DIELECTRIC BARRIER DISCHARGE NON-THERMAL PLASMA STABILITY ANALYSIS BASED ON TEMPERATURE PROFILES USING FIBER BRAGG GRATING SENSOR

MUHAMAD ARIF AIZAT BIN SHAHROM

UNIVERSITI TEKNOLOGI MALAYSIA

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MUHAMAD ARIF AIZAT BIN SHAHROM

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To Allah (SWT),
To my beloved parents,
Shahrom b. Ibrahim and Manisah bt. Md. Omar,
To my siblings,
Nur Adibah and Nur Adilah,
who have always courage, motivated and supported me
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ABSTRACT

This study aims to determine the stability of atmospheric pressure non-thermal plasma generated in dielectric barrier discharge (DBD) based on temperature profiles measured using a fiber Bragg grating (FBG). Two sets of the DBD reactor were fabricated using two symmetrical electrodes separated by 2.31 mm and 3.74 mm discharge gap, respectively with dielectric material of alumina plates. The FBG was used as a temperature sensor by embedded directly into the plasma stream. The temperature was measured at different applied voltages within range of 0 to 7 kV. The results show that the streamer discharge was generated by the DBD reactor with the 2.31 mm discharge gap at 5.5 kV while the DBD reactor with the 3.74 mm discharge gap generated filamentary discharge at 7 kV. The temperature increases proportionally as the applied voltages increases. The stability of the DBD reactor was performed by operated at constant applied voltage for 600 seconds. The temperature profiles of the DBD reactor with the 2.31 mm discharge gap were measured in the range of 210 - 231 ^{o}C with applied voltage of 5.0 kV and in the range of 270 - 286 ^{o}C at 6 kV. For the DBD reactor with the 3.74 mm discharge gap, the temperature profiles were measured in the range of 47 - 67 ^{o}C when operated at 6 kV and in the range of 193 - 245 ^{o}C at 7 kV. A huge temperature difference was found for the DBD reactor with the 3.74 mm discharge gap which results in localized heat generation of the discharge caused by the filamentary discharge. The filamentary discharge disrupted the homogeneity of the plasma and created the instabilities in the DBD reactor. The plasma intensity of the DBD reactor measured by the optical emission spectroscopy (OES) showed more fluctuation pattern when the filamentary discharge was generated compared to the streamer discharge. From this finding, the FBG can be used for temperature profiles of the DBD reactor to determine its stability on the generation of the filamentary discharge.

ABSTRAK

Kajian ini bertujuan untuk menentukan kestabilan reaktor pelepasan halangan dielektrik (DBD) berdasarkan pemprofilan suhu menggunakan parutan gentian Bragg (FBG). Dua set reaktor DBD difabrikasikan menggunakan dua elektrod bersimetri yang dipisahkan dengan jurang nyahcas 2.31 mm dan 3.74 mm bersama bahan dielektrik plat alumina. FBG digunakan sebagai penderia suhu dengan dibenamkan secara terus ke dalam aluran plasma. Suhu diukur pada voltan gunaan berbeza dalam julat voltan 0 hingga 7 kV. Keputusan tersebut menunjukkan nyahcas strim dijana oleh reaktor DBD dengan jurang nyahcas 2.31 mm pada 5.5 kV manakala reaktor DBD dengan jurang nyahcas 3.74 mm menjana nyahcas filamen pada 7 kV. Suhu meningkat secara berkadaran dengan peningkatan voltan gunaan. Kestabilan reaktor DBD dipersembahkan dengan dikendalikan pada voltan gunaan malar untuk 600 saat. Profil suhu reaktor DBD dengan jurang nyahcas 2.31 mm dan 3.74 mm diukur dalam julat suhu 210 - 231 ^{o}C dengan 5 kV voltan gunaan dan dalam julat suhu 270 - 286 ^{o}C pada 6 kV. Bagi reaktor DBD dengan jurang nyahcas 3.74 mm, profil suhu diukur dalam julat suhu 47 - 67 ^{o}C apabila dioperasi pada 6.0 kV dan dalam julat suhu 193 - 245 ^{o}C pada 7 kV. Perbezaan suhu yang tinggi ditemui pada reaktor DBD dengan jurang nyahcas 3.74 mm yang hasilnya pada pembentukan haba setempat dalam nyahcas disebabkan oleh nyahcas filamen. Nyahcas filamen mengendala kehomogenan plasma dan membentuk ketidakstabilan di dalam reaktor DBD. Keamatan plasma bagi reaktor DBD yang diukur dengan spectrometer pancaran optik (OES) menunjukkan lebih pola fluktuasi apabila nyahcas filamen dijana berbanding dengan nyahcas strim. Daripada dapatan ini, FBG boleh digunakan dalam pemprofilan suhu reaktor DBD untuk menentukan kestabilan reaktor dengan penjanaan nyahcas filamen.

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LIST OF ABBREVIATIONS

AC - Alternating current
APGD - Atmospheric pressure glow discharge
ASE-C - Amplified spontaneous emission-C
DBD - Dielectric barrier discharge
DC - Direct current
EHD - Electrohydrodynamic
FBG - Fiber Bragg grating
IR - Infrared
LTE - Local thermodynamic equilibrium
NTP - Non-thermal plasma
OES - Optical emission spectroscopy
OSA - Optical spectrum analyzer
ROS - Reactive oxygen species
SDBD Surface dielectric barrier discharge
SLSR - Single lobe suppression ratio
SMF - Single mode fiber
UV - Ultraviolet
VDBD - Volume dielectric barrier discharge
VOC - Volatile organic compound
VOCs - Volatile organic compounds

LIST OF SYMBOLS

α - Thermal expansion coefficient
γ - Secondary electron emission coefficient
ε - Strain
ε_{alu} - Dielectric constant of aluminium
λ_B - Bragg wavelength
Λ - Grating period
ξ - Thermo-optic coefficient
p_e - Strain-optic coefficient
n_{eff} - Effective refractive index
T_m - Melting point temperature
V_B - Breakdown voltage

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Plasma is classified as the fourth state of matter. It consists of a huge number of energetic ions and free electrons originated from neutral atoms or molecules undergoing an ionization process due to energy received from thermal, light or electrical energy. Plasma can be divided into two types, thermal plasma and non-thermal plasma (NTP). Thermal plasma is a state of energetic particles reaching thermodynamic equilibrium where the temperature of the ions, electrons, and neutral gas atoms or molecules is approximately equal throughout the system. Meanwhile, NTP exist in non-thermal equilibrium state such that most of the kinetic energy absorbed by the electrons and only its temperature is much higher compare to ions and neutral gas temperature.

Owing to the ability to produce more chemical reactions and high ionization rates, there are many ways to generate NTP such as corona discharges, gliding arc discharges, plasma jets, and dielectric barrier discharge (DBD) reactor. The DBD reactor is the most significant utilization of NTP because of plasma formation that yield higher density of free electron and the reactor can be operated at low pressure and atmospheric pressure [1]. The DBD reactor offers solution for many applications such as air pollution control [2-4], wastewater treatment [5-6], sterilization [7-8], volatile organic compounds (VOCs) decomposition [9-10] and aerodynamic flow control [11].

The DBD reactor essentially is an electrical discharge between two asymmetrical electrodes separated by the dielectric material. The DBD reactor has gathered great attention for aerodynamic technologies as a novel type of flow controller device and therefore introduced a potential and promising design called DBD plasma actuator. These light-weight devices are designed fully electronic with no moving parts and quick response time which is favourably for aerodynamic applications [12]. These interesting characteristics of the DBD plasma actuator give rise the studies mainly focusing on improving airflow separation and reducing the vortex formation onto the actual airflow machinery [13-14].

The DBD reactor involves electrical discharges of the gas at atmospheric pressure. The DBD reactor is also employed under the influence of high electric field resulting in ionization of gases where the outer shell electron is being ejected by strong electric fields thus producing free electrons. Then, electric field accelerates the free electrons causing collision between the accelerated electrons and gas molecules or atoms which results in more outer shell electron being ejected and accelerated. This process produced high energetic electrons and ions which are later referred as non-thermal plasma (NTP). Plasma can be generated either in the form of diffuse discharge, filamentary discharge or at more extreme it can turn into plasma arc.

Homogeneous and good uniformity of plasma discharges formed is known as diffuse discharge. However, accumulation of microdischarges on the dielectric surface of the DBD reactor during the discharges creates local electric field which then changed the electric field distribution. The build-up microdischarges create inhomogeneity and disrupt the discharge thus forming plasma filamentation known as filamentary discharge. These discharges are difficult to sustain due to the instabilities of the electric field in the DBD reactor. The complexity and dynamicity of the plasma transition, diffuse-to-filamentary discharge are still being extensively studied. Many studies have been conducted such as charge particles density [15], plasma behaviour [16-17] and plasma temperature [18-19]. However, despite all the previous related literature, few efforts are done on thermal characterization on DBD reactor [20]. Filamentary discharges are formed from the bulk of the microdischarges causing power dissipation in the reactor which eventually results in heat generation thus showing temperature dependent parameters on the plasma discharges throughout the process [17]. Hence, an optical fiber called fiber Bragg grating (FBG) sensors are introduced in recent studies that demonstrated the in-situ measurement of temperature on monitoring the plasma discharges [21-22].

FBG plays an important role as a sensor to determine physical measurement likes pressure, strain, and temperature [23]. In this study, FBG sensor are used to monitor temperature profile of the plasma generated by the DBD reactor. The FBG sensors are embedded in between the plasma reactor which is directly positioned into the plasma stream to obtain temperature measurement [24]. FBG sensors is fast respond optical sensing technique with the capability to operate on high voltage and temperature condition becoming convenient and suitable devices unlike other conventional techniques.

1.2 Problem Statement

Plasma filamentation in the DBD reactor is perplexing to understand its influences on the homogeneous discharge. This plasma transition makes it difficult to find the most preferable high operating voltage and stability for the DBD reactor since plasma aching, big energetic plasma filaments are easily formed. Previous studies highlighted the study on temperature characteristics of the DBD reactor to understand the nature of the plasma discharges using conventional devices like thermocouple, infrared (IR) thermal sensors and emission spectroscopy. These devices can only facilitate the temperature profiles from outside or near the plasma reactor wall due to incapability to withstand high electric field environment. This makes the FBG sensor a new alternative temperature sensor that offer in-situ measurement, high temperature sensitivity and insusceptible to electromagnetic interference. The FBG sensor is capable of being positioned directly onto the plasma stream without disrupting the plasma discharge of the DBD reactor. This makes the temperature measurement by the FBG sensor can be done without disrupt the plasma formation which its suitable to be used as indicator of plasma stability based on temperature behaviour.

1.3 Objectives

The objectives of this research are:

1. To design and fabricate a dielectric barrier discharge (DBD) reactor.
2. To measure the temperature profiles of the DBD reactor using fiber Bragg grating (FBG) arrays at different applied voltages and discharge gaps.
3. To determine the stability of the DBD reactor operating at different applied voltages and discharge gaps.

1.4 Scope of Study

A DBD reactor is designed and fabricated with two asymmetrical copper electrodes assembled with the alumina plates attached in between the electrodes. The alumina plates are used as the dielectric material for the DBD reactor. The reactor is operated with applied voltage of 0 - 7 kV, generated by 20 kHz AC power supply. Different sets of discharge gap are prepared for the DBD reactor using stainless steel flat washers as spacers. The FBG sensors are embedded in between the electrodes for the plasma temperature measurements. The temperature profiles are measured using the optical spectrum analyzer (OSA) by observing the Bragg wavelength shift, $\Delta\lambda_B$.

The DBD reactor also use the optical emission spectrometer (OES) to monitor the plasma intensity of the DBD reactor.

1.5 Significance of Study

Temperature profiles are important parameter of interest to study the plasma stability of the DBD reactor. The DBD reactor are known to generate diffuse and filamentary discharges depending on the applications especially the plasma actuator. These discharges are necessary to discriminate their formation for stability of the DBD reactor. The filamentary discharges are difficult to sustain and manage which could potentially lead to plasma arching thus damaging the plasma reactor. Good dielectric material has high dielectric constant that also could help increases the applied voltage range of the DBD reactor. The use of the FBG sensor in this study is to determine the suitable high operating voltage range of the DBD reactor. FBG sensor offers fast response and multiplex capabilities sensor that enable the device to be used as localized sensor and distributed sensor [23-25] which is essential in profiling the temperature. The FBG sensor is installed inside the plasma stream of the DBD reactor increasing the accuracy of the temperature measurement obtained. By operating the FBG sensor as a temperature sensor, the plasma generated by the DBD reactor help to distinguish the filamentary discharge that disrupting the stability of the DBD reactor. The OES are used simultaneously with the FBG sensor to determine the influences of the filamentary to the plasma intensity of the DBD reactor operating with different applied voltage and discharge gaps. The FBG sensor can be used to determine the influences of the filamentary discharge on the temperature profiles of the DBD reactor at different discharge gaps and applied voltages.

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