Nitrogen Fixation Using a Propeller Arc in Air

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Synthesis of reactive nitrogen species using non-thermal plasmas has been recently proposed as an alternative technology for agricultural nitrogen fixation [1]. Additionally, plasma-liquid interactions with organic fertilizer can improve nitrogen retention, reduce odor, and control bacteria [2]. However, for wide implementation, the plasma energy efficiency needs to be improved which in turn requires that we improve our understanding of the underlying plasma science. We report on development of the Propeller Arc (PA) to better understand nitrogen fixation using air plasma.

The PA device consists of a rotating cathode with a fixed anode. The device can be operated using pulsed or DC power. Plasma is ignited over a 0.5 mm gap as the rotating cathode passes by the anode. The arc is then extended up to a length of ~55 mm or longer (depending on the power) as the cathode rotates away from the anode as shown in Fig. 1. This technique allows for efficient ignition, followed by a quick increase in plasma volume. The PA is similar to the widely used Gliding Arc (GA) [3]. However, unlike the GA, PA does not require gas flow, and frequency of arc formation can be controlled by the motor angular velocity. The energy efficiency of NOx production by PA was measured to be higher than $6.8 \times 10^{16}$ molecules/J at a peak current of 112 mA. PA also shows potential for other applications including fuel conversion, carbon dioxide conversion, waste treatment and hydrogen sulfide treatment. When compared with previously reported works focusing on NOx production, our experimental results (Fig. 2) show a correlation between NOx production energy efficiency ($P_{\text{NOx}}$) and average $E/N$ (electric field/gas density). The empirically derived relation scales as $P_{\text{NOx}} \sim 78\cdot(E/N)^{-0.85}$. However, the fundamental mechanisms associated with this relationship are not clear and requires further investigation.

References
NITROGEN FIXATION USING A PROPELLER ARC IN AIR

- A novel plasma source (Propeller Arc or PA) utilizes a rotating cathode with a fixed anode to investigate basic plasma mechanisms governing $\text{N}_2$-$\text{O}_2$ reactions in air plasma.

- Peak $\text{NO}_x$ production efficiency with the PA is $\sim7\times10^{16}$ molecules/J at 112 mA. Varying conditions enables investigation of mechanisms.

- One goal is to understand why air plasma $\text{NO}_x$ production efficiency varies with average $E/N$, this PA scaling with $P_{\text{NO}_x} \sim 78 \cdot (E/N)^{-0.85}$.

- Time-resolved images (15 Hz)

- Efficiency varies with average $E/N$
Fluid Dynamics Driven Self-Organization of Streamers in a Bubble

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The interaction of plasma with liquid water leads to the introduction of reactive oxygen and nitrogen species into solution. These species are of technological interest in that they can be used to purify water, disinfect surfaces, treat disease or facilitate the synthesis of new materials. This interaction of plasma with liquid water can also initiate fluid dynamical effects at the surface or even drive large-scale convection in solution.[1,2]

Here, we describe the coupling between plasma streamers in a bubble and capillary waves ultimately leading to self-organization, the purposeful development of spatiotemporal patterns that form within the bubble. This self-organization phenomena was observed in the 2-dimensional (2-D) bubble experiment where an essentially flat, 2-D bubble is trapped in a thin layer of liquid water between two closely spaced quartz plates. Flow in this 2-D cell is purely 2-D inviscid, potential flow which facilitates both the imaging and computational analysis of induced fluid flow, not unlike that of a Hele-Shaw cell used fluid dynamics studies. An electrode in the center of the 2-D bubble initiates streamer discharges that make contact with the interface. It has been observed here and elsewhere that the interaction of the streamer with the bubble interface sets the interface in motion giving rise to the propagation of capillary waves.[1] This work is the first such observation of 2-D capillary waves in this plasma liquid context. It was observed that at early times, streamer contact initiates stochastic deformation of the interface. Over short time scales, however, a characteristic capillary wave pattern appears, and associated with this pattern is the apparent self-organization of the streamers, demonstrating coupling between the excited surface waves and the streamer discharge as shown in Fig. 1. Indeed, the attachment points of the streamers apparently self-organized to more or less specific regions. Here the pressure applied on the interface by the streamers may be the driving force while the dominant, characteristic capillary wave mode for this bubble size may be the positive feedback. The streamer attachment points are likely also tied to the variation in the discharge gap between the interface and the central electrode. Such organization is interesting from a basic plasma physics standpoint, but it also suggests novel pathways involving self-organization that may be exploited to increase plasma liquid contact area.

References

Figure 1 – Capillary wave driven self-organization of streamers in a bubble. Top right hand panel shows streamers in bubble before self-organization. Main image shows self-organization pattern with capillary waves.
FLUID DYNAMICS DRIVE SELF-ORGANIZATION OF STREAMERS IN A BUBBLE

- Using a 2-dimensional plasma-in-liquid test cell, 2-D capillary waves initiated by streamer discharges have been observed.

- Chaotic streamers initially striking at the plasma-liquid interface act as forcing function.

- The streamers excite of dominantly capillary wave oscillations propagating along the bubble interface which provides feedback to the streamers.

- The oscillations lead to self-organization of the locations at which streamers strike the interface, which in turn further enhances the dominant oscillation mode.

- Back-lit interfacial capillary oscillations