Theoretical and Experimental Investigation of Microhollow Cathode Discharge for the Application to Micro Plasma Thrusters

IEPC-2009-028

Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009

XIA Guangqing[1]
School of Aeronautics and Astronautics, Faculty of Vehicle Engineering and Mechanics, State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian, 116024, China

MAO Genwang[2] and CHEN Maolin[3]
School of Astronautics, Northwestern Polytechnical University, Xi'an, 710072, China

and

WU Chuijie[4]
School of Aeronautics and Astronautics, Dalian University of Technology, Dalian, 116024, China

Abstract: The development and application of micro-satellites urgently needs new types of micro-thrusters. As an important classification of plasma discharges, microdischarge is favored with considerable interest in the plasma field over the past decade. Microhollow cathode discharge (MHCD) is a kind of high pressure, non-equilibrium gas discharges. The gas temperature determined from the emission spectroscopy with traces of nitrogen added. In argon discharges, the electron density was also evaluated through the Stark broadening of the Balmer H_β line from hydrogen present as trace impurity in the gas. The numerical model which is based on solutions of fluid equations in the drift-diffusion approximation for the electron and ion transport coupled with Poisson's equation was used. In combination of the extremely small dimensions and relative high and controllable gas temperature of the MHCD, it can be used as propulsion system of a new micro electro-thermal thruster. The performance of the micro plasma thruster using MHCD, such as specific impulse and thrust, will be higher than that of the conventional cold gas micro-thruster, because the propellant gas is heated in the microdischarge plasma thruster and then expand through the micro-nozzle to produce the thrust.

Nomenclature

A	=	area
F	=	thrust
I_{sp}	=	specific impulse
M	=	mass
$\dot{m}$	=	mass flow rate

[1] Senior Lecturer, School of Aeronautics and Astronautics, gq.xia@dlut.edu.cn.
[2] Professor, School of Astronautics, maogenwang@nwpu.edu.cn.
[3] Doctor, School of Astronautics, chmaolin@mail.nwpu.edu.cn.
[4] Professor, School of Aeronautics and Astronautics, cjwudut@dlut.edu.cn.

p = pressure
P = input power
T = gas temperature
u = velocity
γ = specific heat ratio
θ = half divergence angle

Subscripts
a = ambient
c = discharge chamber
e = nozzle exit
mol = molar
t = nozzle throat

I. Introduction

THE rapid developments and applications of micro-satellites (mass less than 100 kg) in the various industry, military and science space missions urgently need new types of microthrusters[1]. Since scaling down the traditional propulsion systems in power and size to suit the needs of micro-satellites is still a major engineering challenge, a possibility for the advanced microthrusters would make use of the latest microplasma technology. Microhollow cathode discharges (MHCDs) are high pressure, non-equilibrium gas discharges inside the few hundreds microns of diameter hole drilled in a metal-dielectric-metal sandwich. A stable discharge can be produced and sustained at high pressure in this device with relative low voltage (several hundreds volts) or input power (several hundreds milliwatts to several watts). Currently, potential applications for the devices using MHCD technology include light source, electron source, analytical spectroscopy, material processing, sterilization, microplasma jet, and microplasma propulsion[2]. The mission of FASTRAC in America is designed and integrated using a pair of nano-satellites by University of Texas at Austin[3]. Each satellite will contain a microdischarge plasma thruster which generating low-thrust, high-efficiency propulsion at low power levels using MHCD. In this paper, both experimental investigations by optical emission spectroscopy (OES) and numerical simulation work were used for well researching the fundamentals of MHCD. The study provides important understanding to evaluate and design the microplasma thruster.

II. Experiments on MHCD

The MHCD device is a metal-dielectric-metal sandwich structure. 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 presented here. The pressure ranges from 50 Torr to 750 Torr.

A. Gas Temperature Measurement

In plasma diagnostics, very often the gas temperature is deduced by OES measurements from the rotational distribution of the intensity in a molecular band. In this paper, the rotational structures of the N_2 first positive bands or N_2^+ first negative bands were analyzed for the measurements of the gas temperature. 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[4].

Fig. 1 shows that at 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 2.5 mA[5,6]. The gas temperature is about 1000 K at 750 Torr with the current 3 mA.

B. Electron Density Measurement

In plasma with electron density greater than about 5×10^{13} cm^{-3}, spatially and temporally resolved electron density can be measured from the lineshape of the Balmer β transition (4-2) of atomic hydrogen at 486.133nm[7]. 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). 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 than that 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), and pressure (Van der Waals) broadening (calculated using the relation taken from table 1 of 7) 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. 2 for discharge currents up to 3 mA and gas pressures from 50 Torr to 750 Torr. The electron density is on the order of 10^{14}-10^{15} cm^{-3} and increases with the increasing gas pressure and the discharge current. This value is at least one order of magnitude higher than that obtained for any other high pressure, nonthermal glow discharge[8].

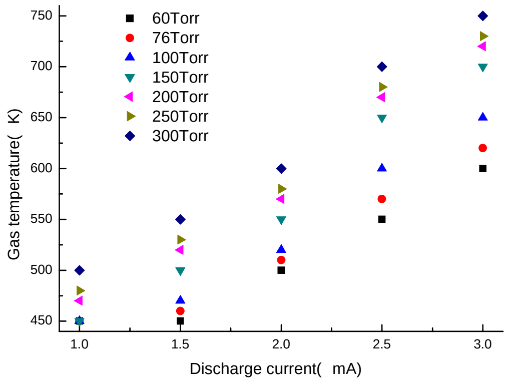

Figure 1. Gas temperature for different pressures as a function of discharge current

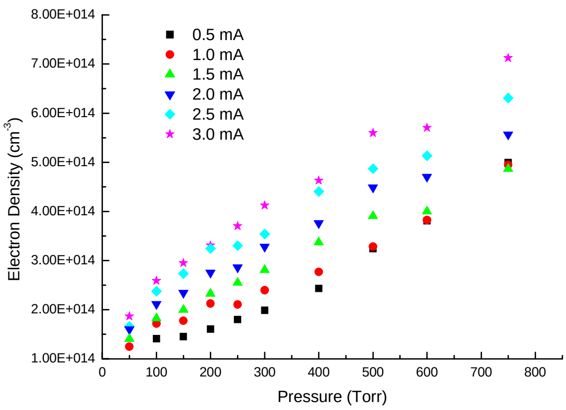

Figure 2. Electron density for different discharge currents as function of argon pressure

III. Numerical Simulation

A. Numerical Model

The two-dimensional numerical model consists of the continuity equations for electron and ion and Poisson's equation for electric field. The model considers the drift-diffusion approximation for the flux of electron and ion and accounts for the mean electron energy dependence of the ionization rate by adding the electron energy equation.

In the numerical study, two molybdenum foils with 100 µm thickness are stacked on an alumina foil with 250 µm thickness. The ports with the hole diameter 100 µm are drilled through the sandwich. The discharge occurs in argon with the pressure 100 Torr and the voltage keeps constant around 200 V under normal glow mode.

B. Calculation Results

The computation results show the potential profile, electron density, ion density and electron temperature spatial distribution. The potential contour shows that the axial component of the electric field is dominant at the discharge initialization and then the radial component of the electric field becomes very important as the forming of the cathode sheath (Fig. 3). The strong radial electric field at the cathode facilitates ionization process. The results indicate the temporal dynamic behavior of MHCD in initialization phase with the electron density of order 10^{19} m^{-3} (Fig. 4), electron temperature of several to tens of eV (Fig. 5). The peak electron/ion density occurs near the region of the cathode and the dielectric as well as near the anode at the discharge initialization, then localizes along the centerline of the hollow near the cathode.

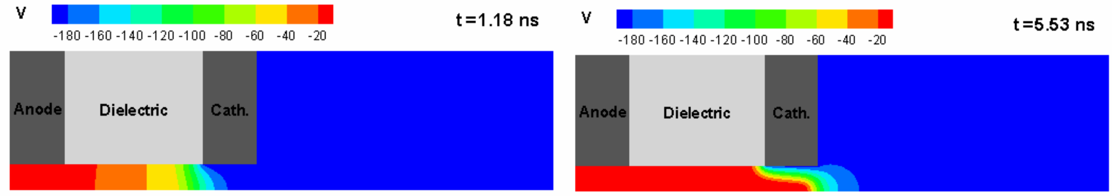

Figure 3. Potential contours at different time (in V)

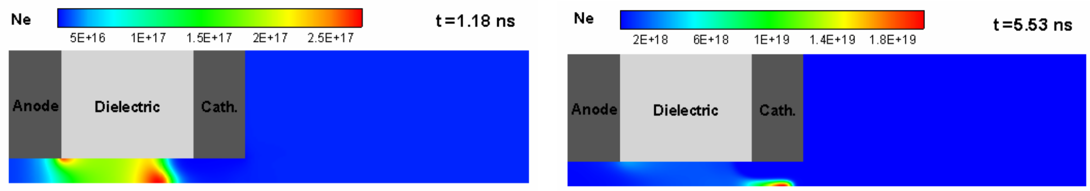

Figure 4. Electron density distributions at different time (in m^{-3})

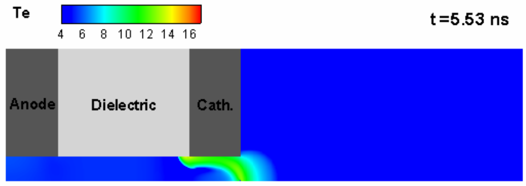

Figure 5. Electron temperature distribution (in eV)

Most of the model predictions are in agreement with experimental data for MHCD under the similar conditions.

IV. Microplasma Thruster using MHCD

MHCD plasma thruster is a new microplasma propulsion system for attitude control and station keeping of nano-satellites. It can provide a micro-Newton level thrust with high efficiency and low power using microdischarge plasma. Fig. 6 shows the schematic structure of a 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[3)]. The method of heating the propellant gas to the temperature of ~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. Actually, the MHCD plasma thruster propulsion device can comprise an array of individual microthrusters that are fabricated on a single substrate/panel.

The throat diameter of the micro-nozzle is about 100 μm, the exit diameter is about 320 μm, and the length is 500 μm. The half divergence angle of the nozzle is 20°, A_e/A_t=10. The pressure inside the plenum and the discharge chamber is about several tens to several hundreds Pa.

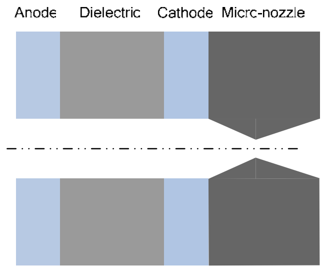

Figure 6. Schematic of MHCD plasma thruster

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

$$I_{sp} = \left[\frac{1}{2}(1+\cos\theta)\right]\sqrt{2R_0\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{T_c}{M_{mol}}\right)\left[1-\left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} + \frac{(p_e-p_a)\pi d_e^2}{4\dot{m}} \quad (1)$$

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

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

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

$$\frac{A_e}{A_t} = \frac{\Gamma}{\left(\frac{p_e}{p_c}\right)^{\frac{1}{\gamma}}\sqrt{\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}} \quad (4)$$

$$\Gamma = \sqrt{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (5)$$

where, $\dot{m} = 0.15 \sim 1.5$ mg/s, $R_0 = 8.314510\ J/(mol\cdot K)$, p_a is assumed 80 Pa.

Fig. 7 and Fig. 8 show the effects of discharge current on specific impulse and thrust, respectively. With mass flow rate of 0.15 mg/s in argon, the specific impulse and thrust are higher for bigger discharge current at the same pressure conditions. And at the same discharge current, the specific impulse and thrust increase with increasing working pressure. The results show that the MHCD plasma thruster can adjust main performance parameters effectively within a certain range.

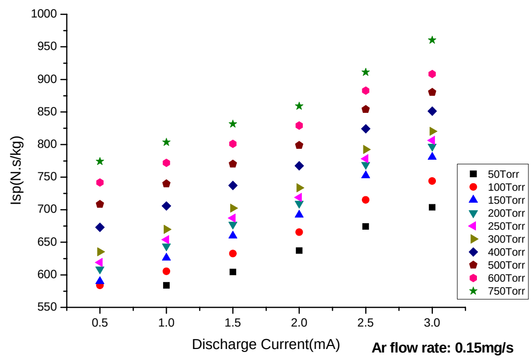

Figure 7. Specific impulse as function of discharge current

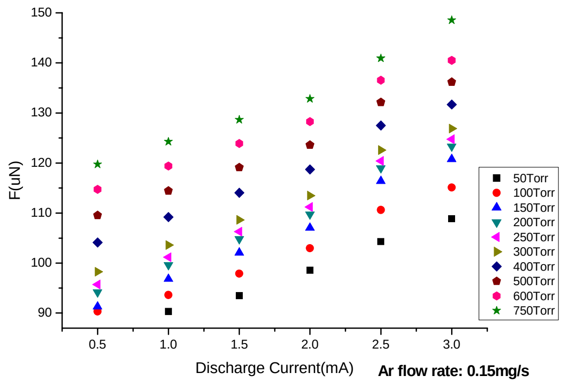

Figure 8. Thrust as function of discharge current

Fig. 9 shows the relation of thrust and input power at the discharge pressure of 750 Torr and mass flow rate of 1.5 mg/s in argon. The thrust increase with increasing input power. For the input power of 0.15~2 W, the magnitude of thrust can reach 1.2~1.5 mN.

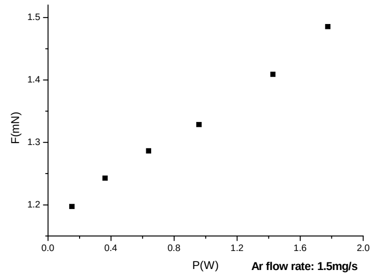

Figure 9. Thrust as function of input power

With the MHCD hole diameter 100 μm and at the pressure 50~750 Torr, input power 0.15~2 W and mass flow rate 0.15~1.5 mg/s, the thrust produced by this kind of propulsion system is preliminary expected to be in the range of several tens to several thousands micro-Newton and the specific impulse is evaluated on the order of 600~1000 N·s/kg when using argon while on the order of 3000 N·s/kg using helium as the propellant gas.

V. Conclusion

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 the temperature of ~1000 K and this gas temperature is strongly depending 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 600~1000 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 thousands 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.

Acknowledgments

The author, Xia Guangqing was financed by the state studying abroad scholarship fund of Doctoral College of France-China to pursue the microdischarge study in the Joseph Fourier University and greatly acknowledged China Scholarship Council. The authors also thank Drs. Nader Sadeghi and Michel Touzeau for helpful discussions and Drs. Xavier Aubert and João Santos Sousa for the help of experimental work.

References

[1] Micci, M. M. and Ketsdever, A. D.: *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, AIAA, Reston, Virginia, 2000, pp. 3-5.

[2] Kothnur, P. S. and Raja, L. L.: Two-dimensional Simulation of a Direct-current Microhollow Cathode Discharge, *Journal of Applied Physics*, **97**(2005), 043305, pp. 1-12.

[3] Holt, G., Stewart, S., Mauldin, J. and et al.: Relative Navigation, Microdischarge Plasma Thruster, and Distributed Communications Experiments on the FASTRAC Mission, Proceedings of the 17th Annual AIAA/USU Conference on Small Satellites, Logan Utah, USA, 2003, XI-04, pp. 1-18.

[4] Kurunczi, P., Abramzon, N., Figus, M. and et al.: Measurement of Rotational Temperatures in High-pressure Microhollow Cathode (MHC) and Capillary Plasma Electrode (CPE) Discharges, *Acta Physica Slovaca*, **54**(2004), 2, pp. 115-124.

[5] Sadeghi, N., Aubert, X., Lagrange, J. F. and et al.: Laser Absorption and Optical Emission Spectroscopy for the Study of Argon Microdischarge, Proceedings of the 13th International Symposium on Laser-Aided Plasma Diagnostics, Takayama, Japan, 2007, pp. 236-237.

[6] Lagrange, J. F.: Study on Microdischarge in Different Gas, Master thesis in Joseph Fourier University, 2006. (in French)

[7] Laux, C. O., Spence, T. G., Kruger, C. H. and et al. : Optical Diagnostics of Atmospheric Pressure Air Plasmas, *Plasma Sources Science and Technology*, **12(**2003), pp. 125-138.

[8] Schoenbach, K. H., Moselhy. M., Shi. W. and et al. Microhollow cathode discharges. *The Journal of Vacuum Science and Technology A*, **21**(2003), 4, pp. 1260-1265.