GROUND EXPERIMENTS OF INTERACTION BETWEEN PLASMA FLOW AND NEGATIVELY BIASED OR CHARGED MATERIALS

Daiki Matsuyama*, Hirokazu Tahara*, Takashi Matsuda*, Toshiki Yasui* and Takao Yoshikawa*

Division of Mechanical Science, Department of Systems and Human Science, Graduate School of Engineering Science, Osaka University
1-3, Machikaneyama, Toyonaka, Osaka 560-8531, JAPAN

Abstract

At Osaka University, a ground facility was developed for simulation of material and space plasma interaction and for study of spacecraft charging and discharge phenomena. In order to understand the interaction between plasma flow and a solar array with a negatively biased voltage, i.e., the ion sheath structure, a sample plate, which of the one side was an electrode collecting ions and of the other side was a dielectric side, was exposed to oxygen plasma flow. The ion current and the spatial plasma potential distribution were changed by the biased voltage and the attack angle of the plasma flow to the plate. Kapton films, located on the center of the negatively biased plate, were exposed to oxygen plasma flow. The x-ray photoelectron spectroscopic analysis showed drastic changes of the chemical structure near their surfaces due to ion bombardment. Polymer films negatively charged by exposure to electron beams and metal plates in series with negatively charged condensers were also exposed to argon plasma flow in order to understand the relaxation of spacecraft charging by plasma flow and the construction of a transient ion sheath.

Introduction

Spacecraft are in a severe environment in space. Their surfaces are exposed to energetic and reactive particles, such as electrons, ions, protons and oxygen atoms and ultraviolet light, during space missions. Furthermore, electrostatic interactions between the surface materials and space plasmas, such as negative or positive sheath creation, charging and arcing phenomena, frequently occur. In future long missions, materials in space will encounter drastic decreases in performance of optical and/or electrical properties by irradiation of the high energy particles and lights to their surfaces, and the surface materials may be destroyed by frequent electrical breakdown, i.e., arcing. Thus, the estimation of the decreases in performance of the physical properties is required in space before long use of materials, and also the mechanism of the material degradation, the structure of electrical sheaths and charging and arcing phenomena must be understood.

Space experiments on material degradation due to oxygen atoms or plasmas, on charging and discharge and on high voltage solar cells and plasma interactions, such as LDEF (Long Duration Exposure Facility), EOIM (Evaluation of Oxygen Interaction with Materials), SCATHA (Spacecraft Charging at High Altitude) and PIX (Plasma Interaction Experiment), were carried out by NASA and USAF. In Japan, flight experiments were initiated with the satellite ETS-V launched in 1987, and currently on ETS-VI and SPU (Space Flyer Unit) many exposure experiments were conducted. On the other hand, ground facilities and computational codes were also developed to simulate the complex phenomena around spacecraft on the ground. In some ground simulations, spacecraft materials were exposed to energetic particles in vacuum chambers, in which the dose of each particle species was matched to a real condition in space. In some experiments and computations, negative charging and arcing, and high voltage solar array and plasma interactions were studied.

At Osaka University, a ground facility was developed for simulation of material and space plasma interaction and for study of spacecraft charging and discharge phenomena. The space plasma simulator consisted of a large vacuum tank, molecular pumps with high pumping speeds and an electron cyclotron resonance plasma source of a magnetic-field-expansion plasma accelerator. Oxygen, nitrogen and argon plasma properties of plasma density, electron temperature, ion incident energy and ion freestream velocity were measured. Using the simulator, the structure of an ion sheath created around a high voltage solar array and the degradation of spacecraft surface materials near the array due to high energy ion bombardment are investigated.

The relaxation of spacecraft negative charging by plasma flow, i.e., the feature of plasma contactor operation, is also studied. Since negative charging of insulators is expected to be relaxed by attracting ions from plasma, a transient ion sheath may be constructed in front of their surfaces.

In general, an ion sheath is created around a metal plate with a negatively biased voltage in a plasma flow. This phenomenon can be observed around a high voltage solar array of spacecraft on an Earth orbit. In space satellites the current generated by a solar array is leaked by impact of ions, and furthermore the solar array is degraded by sputtering and arcing due to the collected ions. Also, a transient ion sheath is expected to be created around a negatively charged insulator when neutralizing it by plasma, resulting in surface degradation as well as in the case of high voltage solar

* Graduate Student, Osaka University.
** Associate Professor, Area of Aerospace Engineering, Graduate School of Engineering Science, Osaka University.
+ Research Associate, Osaka University.
++ Professor, Osaka University.
Copyright © 1999 by the Japan Society for Aeronautical and Space Sciences. All rights reserved.
arrays. Accordingly, it is important to understand the interaction between plasma flow and a metal or insulator plate, i.e., the ion sheath structure.

A metal plate with a negatively biased voltage is exposed to oxygen plasma flow in order to examine the characteristics of ion sheath. The collected ion current is measured for variations in the biased voltage and the attack angle of the plasma flow to the plate. The plasma potential around the plate is also measured with an emissive probe. The shape and thickness of ion sheath are discussed. Spacecraft polymer films of polyimide BPDA-PDA Kapton, located on negatively biased plates, are exposed to oxygen plasma flow. The x-ray photoelectron spectroscopic (XPS) analysis is carried out to examine changes of the chemical structure of the film surface. Furthermore, Kapton and Teflon FEP films negatively charged by exposure to electron beams and metal plates in series with negatively charged condensers are exposed to argon plasma flow in order to examine the relaxation of spacecraft charging by plasma flow. Then, for exposure of the negatively charged material to plasma flow, an ion sheath is expected to be created in front of its surface, although the sheath is becoming small as exposing. The neutralization current is measured for variations in the attack angle.

Experimental Apparatus and Conditions

Space Plasma Simulator

The space plasma simulator developed at Osaka University, as shown in Fig. 1, consists of a vacuum tank, vacuum pumps and a plasma accelerator. The electron cyclotron resonance (ECR) plasma accelerator is set on the flange of the large stainless vacuum tank 0.7 m in diameter x 1.5 m long. The main vacuum pumps are two oil-free turbo-molecular pumps (OSAKA VACUUM: TH5000VA and TH3000VA) with high pumping speeds 5 and 3 m³/s, respectively, each of which is connected to a rotary pump (ANELVA: T2033A). It takes about 90 minutes to achieve some 10⁴ Pa of tank pressure using this pumping system.

The ECR plasma accelerator, as shown in Fig.2, is a type of magnetic-field-expansion plasma accelerators. Plasma is generated by ECR heating of the interaction between microwaves and divergent magnetic fields induced by a solenoidal coil around a discharge chamber and is electrostatically accelerated by micro electric fields induced by charge separation in the magnetic fields. Since the ECR plasma accelerator has negligible contamination because of no electrodes, clean and reactive plasma flows are expected to be generated in the space plasma simulator. Microwaves of maximum 3 kW and 2.45 GHz are introduced into the discharge chamber 125 mm in inner diameter x 100 mm long through a quartz glass window 150 mm in diameter x 12 mm in width. When the relaxation of negative

![Fig.1 Schematic diagram of space plasma simulator with electron cyclotron resonance plasma accelerator.](image1)

![Fig.2 Cross section of electron cyclotron resonance plasma accelerator.](image2)

![Fig.3 Calculated applied magnetic field lines and its strength on central axis.](image3)
charging of Kapton films is examined, an orifice 5 mm in diameter is set to the downstream exit of the discharge chamber to produce a low density plasma flow. As shown in Fig.3, there exists an ECR layer with 87.5 mT about 20 mm downstream from the quartz window at a solenoidal coil current of 95 A. Oxygen, nitrogen and argon are used as the working gas. After the mass flow rate is controlled with a commercially available thermal-conductivity-type mass flow controller, the gas is radially injected from four ports just downstream from the quartz window into the discharge chamber.

Plasma parameters of electron temperature, plasma density and ion velocity are controlled by varying microwave input power, magnetic field shape and strength, and mass flow rate. They were measured with a Langmuir probe and an electrostatic energy analyzer at the sample holder located 700 mm downstream from the exit of the discharge chamber, for oxygen ranging from 2 to 6 eV, from 1x10^15 to 3x10^15 m^-3 and from 9 to 12 km/s, respectively, without the orifice. They ranged from 1 to 2 eV, from 5x10^15 to 1x10^14 m^-3 and from 13 to 20 km/s at 650 mm for argon with the orifice.

**Experimental Setup and Conditions**

1) **Exposure of Negatively Biased Metal Plates**

Square plates 50 mm x 50 mm or 25 mm x 25 mm, made of carbon, are located at 700 mm downstream from the plasma accelerator. The sample plate, which of the one side is an electrode collecting ions and of the other side is a dielectric side, is exposed to oxygen plasma flow. The ion current is measured for variations in the biased voltage and the attack angle of the plasma flow to the plate. The biased voltage is -100 to -2000 V. The plasma potential around the plate is measured with an emissive probe.

In the case of collecting ions, charge limiting occurs. When the electron density is assumed to be determined by Boltzmann distribution, the one-dimensional governing equations of Poisson and collisionless motion of ions derive a scaling law (named P parameter) just like Perveance:

\[ P = \frac{(2eN,U/\epsilon)^{1/2}}{V} \]

where L is characteristic length of metal plates, N, plasma density, U plasma velocity, V absolute biased voltage, e electron charge, m, ion mass and \( \epsilon \) dielectric constant.\(^{4,5} \)

2) **Exposure of Kapton Films on Negatively Biased Metal Plates**

Spacecraft polymer films of polyimide BPDA-PDA Kaplon, as shown in Fig.4, are exposed to oxygen plasma flow. The square films 5 mm x 5 mm are located on the center of carbon plates 25 mm x 25 mm biased to minus 0.1-1.0 kV, illustrated in Fig.5. Surface chemical structure of polyimide films before and after exposure is examined by means of XPS.

3) **Exposure of Negatively Charged Polymer Films**

Figure 6 shows the illustration of the experimental system for exposure of Kapton and Teflon FEP films negatively charged by electron beams to argon plasma flow. An electron gun, which is set on the side flange of the vacuum chamber, generates electron beams 4 mm in diameter with energies of 10-30 keV. A polymer film is set on an aluminum plate in a sample holder with the ground potential, and only a 20-mm-diam part of the film is exposed to argon plasma flow. The current from the Al plate to the ground is measured for
exposure of the film to plasma flow. The current is defined as a neutralization current. The surface potential distribution of the film is also measured by a potential probe before and after exposure to plasma flow.

4) Exposure of Metal Plates in Series with Negatively Charged Condensers

An experimental system with a metal plate in series with a condenser, as shown in Fig.7, is used to simplify exposure experiments of polymer films negatively charged by electron beams to plasma flow. The condenser is charged up to some voltage, and then the metal plate in series with the condenser is exposed to plasma flow. Neutralization of the charge stored in the condenser is expected to rapidly occur. The capacitance is 500 pF, and the metal plate is 20 mm in diameter.

Fig.8 Collected ion current dependent on attack angle of oxygen plasma flow to metal plates at 1.9 P parameter.

Fig.9 Plasma potential distributions at ram, airplane and wake conditions at 1.9 P parameter. (a) Ram condition. (b) Airplane condition. (c) Wake condition.
Results and Discussion

Ion Sheath Structure in Front of Negatively Biased Metal Plates

The collected ion current dependent on the attack angle of oxygen plasma flow to the metal side at 1.9 P parameter is shown in Fig. 8. The ion current is largest at ram condition, and it decreases with decreasing attack angle. Figure 9 shows the plasma potential distributions at ram, airplane and wake conditions at 1.9 P parameter. The ion sheath and its presheath are expected to widely spread in front of the metal plate at every condition with the same P parameter. The equipotential lines at ram condition are intensively compressed in front of the metal plate compared with those at wake condition. The profile at airplane condition extends outward downstream. As a result, plasma flow is expected to influence the motion of ions and the ion sheath structure. Furthermore, the effective area collecting ions is found to spread behind the metal side, i.e., near the insulating surface, resulting in the larger ion current, as shown in Fig. 8, than the current which is the absolute metal area multiplied by the ion flux of the plasma freestream.

Figure 10 shows the thickness of ion sheath, inferred from the measured plasma potential distributions, dependent on the P parameter. The sheath thickness decreases with increasing P parameter, as predicted from the one-dimensional sheath theory. The sheath thickness at ram condition is smaller than that at wake condition at a constant P parameter although the ion current was larger. This result shows that plasma flow influences sheath thickness.

Chemical Structure Changes of Kapton Films on Negatively Biased Metal Plates

Polyimide Kapton films, which are located on the center of carbon plates biased to -400 V, are exposed to oxygen plasma flow. The P parameter is set to 5.3. The exposure time is 15 mm, which corresponds to about 1 month in LEO.

Fig. 10 Thickness of ion sheath dependent on P parameter.

Fig. 11 XPS O1s spectrum of Kapton films before exposure to oxygen plasma flow.

(a)

(b) XPS O1s spectra of Kapton films on carbon plates negatively biased to -400 V after exposure to oxygen plasma flow at ram and wake conditions. (a) Ram condition. (b) Wake condition.
Figures 11 and 12 show the XPS O1s spectra of Kapton films before exposure, and after exposure at ram and wake conditions, respectively. The profile before exposure is deconvoluted into two Gaussian profiles of >C=O and C-O-C. After exposure, the relative intensity of >C=O decreases, and the feature of O-C-O is created only at ram condition. Accordingly, the structural feature of >C=O in inside groups is expected to be destroyed by ion bombardment. At ram condition, an addition reaction of oxygen ions or atoms intensively occur just after the destroy of >C=O bonds, resulting in the creation of the structural feature of O-C-O. The addition reaction at wake condition is expected to be negligible compared with that at ram condition because of a smaller ion flux. Consequently, it is found that the addition reaction and a desorption of structural components occurred on polyimide films by ion bombardment. They are expected to cause the decrease in performance of spacecraft thermal control.

**Relaxation of Negative Charging of Polymer Films**

Figure 13 shows the time variations of surface potentials on Kapton and Teflon FEP films during exposure to 20 keV electron beams. The surface potential rapidly increases with the irradiation time just after the start of exposure and saturates some value after enough minutes. The saturation potentials for Teflon FEP films are around -1500 V, and they are higher than that for a Kapton film. For a Teflon film 25 μm in thickness, arcing is observed with the maximum potential at 5 min.

Just after a Kapton film is negatively charged by a electron beam, it is exposed to argon plasma flow. Figures 14 shows the surface potential distribution of a Kapton film 25 μm in thickness before and after exposure to plasma flow at ram condition, i.e., just after negative charging by 20 keV electron beam and after neutralization of it by plasma flow. Although the potential profile has a peak of about -700 V within 2 mm from the center before exposure of plasma flow, it almost become zero after exposure; that is, neutralization of negative charging is made by exposure of plasma flow.

Figure 15 shows the time variations of the neutralization current from the metal plate behind the negatively charged film to the ground for exposure to plasma flow. The neutralization current intensively increases just after the start of exposure to plasma flow, and it drastically decreases after reaching a peak. Negative charging is expected to be rapidly relaxed by attracting ions from plasma, i.e., a transient ion sheath may be constructed in front of the film surface although

**Fig. 13** Time variations of surface potentials on Kapton and Teflon FEP films during exposure to 20 keV electron beams.

**Fig. 14** Potential distributions on surfaces of Kapton films 25 μm in thickness negatively charged by 20 keV electron beams before and after exposure to argon plasma flow at ram condition.

**Fig. 15** Time variations of neutralization currents from metal plates behind negatively charged Kapton films 25 μm in thickness to ground for exposure to argon plasma flow. The attack angle $\theta = 0^\circ$ corresponds to at ram condition, $\theta = 90^\circ$ at airplane one and $\theta = 180^\circ$ at wake one.
the sheath is becoming small as neutralizing negative charging. Furthermore, the attack angle is found to influence the time variation of the neutralization current. The current history at ram condition has a rapid and drastic change with the highest peak although that at wake condition has a gradual change. This is expected because a more straight-like motion of ions and a higher ion flux is realized at ram condition.

![Graph showing time variation of neutralization current](image)

**Fig.16** Time variation of neutralization current from metal plate in series with negatively charged condenser to ground for exposure to argon plasma flow at ram condition.

![Graph showing time variation of electric charge](image)

**Fig.17** Time variation of electric charge by integration of neutralization current from metal plate in series with negatively charged condenser to ground for exposure to argon plasma flow at ram condition.

**Relaxation of Negative Charging of Metal Plates in Series with Condensers**

The metal plate in series with the condenser charged to -200 V is exposed to argon plasma flow at ram condition. Figure 16 shows the time variation of the neutralization current from the metal plate to the ground. Figure 17 shows the time variation of electric charge by integration of the neutralization current. The neutralization current intensively changes just after the start of exposure. The profile is similar to that for the relaxation of negative charging of Kapton films shown in Fig. 15. The electric charge integrated also agrees with that which has been stored in the condenser before exposure. Accordingly, we can simply simulate relaxation phenomena of negative or positive charging of spacecraft by plasma flow with variations of condenser capacitance and metal plate area etc.

**Conclusions**

At Osaka University, a ground facility was developed for simulation of material and space plasma interaction and for study of spacecraft charging and discharge phenomena. The plasma simulator consisted of a vacuum tank, two turbo-molecular pumps and an electron cyclotron resonance plasma source of a magnetic-field-expansion plasma accelerator. Oxygen, nitrogen and argon plasma properties were measured. The simulator was found to have a high potential for ground tests. Using the simulator, the structure of an ion sheath created around a high voltage solar array and the degradation of surface materials near the array due to high energy ion bombardment were investigated. A negatively biased plate was exposed to oxygen plasma flow. The ion current and the plasma potential distribution were found to be intensively changed by the biased voltage and the attack angle, particularly a scaling parameter derived from the one-dimensional ion sheath theory. Furthermore, in order to examine the influences of ion bombardment on chemical structures of spacecraft surface materials, polymer films of polyimide BPDA-PDA Kapton, located on the biased plate, were exposed to oxygen plasma flow. The XPS analysis showed that an addition reaction of oxygen atoms or ions at wake condition was negligible compared with that at ram condition because of a smaller ion flux. Consequently, the addition reaction and a desorption of structural components were found to occur by ion bombardment. They are expected to cause the decrease in performance of spacecraft thermal control. Furthermore, in order to understand the relaxation of spacecraft charging by plasma flow, i.e., plasma contactor operation, Kapton and Tefton FEP films negatively charged by exposure to high energy electron beams and metal plates in series with negatively charged condensers were exposed to argon plasma flow. Negative charging was rapidly relaxed, and the attack angle influenced the time variation of the neutralization current.

**References**