

Resonances and patterns within the kINPen-MED atmospheric pressure plasma jet

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Abstract: The kINPen MED atmospheric pressure plasma jet is now undergoing clinical studies that are designed to investigate its suitability as a device for use in plasma medicine treatments. This paper describes dimensionless studies of the synchronizing oscillatory gas flow through the nozzle followed by electro-acoustic measurements coupled with the discharge photo emission. The plasma jet operates in the burst mode of 2.5 KHz (duty cycle = 50%), within a neutral argon Strouhal number of 0.14 to 0.09 and Reynolds number of 3570 to 5370. In this mode the jet acts like a plasma actuator with an anisotropic far field noise pattern that is composed of radiated noise centered at 17.5 kHz; +20 dB. It is found that the argon passing through the plasma plume expand with a solid angle of 20 degree to produce a corresponding 'spillover' effect on a PET surface up to 15 mm from the nozzle.

Keywords: atmospheric pressure plasma jet, plasma medicine, gas flow dynamics, acoustic resonance.

1. Introduction

Cold atmospheric plasmas have shown enormous potential in Plasma Medicine for surface sterilization, for wound healing, for blood coagulation and in cancer treatment [1, 2]. This paper is focused on an atmospheric pressure plasma jet (APPJ) system called kINPen MED, which is being targeted for use in Plasma Medicine [3]. However to keep the medical device safe and easy to handle the fixed repetitive pulsed power source is used and the gas supply is limited to argon flow rate of 4-6 standard liters per minute (SLM). To help underpin the ongoing clinical trials this paper presents dimensionless analysis of the jet along with the jets electro-acoustic and polychromic emission.

It has been shown that within the cold limit of ions that the speed of sound can be approximated to the neutral gas molecular temperature [4, 5], see equation 1. Here the fluctuation in the speed of neutrals and ions generate both sound waves and an oscillatory electric field, both of which contribute to the overall local sound pressure level. In the plasma production zone the difference between neutrals and ions, is that the latter (and electrons) absorb electrical energy from the electrical electro-magnetic field as the plasma gas expands and loses electrical energy, when the electrical power is turned off. Whereas the neutral gas gains energy thereby allowing radicals and metastable species to be formed



from the electron-neutral energy transfer per second in the plasma volume and so the electron-neutral reaction acts as an acoustic source. In The kinPen09 [3] and the Med version an argon plasmas comprises Ar^+ ions and hydroxyl (OH) radicals.

$$c_{sound} = \sqrt{\frac{\gamma R T_{gas}}{M}} \quad (1)$$

Where C_{sound} is the speed of sound in the gas medium, R is the gas constant ($8.314 \text{ J K}^{-1} \text{ mol}^{-1}$), T_{gas} is the gas temperature in Kelvin, M is the molar mass in kilograms per mole of the gas (argon = $0.03994 \text{ kg mole}^{-1}$), and γ adiabatic constant of the gas (argon and helium = 1.6).

The Strouhal number (St) [11, 12] of the kINPen MED was compared with 5 other commercial APPJs: the kINPen09 [3], the PVA Tepla air Plasma-PenTM [6], the air-PlasmaTreatTM [7, 8], and two helium linear jets [9, 10]. The St is a dimension-less measure as defined in equation (2), where f_d is the drive frequency, and D is the length scale of the nozzle diameter and v is the gas (in this argon) velocity. Thus for $St \sim 1$, the drive frequency is synchronized through the nozzle orifice to the velocity of the gas exiting the nozzle. For low St , the quasi steady state of the gas dominates the oscillation. And at high values of St the viscosity of the gas dominates fluid flow ("fluid plug"). Thus St acts as a comparator when the jets have similar values of D . Of the 5 plasma jets studied only the kINPen MED has a compound nozzle (double open-end ceramic tube within a stainless-steel outer body with a central electrically driven wire electrode). The linear jets are configured as double open-ended glass tubes.

$$St = \frac{f_d D}{v} \quad (2)$$

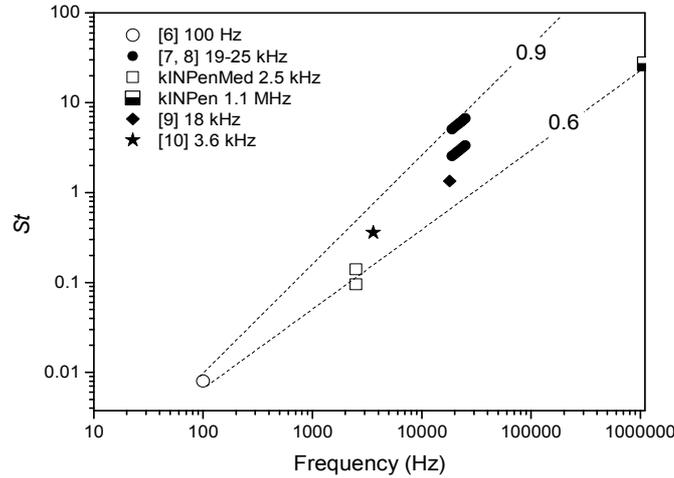


Fig 1: St numbers for 6 air and helium APPJs as a function of f_d and D : 1.7 to 4 mm.

Figure 1 shows the log-log graph relationship between St and f_d for the 6 APPJs, which have a D value between 1.7 to 4 mm. There are two observations of note within the plot. First, the gas type (air, argon and helium) are normalized through their gas velocities (equation 2) and thus there is gas correlation; Second using the Plasma-Pen as references point two interpolation lines are used to map the upper and lower boundary of the data points with the kINPen forming the lower rate boundary ($\exp^{0.6}$) and the PlasmaTreatTM forming the upper rate boundary ($\exp^{0.9}$). From these observations and an examination of equation 1, it can be deduced that the rates corresponded to the length scale D .

2. Experiments

As with aircraft jet engines, low frequency driven APPJs produce two types of acoustic emission patterns within the overall radiated noise emission. The acoustic noise patterns originate from the jet nozzle and from axially aligned jet turbulence. To measure the aircraft jet engine noise patterns the jet engine is normally placed within an anechoic chamber and both near-field microphones and a linear array of far field microphones in are used to measure the noise pattern [11, 12]. In contrast the acoustic noise of APPJs has been measured with a single microphone in some preferred position with the result that the boundary between the two acoustic production sources is ill-defined. Furthermore there has no report of an APPJ being employed as plasma actuator, where the St is an indicator of the acoustic spectrum is attenuation.

For the purpose of this study, a single condenser mini-microphone is used to measure both the electro-magnetic emission and acoustic emission from kINPen MED which uses argon as the ionization gas. The microphone acts as both an E-probe and a sound energy sensor, where both measured quantities are distance dependent. In ordered to capture the nozzle Omni-directional sound energy and sound energy being propagated along the discharge axis, acoustic far field measurement is scaled to a distance of 20 x the jet diameter between 90° perpendicular to the jet exit nozzle to 180° where the microphone is facing the gas flow. From a process control perspective 90° position has a number of advantages; (a) the microphone measures the radiated plasma sound energy emanating from the nozzle; (b) the microphone does not mechanically interfere with the movement of the jet over the treatment surface and; (c) the 90° allows capture of the deflected sound energy from the treated surface to be used as a nozzle to surface height indicator [7, 8], thus by inference the treated surface temperature. In addition to the electro-acoustic measurements, a photodiode (PD) is used to evaluate the jets time-dependent polychromic emission and acoustic pattern is correlated with “spillover” [13] of the plasma jet on treated Polyethylene-terephthalate (PET) polymer using water contact angle measurements. Finally the electro-acoustic and PD measurements were digitally processed using LabVIEW software and correlated as previously described [7, 14].

3. Results

3.1. Electro-acoustic analysis

Figure 2 shows the typical electro-acoustic from the APPJ at a microphone angle 90° with the plasma turned-off, and on, with the argon flowing at 5 SLM (nozzle velocity = 36.78 m.s^{-1}) in both cases. For the plasma conditions the first feature of note is that the f_d (2.5 kHz) has Q-factor ($f/\Delta f \sim 100$) followed by its harmonics: here observed up to 20 kHz. The second feature of note is that 5th and 6th harmonic of the f_d straddle the broad asymmetric structure ($f/\Delta f \sim 35$) centered on 17.5 kHz. Turning off the electric power to the nozzle not only removes the drive frequency component but also reduces the broadband structure at 17.5 kHz by 20 dB. An independent measurement using a sound pressure level meter (YF-20) indicates this reduction equates a drop of 4 to 6 dB in the audible range. A photo of the argon discharge and ceramic nozzle is shown as an insert in figure 2.

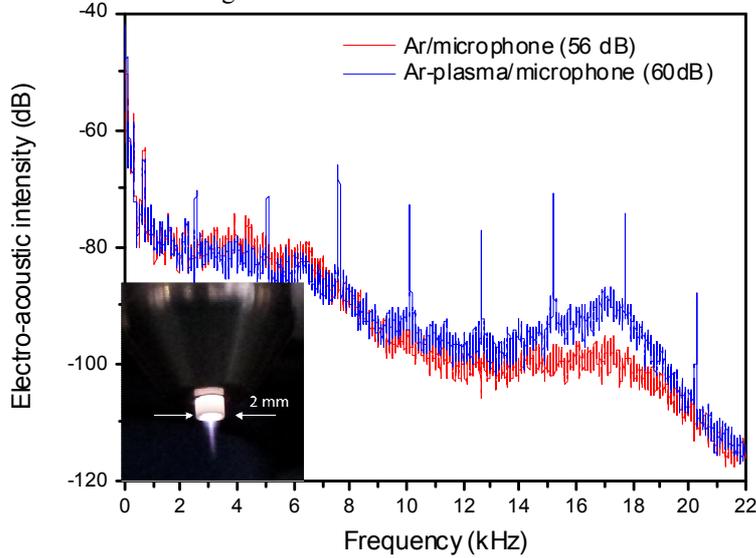


Fig 2: Argon plasma formed using the kINPen MED along with the associated plasma acoustic response.

Using the 2 electro-acoustic traces and the knowledge of the nozzle geometry it possible to model the acoustic response (f_n) and its overtones (f_n) of the nozzle of as either an open-ended gas column (equation 3) or as a Helmholtz resonator (equation 4) [7]. At room temperature (20°C) the speed of sound (c) in argon and air equates to 323 to 346 m.s^{-1} .

$$f_n = \frac{nc}{m(L + 0.6r)} \quad 3$$

$$f_o = \frac{c}{2\pi} \sqrt{\frac{A}{LV_o}} \quad 4$$

In equations 3: L is the length of the ceramic tube beyond the drive electrode (0.01 m), and r is the tube radius end-correction (0.0005 m). Lastly m denotes the resonate mode within the tube (1 = fullwave and 2 = halfwave resonant mode etc...) and n is the overtone number. Whereas in equation 4: A is the area of nozzle, and V_o is the volume of the nozzle.

Equations 3 yields a value range of f_n between 16.5 to 17.7 kHz for a halfwave resonant mode ($m=2$). This calculation agrees well with the broad acoustic peak at 17.5 kHz which is enhanced in amplitude by onset of the plasma. By comparison equation 4 yields a f_o range between 2.57 and 2.75 kHz which is a factor of 5-6 times lower than the observed broadband response. This comparison of the two mathematical models suggests that the open ended nozzle model provides the most representative and robust visualization of the nozzle acoustic response.

3.2. Photodiode analysis

Using a Hamamatsu MPPC photo diode (PD) with a rise time of 10 ns and a spectral range between 320 and 900 nm we now turn to the examining the effect of 2.5 kHz pulse drive frequency on the time-dependent plasma polychromic emission. Discharge emission was collected via a fibre optic and collimating lens focused at the plasma discharge at 1 mm downstream of the nozzle exit.

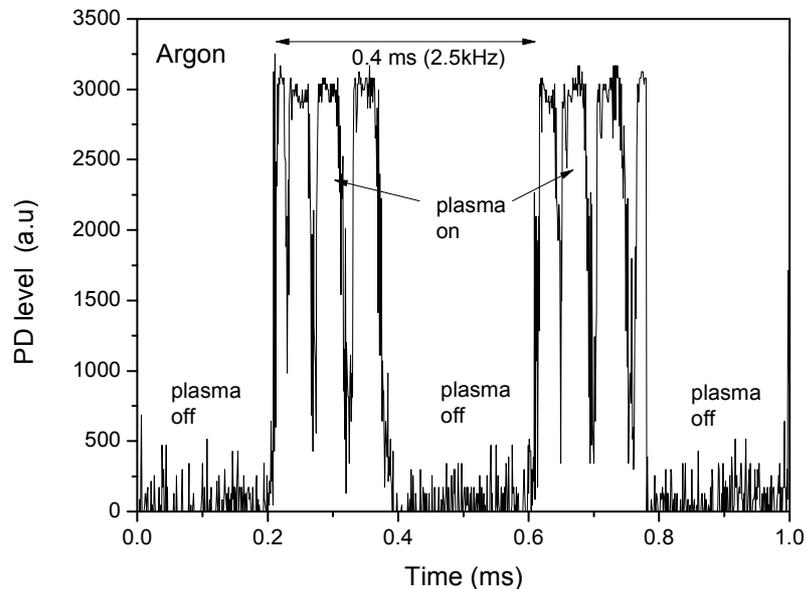


Fig 3: kINPen MED polychromic emission at 1 mm from nozzle.

The measurement results for 5 SLM of argon is shown in figure 3. Here it can be seen that the polychromatic emission has a 2.5 kHz pulse; with a periodic duty cycle of 50% response (duration of the emission to the total period of a repeat signal) with an envelope rise- and fall-time of microseconds. Within the emission envelope four dips in emission can be also seen. Experimental observations using different jet orientations (vertical and horizontal) and the addition of 0.5% (by flow) of nitrogen indicate that the irregular flat top of the pulse enveloped represents both spatial and temporal instabilities in the plasma plume. For limited range investigated, varying the argon flow rate from 4 to 6 SLM does not alter the height of the envelope but the addition of 0.55 by flow of nitrogen reduce the noise within the measurement which may suggest that the plasma jets become more spatially stable.

3.3. Anisotropic acoustic emission pattern

With the drive frequency and its harmonics isolated from the acoustic emission response, the next sets of measurements are aimed to delineate the radiated sound energy from the jet turbulence sound energy. The delineation is achieved by recording electro-acoustic measurement between 90 and 180° (in-line) in steps of 10° degrees. The results of these measurements are shown in figure 4. Here it can be seen that the sound radiation energy does not alter significantly from 90 to 160°. The 170° measurement however increases in amplitude and exhibits a number of additional resonances peaks. In the case of the 180° the measurement acoustic noise amplitude has increased above the electrical emission resulting in the loss of electrical information. In this position, resonance information is also lost and noise amplitude becomes inversely proportional to frequency at a rate of -1.7 dB.kHz^{-1} . The peak at 1.5 kHz varies by $\pm 1 \text{ kHz}$ due to the jet gas flow dynamics over the microphone body.

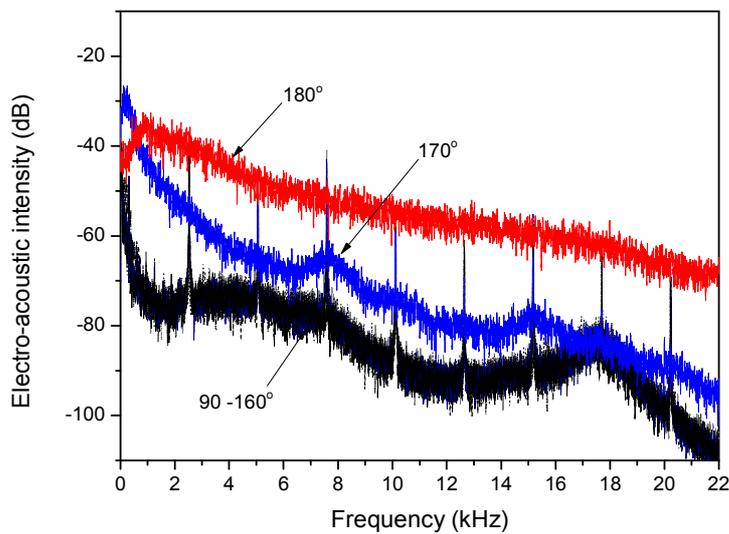


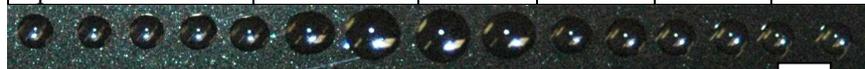
Fig 4: 90 to 180° far field measurements.

The measurements reveal that the neutral argon flow forms an expanding cone with internal angle of 10 degrees to the jet axis. This is in contrast to the 10 mm in length visible pencil-like plasma plume, see figure 2 picture insert.

An investigation was carried out to determine the correlation between the area / diameter treated by the kINPen MED gas plume and the water contact angle of the PET placed under the jet. Measurements were obtained 1 hour after plasma treatment as a function of the gap distance (5, 10, and 15 mm) between the jet and the PET substrate. The contact angle obtained for the untreated PET was 85°. Table 1 shows the results of the measurements and the computed internal cone angle for the treatment gap. This limited gap distance analysis reveals that the treated diameter is much larger than the pencil-like diameter of the plasma plume (~ 2 mm), with an ‘spillover’ ratio (plasma/treatment diameter) of 8 to 10. The treatment becomes less effective with gap distance. Correlating these results with the acoustic mapping it appears that the argon gas passing through the plasma zone and entering the expanding argon cone has a chemical ‘spillover’ effect on the surface properties of PET thus possibly differentiating between ion exposure and radicals and metastable treatment mechanisms.

Table 1: WCA data showing the effect of PET surface to jet orifice gap distance. The centre region of the photograph demonstrates the increased water droplet width obtained after the kINPen MED jet treatment (2 mm scale bar)

	No Plasma	5 mm	10 mm	15 mm	20 mm
WCA	85°	45°	59°	70°	
Spillover diameter	N/A	16 mm	20 mm	18 mm	
Treatment angle	N/A	160	90	62	
Spillover ratio	N/A	8	10	9	



4. Conclusion

This paper has examined the kINPen MED argon flow dynamics using dimensionless analysis, electro-acoustic and photodiode measurements. The *St* analysis of the plasma jet (with 5 other APPJs with similar nozzle diameters ($D = 1.6$ to 4 mm)) reveal similar nozzle oscillating flow mechanisms that produce *St* values that are proportionally to $\text{Hz}^{(0.6 \text{ to } 0.9)}$ between 100 Hz to 1.1 MHz where the rate is defined by the scale length of the nozzle. Electro-acoustic and polychromic emission measurements reveal the APPJ nozzle is operating with a low $St < 0.5$ for an argon flow of 4-6 SLM. The nozzle resonant frequency can be modeled as a closed end column where resonance amplitude undergoes amplification when plasma is applied. One possible mechanism for this acoustic amplification may be due to electric winds [4] that are generated by the positive and negative edges of the drive pulse and which are synchronized to the neutral argon velocity to produce an enhanced molecular vibration at the nozzle exit. The plasma jet therefore appears to act like a dielectric barrier discharge plasma actuator. Electro-acoustic far field pattern measurements reveal an anisotropic

acoustic emission which is composed of sound radiation energy from the nozzle and the axially aligned gas jet pressure. It has been shown that gas passing through the visible plasma zone expands out in warm with a solid cone angle of 20 degree and alters the hydrophobicity of PET surface up a distance of 15 mm.

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