Parameters of Plasma Generated by Diffuse Coplanar Surface Barrier Discharge Used for Inactivation of Escherichia Coli

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Abstract. Diffuse Coplanar Surface Barrier Discharge (DCSBD) is nowadays widely tested for inactivation of chosen fungi on artificially infected plant seeds and chosen bacteria on biocompatible polymer surfaces. In this study we investigated the plasma properties of DCSBD during the degradation of Escherichia coli contamination on polytetrafluoroethylene (PTFE or Teflon) surface in ambient air at atmospheric pressure. The knowledge of plasma parameters is important to determine the role of the plasma components at inactivating of harmful contamination, such as OH, NOγ and N2 molecule systems and UV-radiation observed in the emission of DCSBD plasma. The insignificant changes of plasma properties during the inactivation process were found using electrical characteristics and optical emission spectroscopy measurements.

Introduction

Diffuse Coplanar Surface Barrier Discharge (DCSBD) belongs to the dielectric barrier discharges (DBD) often tested for environmental, bio-medical and industrial applications. DCSBD generates macroscopically homogeneous, non-equilibrium plasma in ambient air at atmospheric pressure. An important advantage of this type of DBD is high volume density of electric power in the plasma [Černák et al., 2011; Černák et al., 2009]. Current study of fungicidal [Zahoranová et al., 2014] and especially bactericidal effects of DCSBD plasma on Escherichia Coli (E. coli) [Tučeková et al., 2015] has shown high germicidal efficiency (> 99 %) for short exposure time (< 1 min).

DCSBD provides generation of active particles such as electrons, ions, excited atoms and molecules (reactive nitrogen species-RNS and reactive oxygen species-ROS, e.g., O3), reactive radicals (NO, OH, metastables and radiation of UV light. The microorganism inactivation includes erosion by free radicals, etching by charged particles and high energy electrons, and UV-radiation damage [Laroussi, 2005], but the role of inactivation agents is widely discussed.

Experimental

The photograph of experimental apparatus used for inactivation of E. coli bacteria on the contaminated polytetrafluoroethylene (PTFE) surface with dimensions 15 x 50 mm is shown in Fig.1. The influence of sample presence above the DCSBD plasma layer was studied by electrical parameters measurement and by optical emission spectroscopy (OES) (Fig.2).

The scheme of DCSBD electrical properties measurement is shown in Fig. 2. The voltage between the electrodes of DCSBD U(t) was measured by two Tektronix P6015A (1:1000) high voltage probes and the current I(t) was measured by Rogowski’s coil Pearson electronic 4100. Both signals were displayed using Tektronix TDS 2024B digital oscilloscope.

Mean value of power supplied to DCSBD system was calculated using formula:

\[ P = \frac{1}{T} \int_0^T I(t)U(t)dt \]  

(1)

We compared the efficiency of HV power supply for DCSBD plasma operating in ambient air (relative humidity approx. 40 %) with and without sample. To estimate dielectric losses of DCSBD plasma system, the electronegative gas SF6 was used to suppress the discharge in isolated chamber with a volume of 150 ml above the DCSBD discharge region. The dielectric losses were defined as mean power in SF6 gas for voltage amplitude corresponding to voltage amplitude (thus to input power) in ambient air.

The DCSBD plasma system properties were estimated using simulation of voltage and current waveforms in program OriginPro using formula:
Figure 1. DCSBD reactor for inactivation of *E.coli* on the contaminated PTFE surface: 1—contaminated PTFE samples, 2—forceps in isopropyl alcohol, 3—DCSBD plasma system, 4—movable sample holder.

Figure 2. Scheme of experimental setup for electrical characteristics and OES measurements.

\[ y = y_0 + A \sin \left( \pi \frac{x-x_c}{w} \right) \]  \hspace{1cm} (2)

and describing following model (Fig.3). The values of \( A, x_c \) and \( w \) were used for calculation of the period \( T \), frequency \( f \), radial frequency \( \omega \) of power supply, phase shift \( \Delta \phi \) of actual current and voltage waveforms, capacitance \( C \) of plasma system and complex impedance \( Z \), reactance \( X \) and resistance \( R \) of plasma, according [Medvecká, 2015].

The measurements of optical emission spectra of DCSBD plasma in ambient air with and without sample were performed by spectrometers *Avantes 2048TEC* with spectral range 300–400 nm and *StellarNet Inc. EPP2000-UVN* with spectral range 185–1125 nm. The values of vibrational temperature were estimated from \( \mathrm{N}_2 (\mathrm{C}^3\Pi_u-\mathrm{B}^3\Pi_g) \) (0–2) heads (starting at 380.5 nm) by *Spectrum Analyser* [Navrátil et al., 2006] and the values of rotational temperatures were obtained by simulation of \( \mathrm{N}_2 (\mathrm{C}^3\Pi_u-\mathrm{B}^3\Pi_g) \) (0–1) head 0–1 (at 357.42 nm) using program *Specair* [Laux, 2002].

**Results and discussion**

The value of real power supplied to DCSBD was determined as power in ambient air with and without contaminated PTFE sample. The real power dependence on input power enabled to determine calibration curve equations (Fig.4). High efficiency of used HV power supply was confirmed while the intercept of calibration curve represented approximately 10 % permanent losses of input power (for example in transformer coil, cooling of power supply, heating of power supply and plasma system). The dielectric losses were determined as power in \( \mathrm{SF}_6 \) gas (non-burning regime). These losses remained less than 3 % of input power.
Figure 3. Actual current and voltage waveforms of DCSBD plasma without PTFE sample (input power 400 W) and model of waveform simulation.

Figure 4. The calibration curves for determination of power supplied to DCSBD plasma generated in air with and without sample with efficiency equation $P_R$ (incl. dielectric losses) and dielectric losses equation $P_D$.

Using the sine function simulation for the voltage and current waveforms measured for various input power with and without the sample the values of different DCSBD plasma system parameters (Tab.1) were estimated.

We can see (Tab. 1) the decrease of HV power supply frequency. The capacitance of whole DCSBD plasma system and resistance of plasma increased with the rising input power. This change was probably caused by enhanced heating of DCSBD plasma system. The presence of the contaminated PTFE sample during $E. coli$ inactivation affected the parameters of DCSBD plasma system minimally.

The values (Tab.2) of vibrational temperature (indicator of non-equilibrium character of plasma) have shown slight increase of $T_v$ during $E. coli$ inactivation caused by the sample holder and PTFE sample presence above plasma. This change is insignificant taking the $T_v$ Error value into account. The values of rotational temperature (~ gas temperature) have not shown significant change during the $E. coli$ inactivation. The value of $T_R$ enables the antimicrobial treatment of heat sensitive samples and indicates that the temperature of gas is not responsible for bactericidal effect. The comparison of $T_R$ and $T_R$ indicates the generation of a highly non-equilibrium plasma in ambient air, as it was confirmed in previous works [Černák et al., 2011; Hergelová et al., 2012].

The emission spectrum of DCSBD plasma with sample and typical emission spectrum of DCSBD in ambient air are shown in Fig. 5. These spectra are dominated by Second Positive System (SPS) of $N_2$ ($C^3Π_u$-$B^3Π_g$). The dominant SPS $N_2$ accompanied by First Positive System (FPS) of $N_2$ ($B^3Π_g$-$A^3Σ_u^+$) is characteristic for many atmospheric non-equilibrium discharges generated in air. The presence of FPS $N_2$ (Fig.6) indicated formation of $N_2 A^3Σ_u^+$ metastables which participate in number of chemical reactions in air plasma.
OH (A^2Σ^+–X^3Π_g) and NOγ (A^2Σ^+–X^2Π_r) system emissions occurred due to the presence of H₂O in ambient air and as the result of combination of dissociated N₂ and O₂. The strong reactivity and bactericidal effect of these systems are important attributes for biochemical decontamination and sterilization [Machala et al., 2007]. The limitation of observed plasma volume in consequence of direct contact of sample with plasma layer during E. coli inactivation caused decrease of spectral intensity in comparison to OES of DCSBD plasma without E. coli sample.

Table 1. The DCSBD plasma system properties for various input power.

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Table 2. The TV and TR of DCSBD plasma during E. coli inactivation.

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<td>Without holder</td>
<td>2400</td>
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Figure 5. Emission spectra of DCSBD plasma with (offset 3000 a.u.) and without E. coli sample.
Figure 6. Detail of emission spectra of DCSBD plasma with (offset 2500 a.u.) and without E. coli sample.

Conclusion

During the decontamination of E. coli bacteria the properties of plasma system and energy efficiency of HV power supply have not been affected by contaminated PTFE sample. The investigation has confirmed the production of reactive species (RNS and ROS) and plasma generated UV-radiation. Also the minimal contribution of gas temperature to bactericidal efficacy during inactivation process using DCSBD plasma has been verified.

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