UNIFORM AND FILAMENTARY NATURE OF CONTINUOUS-WAVE AND PULSED DIELECTRIC BARRIER DISCHARGE PLASMA

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Abstract: Observations of atmospheric pressure DBD plasma were conducted through the transparent electrode in Air, Argon, Helium, Nitrogen and Oxygen gasses at 1 and 3 standard liters per minute (slpm) flow rates through the discharge gap, utilizing three types of excitation waveforms. Three phenomena were observed: (1) plasma filaments travel with the gas at the same speed as the gas for some but not all gases; (2) propagation of excitation is observed in Nitrogen plasma and the filament motion has no directional preference with gas flow direction; and (3) Oxygen, Nitrogen and Helium plasmas were observed to be rather uniform at least over longer time periods.

Keywords: Non-thermal plasma, non-equilibrium plasma, dielectric barrier discharges (DBDs), atmospheric pressure glow discharges (APGDs), sinusoidal plasma excitation, pulsed plasma excitation

1. Introduction

Current applications of atmospheric pressure dielectric barrier discharge (DBD) include ozone production [1,2], treatment of gases [3], industrial surface treatment [4–7], and other applications. DBD's biocidal properties make atmospheric pressure DBD potentially a favorable system for medical applications [8–11]. Uniformity of sterilization should depend on the discharge spatial uniformity. Also, it has been shown experimentally that when exposed to DBD, the patient's discomfort is directly related to the intensity of microdischarges, or filaments, in

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this plasma [12]. Furthermore, the number of microdischarges depends upon the excitation waveform, power, and the type of gas [12]. A change in any of these three variables may result in a higher filament temperature, and thus increases the discomfort experienced by the patient. Thus, comfortable and effective treatment requires plasma with little or no filamentation. This stemmed the need to observe and characterize plasma in which the excitation waveform, gas type, and flow rate were varied to obtain the most uniform lowest power plasma with highest bactericidal abilities (bacterial studies are not presented here, please see [9], [10] for further details).

Three plasma excitation waveforms were used for characterization: a sinusoidal waveform, quasi-sinusoidal continuous waveform, and pulsed excitation. The surface power density was kept at a constant value for each particular gas, ranging from 0.4 to 2 W/cm^2 for different gases. Air, Argon, Helium, Nitrogen and Oxygen were chosen for the experiments reported on in this paper. The three excitation waveforms chosen here are due to the power supply availability in our lab and their previous use in medical and biological studies (see [9], [10]). Presented in this paper are the results and highlights of the observed effects that authors deemed of note.

2. Experimental Setup

The experimental setup (Fig. 1) features a water electrode 25.4 mm in diameter separated from a brushed stainless steel base by a 2 mm perforated aluminum spacer. The water electrode was comprised of a quartz viewing windows at the upper and lower surfaces. Regular tap water was degasified and used as a conducting medium. The Nikon D70 camera was used for digital photography. Photos of the discharge were taken at decreasing shutter speeds from 30 to 1/6,400 s to characterize plasma spatial uniformity at different time scales. The upper (transparent) electrode is water cooled by allowing the water contained within the electrode to circulate to an ice-cooled external container (Fig. 1). Due to the nature

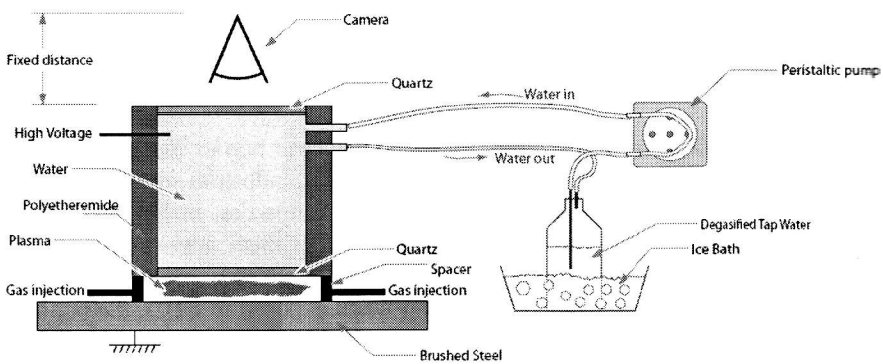


Figure 1. Experimental setup

of the pump and the setup, water recirculation often resulted in bubble formation which is visible in pictures taken at small apertures (less light reaches the camera's Charge Coupled Device (CCD) sensor) and long shutter speeds (the time during which light is collected on the CCD); therefore, approximately 2–3 mm shadows seen in some of the pictures are artifacts of bubbles just below the upper quartz window; these bubbles do not affect the plasma in any way as the lower plasma-contacting quartz is bubble-free. The plasma is formed within a two millimeter gap distance between the brushed steel and the lower quartz face of the electrode. Gas is introduced into the setup through ten out of twelve equidistant tubes which are connected to the perforated spacer in the base of the chamber and exit through the remaining two (Fig. 2).

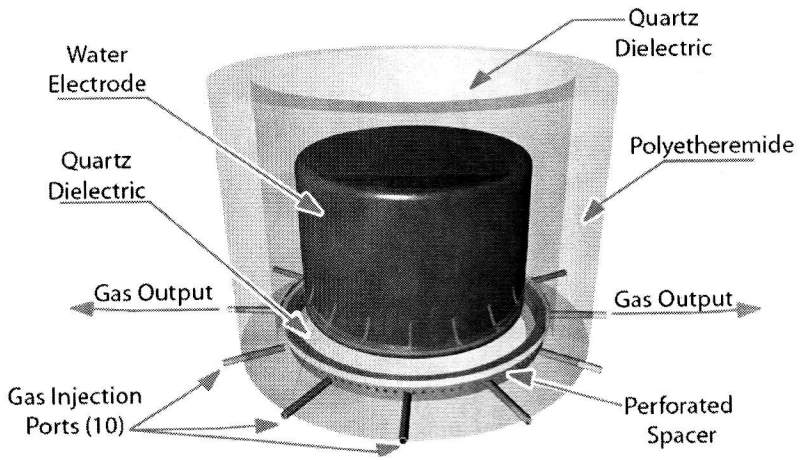


Figure 2. Experimental setup detailing the two gas output ports and the ten gas injection ports

2.1. WAVEFORMS

Sinusoidal, quasi-sinusoidal ('continuous'), and "micro-pulsed" waveforms were applied to the voltage. The pulse duration and characteristics of each waveform are given in Fig. 3.

The pulse durations shown in Fig. 3 are taken to be the full width at half maximum (FWHM). The rise time is time interval for the major pulse to change from 20% to 80% of its maximum amplitude. The typical pulsed waveform has positive or negative polarity pulses at 0.1 to 1 kHz repetition rate, up to 35 kV peak to peak, 1.7 μs pulse duration and 0.75 μs rise time. The continuous waveform generates up to 35 kV peak to peak at 8.7 kHz with a continuous quasi-sinusoidal bipolar wave signal. The sinusoidal waveform is a varying frequency and voltage system where sinusoidal waves were amplified and stepped up to high voltage [19]. For our experiments, the frequency is fixed at 12 kHz.

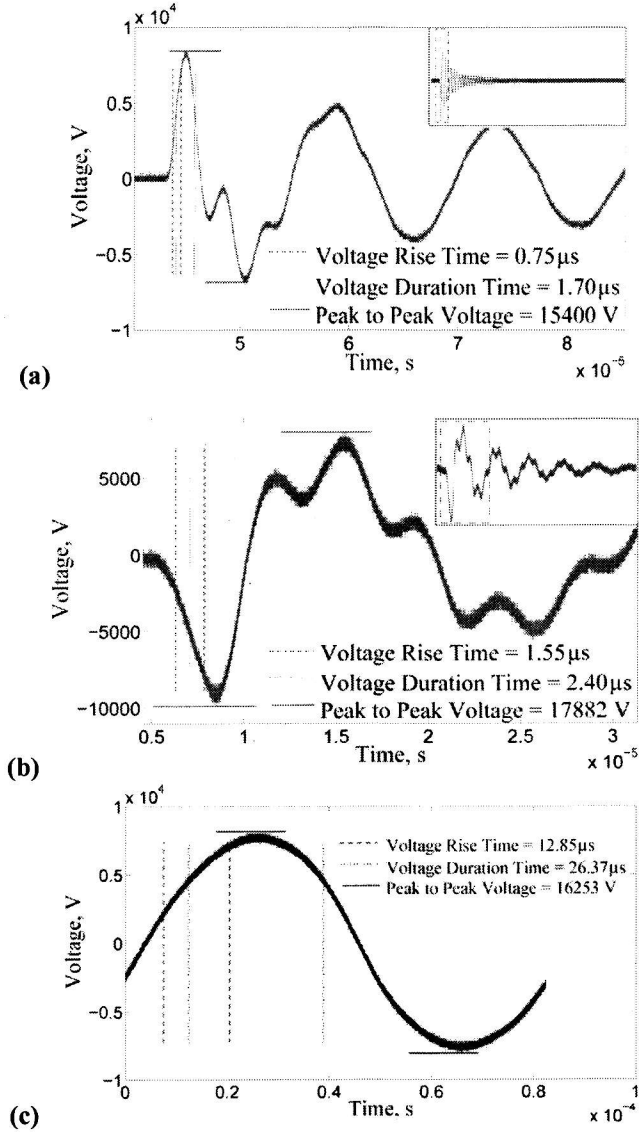


Figure 3. Waveforms generated by the power supplies: (a) pulsed; (b) continuous; and (c) sinusoidal

3. Results and Discussion

3.1. ARGON

When observed at exposition times greater than 0.1 s, Argon plasma is composed of a diffuse background and filaments developing along the direction of flow. At

closer observation with low exposition times, it can be seen that filaments travel in the direction of gas flow and at the velocity close to the estimated velocity of gas flow. This effect is observed only in argon and air plasma. This is due to the memory effect [18] of a filament being bound to the gas and not the surface. Plasma in Argon, for example, is shown in Fig. 4.

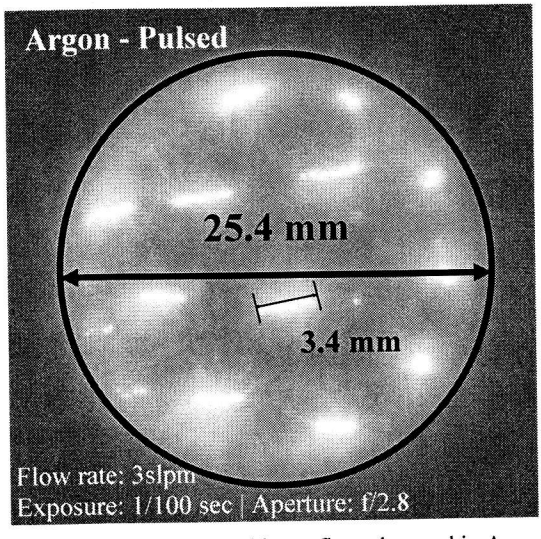


Figure 4. Motion of the filaments with gas flow observed in Argon plasma

A filament travels approximately 3.4 mm in 1/100 s resulting in a velocity of 3.4 m/s. The gas flow rate for this picture is 3 standard liters per minute (slpm) through the volume of a cylinder with height 2 mm and diameter 25.4 mm, meaning that the average residence time of the gas in this volume is about 0.02 s, and in that case the average linear gas velocity will be on the order of 1 m/s, which is comparable with the filament movement velocity. It means that the memory effect in argon or air DBD [16,17] is related not only to charge deposition on the surface but also to the pre-ionization (or high concentration of excited molecules) that exists in the gas after DBD polarity change.

3.2. HELIUM

Previous experiments display the uniform nature of DBD plasma at atmospheric pressure in helium [13]. We also observe uniform plasma in helium at least with long exposition time (but for some cases at short exposure also (see below) and with all three power supplies.

Helium plasma exhibits a uniform background, with some filaments in stationary positions (Fig. 5). We believe that these filaments are artifacts of particulate contamination on the bottom electrode.

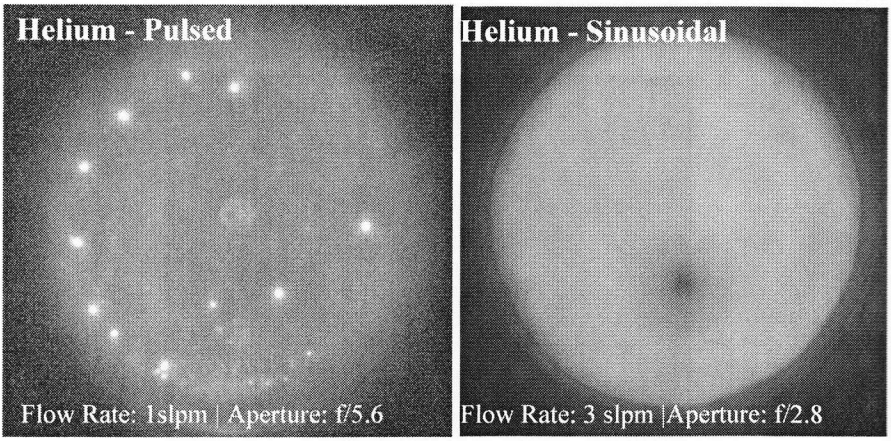


Figure 5. No evidence of excitational propagation observed in Helium. Both pictures are taken at ¼ s exposure time

3.3. OXYGEN

Plasma uniformity was achieved (Fig. 6), as reported for some previous experiments using oxygen plasma [14,15]. The DBD plasma in oxygen is observed to be diffuse and is visible at a minimum exposure time of 1/30 s versus 1/4,000 s for Helium at ~2 W/cm^2. As the exposure time decreases, filamentary structures which create the appearance of diffuse plasma at longer exposures are revealed (Fig. 6).

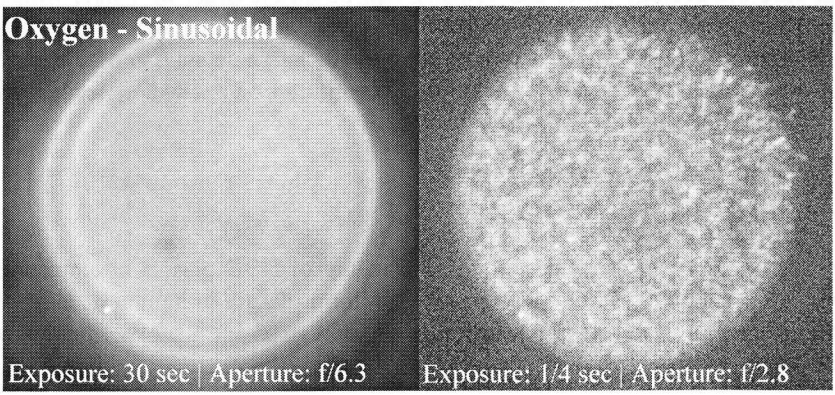


Figure 6. DBD plasma uniformity with sinusoidal waveform in oxygen. Flow rate: 1 slpm

3.4. NITROGEN

Nitrogen DBD plasma uniformity is also observed at long exposures and for all waveforms (Fig. 7). Interesting occurrences are in Nitrogen using sinusoidal waveform. It is possible to see that in plasma generated using the sinusoidal waveform, filaments in Nitrogen have no preferential direction of travel (Fig. 8), contrary to Argon and Air, where streamer channels flows in the direction of gas and at the velocity comparable to the bulk gas velocity.

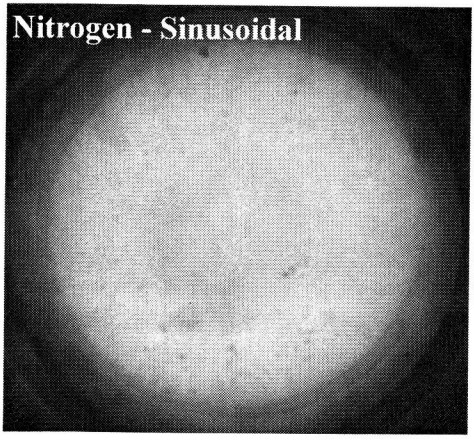


Figure 7. Nitrogen uniformity at 1 slpm flow rate, 30 s exposure time and f/32 aperture

An interesting phenomenon, however, can be observed at short exposures with the sinusoidal voltage waveform at 1.2 W/cm^2. The observed effect in Fig. 9 can be attributed to either the propagation of non-equilibrium vibrational excitation radialy from the filament or to the increase of a reduced electric field, *E/n*. These probable phenomena results in a cylindrical front of weak breakdown approximately 4 mm from the center of the microdischarge (Fig. 9). So, instead of the whole microdischarge current concentrated in one channel that is typical for standard DBD [16,17], a complex radialy symmetrical distribution of the micro-discharge current appears, and characteristic radial size of this current is about 4 mm in the particular case presented in Fig. 6. Therefore interaction between microdischarges that usually have characteristic distance on the level of 0.5–1 mm now have much larger characteristic distance, and microdischarges form two-dimensional quasi-crystal with the lattice size of about 5–8 mm. It looks like this crystal structure is rather 'rigid' and gas flow cannot move 'nodes' of this lattice (in contrast with the argon case, Fig. 4). On the other hand, stochastic processes in microdischarge formation [16,17] case slow stochastic (random) drift of the 'lattice nodes' (Fig. 8).

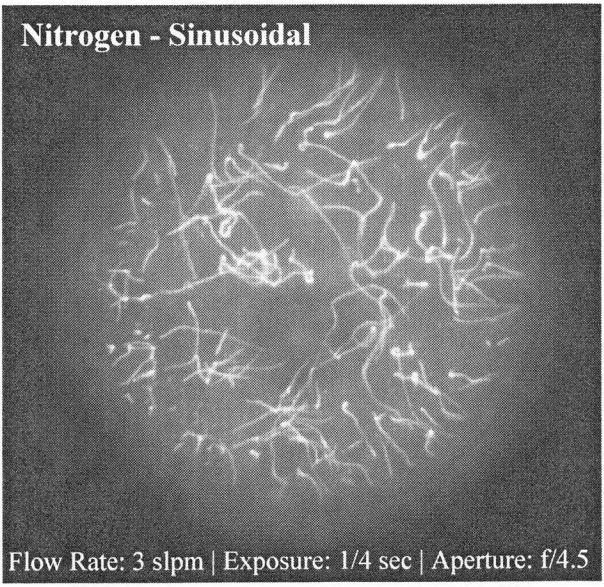


Figure 8. Nitrogen filaments generated using sinusoidal waveform have no preferential motion direction

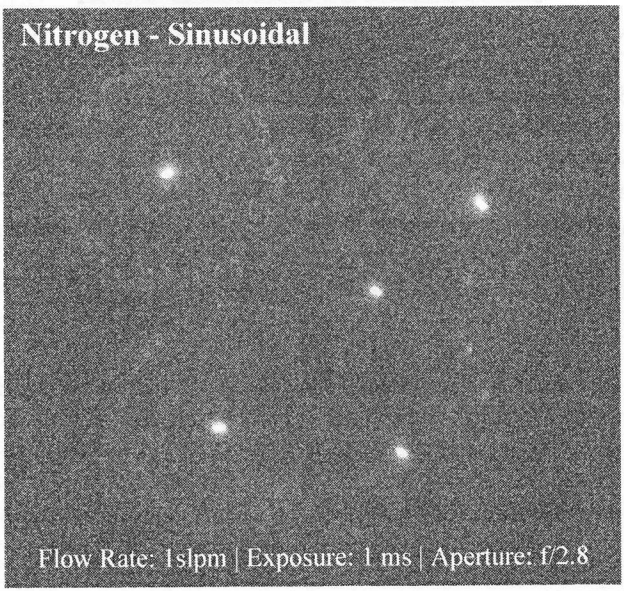


Figure 9. Propagation of excitation observed in Nitrogen at low exposures is exclusive to the sinusoidal waveform

The propagation phenomenon was not observed in the cases of the pulsed and continuous power waveforms for all gasses. A weaker version of the propagation phenomenon may occur, however is not observed.

4. Summary and Future Work

Three phenomena were observed in the discussed experiments: memory effects can be bound to the gas *or* to the surface; a cylindrical front of weak breakdown was observed in Nitrogen plasma where filaments have no directional preference of motion; and there is great uniformity in both Oxygen and Helium plasma without the use of complex electrode structures or special power supplies.

Future work will focus on better understanding and modeling of the mechanisms of excitation propagation observed in Nitrogen plasma.

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