Plasma Medicine, 8(4):403–409 (2018)

Atmospheric Pressure Microwave Plasma Torch for Biomedical Applications

Ivan Tsonev,[a,*] Nikolai Atanasov,[b] Gabriela Atanasova,[b] Frantisek Krčma,[c] & Todor Bogdanov[d]

[a]Faculty of Physics, Sofia University, 1164 Sofia, Bulgaria; [b]University of Telecommunications and Post, 1700 Sofia, Bulgaria; [c]Faculty of Chemistry, Brno University of Technology, 612 00 Brno, Czech Republic; [d]Medical Faculty, Medical University–Sofia, 1431 Sofia, Bulgaria

*Address all correspondence to: I. Tsonev, Faculty of Physics, Sofia University, 5 James Bourchier Blvd., 1164 Sofia, Bulgaria; Tel.: +359-895-969-787, E-mail: ivan.tsonev95@hotmail.com

ABSTRACT: During the past decade, cold plasma sources have gained much attention regarding biomedical applications. The large spectrum of observed effects (programmed cell death, bacterial inactivation, wound healing, etc.) has encouraged scientists to create and use different plasma sources operating at atmospheric pressure. The preferred plasma device to this point has been dielectric barrier discharges. In this work, we present well-known surface-wave–sustained microwave discharge operating at 2.45 GHz. This atmospheric pressure plasma torch can sustain low gas temperature at relatively low gas flow and power output, which makes it suitable for working with different model biological systems. We see a strong relationship among microwave power, torch length, and gas temperature. Moreover, gas flow and tube specifications (inner diameter, wall thickness, and dielectric permittivity) vary temperature and length of discharge. The purpose of this work is to precisely determine the working conditions at which this plasma source can be used in direct contact with biological objects.

KEY WORDS: atmospheric pressure plasma torch, low-temperature plasma, microwave discharge, biomedical applications

I. INTRODUCTION

For the past decade, interest in nonthermal atmospheric plasma–related technologies has increased significantly. Cold atmospheric pressure plasmas induce biological responses by generating reactive oxygen and reactive nitrogen species that make them suitable for an assortment of biological applications including wound healing, bacterial decontamination, and programmed cell death.[1–3] A large variety of new designs are based on either planar dielectric barrier discharges or high-frequency plasma jets. A biological object's surface treatment that acts on these configurations usually occurs in the postdischarge zone. This means that only long-living active species can reach the treated area[4–11]; thus, energy efficiency is rather limited. Helium is typically used in these devices as the working gas, which increases operational costs. A recently developed surface-wave plasma source sustained by a traveling electromagnetic wave allows direct contact with the active portion of the discharge, allowing short-living species to directly interact with the treated surface. The plasma in this case is part of the waveguide structure that includes a microwave generator coupled to a surfatron device.[12–15] Discharge is created in argon flow through a quartz tube in the surfatron

1947-5764/18/$35.00 www.begellhouse.com

resonator by the traveling electromagnetic wave that propagates along the plasma–dielectric (quartz tube or surrounding air) boundary. The resulting plasma torch can be sustained in ambient air with length proportional to the applied power and gas flow. In this case, the plasma column is axially inhomogeneous because of dissipation in the electromagnetic wave. Electrons absorb the wave energy, resulting in excitation and ionization of neutral atoms and ions, therefore reducing the wave power along the plasma torch. As the part of a waveguide structure, the geometry of the quartz tube is important for wave propagation and energy dissipation.[16]

II. MATERIALS AND METHODS

The experimental setup scheme is presented in Fig. 1. The solid-state microwave generator operating at 2.45 GHz (Sairem GMS 200 W; Neyron, France) was connected by coaxial cable to the commercial electromagnetic surface-wave resonator (Sairem surfatron 80). Argon discharge was created inside several quartz tubes (with real dielectric permittivity ε_r = 3.2541 and imaginary ε_i = 0.0062), with an inner diameter of 2 mm and outer diameters of 4, 6, and 8 mm (denoted as 4 × 2, 6 × 2, and 8 × 2, respectively). Working gas was argon 5.0 (purity 99.999%) at the constant mass flow of 2 sccm, controlled by an Omega FMA-A2408 mass flow controller (Spectris; Egham, UK). The system axis was installed vertically with gas flow from top to bottom (see Fig. 1).

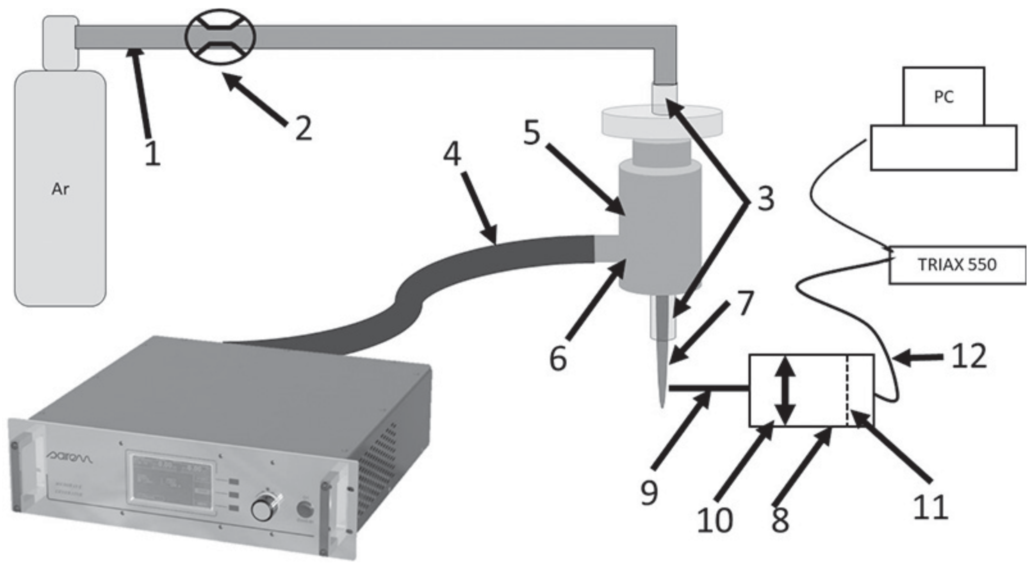

FIG. 1: Scheme of the experimental setup. (1) Gas tube; (2) mass flow controller; (3) quartz tube; (4) coaxial cable; (5) surfatron; (6) antenna; (7) plasma torch; (8) *xyz* movable optical line, composed from (9)–(11); (9) black rectangular nonreflecting light guide; (10) quartz lens; (11) yellow optical filter (optional); (12) multimode quartz optical fiber. PC, personal computer.

We used optical emission spectroscopy for diagnostics of the plasma torch. A quartz lens (diameter 25 mm; focal length 35 mm) focused light that was emitted from the discharge to a multimode optical cable connected to a spectrometer (Triax 550, Horiba; Edison, NJ). We used a 3600-g/mm grating (holographic blazed for 150–450 nm) to measure OH (A→X) 0-0 band (306.0–310.8 nm), from which rotational temperature was calculated using a Boltzmann plot technique with the lowest rotational levels.[17] We used 1200-g/mm grating (ruled and blazed at 550 nm) to register Ar* spectra and calculate argon excitation temperature using integral intensities of the following argon lines: 603.21, 667.73, 675.28, 687.13, and 714.70 nm. Constants used were from the National Institute of Standards and Technology.[18] We calibrated spectrometer sensitivity using the standard Ocean Optics DT-MINI-2-GS source. Experiments were conducted for a series of 20-, 26-, and 29-W applied microwave power.

III. RESULTS AND DISCUSSION

Electron excitation temperatures calculated from argon lines are shown in Fig. 2 for all used tubes and applied powers at the constant argon flow of 2 sccm. Axial inhomogeneity is clearly visible and nearly independent of conditions. Temperature decrease is a result of electromagnetic wave attenuation along the discharge (wave energy is consumed by the plasma), and plasma torch length rises with applied power. Additional details of this effect are described in Marinova et al.[19] Excitation temperature depends on applied power, but it is nearly the same at the plasma torch tip and reaches a value of 4700 K. No significant difference was found among the tubes; all deviations were within the experimental error of 500 K.

The calculated rotational temperatures using a Boltzmann plot technique (presented in Fig. 3) depend on tube dimensions and microwave power. Similar to the electron excitation temperature, rotational temperature decreases along the plasma column for all investigated experimental conditions and increases with applied power (see Fig. 3[a]–[c]). Although temperature decrease along the plasma torch is nearly linear at the lowest applied power, exponential decay is visible at higher power. We suppose that this is due to the change in plasma flow from laminar to more turbulent at higher temperature (i.e., at higher applied power). We are preparing Schlieren imaging to verify this hypothesis. In contrast to electron excitation temperature, rotational temperature at the plasma torch tip increases with applied power. Thus, this limits applicability for surface treatment of very sensitive materials such as tissue at higher applied powers.

The electromagnetic wave propagates along the plasma–dielectric border, energy should be absorbed by the dielectric. One can assume that tube-wall thickness could influence discharge kinetic properties due to less energy absorption by plasma and higher energy absorption by the dielectric for the same microwave power. Variation in wall thickness may lead to variations in rotational, electron excitation, and gas temperature of the discharge. From these results, we can conclude that the influence of tube-wall

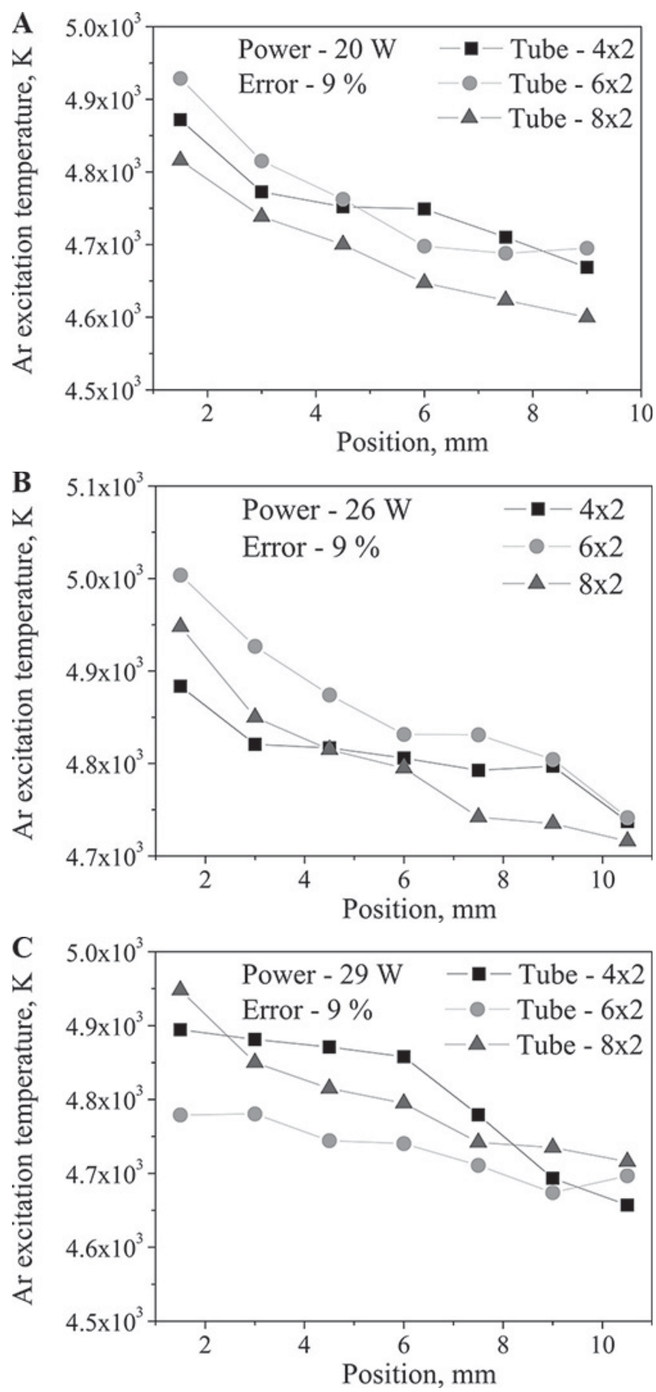

FIG. 2: Neutral argon excitation temperature is calculated from atomic lines that depend on tube-wall thickness for different applied powers of (a) 20, (b) 26, and (c) 29 W. Experimental error of ~ 500 K is not presented in the graphs.

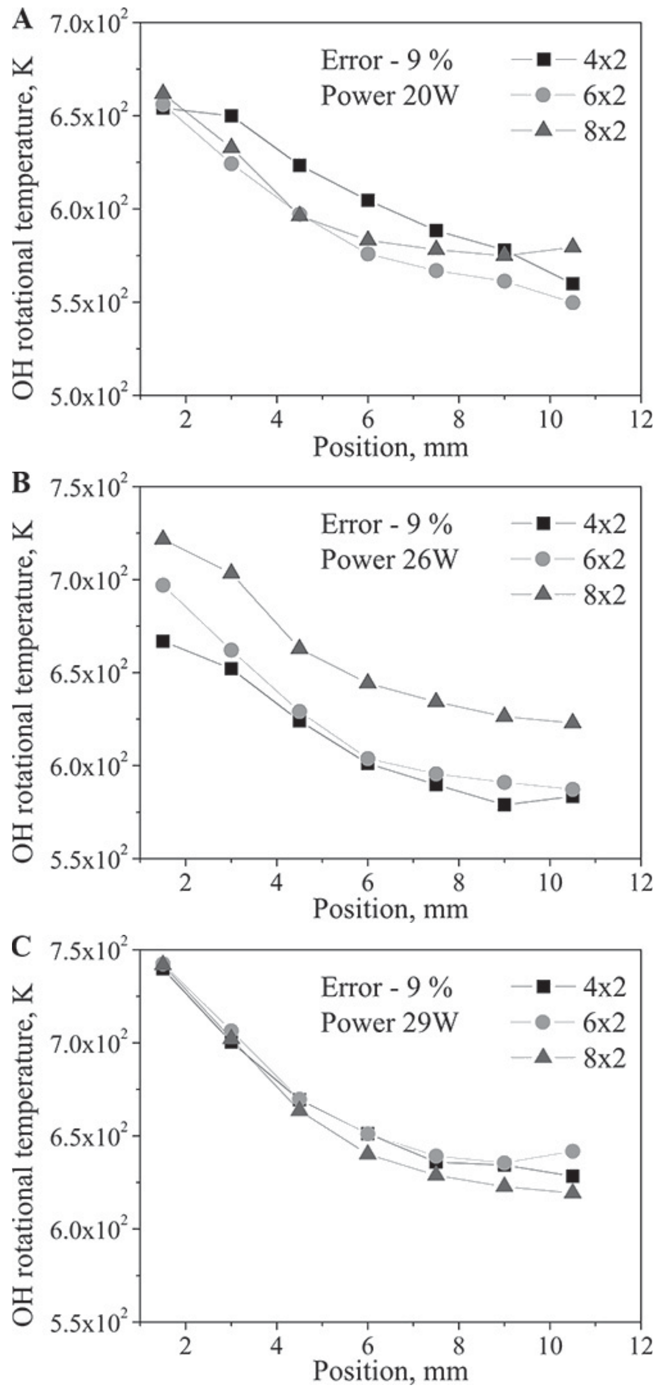

FIG. 3: Rotational temperature is calculated from the OH (A→X) 0-0 band rotational line intensities that depend on tube-wall thickness for different applied powers of (a) 20, (b) 26, and (c) 29 W. Experimental error of ~ 50 K is not presented in the graphs.

thickness on the investigated plasma parameters is negligible in the given experimental conditions.

IV. CONCLUSIONS

We presented neutral argon excitation temperature and rotational temperatures at given discharge conditions. The almost one order of difference between excitation and rotational temperatures confirms the strong nonequilibrium surface-wave plasma torch and its applicability for biomedical applications. Both plasma parameters decrease along the plasma column and do not depend on thickness of the quartz tube for the given experimental conditions. Future experiments investigating the role of the inner radius will be conducted to optimize discharge.

ACKNOWLEDGMENTS

This work is supported by the Bulgarian Ministry of Education and Science under the National Program for Research “Young Scientists and Postdoctoral Students” and by the Bulgarian National Science Fund under the 2016 Grant No. DM 03/3.

REFERENCES

1. Graves DB. Low temperature plasma biomedicine: A tutorial review. Phys Plasmas. 2014;21:080901.
2. Weltmann K-D, von Woedtke T. Plasma medicine: Current state of research and medical application. Plasma Phys Control Fusion. 2017;59:014031.
3. Lu X, Naidis GV, Laroussi M, Reuter S, Graves DB, Ostrikov K. Reactive species in non-equilibrium atmospheric-pressure plasmas: Generation, transport, and biological effects. Phys Rep Rev Sec Phys Lett. 2016;630:1–84.
4. Wei T, Kushner MJ. Long-term effects of multiply pulsed dielectric barrier discharges in air on thin water layers over tissue: Stationary and random streamers. J Phys D Appl Phys. 2015;48:494002.
5. Babaeva NY, Kushner MJ. Dynamics of dielectric barrier discharges over wounded skin. IEEE Trans Plasma Sci. 2011;39:2964–5.
6. Romero-Mangado J, Dey A, Diaz-Cartagena DC, Solis-Marcano NE, Lopez-Nieves M, Santiago-Garcia V, Nordlund D, Krishnamurthy S, Meyyappan M, Koehne JE, Gandhiraman, RP. Efficacy of atmospheric pressure dielectric barrier discharge for inactivating airborne pathogens. J Vac Sci Technol A. 2017;35:041101.
7. Kuzminova A, Kretková T, Kylián O, Hanuš J, Khalakhan I, Prukner V, Doležalová E, Šimek M, Biederman H. Etching of polymers, proteins and bacterial spores by atmospheric pressure DBD plasma in air. J Phys D Appl Phys. 2017;50:135201.
8. Xu Z, Shen J, Zhang Z, Ma J, Ma R, Zhao Y, Sun Q, Qian S, Zhang H, Ding L, Cheng C, Chu PK, Xia W. Inactivation effects of non-thermal atmospheric-pressure helium plasma jet on Staphylococcus aureus biofilms. Plasma Process Polym. 2015;12:827–35.
9. Hensel K, Kučerová K, Tarabová B, Janda M, Machala Z, Sano K, Mihai CT, Ciorpac M, Gorgan LD, Jijie R, Pohoata V, Topala I. Effects of air transient spark discharge and helium plasma jet on water, bacteria, cells, and biomolecules. Biointerphases. 2015;10:029515.
10. Guaitella O, Sobota A. The impingement of a kHz helium atmospheric pressure plasma jet on a dielectric surface. J Phys D Appl Phys. 2015;48:255202.

11. Horváth G, Moravský L, Krčma F, Matejčík Š. Characterization of a low-cost kilohertz-driven plasma pen operated in Ar gas. IEEE Trans Plasma Sci. 2013;41:613–9.
12. Benova E, Atanasova M, Bogdanov T, Marinova P, Krčma F, Mazánková V, Dostál L. Microwave plasma torch at water surface. Plasma Med. 2016;6:59–65.
13. Marinova P, Benova E, Todorova Y, Topalova Y, Yotinov I, Atanasova M, Krčma F. Surface-wave-sustained plasma torch for water treatment. J Phys Conf Series. 2018;982:012009.
14. Krčma F, Tsonev I, Smejkalová K, Truchlá D, Kozáková Z, Zhekova M, Marinova P, Bogdanov T, Benova E. Microwave micro torch generated in argon based mixtures for biomedical applications. J Phys D Appl Phys. 2018;51:414001.
15. Moisan M, Zakrzewski Z. Plasma sources based on the propagation of electromagnetic surface waves. J Phys D Appl Phys.1991;24:1025–48.
16. Moisan M, Nowakowska H. Contribution of surface-wave (SW) sustained plasma columns to the modeling of RF and microwave discharges with new insight into some of their features. A survey of other types of SW discharges. Plasma Sources Sci Technol. 2018;27:073001.
17. Bruggeman P, Schram DC, Kong MG, Leys C. Is the rotational temperature of OH(A–X) for discharges in and in contact with liquids a good diagnostic for determining the gas temperature? Plasma Process Polym. 2009;6:751.
18. Kramida A, Ralchenko Yu, Reader J, NIST ASD Team 2018. NIST Atomic Spectra Database (ver. 5.5.3) [database on the Internet]. Gaithersburg (MD): The National Institute of Standards and Technology. c2018 - [cited 2018 Mar 31]. Available from: https://physics.nist.gov/asd.
19. Marinova P, Benova E, Todorova Y, Topalova Y, Yotinov I, Atanasova M, Krcma F. Surface-wave-sustained plasma torch for water treatment. J Phys Conf Series. 2018;982:012009. 10.1088/1742-6596/982/1/012009.