

Thrust performance of axisymmetric dielectric barrier discharge plasma synthetic jets

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Abstract

Plasma synthetic-jet actuators (PSJAs) are dielectric barrier discharge (DBD) devices capable of injecting zero-net mass flux momentum in atmospheric conditions with nearly instantaneous response and no moving parts. The standard configuration for PSJAs is the linear arrangement of two exposed and ground electrodes, generating opposing wall-jets, which collide and form a wall-normal flow. We examined the electromechanical characteristics of an alternate configuration, the axisymmetric plasma synthetic jet actuator (APSJA). This device consists of a circular embedded electrode and an exposed ring electrode, producing a converging annular wall jet that forms a wall-normal jet similar to a traditional synthetic jet actuator. We present a parametric study of momentum injection and comparison to direct thrust measurement. Variations in geometry and operating conditions yield a significant improvement in APSJA performance.

Keywords: Electrohydrodynamics, plasma actuator, synthetic jet, dielectric barrier discharge, active flow control.

1. Introduction

Plasma actuators generally refer to electrohydrodynamic (EHD) devices that use electrical discharges in air. These include corona discharge, dielectric barrier discharge (DBD), glow discharge, and arc discharge [1-3]. Over the past two decades, DBD plasma actuators have garnered significant attention for active flow control due to their compact design and ability to rapidly alter flow characteristics [4-9]. Corona discharge and DBD non-thermal plasma actuators are zero-net mass flux (ZNMF) jets that operate by generating ions when an electric field exceeds the dielectric strength of the working fluid under the application of a high AC voltage. Despite lower electromechanical efficiency than corona-driven actuators, DBD actuators can provide consistent electrohydrodynamic (EHD) forcing and are more robust in their operation [9, 10].

AC-driven DBD actuators typically consist of an asymmetric electrode pair in which one is exposed to the working fluid and the other is encapsulated, separated by a dielectric layer. Plasma ignition occurs when a high-amplitude AC voltage and resultant EHD force acts on the fluid volume [11]. Straight-edge actuators have been a valuable tool for studies of the DBD mechanics in quiescent, co-flow, or counter-flow environments [6, 7, 12-14]. The interactions between accelerated free ions, walls, and the working fluid can be utilized in aerodynamic drag reduction [15-17], lift augmentation [18, 19], separation control [20, 21], and electric propulsion [22-25].

Synthetic jet actuators (SJAs) are also ZNMF jets formed from surrounding working fluid and have proven effective as flow control devices [26-28]. SJAs generally consist of an oscillating diaphragm inside a sealed cavity, creating suction and blowing cycles through an orifice. This approach has been investigated for load alleviation and expansion of the flight envelope [29]. Research on the integration of synthetic jets and DBD actuation, known as *plasma synthetic jet actuators* (PSJAs), has demonstrated unique capabilities for thrust vectoring [30, 31] and wall-normal jet formation via annular designs featuring concentric electrodes [32-34].

Santhanakrishnan and Jacob introduced the annular PSJA (APSJA) concept in 2006 [35], followed by a series of studies exploring steady-state jet development, self-similarity, pulsing activation, vortex structure, plasma morphology, and performance in external flow conditions [32, 33, 36, 37]. The authors evaluated

annular PSJAs with inner diameters ranging from 12.7 mm to 58 mm over a series of studies with a 1–2 mm gap between the embedded and exposed electrodes. Steady-state operation was investigated at frequencies of $f_{AC} = 5$ kV and 2.8 kHz, pulse frequencies of 1 Hz, 10 Hz, and 100 Hz pulsing frequencies were investigated, achieving a maximum mean axial velocity of ~ 1.05 m s⁻¹ at a 10 Hz pulsing frequency.

Benard *et al.* explored two opposing single DBD actuators spaced 30 mm apart with 160 mm of edge length on a 3 mm thick PMMA plate [30]. The opposing wall jets produced a weak wall-normal flow upon the collision. The two counter-rotating vortices surrounding the potential jet core were formed due to entrainment. Varying voltages, each DBD generated could change their momentum injections, resulting in a directional jet (± 20 degrees jet angle from normal). The authors reported a maximum centerline velocity of 1.9 m s⁻¹ at $V_{pp} = 22$ kV and $f_{ac} = 1$ kHz. Neretti *et al.* explored 11 sizes of linear and annular PSJAs ranging from 10 mm to 50 mm in diameter, operated at $V_{pp} = 11.5$ kV, $f_{ac} = 5$ kHz [38]. They found that for linear PSJAs, maximum velocity was achieved at a gap of 26 mm, with the jet profile remaining relatively constant. For annular PSJAs, they found that a maximum velocity of 6.1 m/s occurred with a diameter of 30 mm.

Table 1 provides a comparative summary of related studies on APSJA geometry in the literature, highlighting specific parameters investigated across each work.

Table 1. Summary of related APSJA studies in open literature.

Author	Primary diameter (mm)	Ring thickness (mm)	Waveform	Frequency (kHz)	Pulse frequency (Hz)	P-P Voltage (kV)	Material (κ)	Dielectric thickness (mm)	Maximum efficiency (η_{max})
This work (2024)	30 – 90	20	Sine	3 – 10		0 – 32	Quartz	1.6	0.397%
Neretti <i>et al.</i> (2017) [38]	10 – 50	5		5		11.5	FR-4	1.5	0.07%
Neretti <i>et al.</i> (2014) [39]	15	5		15		$V_1 = 6$ $V_2 = 3.4 - 6$	Kapton	0.4	Not reported
Santhanakrishnan (2009) [40]	6.35	3.175	Square	2.8	0, 10	5	Alumina ceramic	0.635	Not reported
Santhanakrishnan (2007) [32]	38	10	Square	4.2	0, 1, 10, 100	5	Kapton	0.05	Not reported
Santhanakrishnan (2007) [33]	12.7	6.35	Square	2.5	1, 10, 100	5	Alumina ceramic	0.635	Normalized*
Santhanakrishnan (2007) [36]	6.35 – 25.4		Square	2, 4.5	1, 10	3 W, 4 W	Alumina ceramic	0.635	Normalized*

*These publications reported normalized efficiency to compare relative performance. No reference value was provided.

While a significant range of electrical conditions, geometry, and dielectric properties have been explored in the literature, no single work has explored generalization and optimization for the APSJA concept over a parameter set with variation in voltage, frequency, and electrode radius above the low power (<10 W) regime. Specifically, this study provides insight into the performance of APSJAs over a broad parameter space with diameters ranging from 30 – 90 mm and 1.6 mm quartz glass dielectric material. The peak-to-peak AC voltage is varied in the range $V_{pp} = 5$ kV – 40 kV with continuous operation for frequencies $f_{AC} = 3$ kHz, 5 kHz, and 10 kHz. We demonstrate the extended range of functional APSJA diameters and enhancement of total wall-normal momentum injection and efficiency by an order of magnitude over previously reported values. The increase in performance is related to expansion of electrical, physical, and geometric parameters.

2. Experimental procedures

2.1 Actuator construction

All experiments were performed with APSJA DBD actuators in quiescent atmospheric air. The actuator configuration is shown in Figure 1. The electrodes are fabricated from 0.05 mm thickness copper film with an

adhesive backing. The width of the exposed ring electrode, $t_r = 20$ mm. The electrodes are positioned concentrically with zero gap, $w_g = 0 \pm 0.5$ mm. The actuator size is identified by the inner radius of the exposed electrode edge in the direction $\vec{r}$, $R = 15$ mm, 30 mm, and 45 mm. The electrodes are mounted on a quartz plate with thickness $t = 1.6$ mm, 99.995% SiO₂ purity, and dielectric constant $\kappa = 3.7$. The circular embedded electrode is encapsulated by a 0.5 mm thick Kapton sheet ($\kappa = 3.3$) attached with double-sided adhesive and two layers of 0.25 mm thick Kapton tape ($\kappa = 2.6$). The purpose of the backing is to prevent undesired plasma discharge/ignition on the back side of the actuator. Similar experimental procedures used other materials for this purpose, reducing the power consumption by a factor of two and reducing streamer quantity [41]. The embedded electrode is circular instead of a ring to avoid premature surface saturation due to discharge limitations and electric field concentrations.

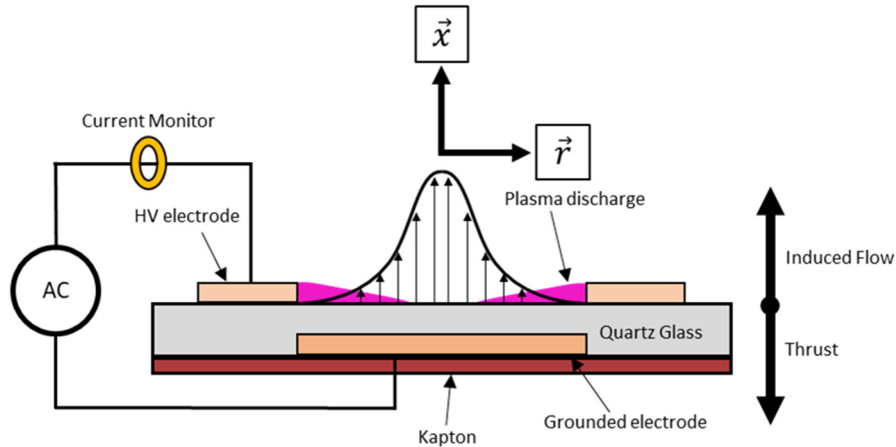


Fig. 1. Diagram of a DBD APSJA where a high AC voltage is applied between the exposed and embedded electrode forming plasma and a wall-normal jet. Thrust is measured with an analytical balance and fluid velocity is measured via pitot tube (not pictured). A high-voltage probe and current monitor are connected to an oscilloscope at 1 Gs s⁻¹ sample rate.

Fig. 2 shows a photograph of the $R = 30$ mm APSJA with a high voltage applied in the streamer regime of the actuator, defined by high applied frequency and voltage. Several other studies have explored the formation and physics behind surface DBD streamers, sustained filamentary discharges, and plasma morphology [42–45]. Note the observed propensity for streamer interaction at the edge of the plasma discharge and circular shape space discharge near the center.

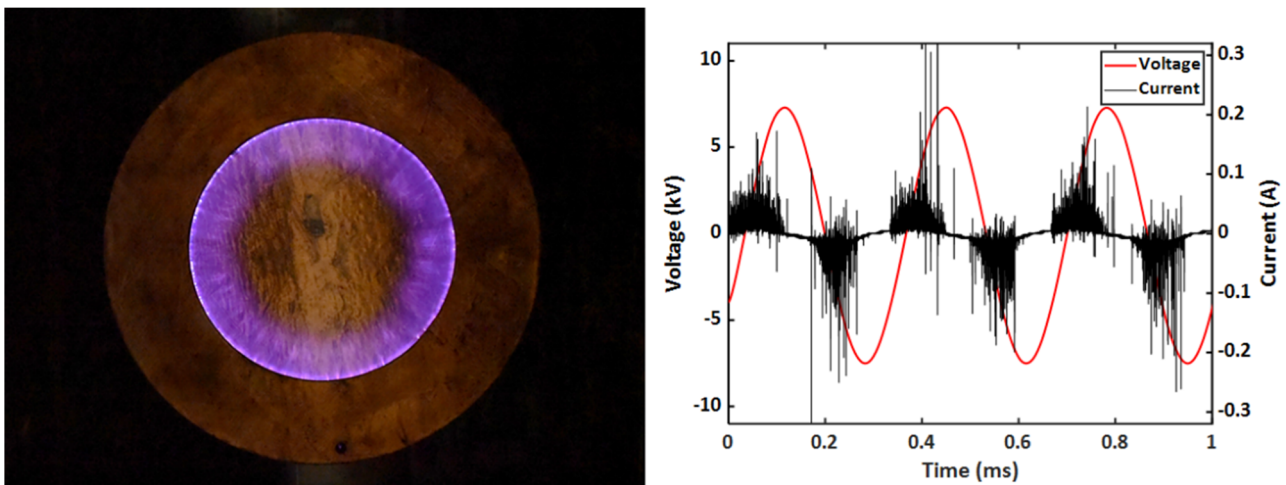


Fig. 2. Photograph of 30 mm radius APSJA in non-saturated regime operating at 14.85 kV (left) and voltage-current-time behavior at identical operating conditions (right). Small filamentary discharges can be seen around the inner edge of the active electrode.

Each actuator was tested across AC frequencies of $f_{ac} = 3$ kHz, 5 kHz, and 10 kHz at $V_{pp} = 0 - 40$ kV. Each experiment was stopped after we visually observed a sustained streamer greater than 3 – 5 mm in length. The electrodes are connected to a custom power supply comprised of a function generator (Siglent SDG1032X), power amplifier (Crown XLI3500), and two custom transformers (Corona Magnetics CM-5557-1), each capable of providing up to 35 kV peak-to-peak voltage, resulting in a total potential difference of up to 70 kV peak-to-peak across the two lines, similar to refs [46, 47]. The maximum current was approximately 0.4 A. The exposed electrode is connected to a primary high-voltage line and the embedded electrode is connected to a secondary high-voltage line with a 180-degree phase shift. All voltage measurements from the power supply and across the system are referenced to an independent ground [48, 49].

2.2 Voltage-current and power analysis

In DBD systems, the electric current in the circuit can be viewed as a low-frequency capacitive current and a separate discharge current. Plasma micro-discharges form the discharge current as a series of rapid pulses [45]. Electrical current is measured using a magnetic-induction Pearson 2877 current monitor with a 200 MHz bandwidth and 2 ns rise time. The probe is positioned around the wire driving the exposed electrode. Voltage is measured using a Tektronix 6015A high-voltage probe between the primary power line and ground. The current monitor and high-voltage probe are connected to a Tektronix DPO 7054 oscilloscope with a sampling rate of 1 Gs s^{-1} and a bandwidth of 500 MHz. The high bandwidth and sampling rate reduces noise during current measurements, enabling the calculation of time-average electrical power consumption [50]. It also accurately captures individual discharges, with an average duration of $\sim 20\text{--}40$ ns [41].

Signal processing was similar to the previous work [41, 45, 51]. Briefly, at least ten voltage-current cycles are recorded and processed using a Hampel filter to remove extraneous peaks. The capacitive current is then determined by the Fast-Fourier transform (FFT) with modes up to five times the input AC frequency. The capacitive current was subtracted from the total current, and the mean was taken from the remainder in both the positive and negative discharge regions to calculate the discharge current. Note that this approach provided results similar to those of the analysis of the peaks above a predetermined threshold [52].

The electrical power consumption, P_{elec} , was calculated by multiplying the voltage and discharge current at all points in the time series and averaging over the AC period.

$$P_{elec} = \int_{t^*=0}^{t^*=1} \phi(t) \times i(t) dt, \quad (1)$$

where f_{ac} is the frequency of the applied voltage in Hz, and $\phi(t)$ and $i(t)$ are the discrete voltage and current measurements throughout the period. The normalized t^* represents a single period. The discharge current and power were calculated over at least ten periods to reduce measurement noise. Fig. 2 (Right) shows a typical DBD applied voltage with the corresponding current.

2.3 Thrust measurement

The mechanical performance was characterized by direct thrust measurement using a battery-powered, electrically insulated analytical balance (Ohaus SPX223) with $1 \mu\text{N}$ sensitivity. The balance was placed in a Faraday cage to avoid electromagnetic interference (EMI). The actuator rests on a non-conductive spacer to transfer the EHD force to the electrically isolated analytical balance. The balance transfers the measurements to a computer via optical cable, and the results averaged over 25 seconds. This captures the injected wall-normal momentum injection due to the actuator compared to the initially quiescent medium.

3. Results and discussion

Actuators with sizes $R = 15$ mm, 30 mm, and 45 mm were tested at $f_{ac} = 3$ kHz, 5 kHz, and 10 kHz. The electrical current and thrust were measured for each size and frequency starting at $V_{pp} = 0$ kV and increasing in increments of approximately 5 kV until visibly sustained filamentary discharge formation. This region corresponded to unsteady actuator thrust production and fluctuations in power draw.

3.1 Momentum injection and thrust

This direct force measurement is supported by comparison to velocity profiles measured with a 0.8 mm OD glass pitot tube through a 0.25-inch water column (IWC) differential pressure transmitter measured at 1 Hz for 25 seconds, similar to reference [5]. The resulting axial velocity profiles qualitatively match results from Neretti and Santhanakrishnan [35, 38]. Velocity profiles for the $R = 45$ mm APSJA are shown in Fig. 3 at the electrical condition $f_{ac} = 3$ kHz and $V_{pp} = 26$ kV. Radial spans of axial velocity measurements were conducted at vertical distances the $\vec{x}$ direction ranging from $0.5R$ to $3R$ away from the actuator surface. The wire position is omitted due to emf interference in the flow field, accounted for by measuring across the full actuator diameter and averaging the velocity magnitude between the positive and negative radial positions. The formation of the wall jet in initially quiescent conditions satisfies the conservation of momentum principle, such that the combined wall-normal jet, viscous, and wall friction losses will be identical to the total axial momentum injected parallel to the wall by the DBD actuator.

The streamwise force produced by the fluid discharge can be determined by using the inviscid second-order momentum integral equation. For the axisymmetric jet, trapezoidal integration yields the following relation for momentum flux in the $\vec{x}$ direction

$$I = \pi \rho \sum_{i=1}^{n-1} \left(\frac{v_i^2 + v_{i+1}^2}{2} \right) (r_{i+1}^2 - r_i^2) \quad (2)$$

where I is the total momentum flux, ρ – the fluid density, and v_i – discrete discrete velocity measurements at the corresponding radial position r_i . Spans were conducted at 0.5 mm increments in radial position for the $R = 15$ -mm and 30-mm configurations and 1 mm increments for the 45 mm APSJA.

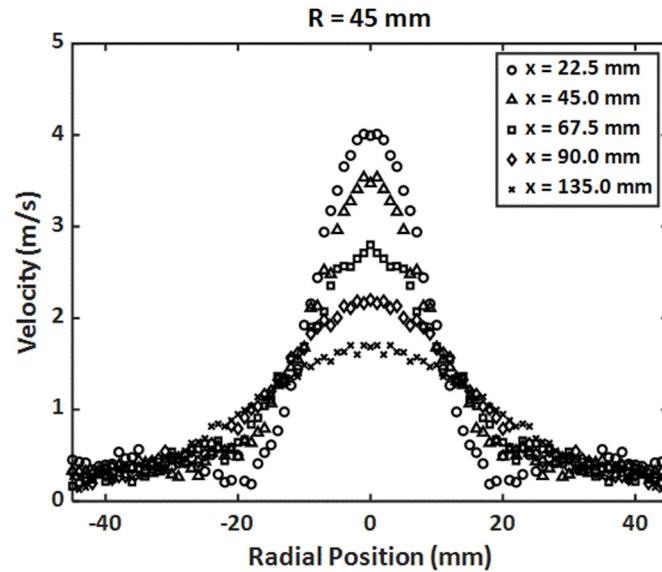


Fig. 3. Axial velocity profiles for $R = 45$ mm APSJA at 3 kHz and 26 kV. Equal magnitude positive and negative locations averaged and plotted with symmetry. Maximum velocity occurs at centerline, $U_{max} = 4.1 \text{ m s}^{-1}$.

Table 2 presents the measured thrust and integrated momentum flux for each actuator radius tested at $V_{pp} = 26$ kV and $f_{ac} = 3$ kHz. The axial momentum is calculated based on velocity profiles at the wall-normal distance $x = R$. At this location, the potential jet is sufficiently developed without significant diffusive losses. The calculated momentum integration is greater than the measured thrust for all cases. The discrepancy is likely due to the complex interaction of fluid during the jet development and entrainment of fluid. Note that the formation of secondary vortices has been documented in the literature [53]. In this work, the normal velocity measurements were taken sufficiently downstream of the surface to account for the transformation of the radial (wall-jet) velocity component to the normal direction; however, characterization of the entrainment profile was challenging due to formations of the secondary structures and the jet instabilities.

The 15 mm actuator shows the highest discrepancy due to the comparatively low forcing, approaching a sensitivity limit of the measurement equipment. Measurement of the direct thrust was limited to $1\text{e-}4\text{ N}$ resolution. The thrust is an order of magnitude smaller than the other two cases, resulting in a significant percent difference between the momentum and thrust measurements.

Table 2. Thrust and momentum flux for each APSJA at $f_{ac} = 3\text{ kHz}$ and $V_{pp} = 26\text{ kV}$.

R (mm)	Thrust (mN)	Momentum (mN)	Difference
15	0.3	0.5	40.0%
30	2.1	2.4	12.5 %
45	3.8	4.8	20.8%

Fig. 4 shows discharge power normalized by the electrode edge length, $2\pi \cdot R$, versus the applied voltage across each of the three actuator sizes at $f_{ac} = 10\text{ kHz}$. The length normalized discharge power increases monotonically with edge length for all three sizes and electrical conditions. At increasing voltages, the discharge power per length disproportionately increases for the $R = 15\text{ mm}$ actuator due to saturation of the space charge and onset of filamentary streamers, which does not correlate with an increase in mechanical performance, as shown in Fig. 5.

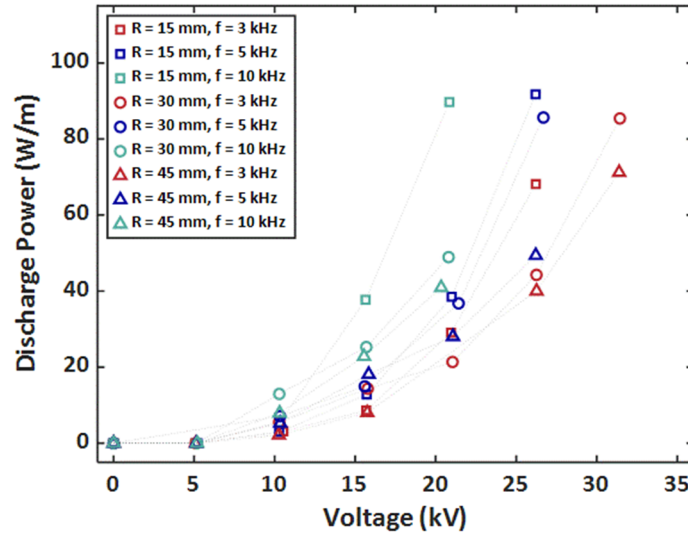


Fig. 4. Discharge power normalized by circumference versus applied voltage. Discharge power is positively correlated with voltage and frequency and inversely correlated with actuator diameter. V_{pp} ranges from 0 to 32 kV with a maximum discharge power of 91.85 W m^{-1} occurring with the 15 mm radius actuator at 5 kHz and 26.21 kV.

Due to the electrode curvature in the axisymmetric geometry, the saturation of the plasma region and onset of filamentary discharges occur at lower voltages for actuators with higher curvature (smaller radius). Persistent filamentary discharges (over multiple cycles) correspond to a decrease in performance and increased heating. The required voltage for saturation is seen to be directly proportional to the actuator size and inversely proportional to the applied frequency. Filamentary streamer formation at 3 kHz near 32 kV for both 30- and 45-mm radii actuators indicates an undetermined threshold saturation parameter corresponding to the dielectric material and thickness. A reduction in filamentary discharge onset voltage occurs from 26 kV to 21 kV for all cases between 5 kHz and 10 kHz. The 15 mm radius actuator develops filamentary discharges at 26 kV for the 3 kHz condition, but the larger actuators show an increase in onset voltage to 32 kV.

The averaged thrust measurements versus voltage are shown in Fig. 5. Within the experimental matrix, the mean thrust monotonically increases with the actuator diameter, applied voltage, and frequency. Generally, larger actuators show the highest thrusts; the maximum measured thrust is 6.2 mN, produced by the $R = 45\text{ mm}$ actuator at $V_{pp} = 31.4\text{ kV}$ and $f_{AC} = 3\text{ kHz}$.

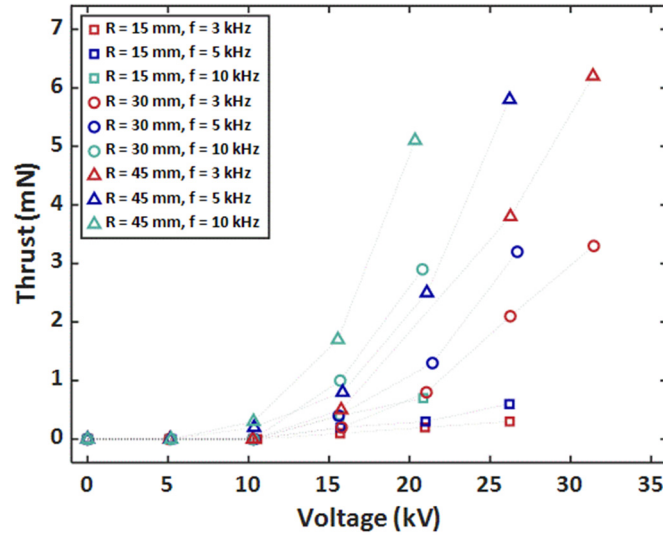


Fig. 5. Thrust versus applied voltage measured for $R = 15$ mm, 30 mm, and 45 mm APSJAs. Maximum thrust is produced by the 45 mm radius APSJA, measuring 6.2 mN at 31.39 kV and 3 kHz. For all size actuators, thrust increases with voltage and frequency.

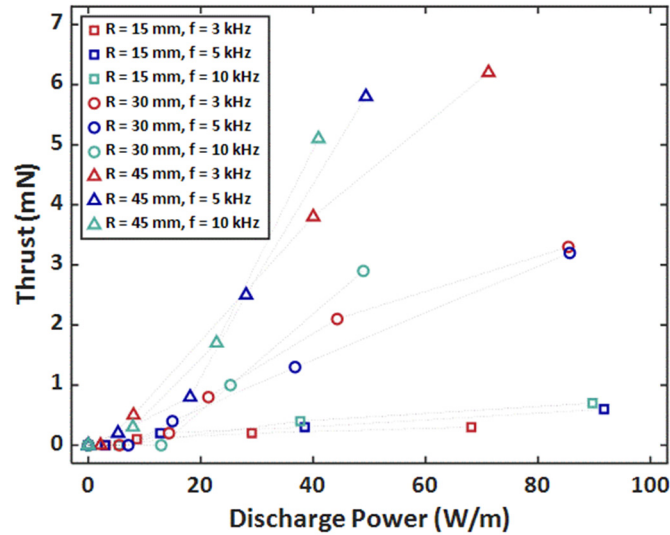


Fig. 6. Thrust versus discharge power normalized by electrode circumference for $R = 15$ mm, 30 mm, and 45 mm APSJAs. Maximum thrust (6.2 mN) is produced by the 45 mm radius APSJA at 20.13 W/m. Thrust performance is approximately linear with normalized discharge power and indicates increased efficiency with actuator size.

Fig. 6 shows the thrust versus discharge power normalized by the electrode edge length. The maximum thrust measurement of 6.2 mN occurred at a discharge power of 71.20 W m^{-1} (20.13 W total). This is expected as the total DBD thrust is proportional to edge length, while the net output of this geometry is a jet with wall-normal thrust [52]. Fig. 6 also shows that the efficiency of wall-normal injection increases with actuator diameter, for all frequencies. Each actuator size exhibits a distinct and linear clustering of thrust vs normalized discharge power. The slope of each diameter cluster increases with radius, indicating a positive correlation between actuator size and the efficiency in converting plasma discharge to injected and consequent wall-normal momentum. Since the frequency term is implicitly included in the discharge power calculation, the plot shows little to no dependency on the frequency of the DBD cycle for a given actuator size. Increasing frequency results in the earlier onset of the saturation regime. It limits the maximum output of the actuator but allows for similar mechanical performance at lower voltage conditions compared to a lower frequency.

Given the correlation between measured thrust and axially injected momentum, we infer that the wall-jet injection performance of the DBD actuator in the axisymmetric configuration generally linearly increases with discharge power. Increasing the electrode radius allows for an extended acceleration region in the wall jet region. Further, it prevents repulsive forces from the opposing potential field opposite of the axisymmetric

geometry. The increase in plasma length towards the actuator center with greater electrode radius corresponds to later saturation and transition to the saturation region.

To the latter point, Fig. 5 and Fig. 6, the $R = 15$ mm case shows that surface saturation limits mechanical output, as described by Santhanakrishnan [33]. E.g., Fig. 4 shows a significant increase in discharge power at $f_{ac} = 10$ kHz, which did not translate to thrust, Fig. 6. At a given size, the output thrust produced by the actuator is well correlated to the discharge power. Of all cases, the maximum thrust produced is 6.2 mN with $R = 45$ mm, $f_{ac} = 3$ kHz, and $V_{pp} = 31.4$ kV. This corresponds to a discharge power, P_{dis} , of 20.13 W or 71.20 W m^{-1} . The discharge power per mm of electrode edge length against the applied voltage, seen in Fig. 4, shows that they are proportional with the voltage as the dominant term.

By the principle of momentum conservation, while ignoring viscous losses, the direct relationship between thrust and wall-normal momentum flux can be used to approximate efficiency. This is defined as the ratio between mechanical and electrical power[38]. The mechanical power based for a unidirectional jet is given:

$$P_{m,A} = \frac{1}{2} \rho \pi \int_a^b r u^3(r) dr \quad (3)$$

Where r is the radial position, $u(r)$ is the axial velocity at position r , and ρ is the density of the working fluid. The efficiency η of the actuator for momentum injection in a quiescent environment can be calculated as the ratio of mechanical and electrical energies.

$$\eta = \frac{E_{out}}{E_{in}} \quad (4)$$

The electrical energy can be calculated as the product of the electrical power input and the waveform period, $T_{ac} = 1/f_{ac}$ s. The mechanical energy transferred from the jet to the surrounding fluid can be given as the product of the mean hydrodynamic force, assumed to be equal to the measured thrust and the characteristic length of the actuator. As done in previous work, we assert that because momentum injection originates from the electrode edge, the appropriate length scale is the inner electrode diameter, d_i [33]. The electromechanical efficiency is then given as

$$\eta = \frac{F_{thrust} d_i f_{ac}}{P_{dis}} \quad (5)$$

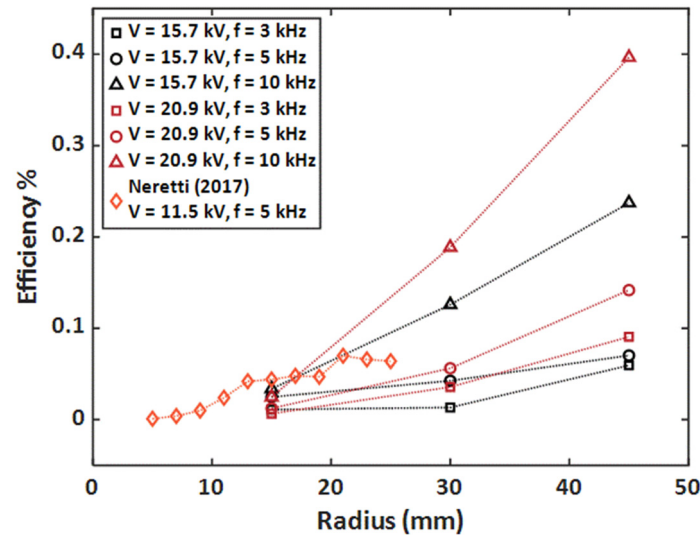


Fig. 7. Electromechanical efficiency for each APSJA radius and frequency via electrical and mechanical energy. 1.6 mm quartz glass dielectric with characteristic lengths $L = 2 \cdot R_i$ at $V_{pp} = 15.7$ kV (blue) and $V_{pp} = 20.9$ kV (red). Compared to results from Neretti *et al.* at 5 kHz and 11.5 kV across 1.5 mm thickness FR-4 dielectric material (orange)[38]. Maximum efficiency $\eta_{max} = 0.397\%$ for $R_i = 45$ mm actuator at 10 kHz frequency and 20.9 kV peak-to-peak voltage.

The resulting efficiency is shown for each actuator diameter and frequency at a constant applied voltage of 20.9 kV in Fig. 7. This shows a direct increase in efficiency with increased frequency and diameter. Results could not be compared to an identical formulation from ref [33] as the reported efficiency values were normalized. Near-zero efficiency is suggested for the $R_i = 15$ - and 30-mm actuators at low frequencies due to insufficient sensitivity in the analytical force balance, resulting in a zero-thrust measurement.

In cases where sufficient thrust is recorded, the efficiency closely matched the findings of Neretti *et al.*, formulated through velocity profile integration (Eq. 3). In their study, actuator sizes ranged from 5 – 25 mm and an applied voltage of 11.5 kV peak-to-peak at 5 kHz was used across a 1.5 m thick glass epoxy substrate (FR-4) with a dielectric constant of approximately 4.4 and dielectric strength of 20 kV mm⁻¹ [38]. Their experiments demonstrated 40% higher maximum jet velocities than observed in this study and similar profile distribution (Fig. 3) but lower overall momentum injection.

Notably, the 30 mm radius actuator in this study exhibited approximately the same efficiency as the 25 mm radius actuator from Neretti *et al.* at identical frequencies and 15.7 kV. However, at 15.7 kV, efficiency increases by 220% when the frequency rises from 3 kHz to 5 kHz and by 196% between 5 kHz and 10 kHz. Additionally, efficiency generally increased with applied voltage. At 5 kHz, the efficiency of the 30 mm APSJA increases by 32.2% when voltage is increased from 15.7 kV to 20.9 kV and 49.9% at 10 kHz. At an applied voltage of 15.7 kV, the rate of change of efficiency with actuator radius is similar to the results reported by Neretti *et al.* (11.5 kV). Increasing voltage is also associated with a greater rate of efficiency improvement with actuator radius in most cases. The maximum recorded efficiency, $\eta_{max} = 0.397\%$ was produced by the 45 mm radius APSJA at a peak-to-peak voltage of 20.9 kV and 10 kHz frequency. Across the full experimental matrix set with measurable thrust, the mean efficiency increased by 0.023% per kHz (SD 0.015%). At the higher voltages tested in this study, the correlation between actuator radius, electrical frequency, and efficiency becomes clearer and efficiency is seen to monotonically increase with both radius and frequency.

4. Conclusion

This study provides a comprehensive experimental investigation into the performance of dielectric barrier discharge (DBD) annular plasma synthetic jet actuators (APSJAs) across a wide range of geometric and electrical parameters. APSJAs with radii ranging from 15 mm – 45 mm were tested with voltages ranging from 5 kV – 35 kV and frequencies from 3 kHz – 10 kHz in initially quiescent air. Opposing flows in the annular DBD geometry form a wall-normal jet. The electrode radius and electrical parameters were varied beyond those reported in the previous work, and both favorably affected the mechanical efficiency of the actuator.

We observe that increasing the size of the APSJA significantly increases momentum injection, wall-normal thrust, and peak velocity. Although increased size must be balanced with viscous dissipative losses, the results suggest that reduction of the inner curvature and increase in total electrode length (circumference) facilitate greater forcing than the previously reported smaller APSJA actuators. The improvement in actuator performance with its diameter is primarily due to changes in the extension of the flow acceleration regions. With a traditional linear DBD actuator, the momentum injection and electrical properties are proportional to edge length, and the instantaneous forces acting on a given charge species by the net electric field are unidirectional. In the case of the APSJA, an electric field equal in magnitude and polarity exists at opposing edges. Since the ion velocity timescale is orders magnitude shorter than the applied electric potential time scale, increasing the actuator diameter has several synergistic effects: (i) creates separation between electric potentials of the same polarity, electrically increasing the acceleration region for ions, (ii) geometrically extends the acceleration region for ions and particles within the working fluid, increasing radially injected momentum, (iii) reduces a curvature effect where the space and surface charge becomes more concentrated (saturated) towards the center of the actuator, resulting in space discharge and streamer-streamer interaction. This work is the first to consider all three mechanisms affecting APSJA performance together. As a result, larger actuators are more efficient in converting electrical power to mechanical thrust, with the 45 mm radius actuator producing the maximum thrust of 6.2 mN at 31.4 kV and 3 kHz. APSJA efficiency is also directly proportional to radius and frequency in sustained actuation modes within the tested configurations. We expect this trend to hold up to a threshold radius at which viscous dissipation of the symmetric DBD wall jet and wall-normal expulsion overcome the trend of increasing power efficiency with electrode radius.

This study highlights the APSJA geometry as a low-profile, non-thermal, steady-state alternative to traditional cavity synthetic jets for low-magnitude momentum injection. The main limitation of this work is

the limited spatial-temporal resolution of pitot tube velocity profiles, which do not allow for investigation of localized flow structures within the jet for each geometry and electrical condition. Further, qualitative analysis of the coupling between electrode curvature and performance metrics does not provide specific relations to generalize the proposed mechanisms. Future work should explore the generalized relationship for APSJA actuators and develop numerical and empirical models that can be used for their optimization.

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