Characterization of plasma based on the electrode size of atmospheric pressure plasma jet (APPJ)

Jeyashri Veeraiah 1, Siti Khadijah Zaaba1,2*, Mohammad Taufiq Mustaffa3

1School of Mechatronic Engineering, Universiti Malaysia Perlis, Arau, Perlis, Malaysia
2Centre of Excellence for Advanced Sensor Technology (CEASTech), Universiti Malaysia Perlis
3School of Manufacturing Engineering, Universiti Malaysia Perlis, Arau, Perlis, Malaysia

*khadijah@unimap.edu.my

Abstract. Atmospheric Pressure Plasma Jet recognize as non-thermal plasma or cold plasma where known as APPJ which is generated under pressure of the atmospheric environment, currently APPJ using in many kind of application especially in biomedical application to reduce microbial activity. In APPJ, there are various type of configuration can be set to produce plasma discharge. This project began by changing the configuration of electrodes thickness, electrodes distance, and quartz tube’s inner and outer diameter to generate ideal plasma discharge. The ideal plasma discharge can be choose from Optical Emission Spectroscopy (OES) analysis by using SpectraWiz software and bacteria inactivation method. This OES analysis used to analyze the charged species and chemical reactive species that present in the plasma plume. The length and reactive species of plasma discharge is all depend on the APPJ configuration used. From the result of OES analysis, the best parameters can choose to perform the bacteria inactivation method. It was found that the bacterial inactivation depend on the oxygen radical was introduced into the plasma jet system. The ideal configuration that was chosen from this research can be applicable in future plasma process to get an effective result.

1. Introduction

Nowadays, development in life science technology becomes more promising and plays a great role in the daily lives of people and making their lifestyle advance. One of the recent science technologies is atmospheric-pressure plasma jets (APPJ). APPJ have attracted major attention due to their widespread applications in plasma medicine, nanotechnology, as well as surface and materials processing [1]. The application of APPJ in plasma medicine is plasma surface modification, plasma bio-decontamination, and therapeutic plasma application [2].

Besides, APPJ technology is driven by electrons, which gain energy from applied voltage and carrier gas. This is due to several orders of differences in mass between electrons makes vigorous collision between energized electron and heavy particle cause excitation, dissociation and ionization. Plasma jet contains neutral particles and electron, ions, molecules, including atom, radicals and UV photons. Carrier gas which commonly for bio-decontamination process is Helium (He) because it can produce a homogeneous glow discharge much easier at the lower voltage [2]. Helium gas also has long lifetime of meta-stable excited atoms and highest electron energy level among all material, easy
dissociation of mixed gas molecules, and generation of ions and radicals [3]. The plasma generated inside the tube and expands into the open air molecules forming reactive species. In this research, plasma are generated by applying a certain voltage to High-Voltage (HV) electrode. When the voltage exceeds a threshold value called the breakdown voltage, the gas ionization becomes self-sustaining, and the kinetic process occurs in the electrodes induced the plasma to generate [4].

A different number of reactive species will obtain in plasma plume with different type of APPJ configuration [5]. In this study, a certain configuration of quartz tube’s diameter, electrode thickness of atmospheric APPJ, and electrode distance is examined to determine the optimum plasma parameters for the plasma process. Moreover, to generate and utilize stable plasma process, it is crucial to determine all the parameters that lead to a stable plasma discharge and produce a very reliable disinfection device and surface modification device [6].

This study focuses on determining the ideal plasma parameters by changing the configuration of electrodes thickness, electrodes distance, and quartz tube’s inner and outer diameter to generate stable plasma discharge by reducing the usage of carrier gases, applied voltage, and electrodes. To analyze the ideal plasma discharge, we use optical emission spectroscopy (OES) analysis to investigate the spectrum emitted by the plasma jet. The expected result would be if the plume have longer plume with higher intensity and number of reactive species present in it can carry out sterilization and disinfection process effectively. This result can be prove by taking bacteria to perform the plasma treatment with the suggested configuration of APPJ in order to examine the density of bacteria present after the treatment. From this, we can determine the best parameter to perform the plasma treatment in many field by giving best output.

2. Methodology

2.1. Atmospheric pressure plasma jet device configuration

The principle operation of the atmospheric plasma is high voltage supplied to the flowing gas in a glass tube. Firstly need to analyze the requirement of this project by understanding the operation of atmospheric pressure plasma jet (APPJ) in detail and study the effect of different configuration on the plasma discharge. In this work, the development of plasma system consists of plasma generating devices, including electronic instrument, power supply, helium gas, pulse inverter, and plasma jet.

The experimental arrangement is shown in Figure 1. The set up composed of fours mains parts; gas control system, pulse inverter, plasma jet setup, and spectrometer device. The gas control system includes the flow meter system, valve, power system, control system, gases and Labview® (2011) software. Plasma jet setup consists of two electrodes where the ionization occurs. These electrodes are placed 25 mm between each other on the glass tube (diameter 1.50 mm). Helium gas with flow rate 1000 ml/min are used as a main gas source.

The emission line spectrums for plasma jet plume were measured using EPP2000-HR High Resolution spectrometer from Stellar. The plume was collected by using fiber optic probe (UV-VIS-NIR). The fiber optic probe was held 0.5 mm away from plume at 45°. The recorded spectrum line was observed using SpectraWiz OS v5.3(c) 2013 software.

Power supply is an important component in this setup which will affect the production of the plasma. The power supply is a device that supplies the electric power to the electric load. It converts the AC or DC power into the required voltage according to the user setting such 16.5V [7]. In this experiment, pulse inverter was used to convert 8VDC to 16KV AC.
2.2. The changing parameters for APPJ configuration

The optimum plasma plume can obtain with proper configuration by following all the parameters as listed in the Table 1 and refer figure 2 which show the parameter need to change as well. Table 1 shows the parameters that need to use for the investigation of distance change between two electrodes. Table 2 shows the parameters that need to consider for the investigation of thickness changes of High-Voltage (HV) electrode by remaining constant of ground electrode’s thickness.

![Figure 1. Atmospheric-Pressure Plasma Jet (APPJ) device configuration](image1)

![Figure 2. Changing parameters](image2)

| Constant parameters | Changing parameters |
|---------------------|---------------------|
| 1. HV electrode thickness = 0.5 mm | Distance between the two electrodes; 10 mm, 15 mm, 20 mm, and 25 mm |
| 2. Ground electrode thickness = 0.5 mm | |
| 3. Inlet gas = Helium | |
| 4. Flow rate of gas = 1000 ml/min | |
| 5. Quartz tube’s thickness = 1.50 mm | |

| Table 1. Parameters of distance (mm) between the two electrodes |

| Constant parameters | Changing parameters |
|---------------------|---------------------|
| 1. Distance between the two electrodes = 25 mm | HV electrode thickness = 0.5 mm, 0.7 mm, 0.9 mm, and 1.2 mm |
| 2. Ground electrode thickness = 0.5 mm | |
| 3. Inlet gas = Helium | |
| 4. Flow rate of gas = 1000 ml/min | |
| 5. Quartz tube’s thickness = 1.5 mm | |
Table 3 shows the parameters that need to consider for the study of thickness changes of ground electrode by remaining constant of High-Voltage (HV) electrode’s thickness. Other parameters such as constant flow rate, quartz tube’s thickness, and type of inlet gas are fixed.

| Constant parameters                                | Changing parameters                        |
|---------------------------------------------------|-------------------------------------------|
| 1. Distance between the two electrodes = 25 mm    | Ground electrode thickness = 0.5 mm, 0.7 mm, 0.9 mm, and 1.2 mm |
| 2. HV electrode thickness = 0.5 mm                |                                           |
| 3. Inlet gas = Helium                              |                                           |
| 4. Flow rate of gas = 1000 ml/min                 |                                           |
| 5. Quartz tube’s thickness = 1.50 mm              |                                           |

Table 4 shows the configuration that need to use for the study of thickness changes of quartz tube’s thickness by remaining constant of other parameter such as constant flow rate, High-Voltage (HV) thickness, ground electrode, and type of inlet gas are fixed. Quartz tube has two different thickness which is from aspect inner diameter and outer diameter. Both dimension play the important role in producing plasma discharge.

| Constant parameters                         | Changing parameters               |
|--------------------------------------------|----------------------------------|
| 1. Distance between the two electrodes = 15 mm | Outer Diameter (OD) 3 mm Inner Diameter (ID) 1.5 mm |
| 2. HV electrode thickness = 0.5 mm         | 5 mm 3 mm                         |
| 3. Ground electrode thickness = 0.5 mm     | 8 mm 5 mm                         |
| 4. Inlet gas = Helium                       | 13 mm 10 mm                       |
| 5. Flow rate of gas = 1000 ml/min          |                                  |

2.3. Analyzing method of plasma properties

The plasma plume that discharges from the plasma jet can be analyzed using Optical Emission Spectrometry technique. This method can be done by using an EPP2000-HR High-Resolution spectrometer from Stellar [8]. The plume was collected by using a fiber optic probe (UV-VIS-NIR). The fiber optic probe was held 0.5 mm away from plume at 45°. The recorded spectrum line was observed using SpectraWiz OS v5.3(c) 2013 software [9]. The spectrometer will detect the reactive species obtain in the plume and generate a line emission spectrum with the ions intensity and wavelength [10].

3. Results and Discussions

Two different research is carried out in this project which are choose the ideal configuration of Atmospheric Pressure Plasma Jet (APPJ) by varying quartz tube diameter, electrode thickness, and electrodes distance.

The distance between two electrodes at 25 mm give the most stable plasma discharge as shown in Figure 3 (a) due to the stable energy distribution of electrons/ions and many type of reactive species present in the line emission spectrum as in Figure 3 (b). The plasma discharges by using electrodes distance at 25 mm are suitable for bacteria inactivation process and plasma surface modification because of the presence of reactive oxygen radicals and hydroxyl, OH radicals and N\textsubscript{2}. 

4
Figure 3. (a) Plume length and (b) plasma Line Emission Spectrum for the distance changes of electrode at 25 mm

The high-voltage electrode thickness of 0.9 mm with ground electrode thickness of 0.5 mm give the most stable plasma discharge as shown in Figure 4(a), because it drift more electrons/ions to ionize and transmit to ground electrode to discharge through the nozzle of quartz tube[8].

Figure 4. (a) Plume length and (b) plasma emission when high-voltage electrode thickness is 0.9 mm with ground electrode thickness is 0.5 mm

The ground electrode thickness of 0.9 mm with High Voltage (HV) thickness of 0.5 mm give the most stable plasma discharge as shown in Figure 5 (a) due to the high intensity value and different type of reactive species presented in the line emission spectrum (Figure 5 (b)) among others especially the intensity of OH radical is higher at 6033 W/m2 that can used in bacteria inactivation.
Figure 5. (a) Plume length and (b) emission Line emission spectrum for the High-Voltage electrode thickness 0.90 mm

The quartz tube thickness of outer diameter 3 mm and inner diameter 1.5 mm give the most stable plasma discharge as shown in Figure 6 (a) due to the small inner space of the quartz tube to discharge the plasma and have different reactive in line emission spectrum (Figure 6 (b)). The other quartz tube size produce a non-stable plume by splitting into two plume and discharge inside the quartz tube because of inadequate flow rate, larger volume, and low collision of electrons and neutral particles.

Figure 6. (a) Plume length and (b) emission Line emission spectrum for the Quartz tube’s thickness of (OD= 3 mm & ID = 1.5 mm)

4. Conclusion
The result of present study demonstrated that atmospheric pressure plasma jet with thickness of 0.9 mm High-Voltage electrode and 0.5 mm ground electrode by using flow rate 1000 ml/min, electrode distance 25 mm, and thickness of quartz tube 1.5 mm showing the strongest configuration because it has higher intensity reactive oxygen species and nitrogen species in optical emission lines 300 nm until 400 nm which had an important effect on the bacterial inactivation. These species causes damage by providing abnormal load oxidation process to bacteria [11]. This then, will cause death of bacteria.

The purpose of electrodes folded around quartz tube (dielectric material) in this atmospheric pressure plasma jet (APPJ) is to stop the development of the arc discharge by the reverse charge effect of the real charges in the discharge [11]. Thus, if thicker the copper electrode, the higher the reverse charge effect in producing the plasma discharges. Other elements inside plume such as ions, electrical field and UV plays secondary role but still important in inactivation purpose. The developed atmospheric plasma jet device is comparatively a simple device which possesses good potential as microbial inactivation device since it is able to inactivate the pathogen in short time [12].
Acknowledgement
The author would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under grant number FRGS/1/2015/SG02/UNIMAP/02/5 from the Ministry of Education Malaysia.

References
[1] Laroussi M and Lu X 2005 Room-Temperature Atmospheric Pressure Plasma For Biomedical Applications, *Appl. Phys. Lett.* **87** 1–3.
[2] Nordin N A, Zaaba S K, Baharuddin B, Zakaria A, Wan K and Shahriman A B 2015 Study on the surface characteristic of PTFE after atmospheric plasma treatment *Proceedings 2015 2nd International Conference on Biomedical Engineering (ICoBE)* 30–31.
[3] Nur M, Kinandana A W, Winarto P and Muhlisin Z 2016 Study of an atmospheric pressure plasma jet of Argon generated by column dielectric barrier discharge, *Journal of Physics: Conference Series* **776**(1).
[4] Saad N A et al. 2015 Optical emission spectroscopy analysis of atmospheric plasma jet plume on bacteria inactivation, *J. Teknol.* **6**(77) 77–81.
[5] Fridman G, Friedman G, Gutsol A, Shekhter A B, Vasilets V N and Fridman A 2008 Applied plasma medicine, *Plasma Process. Polym.* **5**(6) 503–533.
[6] Jha N, Ryu J J, Choi E H and Kaushik N K 2017 Generation and Role of Reactive Oxygen and Nitrogen Species Induced by Plasma, Lasers, Chemical Agents, and Other Systems in Dentistry. *Oxid. Med. Cell. Longev*.
[7] Schütze A, Jeong J Y, Babayan S E, Park J, Selwyn G S and Hicks R F 1998 The Atmospheric-Pressure Plasma Jet: A Review and Comparison to Other Plasma Sources, *IEEE Trans. PLASMA Sci.* **26**(6).
[8] Gorbanev Y, Soriano R, O’Connell D and Chechik V 2016 An Atmospheric Pressure Plasma Setup to Investigate the Reactive Species Formation. *J. Vis. Exp.* **117**.
[9] Donnelly V M 2004 Plasma electron temperatures and electron energy distributions measured by trace rare gases optical emission spectroscopy *J. Phys. D. Appl. Phys.* **37**(19).
[10] Fused Silica/Quartz Glass - Properties and Applications of Fused Silica/Quartz Glass by Goodfellow Ceramic & Glass Division. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=4766. [Accessed: 08-Dec-2017].
[11] Zhao S et al. 2013 Atmospheric Pressure Room Temperature Plasma Jets Facilitate Oxidative and Nitritative Stress and Lead to Endoplasmic Reticulum Stress Dependent Apoptosis in HepG2 Cells *PLoS One* **8**(8) 1–14.
[12] Seo Y S, Mohamed A A H, Woo K C, Lee H W, Lee J K and Kim K T 2010 Comparative studies of atmospheric pressure plasma characteristics between He and Ar working gases for sterilization *IEEE Trans. Plasma Sci.* **38**(10) 2954–2962.