Design and optimization of a radio frequency plasma jet for biomedical applications

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In the last 25 years, following the growth of plasma medicine, a wide spectrum of cold atmospheric plasma sources has been developed. Their reactivity, given by the simultaneous action of reactive oxygen and nitrogen species, charged species, UV radiation and electric fields, can be exploited to trigger biochemical processes. At the same time, the non-equilibrium property, and therefore the low ionization fraction and the massive presence of room-temperature neutrals and ions, prevents thermal damage to the treated surface. As of today, studies are carried out in the applications of atmospheric pressure plasma sources for several medical applications, the most prominent being disinfection and wound treatment [1].

Cold atmospheric plasma sources still require developments both in modeling and diagnostics; moreover, a wide panorama of different ones is available. They can be categorized according to the operating gas (typically helium or argon) and the power supply frequency: examples in the whole range from DC or pulsed-DC to microwaves exist [2].

In the present study, a newly built radiofrequency plasma jet, shown in fig. 1, is characterised in terms of plume length and development. The plume is generated through a tungsten needle, supplied with a high-voltage radiofrequency waveform. The needle is enclosed in an alumina coating, and only the final part of about 13 mm length is exposed. It is contained inside a nozzle formed by a cut Pasteur pipette, in which helium or argon are flown at 3 L/min. Noble gas plasma is formed inside the pipette, and a plume develops outside the nozzle. A ground ring is placed around the nozzle, to minimize the sensitivity of the plume behavior on the distance from the treated substrate. The power supply is formed by two generators. A first generator provides a pulse in the form of a square wave with 5% duty cycle and tunable frequency. It acts as a gate for a second generator, which provides a radiofrequency wave, then amplified by a broad-band RF power amplifier. The latter is connected to the source; only an inductor is used as a matching network: it resonates with the capacitance of cables, connectors and of the source itself.

Figure 1: The apparatus.

The resulting voltage on the central needle, which allows for plasma to ignite, is between 1 and 3 kV peak-to-peak; an electrical analysis on the same apparatus, performed using a Rogowski coil to measure the current, found that the power dissipation on the plasma is between 1 and 10 W, depending on the electrode voltage. It must be underlined that, when considering the average dissipated power, one should consider the 5% factor due to the pulse, obtaining an average power of less than 0.5 W.

A first observation regards the different appearance of the plume using the two gases (fig. 2). In helium, a uniform glow develops inside the nozzle, and the plume is cone-shaped with smooth dissolving boundaries. In argon, instead, a more filamentous character can be recognized already inside the nozzle: separate streamers are visible, continuously evolving and moving. The plume, moreover, typically appears as a main straight central streamer, surrounded by a weak glow. The length of the plume is studied as a function of the electrode voltage, measured using a Tektronix P6015a probe. It is portrayed using a common smartphone camera, both with helium and argon flow, at different voltages and at different radiofrequencies. In fig. 3 the length of the plume, as function of the applied voltage, is reported for different radiofrequency and using a 1 kHz pulse frequency. As expected, the length of the plume increases as the voltage increases. For helium the frequency seems to have only a secondary effect, while for argon the frequency appears to be more important: at higher frequencies, in fact,

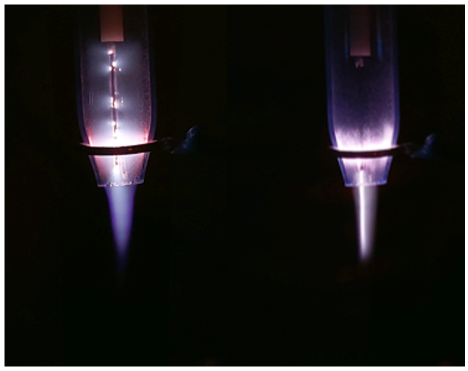


Figure 2: Examples of plume shapes: on the left with helium, on the right with argon.

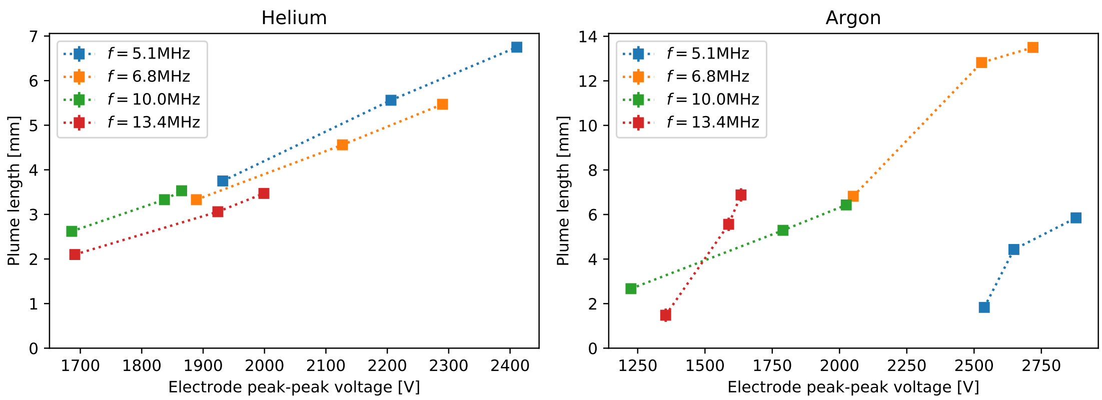
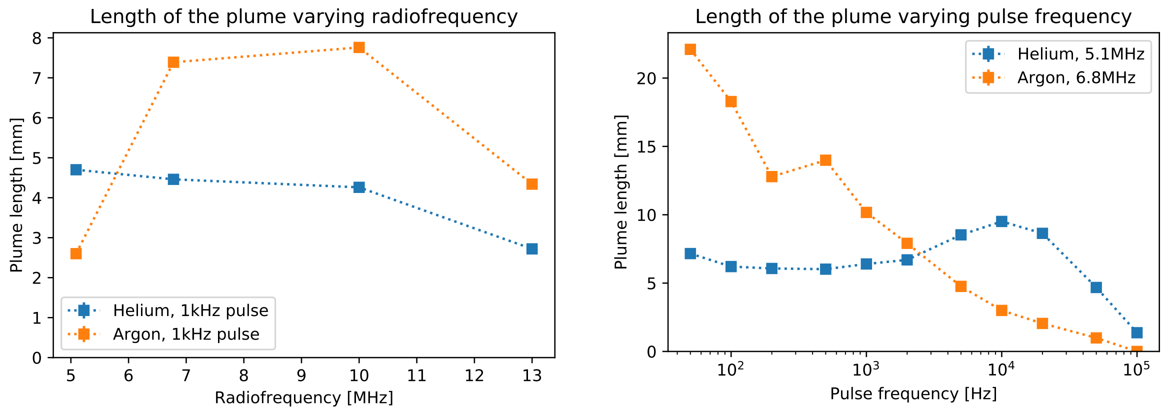


Figure 3: Length of the plume as function of the electrode voltage, with 1kHz pulse frequency.



(a) Length of the plume as function of the radiofrequency at fixed driving voltage.

(b) Length of the plume as function of the pulse frequency.

Figure 4: Dependence of the plume length on the two characteristic frequencies.

a lower voltage turn out to be necessary to ignite the plasma, and higher lengths are reached.

The dependence of the plume length on the two characteristic frequencies of the system is then studied; the length is measured keeping all the system parameters fixed and varying the radiofrequency (fig. 4(a)) or the pulse frequency (fig. 4(b)). The radiofrequency turns out to not have a strong effect on the length of the helium plume, while for argon the dependence is stronger, seemingly displaying a range of optimal frequencies.

Regarding the dependence on the pulse frequency, again the behavior of helium and argon plumes are different. Argon shows a monotonic reduction of the plume as the frequency is increased; a larger plume seems to be reachable relaxing even more the pulse frequency, but the available apparatus is limited by overheating of the inductor. For helium, instead, at low frequency the dependence is almost absent, while a optimal situation appears around 10 kHz and the plume almost disappears at higher frequencies.

Using an image intensifier and a trigger with a variable gate which can reach 15 ns open windows, synchronized with the signal generators, the shape of the plume is acquired during its evolution. In fig. 5 are reported the shapes of the plume, in helium and in argon, following the radiofrequency. The behavior is found to not reflect the symmetry of the waveform. When the needle is positively charged, the plasma appears to be focused around the needle itself, reflecting the attracted electrons which spread over all the exposed length of the electrode. When the needle is negatively charged, instead, a more uniform glow appears: the plasma develops between the needle and the ground ring, in a flat glow which elongates over the whole nozzle diameter. It is in this phase, and in particular in the rising-potential phase, that the outstreaming

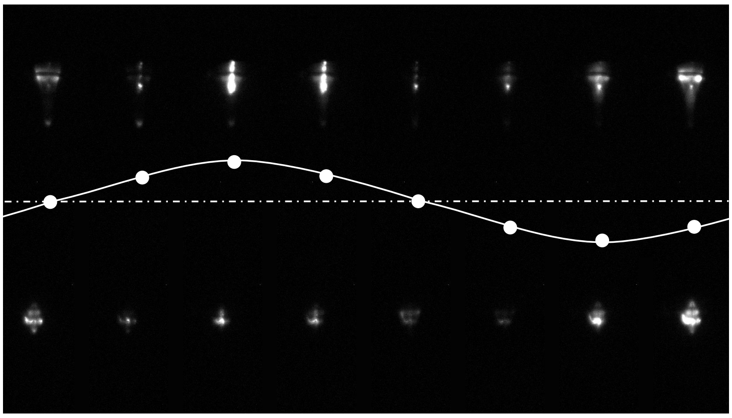


Figure 5: Evolution of the plasma inside the nozzle following the radiofrequency voltage evolution. The upper series is in helium, while the lower one in argon; both are with 5.09MHz radiofrequency.

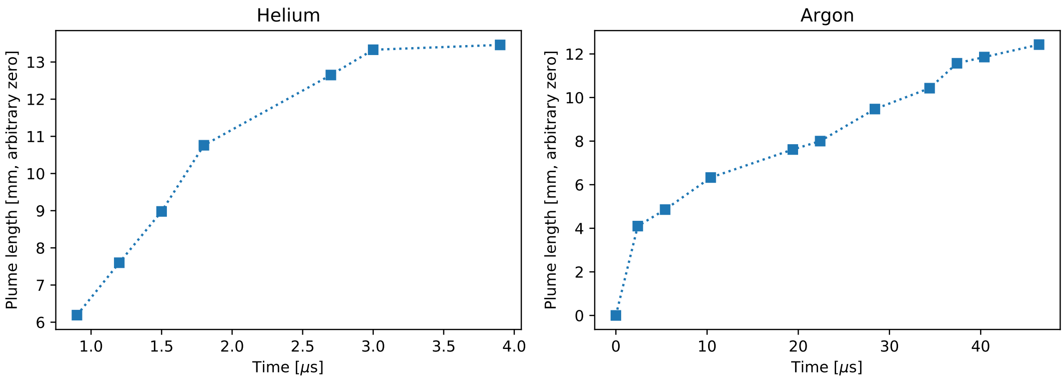


Figure 6: Length of the plume in time, following the pulsing time scale. Note the different time scales.

plume develops. A similar study is carried out following the pulsing time scale (fig. 6). In helium the plume growth has a fast rising in the first microseconds and then already saturates after 3μs. Remembering that duty cycle is at 5%, a window of 3 μs is obtained with a frequency of around 20 kHz, in agreement with fig. 4(b) which shows a saturation of the plume length at a similar frequency. For argon, instead, a saturation of the plume length is not observed, and the plume appears to continuously grow as the pulse width enlarge. The two different behaviors of helium and argon suggest that different parameters should be used for achieving the optimal condition for the two gases. The study is intended to proceed performing wider and more resolved scans, and relating the plume appearance results with electrical and thermal features.

References

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