Characterisation of an air plasma torch for in-situ surface processing

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Abstract

This study presents the characterisation of an atmospheric pressure plasma (APP) generated using a novel torch device created for cleaning of Concentrating Solar Power (CSP) heliostats. Optical emission spectroscopy (OES) is employed to investigate photonic intensity, and thus energy, of the plasma temporally and spatially. Plasma generated from air is shown to consist mostly of ionised nitrogen species at relatively low intensities, demonstrating the inefficiency of generating plasma from air. Spatial maps of air plasma show an uneven distribution of plasma over the measured area, indicating the need for either reconsideration of torch design, or development of an appropriate tool path to account for this. The relationship between plasma intensity and input parameters such as power and gas flow are investigated, with power shown to have a strong effect on intensity, whereas the effect of the gas flow rate was minimal. Intensity of the air plasma was shown to increase over a period of approximately one hour, which was dependant on the temperature of the input gas, showing the need to include a warm-up period before any processing is undertaken.

1 Introduction

Plasma is an invaluable tool in industry and has a vast field of utilisation: for example in surface cleaning, etching, and surface energy modification for applications such as enhanced wettability and improved adhesion to a substrate [1][2][3][4]. Most frequently, plasma processing occurs under vacuum conditions, necessitating longer processing times, specialist equipment, and in turn higher costs. Atmospheric Pressure Plasma (APP) is a promising alternative for a wide array of applications and is increasingly the subject of research for both conventional and novel applications, with interesting and favourable results reported in areas such as aerodynamics, generation of electromagnetic radiation (UV), biomedical applications[5][6]. As it does not necessitate a vacuum chamber, samples to be processed can be of any size or shape. It also provides the possibility of processing of samples in-situ with portable plasma systems, opening a huge avenue of applications.

APP, in particular of the Dielectric Barrier Discharge (DBD) design, are a field of increasing interest and research, as their comparatively simple design and ability to produce plasmas without bulky and expensive vacuum systems often seen in industrial applications of plasma, makes them an attractive prospect for the processing of various materials. However, generation of plasma outside of the vacuum systems typically employed in industrial applications presents challenges in obtaining and maintaining a plasma that is stable both spatially and temporally, where failure to do so can result in processing errors and repeatability issues. Consequently, characterisation of the plasma produced is an important tool in understanding and controlling plasma discharge characteristics.

Plasma generated at atmospheric pressure can suffer from temporal and spatial instability, as well as contamination from components in the air such as humidity [7], which can result in processing flaws and repeatability errors. Previous studies were carried out to understand the thermodynamic properties of RF plasma [8][9] and OES characterisation of microwave plasma [10][11] , making them available for glass surface modification and polishing. In order to minimise these effects and create an adequately stable plasma, characterisation of the produced plasma was undertaken in this study, such that in process real-time adjustment of the input parameters can be made to control and counter instabilities as they arise.

2 Methodology

2.1 Experimental set-up

In this work, characterisation of the plasma was conducted via spectroscopy, a technique that detects the photons emitted from molecular and atomic transitions in the plasma that occur as a result of decay, when an electron in an excited species falls to a lower energy level, or when a free electron becomes bound to an atom [12]. Substances are generally able to undergo multiple energy transitions which make up emission spectra that are defined, unvarying, and unique to each element, allowing accurate analysis of the composition of a substance. Ultraviolet-visible spectroscopy was chosen as the emissions from air plasmas found in literature typically fall within this range, most prominently from the 2nd Positive system of Nitrogen, the major peaks of which occur between 295 nm and 449 nm [13].

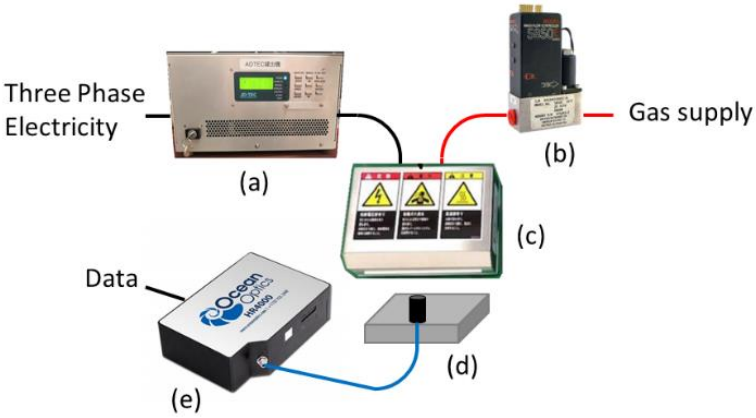

Figure 1: Experimental setup showing: a, generator; b, mass flow controller; c, plasma generating device (torch); d, motion stage; e, spectrometer.

In this work, Ocean Optics HR4000 spectrometers in the wavelength range 300-400 nm and 400-850 nm were used, with optical resolutions of 0.06 nm and 0.24 nm (FWHM) respectively, which were connected to a lens via fibre-optic cables. As displayed in Figure 1, this lens was mounted on a motion stage positioned 10 mm below the torch, to accommodate for the focal length of the lens. The torch was mounted on a bracket and remained stationary throughout. Spectroscopy was used to map the spatial intensity distribution of the plasma, with the lens moving in a series of passes below the torch, thus creating a map of emissions. Conversely, temporal stability was assessed with the lens positioned beneath the torch and retained stationary for the duration of data collection. For all analyses, the spectrometers were set to an integration time of 100 ms with a data refresh interval of 5 ms. All intensities listed are relative, not absolute.

2.2 Plasma parameteres

Generation of plasma was obtained via bespoke equipment provided by Adtec Plasma Technology Co. Ltd.. such equipment is is a dielectric barrier discharge (DBD) torch type, conntected to a custom made generator through which power in the plasma was controlled via current, with values between 0.2 A and 0.9 A. The torch was cooled via an inbuilt cooling jacket using a circulating coolant solution at 20 °C. Flow of gas into the torch was controlled via a mass flow controller across the range 10 L/min to 60 L/min.

3 Results and discussion

3.1 Static spectrum

Data obtained from the static measurements of the plasma over the entire range measured are shown in Figure 2. The spectrum shows peaks that were identified from literature as originating from nitrogen species, with the most prominent being at 337.13 nm from the (0,0) band of the nitrogen Second Positive system [13][14]. Ozone was produced, as indicated by its distinct smell as well as the triggering of an Ozone detector alarm placed around the measurement enclosure. However this was not detected in the emission data as ozone is a strong absorber of UV, therefore quantitative detection and analysis was not possible [15].

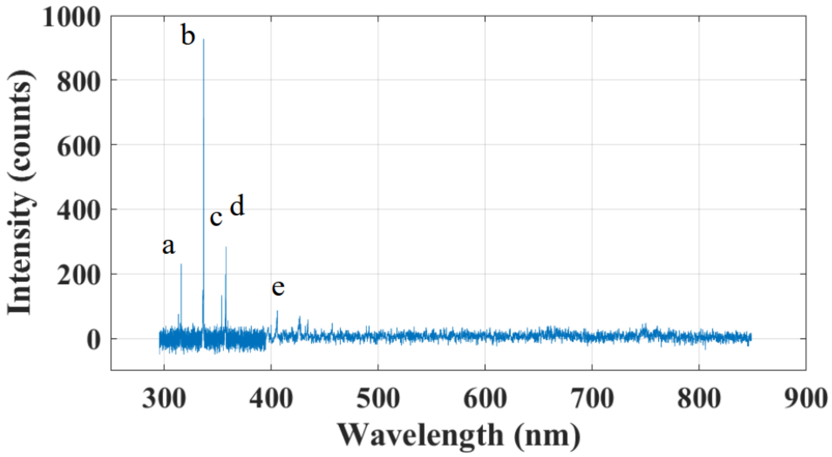

Figure 2: Emmision spectrum of air plasma with peaks labelled as follows: a, NO A-X (0,4); b, N_2 C-B (1,0); c, N_2 C-B (0,0); d, N_2 C-B (0,1); and e, N_2 C-B (0,3).

All subsequent analysis is of the aforementioned 337.13 nm peak in air generated plasmas owing to its higher intensity.

3.2 Temporal Stability

Emissions at 337.13 nm peak were analysed at torch start up and during a run for the subsequent two hours, as show in in Figure 3. Results demonstrated that, although the immediate ramp up is effectively instantaneous, it can take some time for the torch to become stabilised and to maximise plasma intensity, with average intensity increasing by 6.2 % over the first hour before stabilising. This effect was particularly evident during cold days, as the air supply to the torch is pulled from the external ambient air, which during the period of data collection was as low as -2 °C.

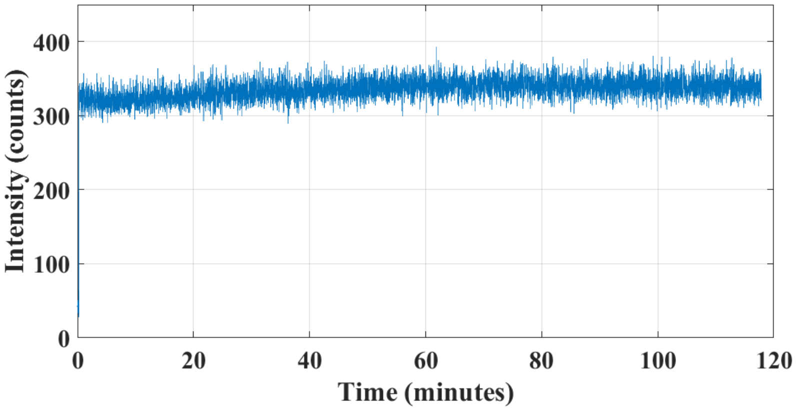

Figure 3: Temporal stability of plasma generated from air at a flow rate of 60 L/min, with current from the generator set to 0.9 A.

3.3 Spatial Mapping

When the intensity of the plasma is mapped spatially, 7 distinct regions of plasma generation were observed, as displayed in Figure 4 at the four combinations of parameters extremes (Gas flows of 60 L/min and 10 L/min, and currents of 0.9 A and 0.2 A). . This distribution is as a result of the torch design, currently protected intellectual property therefore not discussed in this work.

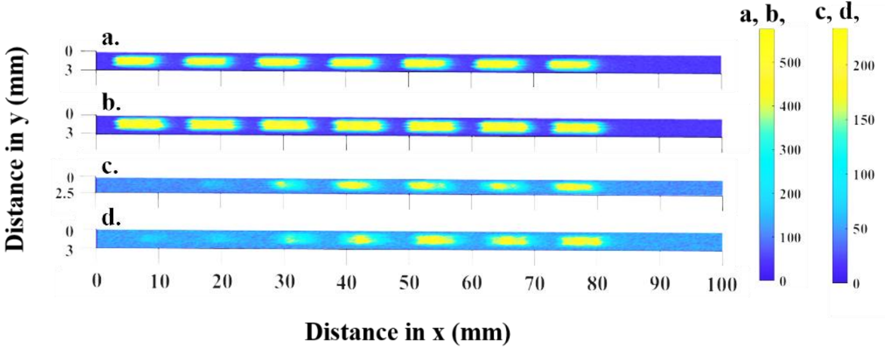

Figure 4. Spatial maps of intensity of 337.13 nm peak in plasma generated from air with the parameters: **a.** 60 L/min 0.9 A,. **b.** 10 L/min 0.9 A, **c.** 60 L/min 0.2A, **d.** 10 L/min 0.2 A.

The intensity of these regions was shown to correlate strongly with the current from the generator (Figure 5), but was negilgibly linked to the gas flow (Figure 6). Also observed was that the intensity of the plasma was linearly correlated to the current at values between 0.4 A and 0.9 A, however at 0.2 A and 0.3 A the plasma generated at the first two regions was significantly lower in intensity than in the regions 3 to 7. This may be due to a combination of the locations of the electrode structures within the torch, and the distribution of flow of air across these electrodes.

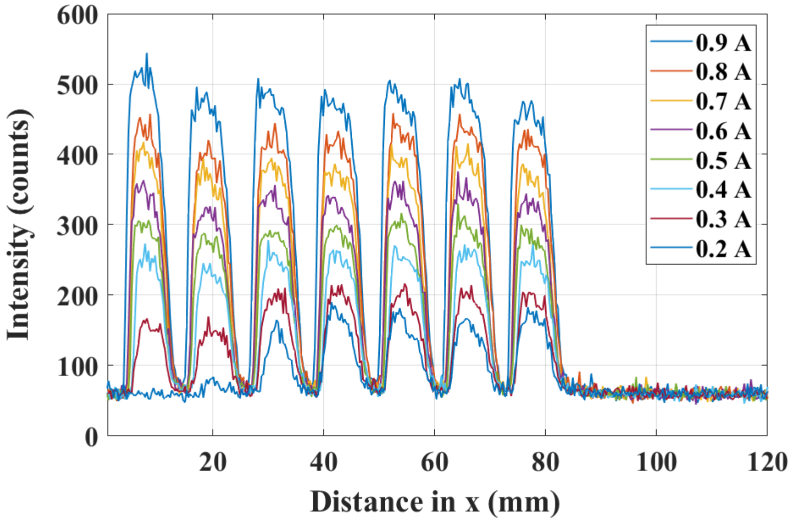

Figure 5. Intensity of the 337.13 nm peak in plasma generated with air at 60 L/min, with a range of currents.

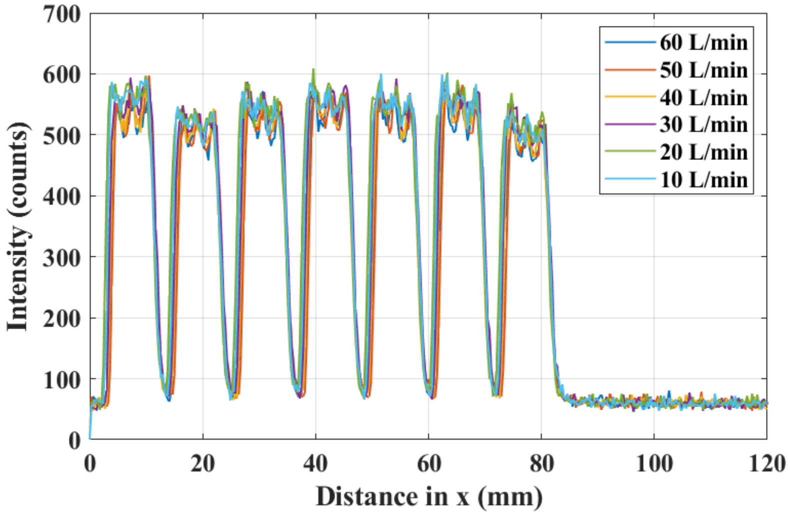

Figure 6. Intensity of the 337.13 nm peak in plasma generated with air at 0.9 A, with a range of gas flow rates.

4 Conclusion and Future Work

The work presented here shows the value offered by spectroscopic characterisation of plasma. The knowledge gained from this work will provide invaluable feedback for optimal torch design and processing procedures. It has been demonstrated that, although DBDs are a robust technology that are generally able to produce a stable plasma, energy coupling and thus plasma intensity are affected by a number of input parameters and environmental conditions that should be carefully understood and where possible controlled, in order to produce a plasma that is stable both spatially and temporally. For plasma processing, such a stable plasma is vital for processes that need to be controllable, repeatable, and precise. Whilst this work was conducted on a torch that was separate from any processing system, it is possible to mount a lens so that spectroscopy can be conducted in-situ, with appropriate data processing enabling real time characterisation of the plasma, which would allow instabilities to be immediately detected and plasma parameters adjusted accordingly to ensure stability in the plasma and reduce processing errors.

The authors envisage that future work will compound understanding of the distribution of plasma generated from the torch, and how this is affected by input parameters including temperature of the source gas. Three dimensional spatial maps would be beneficial to investigate intensity of the plasma within the plume for different stand-off distances between torch tip and substrate. This would reveal the effect of a parameter identified as key for processing by previous work [16]. Also to be investigated is the temperature of the plasma and its energy transfer mechanisms to the surface, knowledge of which could determine which materials could be processed and how thermal effects influence such processing

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