TSINGHUA SCIENCE AND TECHNOLOGY
ISSN 1007-0214 10/21 pp49-53
Volume 14, Number S2, December 2009

Experimental Investigation of Microhollow Cathode Discharge for the Application to Microplasma Thrusters*

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Abstract: As to microhollow cathode discharge (MHCD) in argon, the discharge characteristic was analyzed, the gas temperature was determined from the emission spectroscopy with traces of nitrogen added, and the electron density was also evaluated through the Stark broadening of the Balmer H_β line from hydrogen as trace impurity in the gas. The electron density is in the order of 10^{14} cm^{-3} and increases with the increasing gas pressure and discharge current. The gas temperature also increases with the increasing pressure and current, and can reach 1000 K in the stable glow regime. The results show that the extremely small dimensions of the MHCD combining with relative intense and controllable gas heating can be applied as a new micro electro-thermal thruster for micro-satellite propulsion. Due to the heating of the propellant gas in the microdischarge plasma and its expansion through the micro-nozzle, the performance of specific impulse and thrust of the microplasma thruster using the MHCD will be higher than the conventional cold gas microthrusters.

Key words: microhollow cathode discharge (MHCD); electric propulsion; microthruster; optical emission spectroscopy (OES)

Introduction

The micro, nano, and pico-satellite technology has rapidly progressed over the past few years and becomes an important research direction of the international aerospace industry. It particularly makes benefit of the development of micro electronic technology, especially with the rapid development of micron/nanometer size technologies like micro electromechanical system (MEMS) and micro-optical electromechanical system (MOEMS). Micro-satellites possess the advantages of small volume, low weight, good performance, high reliability, relatively quick manufacture, and low cost. They not only perform the main functions of the traditional large size satellites, but also accomplish different and high demands with distributed satellites constellation. Therefore, they have wide applications. The formations of micro-satellites will play an important role in the future utilization of the space. With the development and application of micro-satellites, new types of advanced microthrusters are developed for station keeping along with attitude control and precise pointing. Apart from the traditional cold gas thruster, the micro thrusters such as micro field emission electric propulsion, micro colloid thruster, micro pulsed plasma thruster, micro hall thruster, MEMS microthruster, free molecular microresistojet, and microdischarge plasma thruster are now in the way of development.

Received: 2009-05-08; revised: 2009-06-20

* Supported by the China Scholarship Council (No. 2006[3074])

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The microhollow cathode discharge (MHCD) is a kind of micro non-equilibrium gas discharge. One of the important advantages of MHCD is that it can be generated and maintained at high pressure with a very low applied voltage or input power. Potential applications for the devices using MHCD technology include light source, electron source, analytical spectroscopy, material processing, sterilization, microplasma jet, and microplasma propulsion[1].

In the USA, several planned missions to perform experiments with distributed multiple micro-satellites are supported by National Aeronautics and Space Administration (NASA) and United States Air Force (USAF). The mission of FASTRAC (Formation Autonomy Spacecraft with Thrust, Rel-Nav, Attitude and Crosslink) is designed and integrated using a pair of nano-satellites by University of Texas at Austin. The satellites will be launched from Kodiak Island, Alaska in the fall of 2009 on a Minotaur IV rocket. Three specific new and innovative technologies will be demonstrated during the mission, including GPS relative navigation, distributed communications, and microdischarge plasma thrusters[2]. Each satellite will contain a microplasma thruster which generating low-thrust, high-efficiency propulsion at low power levels using MHCD.

1 Experiments on MHCD

Optical emission measurements were performed to characterize the MHCD plasma. This spectroscopic method is non-invasive, easy to apply, and very reliable, especially for microplasmas for which other diagnostic methods, like Langmuir probe or microwave interferometry, are not applicable because of the extremely small plasma volume. Optical emission spectroscopy (OES) is a powerful method to obtain information about the most important characteristics of plasmas operating in low or high pressure. In order to measure the basic plasma parameters to well understand the mechanism of the microdischarge, we have used diagnostic techniques, such as analyzing the Stark broadening of the hydrogen Balmer H_β (486.133 nm) line for the determination of the electron density and analyzing the rotational structures of the N_2 first positive $(B^3\Pi_g - A^3\Sigma_u^+)$ bands or N_2^+ first negative $(B^2\Sigma_u^+ - X^2\Sigma_g^+)$ bands for the measurement of the gas temperature.

1.1 Experimental facilities

The experimental setup is shown in Fig. 1. The MHCD device is a metal-dielectric-metal sandwich structure.

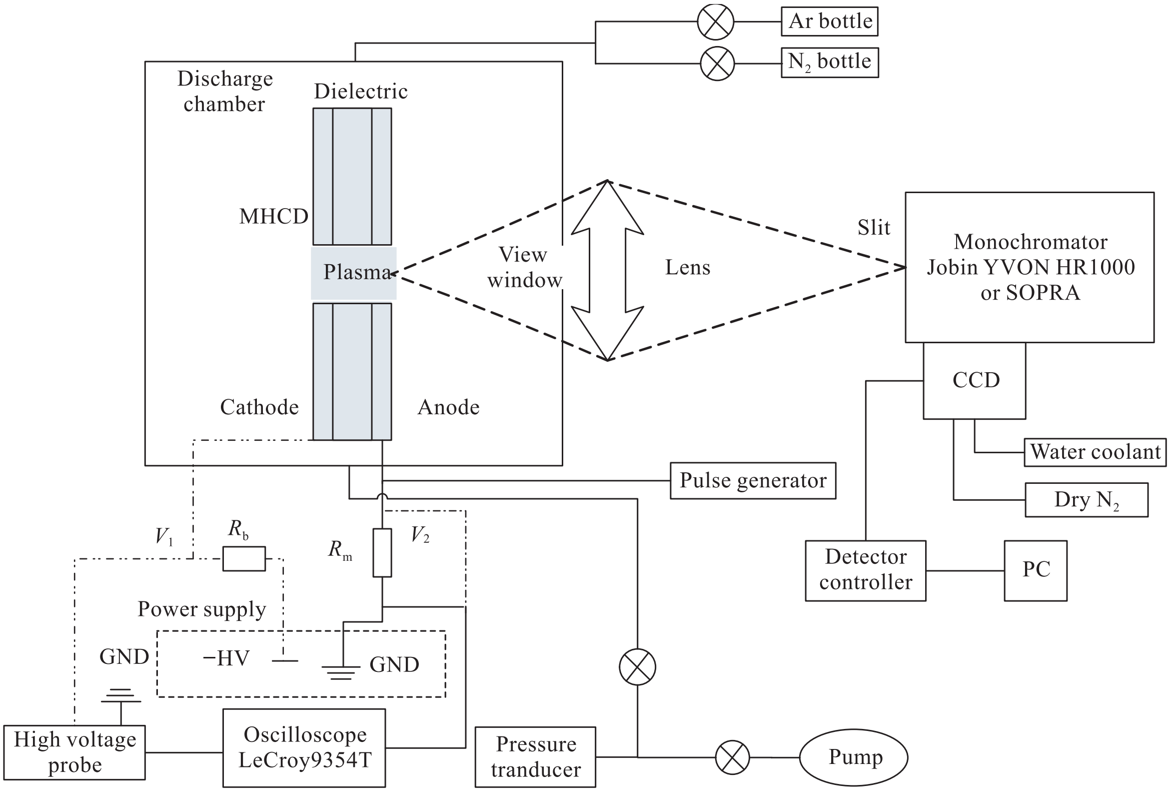

Fig. 1 Experimental setup for the optical emission spectroscopy measurements with the MHCD

Two 100 μm thick molybdenum foils, acting as electrodes, are stacked on a 250 μm thick alumina foil. A hole is drilled through the sandwich with the hole diameter of 100 μm in the experiments. The pressure ranges from 50 Torr to 750 Torr (1 Torr=133.3 Pa). A fixed argon flow rate of 5 sccm is maintained during measurements to avoid any gas contamination due to sputtering of the electrodes or degassing from the plasma charmber surfaces. An R_b=500 kΩ ballast resistor is located on the cathode side and an R_m=100 Ω resistor on the anode side serves for the current measurements. Both the voltage between electrodes (V_1), measured with a 1:1000 high voltage probe (Tektronix P6015) and the discharge current (V_2/R_m) are directly recorded on a 500 MHz digital oscilloscope (LeCroy 9354T)[3].

The diagnostic system for spectroscopy consists of a 1 m focal length monochromator (Jobin Yvon HR1000) with a 1200 line/mm grating or a 2 m focal length monochromator (SOPRA) with a 1200 line/mm grating working in the third diffraction order and different CCD detectors. An 18 mm focal length len forms the image of the MHCD from the anode side, on the entrance slit of the monochromator with a magnification factor of about 10. The diameter of the MHCD is aligned with the slit so different spectral lines are got in different horizontal pixels of the CCD camera and for each line the amplitude of the vertical pixels of the CCD provides the radial intensity distribution of MHCD. The gas temperature, the electron density, and the spatial distribution of the particles are determined from the OES measurements.

1.2 Discharge characteristics

For lower pressures, the voltage-current (V-I) characteristics have three domains as the current increases. For higher pressures the first domain disappears. In the first domain, a small increase of the current needs a steep increase of the voltage and the plasma is confined inside the MHCD hole. This region corresponds in fact to an abnormal regime. In the second domain, the discharge current and the voltage are modulated in a self-pulsing regime. The averaged voltage decreases when the averaged current increases. The upper limit of the averaged current is around 1 mA and it strongly depends on the pressure[4]. In the last domain, the voltage is constant around 200 V while the current increases from 1 to 3 mA. This region corresponds to a normal glow discharge, where the plasma largely spreads over the backside surface of the MHCD cathode.

1.3 Gas temperature measurement

In plasma diagnostics, usually the gas temperature is deduced by optical emission spectroscopy (OES) measurements from the rotational distribution of the intensity in a molecular band. Assuming that the emitting N_2 molecules or N_2^+ ions can be described by a Maxwell-Boltzmann distribution characterized by a single rotational temperature T_R, this temperature can be determined from a fit of the measured emission spectrum, usually from a single, isolated vibrational band, to a synthetic spectrum with T_R as the free parameter. The measured rotational temperature of N_2 or N_2^+ can be interpreted as the gas kinetic temperature in the plasma if the emitting species are in equilibrium with the bulk gas in the plasma[5].

Figure 2 shows that at the stable glow regime for different pressures, the gas temperature in the MHCD hole increases as a function of the discharge current. It can reach 700 K at 300 Torr with the current of 2.5 mA[6,7]. The gas temperature is about 1000 K at 750 Torr with the current of 3 mA.

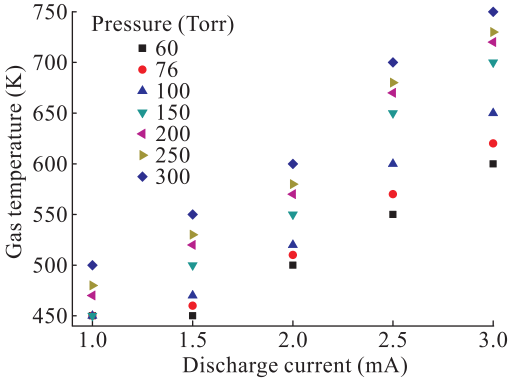

Fig. 2 Gas temperature for different pressures as a function of discharge current

1.4 Electron density measurement

In plasma with electron density greater than about 5×10^{13} cm^{-3}, the spatially and temporally resolved electron density can be measured from the lineshape of the Balmer β transition (4-2) of atomic hydrogen at 486.133 nm[8]. The technique requires the presence in the plasma of a small amount (typically less than 0.1%

mole fraction) of hydrogen, which in our case came from the dissociation of impurities in the argon gas (water vapour desorbed from the surface or oil vapour from the pump). Compare to the other hydrogen Balmer lines, the H_β line is often preferred because it has an adequate emission intensity, a high sensitivity to the electron density, and a low susceptibility to the self-absorption.

Stark broadening arises from the interaction of charged particles, i.e., ions and electrons with the excited emitters. Both ions and electrons induce Stark broadening, but electrons are responsible for the major part because of their higher relative velocities. In order to obtain the precise electron density contributing to the line broadening, some other mechanisms besides those related to the electrons were considered, such as instrumental broadening (deduced from the spectral profile of an Ar^+ line recorded at low pressure), Doppler broadening (calculated using the gas temperature measurements of 2.3), and pressure (Van der Waals) broadening (calculated using the relation taken from Table 1 of Ref. [5] and the gas temperature).

The electron density obtained from Stark broadening of the Balmer H_β-line of MHCD in argon is shown in Fig. 3 for discharge currents up to 3 mA and gas pressures from 50 to 750 Torr. The electron density is in the order of 10^{14} cm^{-3} and increases with the increasing gas pressure and discharge current. This value is at least one order of magnitude higher than those obtained for any other high pressure, nonthermal glow discharge[9].

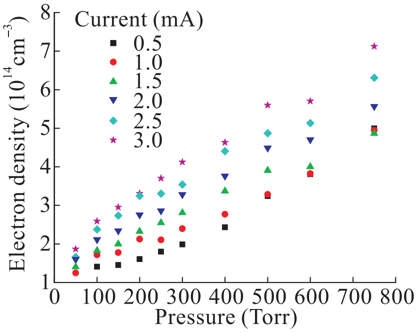

Fig. 3 Electron density measured from Stark broadening for different discharge currents as function of argon pressure

2 Microplasma Thruster Using MHCD

MHCD plasma thruster is a new microplasma propulsion system for attitude control and station keeping of nano-satellites, which can provide a micro-Newton level thrust with high efficiency and low power using microdischarge plasma. Figure 4 shows the schematic structure of an MHCD plasma thruster. It has a very simple configuration and comprises two main parts: one is the MHCD and the other is the micro-nozzle. The method of heating the propellant gas to combustion-like temperature of about 1000 K using MHCD is an innovative way in nano-satellite propulsion technology. The hot gas heated is expanded through a Laval-type converging-diverging micro-nozzle to produce thrust[10]. Actually, the MHCD plasma thruster propulsion device can comprise an array of individual microthrusters that are fabricated on a single substrate/panel.

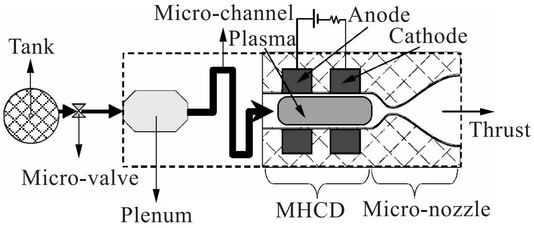

Fig. 4 MHCD plasma thruster

The size of the individual microthruster is about 1 cm^3 and the discharge chamber is 1000 μm×200 μm×200 μm. The throat diameter of the micro-nozzle is about 107 μm, the exit diameter is about 303 μm, and the length is 500 μm. The pressure inside the plenum and the discharge chamber is about 1 atm. The micro-channel, 1500 μm long, with a rectangular cross-section, 29 μm×50 μm, and 90° bends, is acting as an injector that supplies the discharge chamber with propellant regulated for both the pressure and the mass flow rate. The injector will provide the regulated propellant flow to the discharge chamber by eliminating the pressure fluctuation[11].

According to the principle of the traditional rocket engine, the specific impulse and thrust can be calculated as follows[12]:

$$I_{sp}=\sqrt{2R_0\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{T_c}{M_{mol}}\right)\left[1-\left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}+\frac{(p_e-p_a)A_e}{\dot{m}} \tag{1}$$

$$F=\dot{m}u_e+(p_e-p_a)A_e \tag{2}$$

$$u_e=\sqrt{2R_0\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{T_c}{M_{mol}}\right)\left[1-\left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{3}$$

The relation between the area ratio of the nozzle and the pressure ratio is expressed as

$$\frac{A_{\mathrm{e}}}{A_{\mathrm{t}}}=\frac{\Gamma}{\left(\frac{p_{\mathrm{e}}}{p_{\mathrm{c}}}\right)^{\frac{1}{\gamma}}\sqrt{\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{p_{\mathrm{e}}}{p_{\mathrm{c}}}\right)^{\frac{\gamma-1}{\gamma}}\right]}} \tag{4}$$

where $\Gamma=\sqrt{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$, T_{c} is the heated gas temperature, γ is the specific heat ratio, M_{mol} is the molar mass, $\dot{m}$ is the mass flow rate, $\dot{m}=0.15$ - 1.5 mg/s, $R_0=8.314\ 510$ J/(mol•K), A_{e} is the exit area of the nozzle, A_{t} is the throat area of the nozzle, u_{e} is the exit velocity, p_{c} is the pressure in the discharge chamber, p_{e} is the exit pressure, and the ambient pressure p_{a} is assumed 80 Pa.

The thrust produced by this kind of propulsion system is expected to be in the range of several tens to several hundreds micro-Newton and the specific impulse is evaluated on the order of 1000 N•s/kg using argon while on the order of 3000 N•s/kg using helium as propellant gas.

3 Conclusions

A stable, direct current microplasma, operating in a very large range of high gas pressure, can be generated and maintained in the MHCD configuration. An important physical phenomenon of this kind of microdischarge is the efficient thermal heating of the gas flow to a combustion-like temperature of about 1000 K and this gas temperature strongly depends on the gas pressure and the discharge current. Therefore, the microdischarge technology can be applied to the microplasma propulsion system for nano-satellite. The MHCD plasma thruster has several advantages, including simple structure, stable discharge at high pressure, operating in a variety of propellants such as argon, helium, or xenon, and the possibility for forming a large array of individual microthrusters on a single substrate/panel to produce large range thrust. The evaluated specific impulse is on the order of 1000 N•s/kg when using argon while on the order of 3000 N•s/kg using helium and the thrust is in the range about several tens to several hundreds micro-Newton. Since the typical specific impulse level of the cold gas thruster is about 600 N•s/kg, the performance of the microplasma thruster using the MHCD is higher than the conventional cold gas microthrusters.

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