Novel non-equilibrium plasma source: Propeller Arc

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Abstract: A novel atmospheric pressure non-equilibrium plasma source named the "Propeller Arc" (PA) is developed using the concept of rotating electrodes. The PA device consists of a rotating cathode, driven by a motor, with one or more fixed anodes. Plasma is ignited at or near the narrowest gap as the rotating cathode passes by the anode and then it is extended up to a length of ~66mm or longer depending on the supplied power. This allows for efficient ignition, followed by a quick increase in plasma volume. The PA is similar to the widely used gliding arc (GA); however, unlike the GA, PA does not require imposed gas flow, and the PA discharge frequency can be easily controlled by the motor angular velocity. The basic characteristics of PA are investigated using two different operation modes: pulse modulation and DC power. As the PA has a compact design and is relatively easy to stabilize and control without the need for applied gas flow, it has potential to be adapted for many different applications such as nitrogen fixation, fuel and carbon dioxide conversion, waste, odor and hydrogen sulfide treatment, etc.

Keywords: Non-equilibrium plasma source, Propeller arc, Gliding arc

1. Introduction

Many different atmospheric pressure non-equilibrium plasma generation methods have been reported to address the multiple and sometimes unique requirements of different applications (medicine, disinfection, water treatment, material treatment, nitrogen fixation, food processing and agriculture etc). One widely used plasma source is the gliding arc (GA) discharge which has been successfully used in a variety of technological applications [1-2]. The traditional 'flat' GA discharge looks similar to the "Jacobs ladder" configuration. These devices are commonly driven by a high voltage applied across adjacent, vertically aligned and diverging electrodes. Gas breakdown to form the plasma column usually occurs at the closest gap between the two diverging electrodes. After breakdown, the discharge 'glides' up the electrodes due to natural convection from the locally heated neutral gas or external gas flow.

GA has proven useful for many applications by reason of its simple structure, chemical selectivity, relatively high-power densities, etc. Perhaps most importantly, the moving GA discharge can treat relatively large volumes of gas at the relatively low applied voltages compared to the common pin-to-plane or pin-to-pin discharge structures. However, there are also some drawbacks to the traditional GA discharge configuration [3]. Sometimes the GA configuration can be difficult to control due to instabilities and the inherently transient character of the discharge. Numerous authors have addressed the issues of GA slip velocities, plasma column lengths, and related issues [4-5]. Another aspect that can complicate use of this configuration is the need for a relatively strong gas flow which can tend to intensify the natural instabilities of GA by turbulence. Furthermore, non-uniform gas flows and relatively low gas residence time in the plasma region can limit some applications. In response to these perceived limitations, some authors have suggested structural improvements on the original GA design. [6-7]

In this report [8], we will report on an alternative elongating non-equilibrium plasma source that we refer to as the "Propeller Arc" (PA) discharge. Briefly, PA consists of a rotating cathode (ground electrode), driven by a motor, with a fixed anode (HV electrode). The plasma column length and the discharge frequency can be adjusted and controlled accurately without applied gas flow. Some basic characteristics of PA are investigated in this report including electrical characteristics; time-resolved optical emission imaging; plasma electrical properties such as resistance and average electric field (discharge voltage divided by gap distance) and plasma power consumption.

2. Design and operation of the Propeller Arc

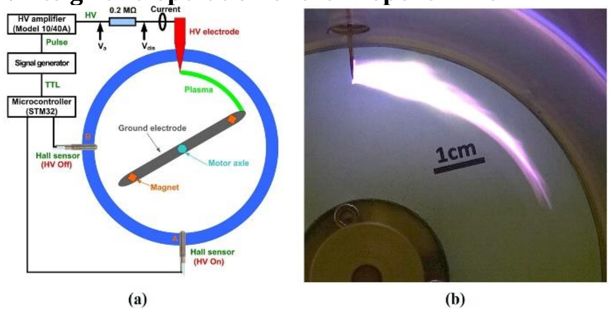

Fig. 1. (a) Configuration of the PA discharge using pulse modulation. Note the electrode is moving clockwise; (b) discharge photograph with an applied voltage of 9 kV and frequency of 60 Hz.

The configuration of PA using pulse power modulation as show in Fig. 1. The propeller-like blades of the rotating (grounded) cathode are made by stainless-steel. The distance between the center of motor axis and the tip of the cathode is 35 mm. A stainless-steel pin with a diameter of 0.8 mm is used as the stationary anode electrode. Using pulse modulation, the plasma is ignited at the narrowest gap (~0.5mm) between cathode and anode, and is then drawn away by the rotating electrode to a length up to ~55mm. Two vertical distribution of hall sensors (A3144E) were used to capture the position of the rotating cathode (see Fig. 1 (a)). This information triggers the HV amplifier connected to the anode, controlling the ignition and extinguishment of the discharge based on the propeller location. With this design, the amplifier can apply HV to the anode when the cathode tip is at the narrowest gap. The discharge frequency is controlled by the motor angular velocity. In the results reported here, frequency can be adjusted from ~1 Hz to 200 Hz. A ballast resistor of 0.2 MΩ is used to limit the current to less than 45mA which is the highest current allowed for stable operation of the amplifier used (TREK MODEL 10/40A). In this way, a relatively large plasma volume can be produced while achieving breakdown at a relatively low voltage. Fig. 1(b) is a photograph of the PA discharge at 9 kV applied voltage and 60 Hz (corresponding to motor speed of 1800 revolutions per minute, rpm).

If a DC power supply is used to drive the PA discharge, the configuration of the setup is simpler. There is no need for hall sensors, signal generator or amplifier. In this case, the plasma is ignited automatically at a gap of ~6 mm before the cathode reaches the narrowest gap, where the breakdown voltage is 9 kV. After breakdown, the development of the plasma is similar to the case with pulse modulation. The key difference is that the plasma extinguishment is not controlled and occurs naturally when the cathode is sufficiently far from the anode and the power supply is unable to deliver enough energy to maintain a plasma at the increasingly longer discharge.

3. Results

Fig. 2 shows the waveforms of PA discharge voltage and current using pulse modulation with three increasingly high time resolutions around the breakdown region. Breakdown occurs when the gap voltage reaches ~3 kV, then discharge voltage (V_{dis}) drops to nearly zero. As the plasma plume extends in length, the V_{dis} increases to about 5 kV before the applied voltage (V_a)is set to zero (controlled by hall sensor B). At the same time, discharge current (I_{dis}) appears with a ~20 nanosecond pulse with a peak of ~7 A during breakdown. The current peak drops to ~45 mA within ~0.1 µs. The discharge current decreases to ~20 mA just before V_a is zeroed. The PA plasma total power consumption reaches ~36 W which is significantly higher than dissipated power recorded with a pin-to-plane (2 mm gap) discharge under the same experiment conditions (~11 W). As the discharge is ignited at the point in time when the gap is narrowest (0.5 mm) and the discharge frequency (15 Hz) is low, the power consumption in the breakdown region is only ~5 mW (Fig. 2(c)). This value is negligible compared with the overall

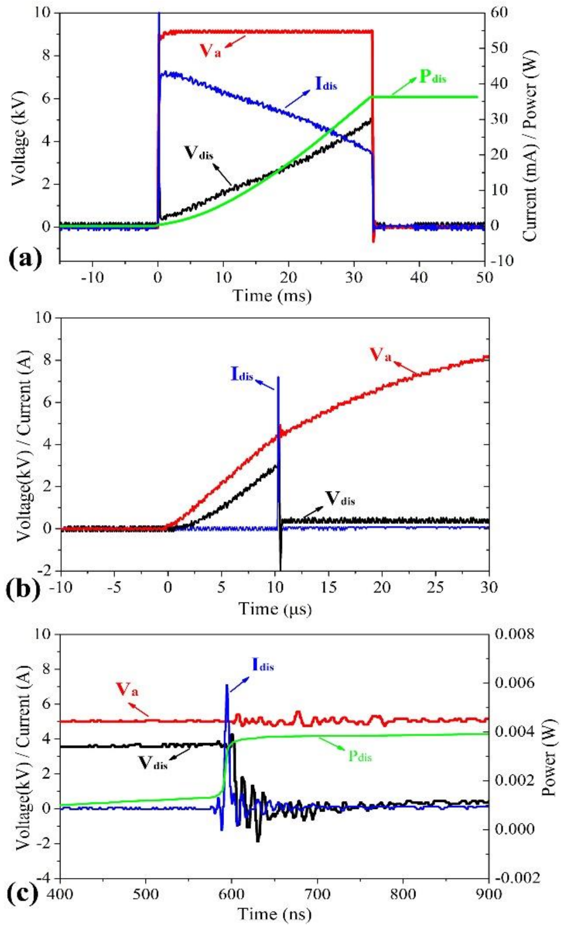

Fig. 2 Waveforms of PA discharge voltage and current using pulse modulation in the time scale of ms (a), µs (b) and ns (c) with an applied voltage of 9 kV and frequency of 15 Hz. The calculated power during the pulse is illustrated in (a) for the whole discharge (~33 µs) and (c) for the breakdown region (~ 500 ns).

plasma power consumption (~36 W).

Fig. 3 shows time-resolved images of the PA discharge under the pulse modulation conditions associated with Fig. 2. A high-speed camera (Sony Cyber-shot, DSC-RX100 IV) is used to capture the images synchronized with the discharge current (cf. Fig. 2(a)). The frame rate is set at 1000 per second with a corresponding image exposure time of 1 ms. The plasma ignites at the narrowest gap (~0.5 mm) between cathode and anode. The plasma plume is subsequently stretched by the rotating cathode. The PA discharge is visually stable and the brightest part of the visible plume is arc-shaped. A cathode spot can be seen near the tip of the rotating cathode during the pulse (0-33 ms).

To further investigate the characteristics of the PA discharge, the plasma resistance and the spatially-averaged electric field (V_{dis}/d) are calculated as shown in Fig. 4. PA instantaneous resistance is defined as V_{dis}/I_{dis}. In part, we compute these quantities because they may help in future

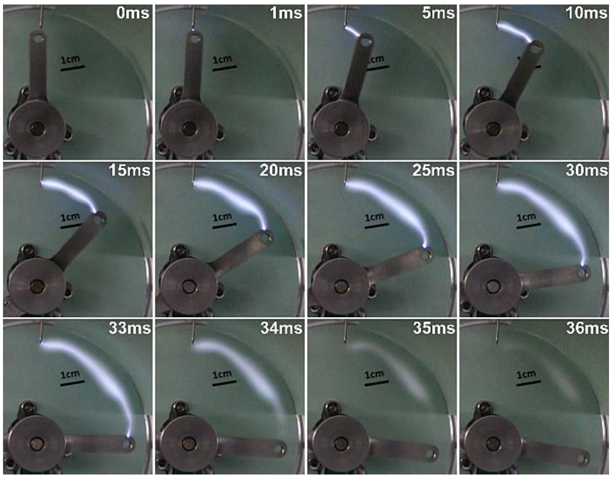

Fig. 3 Time-resolved imaging of the discharge at 15 Hz and 9 kV using pulse modulation.

attempts to understand the physico-chemical properties of the PA discharge.

In the pulse modulation case, the plasma resistance increases rapidly from ~8 kΩ to ~250 kΩ from breakdown to plasma extinction. For the DC power supply case, the plasma resistance first decreases to ~8 kΩ, after initially reaching ~40 kΩ, it then increases to almost 1000 kΩ as the plasma is extinguished. In the DC case, after 5 ms (corresponding to the point of the narrowest gap), the resistance profile matches that seen for pulse modulation. The spatially-averaged electric field is defined by V_{dis}/d, where V_{dis} is the instantaneous gap discharge voltage and d is the instantaneous visible length of the PA plasma. From the time-resolved images, d is nearly equal to the arc length from the tip of the anode to the tip of the cathode.

Fig. 4(b) plots average electric field V_{dis}/d vs. discharge time using pulse modulation and the DC power supply. In the pulse modulation case, the average electric field starts at a value of ~4 kV/cm at breakdown, then drops within the first few ms. After about 5 ms, it maintains a relatively stable value of ~0.8 kV/cm up to ~33 ms with a slight rise at the end. It should be noted that plasma length and the electrical characteristics of PA change significantly during this time. In the DC power supply case, V_{dis}/d first increases to a peak of ~7.5 kv/cm at ~ 5 ms after ignition from ~1.2 kV/cm. After this peak value, corresponding to the minimum gap position, it qualitatively follows the trend seen in the pulse modulation case, with a value of ~0.9 kV/cm from 15 ms to 35 ms. In the final region before the discharge is extinguished, V_{dis}/d increases again to ~1.8 kV/cm. Both in plots of plasma resistance and average electric field, a 'kink' is apparent for the DC power supply case, associated with the early breakdown and voltage oscillation.

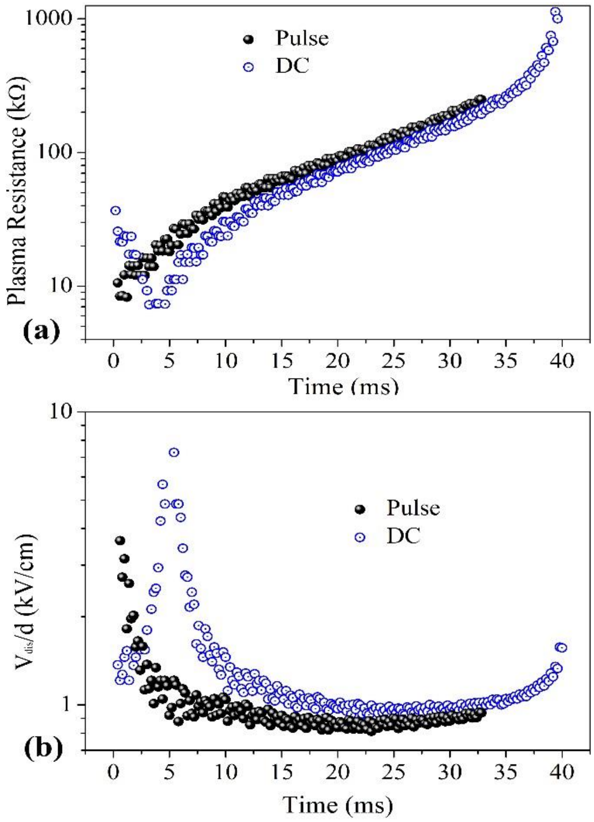

Fig. 4 (a) Plasma resistance (V_{dis}/I_{dis}) and (b) average electric field V_{dis}/d vs. discharge time using pulse modulation (black symbols) and DC power supply (blue symbols).

4. Conclusions

A new non-equilibrium plasma source - the "propeller arc" (PA) - has been designed to produce a controllable, stable and relatively large volume plasma for high throughput gas processing applications. It can be operated using pulse modulation or a DC power supply. The various aspects of the PA discharge is controlled more effectively using pulse modulation, including plasma plume length and the point of gas breakdown. However, pulse modulation requires a more complex device configuration including various sensing equipment, and time-triggered signals. The use of DC power is a simpler option, but the plasma ignition and extinguishment are not completely controlled and occurs naturally. Depending on the requirements of the specific applications, both operation modes may find a use.

In this work, relatively simple examples using the concept of rotating electrodes have been presented. It is not difficult to imagine more complex and specialized versions of the design, including the use of multiple cathodes and anodes; modified diameter and shape of the rotating blade cathode; various changes in discharge power supply; coupling with gas flow control devices, etc. Due to its compact design, controllability and stability, the PA device configuration appears promising for many applications including nitrogen fixation, fuel conversion, carbon dioxide conversion, waste treatment, and hydrogen sulfide treatment, among others.

5. References

[1] A. Czernichowski, Pure and Applied Chemistry, **66**, 1301-1310, 1994.
[2] T. Nunnally et al., Journal of Physics D-Applied Physics, **44**, 274009, 2011.
[3] S. P. Gangoli et al., Plasma Sources Science & Technology, **19**, 065003, 2010.
[4] F. Richard et al., Journal of Applied Physics, **79**, 2245-2250, 1996.
[5] J. Sperka et al., European Physical Journal D, **67**, 261, 2013.
[6] C. S. Kalra et al., Review of Scientific Instruments, **76**, 025110, 2005.
[7] M. J. Gallagher et al., Fuel, **89**, 1187-1192, 2010.
[8] X. Pei et al., Plasma Sources Science & Technology, **27**(12) 125007, doi: 10.1088/1361-6595/aaf7ef, 2018.
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