

He+O₂+H₂O plasmas as a source of reactive oxygen species

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The effect of water in the chemistry of atmospheric-pressure He+O₂ plasmas is studied by means of a comprehensive global model. Water enables the generation of reactive oxygen species (ROS) cocktails that are rich not only in O, O₂^{*}, and O₃ but also in OH and H₂O₂. Due to its polar nature, water also leads to cluster formation, possibly affecting the plasma dynamics. Since the lifetime of many of the ROS is short, the plasma chemistry plays two roles: (i) direct interaction with superficial cells and (ii) triggering of a secondary chemistry that propagates the plasma treatment to regions away from the plasma-surface interface. © 2011 American Institute of Physics.

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Atmospheric-pressure plasmas have received growing attention in recent years for their potential use in many scientific disciplines. In particular, we focus here on the use of low temperature atmospheric-pressure plasmas in “plasma medicine,” an emerging scientific discipline that exploits the interaction of gas plasmas with biological materials for therapeutical purposes.^{1,2} In many plasma medicine applications, reactive oxygen species (ROS) are believed to be of critical importance and therefore He+O₂ admixtures have often been used.

In most plasma medicine applications, however, water is also present. Since these plasmas are typically operated in open air, they are in contact with an environment that contains water vapor at typical concentrations of thousands of parts per million (ppm). More importantly, living cells are mostly found in moist environments. So even if water is not deliberately fed into the gas plasma, it is almost impossible to prevent the presence of water in the discharge. This could change the chemistry at play and thereby alter (for better or for worse) the effectiveness of the plasma treatment.

Motivated by this ubiquitous presence of water in plasma medicine applications, this letter reports on the influence of H₂O in the chemistry of otherwise reasonably well-understood He+O₂ plasmas. Particular emphasis is placed on the generation of ROS that are relevant in plasma medicine applications.

Building on comprehensive plasma chemistry models of He+O₂ and He+H₂O plasmas,³⁻⁵ we created a global model for He+O₂+H₂O discharges. The model incorporates 55 species (see Table I) and accounts for 855 chemical reactions. Details of the numerical scheme can be found in Ref. 4.

According to previous computational and experimental studies, He+O₂ and He+H₂O plasmas produce a maximum amount of ROS when the precursor (O₂ or H₂O) concentration is between 0.1% and 1%.^{3,4,6} Therefore, in this work the total amount of precursor ([O₂]+[H₂O]) is fixed at 0.5%. To study the changes in plasma chemistry as a function of the precursor composition, the ratio (*r*) of H₂O concentration to

O₂ concentration, i.e., $r=[\text{H}_2\text{O}]/[\text{O}_2]$, is swept from 0.01 to 100. All other parameters of the discharge are kept constant and the discharge geometry and input power (40 W/cm³) reflect those used in previous studies.^{4,7}

The influence of the [H₂O]/[O₂] ratio on the ionic composition of the plasma is shown in Fig. 1. Due to the polar nature of water molecules, hydrated ions form even at low water concentrations ([H₂O]=50 ppm; $r=0.01$). As a result the dominant ions even at low water concentration are O₂⁺·(H₂O)₂ and O₃⁻·(H₂O)₂. This contrasts with the dominant role of O₄⁺ and O₃⁻ in a water free He+O₂ discharge (see Ref. 4). Hydration changes the mass of the ions and their transport coefficients, thereby influencing the plasma dynamics in ways not possible to analyze with the global model used in this study. These results, however, indicate that clusters should be accounted for in fluid and kinetic models of water containing plasmas. At high water concentrations, the density of nonhydrated ions, e.g., O₂⁺ and O⁻, become negligible and the discharge chemistry evolves to that of He+H₂O plasmas.³ An ion that is of particular relevance for biological systems is O₂⁻.⁸ This is produced in the plasma in decreasing quantities when *r* increases above ~0.1, and even at low

TABLE I. Species included in the model.

Simple ions	Cluster ions	Metastables and excited states	Ground state neutrals
He ⁺	HeH ⁺	O(¹ D)	He
He ₂ ⁺	H ₃ ⁺	O(¹ S)	O ₂
H ⁺	O ₄ ⁺	O ₂ (b ¹ Σ _g ⁺)	H ₂ O
H ⁻	O ₆ ⁻	O ₂ (a ¹ Δ _g)	H
H ₂ ⁺	H ₂ O ₂ ⁺	OH(A)	O
O ⁺	H ₄ O ₂ ⁺	He(2 ³ S)	H ₂
O ⁻	H ⁺ ·(H ₂ O) _{n=1-7}	He(2 ¹ S)	OH
O ₂ ⁺	O ₂ ⁺ ·(H ₂ O) _{n=1-2}	He ₂ (a ³ Σ _u ⁺)	HO ₂
O ₂ ⁻	O ₃ ⁻		H ₂ O ₂
OH ⁺	O ₄ ⁻		O ₃
OH ⁻	H ₂ O ₂ ⁻		
H ₂ O ⁺	OH ⁻ ·(H ₂ O) _{n=1-2}		
HO ₂ ⁺	O ₂ ⁻ ·(H ₂ O) _{n=1-2}		
	O ₃ ⁻ ·(H ₂ O) _{n=1-2}		

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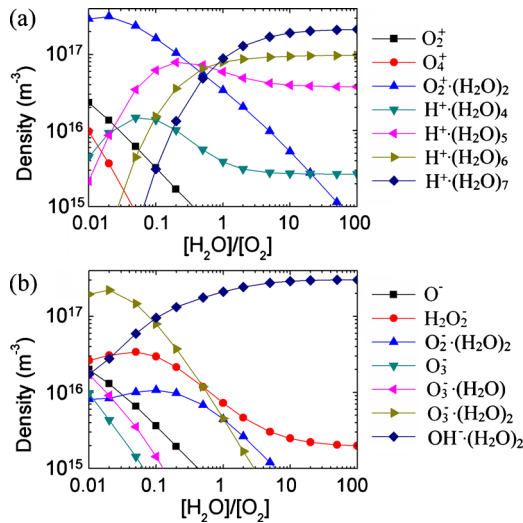


FIG. 1. (Color online) Density of (a) cations and (b) anions in a He+O₂+H₂O plasma as a function of [H₂O]/[O₂]. [H₂O+O₂]=0.5%.

water concentration ($r=0.01$) O₂⁻ is found in hydrated form.

Only species crossing the plasma sheath will react with the biological target. The fluxes of key plasma species as a function of the [H₂O]/[O₂] ratio are shown in Fig. 2. The flux of neutral ROS is orders of magnitude larger than that of ions and helium metastables. Therefore, ROS are expected to dominate the chemical interaction. Ions could in a first approximation be neglected because their flux is small and at atmospheric pressure they are not very energetic.⁹ However, charge accumulation from ions (and electrons) on the sample may create electric fields that could lead to important biological responses such as electroporation,¹⁰ and these could interplay synergistically with the ROS chemistry. In continuous plasmas, the flux of anions (including superoxide) will be strongly limited by the confining effect of the plasma ambipolar field.

The actual composition of the thermal flux of neutral ROS from He+O₂+H₂O plasmas is shown in Fig. 3. The main ROS are O, O₂^{*} [including O₂(b¹Σ_g⁺) and O₂(a¹Δ_g)], O₃, OH, HO₂, and H₂O₂. As the ratio r increases from 0.01 to 100, the fluxes of O, O₂^{*}, and O₃ decrease monotonically while the ones of OH, HO₂, and H₂O₂ increase and reach a maximum at around $r=2$. The total flux of ROS remains within the same order of magnitude as the precursor composition changes over four orders of magnitude although it drops slightly when the ratio r increases above 1. This suggests that both O₂ and H₂O are good sources of ROS and that they can be used in conjunction to adjust the composition of the cocktail of ROS created in the plasma. At low

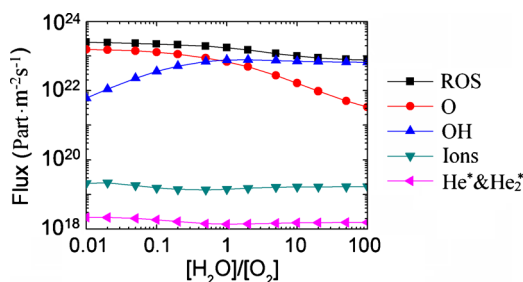


FIG. 2. (Color online) Electrode fluxes in a He+O₂+H₂O plasma as a function of [H₂O]/[O₂] ratio. [H₂O+O₂]=0.5%.

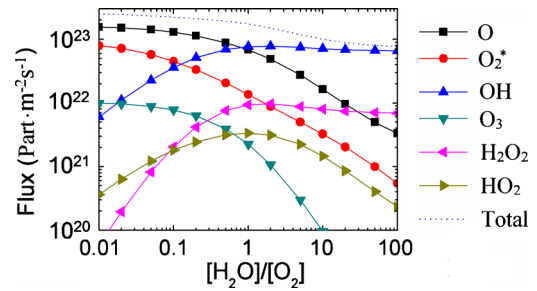


FIG. 3. (Color online) Flux of the main ROS in a He+O₂+H₂O plasma as a function of the [H₂O]/[O₂] ratio. [H₂O+O₂]=0.5%.

water concentrations ($r \ll 1$) the main ROS are O, O₂^{*}, and O₃ whereas at high water concentrations ($r \gg 1$) OH and H₂O₂ dominate. A mixture containing reasonable amount of the five species can be obtained when $r \sim 1$. The slight higher production of ROS in O₂ rich admixtures can be attributed to the higher dissociative rate coefficient of oxygen molecules and the presence of reductive products, e.g., H, in H₂O rich plasmas.

The main reactions leading to the production of O and OH, i.e., the most abundant ROS (see Fig. 2), are electron impact dissociation (include dissociative excitation and dissociative attachment) of O₂ and H₂O, respectively. Since O can be produced from H₂O [$e+H_2O \rightarrow H_2+O(^3P, ^1D, ^1S)+e$], the decrease in O concentration as r increases is slower than the decrease in O₂^{*} and O₃. The decrease in O₃ is actually the fastest of the three as its main production reaction is $O+O_2+He \rightarrow O_3+He$ and both O and O₂ decrease when r increases. H₂O₂ and OH have a similar trend because H₂O₂ forms mainly by OH recombination.

Finally, it is noted that in many plasma medicine applications, the plasma treatment is required to reach beyond the surface of the biological sample, often through an aqueous environment with organic content. Regarding organic molecules, OH, O, and O₂^{*} have large rate coefficients ($10^7-10^9 \text{ M}^{-1} \text{ s}^{-1}$), orders of magnitude larger than those of O₃ and H₂O₂ ($<10^7 \text{ M}^{-1} \text{ s}^{-1}$).¹¹⁻¹⁴ As a result the latter are longer lived and can reach further away from the surface. Two extreme scenarios can be considered:

- Scenario 1—Target with very low concentration of organic compounds ([organic] \ll [ROS]): the inter- and self-reactions of ROS and potentially with water molecules dominate the destruction of ROS.
- Scenario 2—Target with high concentration of organic compounds ([organic] \gg [ROS]): in this case the inter- and self-reactions of ROS become negligible. This is the typical scenario one would encounter when treating human tissue.

As an example, we consider here the case of singlet delta oxygen O₂(a¹Δ_g). Its lifetime decreases from tens of minute in the gas plasma where its main loss is due to diffusion out of the discharge, to microsecond in a diluted aqueous solution (scenario 1) where it is quenched by water molecules, and to tens of nanosecond in a cell environment (scenario 2) where it reacts with organic compounds.^{15,16} In the latter case, assuming a diffusion constant of $\sim 5 \times 10^{-5} \text{ cm}^2/\text{s}$, singlet oxygen diffuses $\sqrt{Dt} \sim 10 \text{ nm}$, i.e., less than the size of a single cell. This simple calculation reflects the well-

known superficial nature of plasma treatments and supports, for example, the rapid decrease in the bactericidal properties of plasmas when bacteria are piled up or buried in biofilms.¹⁷ Nevertheless, there is also evidence of long range effects of plasma treatments, for example, through liquid media.² This seems to suggest that stable compounds of biological relevance capable of reaching far beyond the size of a cell are generated at the plasma-medium interface.

In conclusion, He+O₂+H₂O admixtures can be used to generate cocktails of ROS that contain all the main species typically encountered in He+O₂ and He+H₂O plasmas. The overall amount of ROS generated in the plasma is relatively insensitive to the [H₂O]/[O₂] ratio in the feed gas, although it decreases slightly with increasing water content due to the smaller dissociation rate of H₂O and the generation of reducing species such as H. The [H₂O]/[O₂] ratio can be used to control the actual composition of the cocktail of ROS and maximum simultaneous production of O and OH is accomplished when [H₂O]/[O₂] ~ 1. ROS are expected to interact with biological samples by (i) reacting directly with superficial cells and (ii) triggering a secondary chemistry that will transport the effects of the plasma treatment beyond the gas/sample interface. Even at low water concentrations hydrated ions are found to be abundant, indicating that in most plasmas used for plasma medicine ionic clusters should be considered.

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- ¹M. G. Kong, G. Kroesen, G. Morfill, T. Nosenko, T. Shimizu J. van Dijk, and J. L. Zimmermann, *New J. Phys.* **11**, 115012 (2009).
- ²G. Fridman, G. Friedman, A. Gutsol, A. B. Shekhter, V. N. Vasilets, and A. Fridman, *Plasma Processes Polym.* **5**, 503 (2008).
- ³D. X. Liu, P. Bruggeman, F. Iza, M. Z. Rong, and M. G. Kong, *Plasma Sources Sci. Technol.* **19**, 025018 (2010).
- ⁴D. X. Liu, M. Z. Rong, X. H. Wang, F. Iza, M. G. Kong, and P. Bruggeman, *Plasma Processes Polym.* **7**, 846 (2010).
- ⁵J. R. Podolske and H. S. Johnston, *J. Phys. Chem.* **87**, 628 (1983).
- ⁶N. Knake, K. Niemi, S. Reuter, V. Schulz-von der Gathen, and J. Winter, *Appl. Phys. Lett.* **93**, 131503 (2008).
- ⁷D. Liu, F. Iza, and M. G. Kong, *IEEE Trans. Plasma Sci.* **36**, 952 (2008).
- ⁸W. A. Pryor, K. N. Houk, C. S. Foote, J. M. Fukuto, L. J. Ignarro, G. L. Squadrito, and J. A. Davies, *Am. J. Physiol. Regulatory Integrative Comp. Physiol.* **291**, R491 (2006).
- ⁹J. Choi, F. Iza, J. K. Lee, and C. M. Ryu, *IEEE Trans. Plasma Sci.* **35**, 1274 (2007).
- ¹⁰N. Y. Babaeva and M. J. Kushner, *J. Phys. D: Appl. Phys.* **43**, 185206 (2010).
- ¹¹W. H. Glaze, *Environ. Sci. Technol.* **21**, 224 (1987).
- ¹²G. Bucher and J. C. Scaiano, *J. Phys. Chem.* **98**, 12471 (1994).
- ¹³E. A. Lissi, M. V. Encinas, E. Lemp, and M. A. Rubio, *Chem. Rev. (Washington, D.C.)* **93**, 699 (1993).
- ¹⁴NDRL/NIST solution kinetics database, <http://kinetics.nist.gov/solution/>.
- ¹⁵R. W. Redmond and I. E. Kochevar, *Photochem. Photobiol.* **82**, 1178 (2006).
- ¹⁶C. Schweitzer and R. Schmidt, *Chem. Rev. (Washington, D.C.)* **103**, 1685 (2003).
- ¹⁷M. Vleugels, G. Shama, X. T. Deng, E. Greenacre, T. Brocklehurst, and M. G. Kong, *IEEE Trans. Plasma Sci.* **33**, 824 (2005).