Proceedings of the
International Conference on Mechanical Engineering and Renewable Energy 2015
(ICMERE2015) 26 – 29 November, 2015, Chittagong, Bangladesh

ICMERE2015-PI-002

AN EXPERIMENTAL STUDY OF GENERATING LARGER VOLUME MICRO-DISCHARGES AND PREDICTION OF ITS PROBABLE ENGINEERING APPLICATION

Ratan Kumar Das[1,*] **and A. Z. A. Saifullah**[2]

[1,*]Department of Mechanical Engineering, CUET, Bangladesh
[2] Department of Mechanical Engineering, IUBAT, Bangladesh
[1,*]ratanme06_cuet@yahoo.com, [2]d_saifullah@iubat.edu

Abstract- *Micro discharges are direct current micro plasmas that can be operated near atmospheric pressure in a small geometric configuration. Micro Hollow Cathode Discharge (MHCD) can be used as an electron source to sustain a larger volume diffuse glow discharge. This enlarged volume micro plasma serve as a source of high temperature electrons, ions and other excited species. Many engineering application such as micro plasma reactor technology either for fuel reforming or material processing is based on using the energy of high temperature electrons and other charged particles. Larger volume of higher density diffuse plasma at various pressures is generated experimentally by micro hollow cathode sustained discharge (MCSD) in a split third electrode configuration. Analysis of detailed electrical and optical characteristics is reported in this study. When the split third electrode is positively biased, a maximum expansion of sustained glow discharge is measured as large as 10 mm at 700 Torr with five split third electrodes.*

Keywords: Micro discharge, MHCD, MCSD, Discharge Characteristics, Engineering Application.

1. INTRODUCTION

Plasma, often termed the fourth state of matter, is an ionized gas consisting of positively and negatively charged particles with some unique properties to distinguish it from three other states solid, liquid and gases [1]. Interestingly, much of the visible matter in the universe, viz., stars, all visible interstellar matter, is in the plasma state comprising 99% of the universe, both by mass and by volume. Since its first discovery in 1879 by Sir William Crookes [2], plasma has been produced in a variety of discharge configuration with different mechanism including dielectric barrier (DBD) discharge, microwave discharge, radio frequency (RF) discharge, direct current (DC) glow discharge etc. These plasma discharges shows collective behavior creating a highly reactive environment that contains charged particles, excited species, and radicals. The ionization degree of plasma discharges can vary from 100% (fully ionized gases) to very low values (e.g. 10^{-4}–10^{-6}; partially ionized gases). In a laboratory, one of the simplest ways to produce plasma is applying an electric field to a neutral gas. These artificially generated plasmas can be classified into two main categories: thermal and non-thermal ones. Thermal plasmas are characterized by high temperature of the gas maintaining same temperature of all species (electrons, ions, and neutral species). High pressure arc discharges are the common example of the thermal plasma. In non-thermal plasma, most of the electrical power is consumed for generating high energy electrons. As a consequence, the temperature of electrons is higher than other species (ions, atoms, molecules) maintaining relatively low gas temperatures due to less heating of gas. Common examples of non-thermal plasma are low pressure glow discharges. Glow discharges generally operate at low pressures. At higher pressure, the onset of instabilities prevents stable glow discharge operation. For example, thermal instabilities can switch the discharge mode from glow to arc mode. Operating the plasma at low pressure has several drawbacks, which include expensive vacuum systems and high maintenance costs of such systems. According to the similarity laws of classical theory, it is possible to increase the gas pressure (P) if the linear dimension of the device (d) is decreased. This special high pressure glow discharges, which properties fall in between glow and arc discharges [3], is called micro discharges. Micro discharges are being developed to answer the increased interest in generating stable non thermal plasma at high gas pressure. One such discharge configuration is the Micro Hollow Cathode Discharge (MHCD) [4], which is a glow discharge consisting of two parallel electrodes, one anode and another cathode, separated by an insulator with a center cylindrical hole. High pressure operations with larger surface to volume ratios make them useful in various applications from photonic device [5] to biomedical treatment [6]. However, due to limited volume of MHCDs, practical applications are still limited. Limited volume of MHCD is expanded placing another electrode outside the MHCD hole [7],which pulls the electrons toward the third electrode and form discharge in between MHCD and electrode called micro hollow cathode sustained discharge (MCSD). A schematic diagram of such configuration is shown in Fig.1.

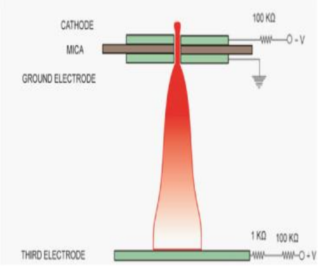

Fig.1: Schematic diagram of micro hollow cathode sustained discharge (MCSD)

Here MHCD has been utilized as cathode which behaves as an electron source for generating a stable diffuse discharge which extends from the micro hollow cathode to third positively biased electrode. Some application of MCSD has been reported like micro reactor for singlet oxygen generation [8], plasma sources of singlet delta oxygen (SDO) for biomedical application [9], DNA oxidization[10] etc. The volume of the MHCD is very small to use in industrial purposes. To increase the volume of the high pressure glow discharge, researchers has developed another discharge namely micro hollow cathode sustained glow discharges where the discharge is sustained by the plasma cathode which act as a source of electron in the discharge. This kind of large volume discharge can be used for fuel reforming and gas treatment purpose as well. Conventional technique for fuel reforming and gas treatment process includes steam reforming by oxidations. Thermal oxidation requires heating of the ambient gas and raises the capital cost for cooling system. Bio filtration and UV-oxidation requires long residence time. Non thermal micro plasma reactor is a good solution regarding these issues. Main advantage of non-thermal plasma is the presence of high energy electrons which reacts with the fuel particles and causes significant reforming. Residence time for the gas is very short in case of non-thermal plasma with low power requirement. This study approaches to generate the larger volume discharge with split multiple third electrodes. This configuration can expand a weak electric field between MHCD hole and the third split electrodes more wider so that a larger volume glow discharge can be achieved which is eventually applicable in fuel reforming and gas treatment processes.

2. EXPERIMENTAL SETUP

Experimental setup consists of vacuum system, optical measurement system, electrical measurement system and gas flow system. Vacuum system consists of vacuum chamber, vacuum pump and pressure sensor. Optical measurement system consists of digital single lens reflex camera which is placed firmly on the steady stand, as macro lenses are very sensitive and small displacement may cause change the magnification of the different discharges. 105 mm Macro lens have been used with lowest F number 2.8 for proper focusing. During capturing the pictures dark environment was provided to see the actual visual characteristic of the plasma discharge and physical scale length was measured before capturing the pictures. Gas flow system consists of gas chamber, gas flow tubes, gas flow meter.

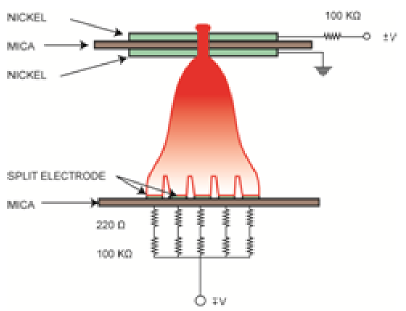

Fig.2: Schematic diagram MCSD with split third electrodes.

Figure 2 presents a schematic drawing of the MCSD configuration with split third electrodes and the corresponding discharge structure. The MHCD layer placed on the top of the system consists of nickel electrodes of a 0.2mm thickness pasted by epoxy on both sides of a 0.2-mm-thick mica dielectric. A cylindrical hole of 0.3mm diameter is drilled through three layers of the MHCD configuration. The third electrode placed 5mm away from the MHCD layer is split into 5 rectangular pieces. Each split electrode is 0.5 x 3mm^2 and is separated by 2 mm. The sharp edges on each split electrode are rounded in order to avoid a high local electric field which can cause a non-uniform glow. One of the MHCD electrodes facing the third electrode is always grounded, as shown in Fig. 2, while the voltages on the top-layer electrode and the third electrode are biased with opposite polarities of maximum ±2.5 kV. The split third electrodes are connected in series with individual 100 kΩ ballast and the current through each electrode is measured across a 220Ω current view resistor. The entire setup is placed in a vacuum chamber and the chamber is replenished by argon gas in every run. The current through each split electrode is measured with a digital oscilloscope (LeCroy LT374L). A high-speed CMOS camera (Photron SA3 120K) and a digital handheld camera are used to visualize sustained discharge structures.

3. RESULT AND DISCUSSION

Experimental results are discussed below sequentially.

3.1 I-V Characteristics

Figure 3 shows simultaneous VI characteristics of the MHCD and MCSD at various pressures with 5 mm electrode span. MHCD voltage drop (a) and MCSD voltage drop (b) are measured for various MCSD current values while the MHCD current is fixed at 2 mA. At lower MCSD current levels of less than the 2 mA MHCD set-point current, voltage drop across MCSD is lower than that of MHCD. In this case, MCSD initiates with an expansion of small amount of electrons from the MHCD at very high third electrode potential and thus MCSD current is mainly from the electrons. At this stage, very resistive plasma forms in MCSD region in almost linear potential drop across the gap such as in Townsend discharge. As MCSD current reaches the MHCD set-point current value, MCSD voltage drop decreases and MCSD expands over the entire electrode span by connecting the MHCD and all third electrodes. When the MCSD current becomes higher than the 2 mA MHCD set-point current, little increment of current causes a large increase in MCSD voltage drop which is an indication of higher plasma resistance while the MHCD voltage drop decreases simultaneously. However total voltage drop (Fig. 3) across the entire system remains more or less similar with an increase in MCSD current. In this regime, the third electrode work as an anode for the whole system and the system has been changed to single anode (third electrode) and double cathode electrodes system. Until the system reaches to an arc regime, MCSD operates as a normal glow discharge as indicated in Fig. 39 (c). This implies that with a split third electrode, large volume stable glow discharge similar to a conventional parallel plate discharge can be achieved at high pressures.

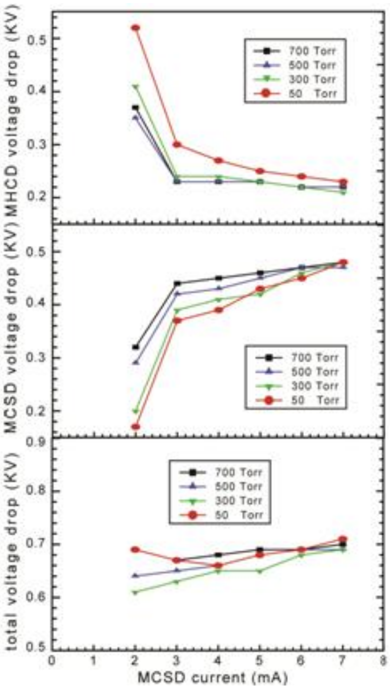

Fig.3: I-V characteristics of MHCD and MCSD at various pressures.

3.2 Optical Imaging

In this section optical images of MCSD will be demonstrated at different pressures with split third electrodes captured by high speed digital camera. Split third electrodes are biased as positive potential. The pressure effect is illustrated in different images.

For anode third electrode case at 50 Torr pressure, MCS discharge starts at very low third electrode current connecting all 5 split electrodes with MHCD. MHCD current was fixed at 2mA and third electrode current increases from lower value to higher value. As the current increases, current density and electron density also increases and the glow becomes more luminous which is shown in the Figure 4 for 3mA and 5mA case. At 7mA of third electrode anode current, suddenly the glow disappears at the gap between MHCD and third electrode. In this case discharge appears at the MHCD cathode side and photogenic glow like discharge appears from each split electrodes. At the current level more than 7mA, this glow from the third electrodes again connect to the MHCD and large volume bulk discharge form in the gap between MHCD and split third electrodes.

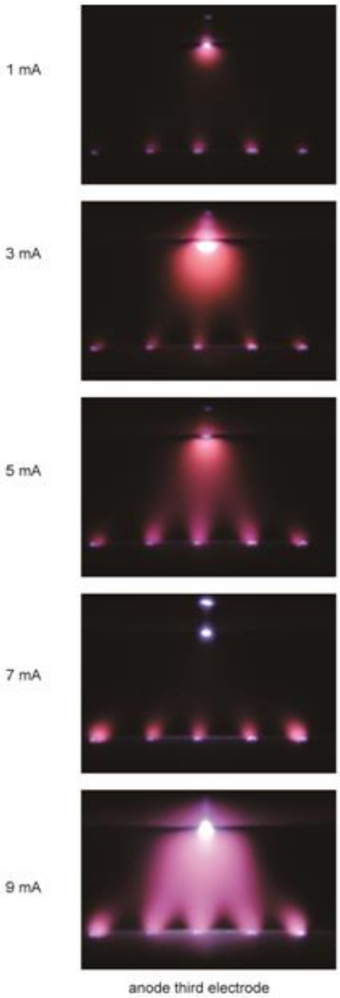

Fig.4: MCSD with 10 mm span 5 split electrodes biased as anode at 50 Torr.

For 300 Torr split third electrode cases, denser plasma glow discharge forms in all current levels than the 50Torr cases. Photo images of the discharge at 300 Torr is shown in Figure 5 for both positive and negative polarities. At 1mA of anode current discharge connects to three electrodes and at 6mA of current it connects to all the 5 split electrodes. With increasing anode current, denser and brighter plasma forms in the gap without some major changes in the structure. At very high applied electric field this glow like discharge will transfer to the arc regime.

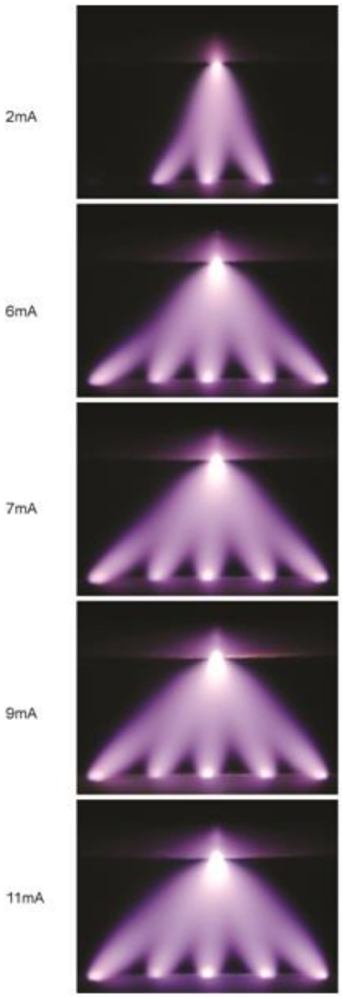

Fig.5: MCSD with 10 mm span 5 split electrodes biased as anode at 300 Torr.

3.3 Comparative Study

In this section we will discuss about the comparisional behavior between the MCSD with single planar and split electrode biased as anode.

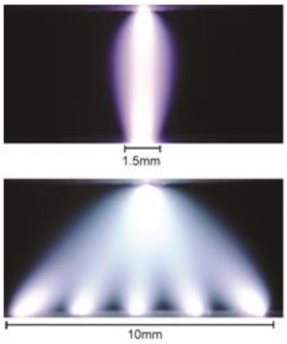

Fig.6: MCSD images at 700 Torr with a single planar third electrode (upper) and with a split third electrode (lower).

Figure 6 presents photo images of MCS glow discharge at 700 Torr with a single planar third electrode (upper) and with five split third electrodes (lower). The third electrodes at the bottom layer is positively biased in both cases. The MHCD current (I_{MHCD}) and MCSD current (I_{MCSD}) are kept constant at 2 mA and 7 mA, respectively. Supplied voltage to MHCD (V_{MHCD}) and MCSD (V_{MCSD}) are -200V and +500V, respectively. The upper image in Figure 6 shows a narrow bell-like shape MCS glow expands toward the single third electrode. Discharge area on the third electrode is about 1.5 mm in diameter and the maximum diameter of 2.5 mm occurs in the middle part of MCSD. In lower pressures, the discharge structure expands more like a bell shape as presented in Ref. [4]. However as shown in the lower image of Fig. 6, it is clear that much larger volume of MCS discharge can be produced by emplying a split third electrode albeit the same operating pressure and total current draw. Note that exposure time and shutter speed of the camera are set identical for both cases. At very low third electrode currents, MCSD starts near the MHCD hole and connects with only a few split electrodes. Above a certain value of the MCSD current (7 mA in the above case) all five electrodes are turned on. It is expected that the discharge gap between split electrodes could be filled up more with wider electrodes. Maximum possible expansion of the MCSD at 700 Torr is observed to be as large as 10 mm with 5 split electrodes. At lower pressures it could be much larger. In single third electrode case discharge volume changes only with the third electrode current. As MCSD current increases the discharge volume slightly increases at a certain current value and decreases again until the current reaches a threshold value where a very intense arc-like discharge forms near the MHCD hole. Maximum expansion is only about 3 mm at 10 mA MCSD current. But in the split electrode case, a transition to arc is not observed mostly due to more distributed plasma with a lower density and hence the discharge structure maintains more or less the same upto a maximum current draw (20 mA) that the power supply can provide. In addition to the enlarged discharge volume it is expected to be possible with more number of finer electrodes that plasma volume, density and its location can be controlled by addressing the desired split electrodes or by changing an arrangement of the split electrodes. However with a single third electrode this controllability of the discharge is very limited and only plasma density can be adjusted by MCSD current.

4. SUMMARY

In this report, a unique approach has been demonstrated that a larger volume glow discharge at atmospheric pressure is possible with MCSD configuration which has split third electrodes. This large volume non equilibrium plasma discharge can be used as a reactor to reform fuel and gases. Discharge area of MCSD with positively-biased split electrodes is about 8 times larger than a single electrode case. Maximum increase in span over the third electrode is measured as large as 10 mm at 700 Torr. The discharge volume is more or less invariant over larger range of MCSD current levels compared with a single electrode configuration. Since the split electrodes are individually addressable, expansion in the discharge volume and its location can be selectively controlled. Current density distribution over the span of split electrodes shows marginally uniform especially at higher power density of the MCSD indicating that the expansion effect is not localized. The result of I-V characteristics exhibits that at lower MCSD currents the discharge operates as Townsend-like discharge and at MCSD currents higher than MHCD set-point current the whole system operates as a normal glow discharge, which implies a stable glow discharge at atmospheric pressure over a larger area is possible with a split third electrode configuration.

5. REFERENCES

[1] D. A. Gurnett and A. Bahattacharjee. Introduction to plasma physics: with space and laboratory applications. *Cambridge University Press, Cambridge, UK*, 2005.

[2] William Crooks. Radiant matter, a resume of the principal lectures and papers. *Technical report, Royal Society of London and British Association for the Advancement of Science, James W. Queen & Co.*, 1879.

[3] R. Foest, M. Schmidt, and K. Becker. “Microplasmas, an emerging field of low-temperature plasma science and technology”, *International Journal of Mass Spectrometry,* 2006:87–102, 2005.

[4] R. H. Stark and K. H. Schoenbach, “Direct current high-pressure glow discharges,” *J. Appl. Phys.* vol. 85, no. 4, pp. 2075–2080, Feb. 1999.

[5] S.-J. Park, J.G. Eden J. Chen and C. Liu, “Microdischarge devices with 10 or 30 mm square silicon cathode cavities:pd scaling and production of the XeOexcimer”,Appl. Phys. Lett., Vol. 85, No. 21, 22 November 2004.

[6] Joao Santos Sousa, Gerard Bauville, Bernard Lacour,VincentPuech, Michel Touzeau, and Jean-Luc Ravanat, “DNA oxidation by singlet delta oxygen produced by atmospheric pressure microdischarges”, *Applied Physics Letters* 97, 141502 (2010).

[7] K. Makasheva, G. J. M. Hagelaar, J.-P. Boeuf, T. Callegari, and L. C. Pitchford, “Ignition of microcathode sustained discharge,” IEEE Trans. Plasma Sci., 36 1236–1237 (2008)

[8] J S Sousa, G Bauville and V Puech, “Arrays of microplasmas for the controlled production of tunable high fluxes of reactive oxygen species at atmospheric pressure”, *Plasma Sources Sci. Technol.*22 (2013) 035012.

[9] Joao Santos Sousa and Vincent Puech, “Pressure Effects in the Spatial Development of Microcathode Sustained Discharges in Rare-Gas Oxygen Mixtures,” IEEETrans. Plasma Sci., 39 (2011).

[10] Joao Santos Sousa, Gerard Bauville, Bernard Lacour,VincentPuech, Michel Touzeau, and Jean-Luc Ravanat, “DNA oxidation by singlet delta oxygen produced by atmospheric pressure microdischarges”, *Applied Physics Letters* 97, 141502 (2010).

6. NOMENCLATURE

Symbol	Meaning	Unit
I	Current	(mA)
P	Pressure	(Torr)
V	Voltage drop	Volt