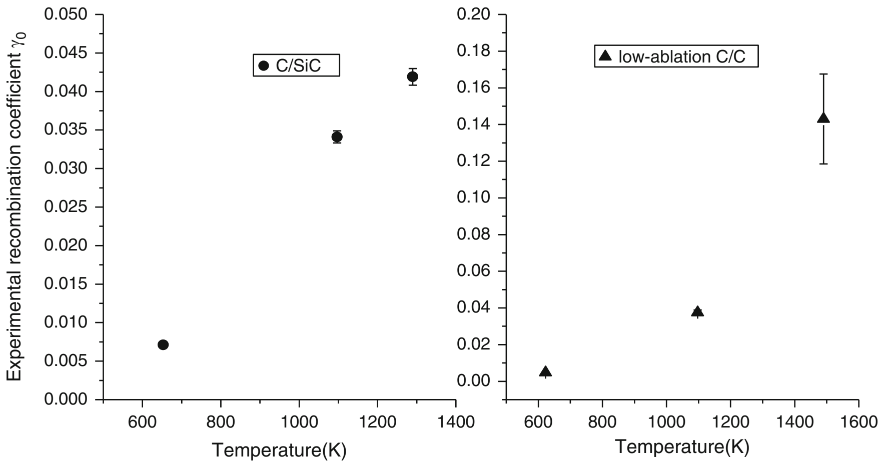

Fig. 4 Experimental recombination coefficient γ_O for atomic oxygen at 180 Pa total air pressure for C/SiC and low-ablation C/C at different temperatures

Through the catalytic reaction mechanism of the material, catalytic recombination coefficient of atomic oxygen will reach the maximum at a critical temperature [10]. Below the critical temperature, the coefficient meets the Arrhenius temperature law. The phenomena were also observed in this study. The values of the recombination coefficient γ_O have been calculated for each material as shown in Fig. 4.

4 Conclusion

By using atomic emission spectroscopy, the recombination coefficients of atomic oxygen γ_o for thermal protection materials, silicon carbide (SiC) and silica at different temperatures were obtained. The present experiments are very important for heat shield design of future space vehicles.

References

1. Y. Bian et al., *Aerothermodynamics* (USTC Press, Hefei, China, 1997)
2. J.D. Anderson, *Hypersonic and High Temperature Gas Dynamics* (McGraw-Hill Co, New York, 1989)
3. M. Balat-Pichelin et al., Chem. Phys. **291**, 181 (2003)
4. P. Kolodziej et al., AIAA **87**, 1637 (1987)
5. D.A. Stewart et al., NASA CP **2283**., Part 2, 827 (1983)
6. R.J. Willey, J. Thermophys. Heat Transf. **7**, 55 (1993)
7. C.D. Scott, *Aerothermodynamics and Planetary Entry*, Prog. Astronaut. Aeronaut. AIAA **77** (New York, 1981), pp. 192–212.
8. M. Balat et al., Appl. Surf. Sci. **120**, 225 (1997)
9. M. Balat-Pichelin, Chem. Phys. **340**, 217 (2007)
10. E.J. Jumper, J. Thermophys. Heat Transf. **8**, 460–465 (1994)