On the comparison of direct and remote plasma treatment with UV disinfection for virus inactivation

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Abstract: The applicability of cold atmospheric pressure plasma technology for food-borne pathogen decontamination has been a field of growing interest. In this contribution, dielectric barrier discharges are compared with UV disinfection technology in terms of viral inactivation and energy efficiency. The role of different plasma-generated species (short- and long-lived) is qualitatively demonstrated through viral inactivation by direct and remote treatments. While the direct plasma treatment results in a higher energy consumption of the plasma treatment compared to UV treatment, a simple batch reactor model based on the experimental findings suggests that remote plasma-based decontamination would be feasible at similar energy efficiencies as UV. The lack of shadowing effects for more complex food substrates for remote plasma treatment compared to UV is an additional advantage. The underpinning reasons of the observed differences are discussed.

Keywords: cold plasma, ultraviolet radiation, remote and direct DBD, viral inactivation, shadowing effect.

1. Introduction

Recently, the plasma community has witnessed a steep rise in interest in applying cold atmospheric pressure plasmas (CAPs) for disinfection and decontamination of surfaces contaminated with pathogens [1–3]. Due to the high reactivity of CAP at ambient gas temperatures, CAPs operated in air have been shown to be an effective and efficient disinfection tool [4–6]. The disinfection is due to the plasma-produced non-equilibrium chemistry that involves numerous reactive oxygen and nitrogen species as well as ultraviolet (UV) photons or radiation [6].

The efficacy of plasma-generated species as well as UV photons against bacteria has been studied in detail [7–9]. Chemically reactive species generated by plasma cause inactivation of bacteria by oxidation of the cytoplasmic membrane, proteins and DNA, or by lysis of the bacteria caused by charged particles [10–12]. Only a few studies report that plasma-produced UV photons cause lethal damage to the nucleic acid by photochemical lesions and/or by carrying enough energy to break bonds in the coat materials of bacterial spores [13,14]. These findings were reported for low-pressure plasmas. Nonetheless, these studies suggest that the role of UV cannot be a priori neglected at atmospheric pressure.

While there exists a large amount of studies on plasma-induced inactivation of bacteria, only a few studies have been reported for viruses [15–17]. Considering the importance of viruses in the context of food safety, a comparison of plasma-based inactivation efficacies of viral inactivation with UV-based disinfection is important to assess the potential of plasma-based disinfection technologies.

In this contribution, we focus on the comparison of dielectric barrier discharge (DBD) reactors with a UV-C lamp (low pressure mercury lamp) for decontamination of stainless-steel discs spiked with feline calicivirus (FCV). FCV is used as a surrogate for human norovirus, which is a major cause of foodborne illnesses [18]. We use an AC-driven (kHz) two-dimensional array of micro-discharges (2D-DBD) and a direct discharge excited by modulated AC (kHz) and pulsed signals as plasma sources, which are operated with dry air as feed gas or in ambient atmospheric pressure air, respectively. The comparison between the setups is focused on virucidal efficacy and energy efficiency. The reasons underpinning the observed differences are discussed.

2. Methods

The schematic of the different DBD plasma sources and the UV-C lamp used in this work including the treatment configuration are shown in figure 1. The 2D-DBD (figure 1a) was a multi-layered electrode arrangement consisting of an array of 600 μm diameter holes punched through it and covered by a dielectric material (Alumina) [17]. This reactor was driven by a 20 kHz sinusoidal signal in dry air supplied through the array at a flow rate of 16.4 standard litres per minute (slm) at a fixed discharge power of 14.5 W. The gas residence time in the active discharge zone was ~160 μs. The FCV samples (stainless steel discs spiked with 15 μl of virus) were treated with the discharge effluent downstream of the plasma source at an exposure distance of 13.5 cm. An enclosure was attached to the bottom of these sources to avoid radial losses of plasma-generated species to the ambient air before they reached the sample. In this case, the virus sample was not in direct contact with the plasma and was treated by reactive oxygen and nitrogen species in the plasma effluent.

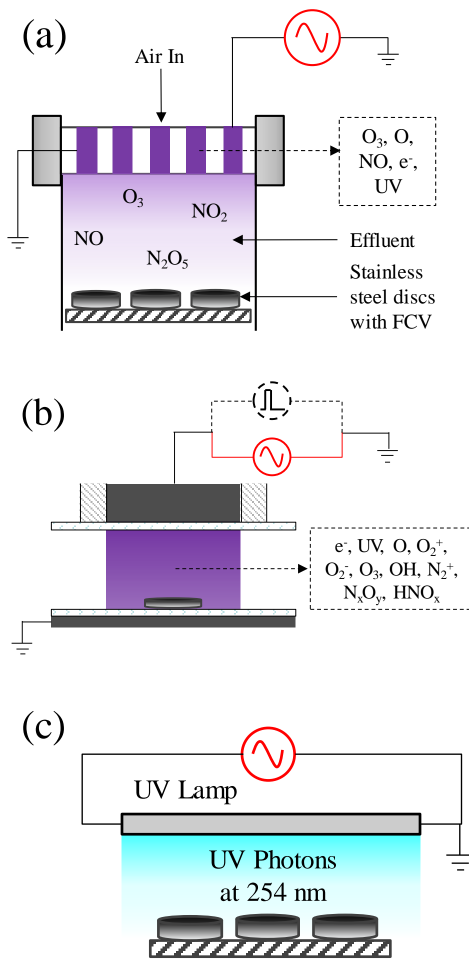

Fig. 1. Experimental schematic of the plasma sources (a) remote 2D-DBD, (b) continuous and/or pulsed direct DBD, and (c) commercial UV-C lamp used for FCV inactivation.

The direct DBD (figure 1b) consisted of a copper rod of 25.4 mm diameter, which acted as the high voltage electrode, and was housed in a polytetrafluoroethylene holder. The base of the electrode was covered with a 380 µm thick alumina sheet. The plasma was formed between the alumina sheet and the FCV-coated metal disc with a surface area of 1 cm^2 placed on top of the lower grounded aluminum plate. The direct DBD plasma was generated by two different approaches: (a) 25 kHz driven sinusoidal voltage waveform (AC) modulated with a duty cycle of 20%, and (b) nanosecond-pulsed voltages at a repetition frequency of 100 Hz with a pulse width of 10 ns although with many reflections up to 5 µs. The voltage pulse had an amplitude of 20.4 kV. The modulated AC discharge was operated at 12 W, and the pulsed DBD was operated at an energy input of 1 mJ per pulse. The distance between the dielectric barrier and the sample was 1 mm and 2 mm for pulsed DBD and AC DBD, respectively.

The UV-C lamp (figure 1c, Analytik Jena, UVP 34-0007-01) was operated at a power of 8 W. The FCV samples were exposed to UV at a distance of 30 cm from the lamp.

The treated FCV samples were titrated following the procedures described in [19]. The virus titer was calculated and expressed on a logarithmic scale of 50% tissue culture infective doses per 100 µl (log_{10} $TCID_{50}$/100 µl) of eluent using the Kärber method as described in detail in [20]. The initial number of virus present on the metal disc was ~5.5 log_{10} $TCID_{50}$/100 µl.

The power of the plasmas was measured by the Lissajous method for both the AC-driven direct and remote DBDs, and by the multiplication of measured current and voltage traces for the nanosecond-pulsed excitation. The UV fluence of the remote plasma sources and the UV lamp was measured using a UV-meter (UVC Light Meter 850010, Sper Scientific Environmental Measurement Instruments, Scottsdale, AZ, USA) at the same distance from the source as the FCV samples. O_3 concentrations were measured by UV absorption [21], and NO and NO_2 were measured by an emission analyser (Enerac 500).

3. Results and discussions

The UV-fluence required for complete virus inactivation was determined to be 50 mJ/cm^2. Although the UV-C lamp is operated at a rated power of 8 W, the actual radiated power at a distance of 30 cm is determined to be 1.47 W. This energy to UV conversion efficiency is considered in the calculation of the energy consumed per unit area for complete inactivation using UV treatment. A previous study reported similar UV fluence required for 3 log_{10} reduction in virus titer [22]. We observed that the log reduction in virus titer does not decrease linearly with UV energy flux for complete inactivation.

Table 1 shows a comparison of all the decontamination sources used in terms of electrical power and energy consumed per unit volume of gas treated for complete inactivation (~5 log_{10}). The surface temperature of the treated FCV-coated metal discs for all plasma sources remained below 45 °C, confirming that inactivation due to thermal effects is negligible [23].

Virus inactivation is achieved by using the AC-driven direct DBD, for a treatment time of < 5 s. To generate a direct discharge at lower energies, we compared the efficiency of an AC-driven direct DBD with the same DBD driven by a nanosecond pulsed power supply. Complete inactivation is achieved with a burst of 2000 pulses corresponding to an energy consumption of 2 J. This corresponds to an energy flux of 2.0 J/cm^2. Nonetheless, the energy consumption remains almost a factor 10 higher compared to the UV-C lamp.

For the remote treatment, using the 2D-DBD, complete virus inactivation is achieved at a much larger exposure time of 3 minutes as compared to direct AC-driven DBD treatment. This suggests that in the direct discharge the presence of short-lived reactive species enhances the virus inactivation. The virus inactivation at an exposure distance of 13.5 cm suggests the role of long-lived reactive species (such as O_3 and NO_2) [17]. The gas-phase densities of O_3

and NO_2 are 140 ppm and 83 ppm, respectively. Previous results have shown the importance of reactive nitrogen species in the inactivation of virus [17]. In addition, the UV radiation from the plasma source is insufficient to contribute to the inactivation of FCV.

In remote treatment using the flow-through reactor, the plasma is treating the gas rather than the sample directly. A treatment time of 3 minutes in this case corresponds to an energy consumption of 53 J/l. To compare the volumetric gas treatment efficiencies with direct DBD and UV-C treatments, which are inherently surface treatments, we need to make assumptions. As the flow-through reactor used is not effective in using the produced RONS by the discharge, we assume that the treatment can be performed in a batch reactor with a capacity of 1 litre (20×20×2.5 cm^3 or 10×10×10 cm^3). We can, in this case, perform an area treatment of the lower surface (400 cm^2 or 100 cm^2) by treating only one litre of air and leaving it in the reactor for 3 minutes to produce similar inactivation effect as in the flow-through reactor. This is a realistic assumption in view of the long lifetimes of the reactive species responsible for decontamination.

Table 1. Comparison of power/energy and energy required to decontaminate 1 cm^2 containing ~5.5 log_{10} virus particles for the investigated plasma sources and UV. For details, see text.

Source	UV-C Irradiance ($\mu W/cm^2$)	Power or Energy	E/V (J/l)	E/A (J/cm^2)
UV-C Lamp	340	8 W	-	0.24
Direct AC	?	12 W	-	< 58.7
Direct ns-Pulsed	?	1 mJ/pulse	-	2.0
2D-DBD	< 1	14.5 W	53	0.13 – 0.53*

*Estimates based on simple model reactor

This implies that the energy consumption for complete inactivation using the remote DBD could, in principle, reach the efficacy exhibited by the UV-C lamp with an appropriate batch reactor design. In addition, the UV-C lamp can only inactivate virus along the line-of-sight of the UV photons. This highlights the versatile nature of remote plasma decontamination over UV as the plasma-generated species are not limited by shadowing effect and can be used to decontaminate more complex 3-D objects in an enclosed environment to contain the plasma-produced reactive species.

4. Conclusion

A comparative study of different plasma sources and a conventional UV-C lamp for viral inactivation has been performed in terms of virucidal efficacy and energy efficiency. All plasma sources and the UV-C lamp demonstrate complete inactivation, although for different treatment times and energy consumption. Although the direct plasma treatment is more energy intensive compared to UV-C treatment for similar inactivation effect, improved energy efficiency might be possible by further optimization of the plasma source and its operating conditions. The presented results and estimates suggest that a simple batch reactor design could make the energy efficiency of the remote plasma-based decontamination comparable to that of UV-C lamp. Additionally, plasma treatment of complex food substrates is not limited by the shadowing effect encountered by UV lamp treatment.

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6. References

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