

Microwave Plasma Torch at a Water Surface

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ABSTRACT: An argon plasma torch sustained by a 2.45-GHz electromagnetic wave can be in contact with a water surface or can penetrate inside the water, depending on the wave power. The propagation of the electromagnetic wave sustaining the discharge in water is problematic because the water relative dielectric permittivity greatly depends on the wave frequency and the temperature and varies between 6 and 86. At a wave frequency of 2.45 GHz and room temperature (20°C) the dielectric permittivity is 80, which leads to the very fast decay of the electromagnetic wave. We have studied both theoretically and experimentally the plasma properties and the electrodynamics of the wave propagation when the gas discharge is in contact with water. Depending on the wave power and the gas flow, it is possible to produce plasma at a low (room) temperature. The plasma is in nonequilibrium, with the electron temperature much higher than the gas/liquid temperature. Because of this, many radicals and chemically active particles can be produced even at low temperatures. Depending on the operating conditions, this kind of discharge can have various applications in surface treatment, sterilization, and surface energy change, among others, including temperature-sensitive materials and liquids treatment.

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

I. INTRODUCTION

Nonequilibrium plasmas at atmospheric pressure are being studied intensively. Many types of plasma sources operating in open spaces have been developed. They have 2 main advantages: (1) a simple and less expensive plasma source because of the lack of vacuum systems, and (2) plasma operating in an open space can be used for the direct treatment of samples and living tissues that cannot be immersed in a vacuum chamber. The electron temperature (1–2 eV) is much higher than the gas temperature, which, depending on the discharge conditions, can be above 1000 K or close to room temperature. Active species, radicals, and ultraviolet radiation are produced at these conditions. Many promising plasma applications have been developed in various fields: materials processing,^{1,2} reduction of greenhouse gases,³ inactivation of toxic substances,⁴ nanotechnology,⁵ biomedical applications, sterilization, and chemical neutralization.

Nonequilibrium atmospheric pressure plasma can be produced by various types of sources, one of which is surface wave discharge (SWD). Plasma is produced by an electromagnetic wave traveling along the plasma–dielectric interface. Because there are

no electrodes, this kind of plasma is clean, and various atomic gases, molecular gases, and gas mixtures can be used. In this work we studied a surface wave–sustained argon plasma in air, in contact with the water surface, and the possibilities of plasma penetrating the water.

II. MATERIALS AND METHODS

An 2.45-GHz electromagnetic wave is excited by a surfatron resonator⁶ (Fig. 1A). The plasma is produced inside a dielectric tube coaxial to the surfatron axis. The waveguide structure consists of the plasma, dielectric, and air, and the maximal electromagnetic field is at the plasma–dielectric interface. This is why the electromagnetic wave is assumed to be surface wave and the plasma produced by this wave is called surface wave–sustained plasma. The following mechanism sustains the plasma: The electromagnetic wave hits the electrons, which expend the absorbed wave power through ionization, excitation, and other processes, producing charged particles. The wave power decreases from the surfatron to the end of the plasma column, and the plasma density decreases in the axial direction, too. The surface wave–sustained plasma is both radially and axially inhomogeneous. The length of the plasma column depends on the wave power at the surfatron. The plasma length increases with increasing wave power, but the plasma density and its gradient in the initially existing part closer to the column end does not change. A new part with a higher density is only added near the surfatron. The dielectric tube can be moved in axial direction and, at a fixed wave power, can be taken back to the surfatron so that only a small part of it is out of the surfatron. This does not stop the electromagnetic wave propagation along the plasma–air boundary; a plasma torch is produced in this way. In our experiments the wave power is 35 W, with argon gas flow of 0.84 standard L/minute. The inner radius R of the tube is 0.2 cm. The discharge at these conditions is stable, well reproducible, has no filamentation, and the tube is completely filled with the plasma; thus the plasma radius coincides with R . The length of the plasma from the surfatron to the column end is ~ 4 cm. When the tube is taken back to the surfatron so that the plasma is partially in the air, a plasma torch appears in the open space (air). Its length slightly changes, and 2 cm of the plasma (measured from the surfatron) are in the tube, whereas the plasma torch has length of ~ 1.2 cm. The plasma is in strong nonequilibrium with room gas temperature and can be touched (Fig. 1B, C). This allows such plasma to be used for the treatment of temperature-sensitive materials, including living tissues and other biomedical applications.

Living tissues contain a large amount of water. This plasma can also be used for water treatment and purification. Therefore we investigated here the interaction of a SWD with water. We studied both experimentally and theoretically the processes at the water surface and the possibility of the plasma torch penetrating the water (Fig. 1D).

The propagation of an electromagnetic wave sustaining the discharge in water is problematic: the relative dielectric permittivity of the water strongly depends on the wave frequency and the temperature, and varies between 6 and 86. At a wave frequency of 2.45 GHz and a temperature of 100°C, the relative dielectric permittivity is 50, which

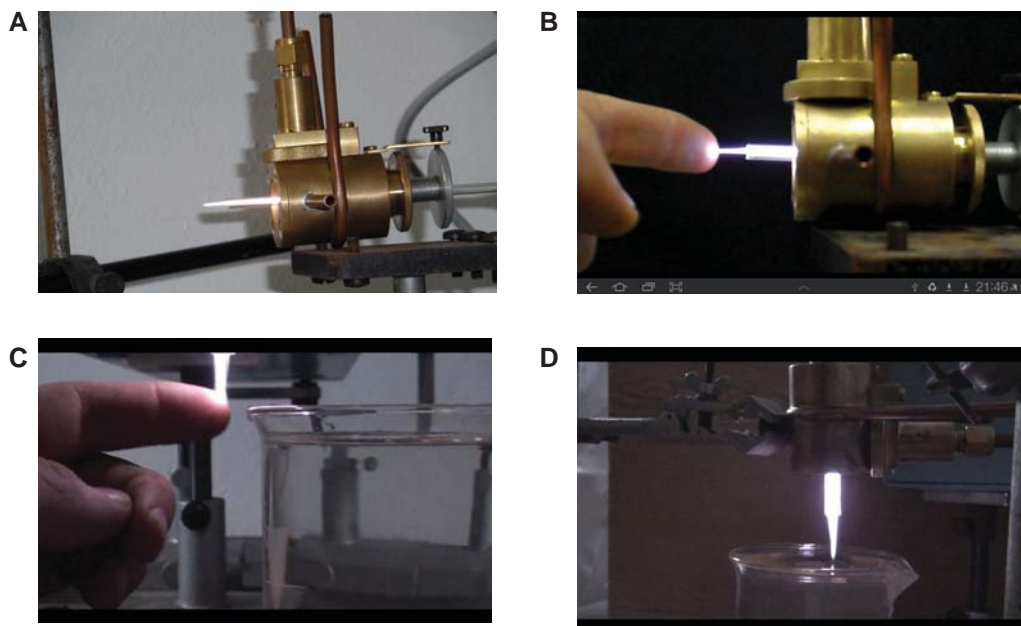


FIG. 1: (A) A plasma torch excited by surfatron. (B) A plasma torch with room gas temperature can be touched. (C) A surfatron-excited plasma torch in the vertical position. (D) Plasma in contact with a water surface.

leads to the fast decay of the electromagnetic wave. If the water temperature is lower, the relative permittivity is even higher and can reach 80 at room temperature (20°C). Because of this, at a low wave power the plasma torch does not penetrate the water, but a light spot can be seen on the water's surface.

We used a fast camera (FASTCAM SA-X2, model 1000K-M2) and, with 5000 frames/second, found that the light spot actually has a complicated structure, with “fingers” sliding on the water's surface (Fig. 2; the lines near the bottom of the figure). The fingers have their own structure.

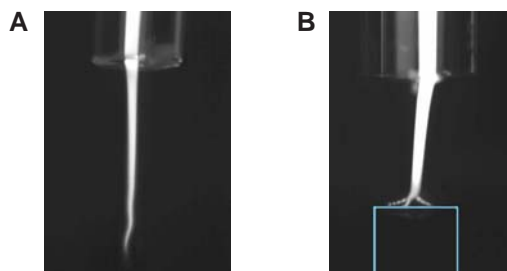


FIG. 2: (A) A plasma torch in air. (B) A plasma torch in contact with a water surface (lines near the bottom of the figure). “Fingers” with complicated structure can be seen in photographs taken with a camera using a fast shutter speed.

Experimental results have shown that at a wave power above 1 kW, a plasma torch sustained by a traveling electromagnetic wave at 2.45 GHz can penetrate water;⁷ in this case the gas temperature is much higher (>1000 K). However, the processes occurring where the plasma contacts the water surface, and inside the water, have not yet been investigated.

Theoretical investigations of SWD show a strong dependence of wave and plasma characteristics on the geometric parameters (e.g., plasma radius R , thickness of the dielectric tube) and the dielectric permittivity of the material surrounding plasma.⁸ To investigate this dependence in our discharge conditions, we applied a simple, 1-dimensional fluid model^{9–11} describing the electromagnetic wave propagation. One of the main advantages of surfatron-excited plasma is the single-wave mode of operation. The plasma inside the tube is usually produced by only the azimuthally symmetric TM mode. The model is based on the Maxwell equations, from which the local dispersion relation and the wave energy balance equations are obtained. They are solved simultaneously to obtain the axial distributions of plasma density and wave power.

III. RESULTS

We calculated the wave and plasma characteristics (wave power and plasma density, respectively) of argon plasma in the following configurations: (1) a plasma torch in air (dielectric permittivity $\epsilon_d = 1$; plasma–air [p–a] configuration), (2) plasma in a dielectric tube ($\epsilon_d = 3.8$; plasma–dielectric–air configuration), and (3) plasma surrounded by a layer of water (with dielectric permittivity of water $\epsilon_w = 50$ and 80 ; plasma–water–air [p–w–a] configuration). For the latter, we assumed that if the plasma penetrates the water, there will be a water layer around the plasma torch surrounded by air. The thin glass of the container's wall is not taken into account.

The axial distributions of plasma density n and wave power S for the 3 configurations are presented in Figs. 3A and 3B, respectively. The parameter $\sigma = \omega R/c$ is defined by the plasma radius R (0.2 cm), the electromagnetic wave angular frequency ω ($\omega/2\pi = 2.45$ GHz), and the speed of light c . The parameter $\gamma = R_d/R = 1 + d/R$ depends on the thickness of the dielectric tube d (0.2 cm in our experiment) or the water layer; R_d is the outer radius of the dielectric tube or the water layer around the plasma. For all configurations, $\sigma = 2$; for the p–a configuration, $\epsilon_d = \gamma = 1$; for the plasma–dielectric–air and plasma–water–air configurations, $\gamma = 2$. For convenience, the axial position $z = 0$ corresponds to the end of the plasma, and the wave exciter (surfatron) is at $z = 4$ cm. In this way we can compare the plasma density and the wave power necessary for sustaining plasma with the same length. The second-lowest lines in Figs. 3A and B correspond to the experimental case, where the plasma (4-cm length) is produced inside the dielectric tube using a 35-W wave power. The plasma torch (p–a configuration) is sustained by a lower wave power but has a lower plasma density (lowest lines in Figs. 3A and B). When the plasma end of the plasma torch is close to the water's surface, a decrease in the plasma length is observed. We needed to increase the wave power to 50 W to increase the plasma length so that it could touch the surface. One of the reasons for this behavior may be the fact that the

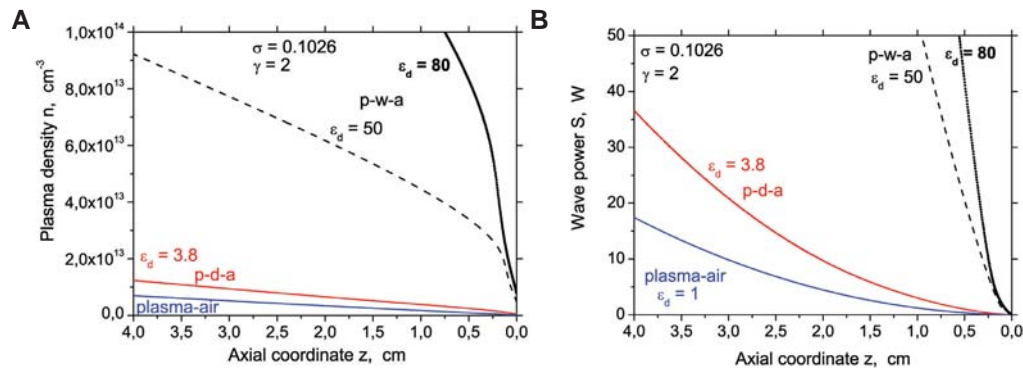


FIG. 3: Axial distribution of plasma density (A) and wave power (B) for 3 configurations: plasma-air (p-a; blue line), plasma-dielectric-air (p-d-a; red line), and plasma-water-air (p-w-a; a black solid line for dielectric permittivity in water $\epsilon_w = 80$, and a black dashed line for $\epsilon_w = 50$). ϵ_d , dielectric permittivity.

water absorption coefficient of electromagnetic waves at 2.45 GHz is high which leads to the quick decay of the wave in the water. But this effect can be observed even in plasma afterglow, when there is no electromagnetic wave propagation to the water's surface. This requires additional investigation and is a subject of further work.

One can see from Fig. 3A that the plasma density increases with an increase in the dielectric permittivity of the medium surrounding the plasma. So, the plasma density would be very high when there is room-temperature water around the plasma torch; this density is more than 10 times higher than that of the p-a configuration. The wave power necessary for producing plasma with a higher density also becomes more than 1 order higher. For instance, the wave powers necessary for producing plasma with a length of 0.5 and 2 cm, and plasma densities at the positions $z = 0.5$ cm and $z = 2$ cm from the plasma column end in the configurations shown in Fig. 3, are presented in Table 1.

One can see from the results presented in Table 1 that the wave power necessary to sustain plasma surrounded by water at room temperature is about 2 orders higher than for sustaining a plasma torch with the same length. The plasma density is also about 2 orders higher. Keeping in mind the short plasma length (0.5 cm) and the sharp decrease of the wave power from the surfatron to the plasma end (where $S_{\text{end}} = 0$) shown in Fig. 3, it is clear that plasma surrounded by water can theoretically be produced only with a very high wave power. We have not taken into account the wave absorption by the water at 2.45 GHz nor other effects that may occur at the water's surface.

This means that to have a plasma torch penetrating the water, a high wave power is needed. This was experimentally shown by Barkhudarov et al.⁷: plasma penetrated the water at a wave power above 1 kW.

To find conditions at which the plasma can interact with a larger water surface, we also calculated the plasma density and wave power of a p-w-a configuration at different water layer thicknesses. The results are shown in Fig. 4.

TABLE 1: Plasma density and necessary wave power for sustaining a surface-wave-discharge with a given length at various configurations*

Configuration	Axial position z (cm)	Plasma density n (cm^{-3})	Wave power S (W)
plasma–air, $\epsilon_d = 1$	0.5	9.68×10^{11}	0.36
plasma–dielectric–air, $\epsilon_d = 3.8$	0.5	2.48×10^{12}	1.01
plasma–water–air, $\epsilon_d = 50$	0.5	3.41×10^{13}	20
plasma–water–air, $\epsilon_d = 80$	0.5	8.33×10^{13}	42
plasma–air, $\epsilon_d = 1$	2.0	3.42×10^{12}	4.46
plasma–dielectric–air, $\epsilon_d = 3.8$	2.0	6.55×10^{12}	9.68
plasma–water–air, $\epsilon_d = 50$	2.0	6.18×10^{13}	137
plasma–water–air, $\epsilon_d = 80$	2.0	1.64×10^{14}	344

*These configurations are shown in Fig. 3.

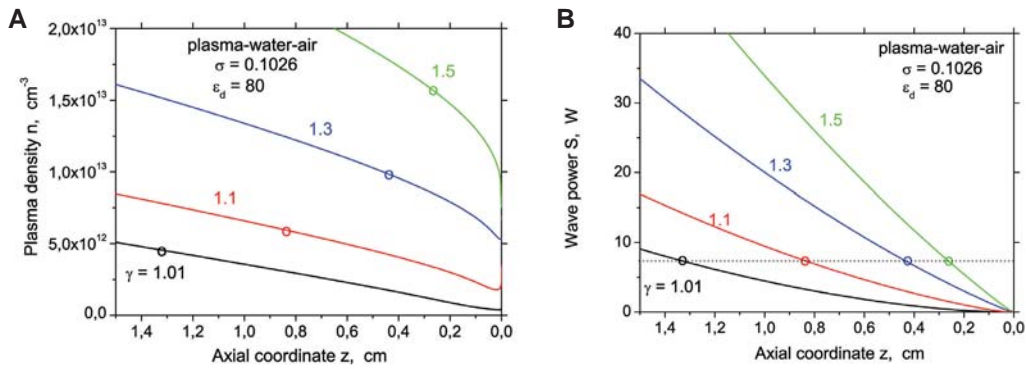


FIG. 4: Axial distribution of plasma density (A) and wave power (B) for a plasma–water–air (p–w–a) configuration at various water layer thicknesses (parameter γ). ϵ_d , dielectric permittivity.

One can see that with an increasing water layer thickness, the length of the plasma produced with the same power decreases. This is a result of the faster decay of the 2.45-GHz electromagnetic wave in the water. If the water layer is thin (a small value of γ), a much longer plasma torch surrounded by water can be produced with the same wave power. These conditions are more appropriate for interactions between microwave plasma and water than if the plasma touches only the water’s surface.

IV. CONCLUSION

A plasma torch sustained by a traveling electromagnetic wave at 2.45 GHz can interact with water. At a low wave power, the plasma only slides on the water’s surface and cannot penetrate it. The sliding plasma has a “finger”-like structure at the water’s surface. The electromagnetic wave sustaining the plasma decays very quickly at the water’s

surface. If the water is flowing in a thin layer around the plasma torch, the electromagnetic wave does not decay so quickly, and the plasma torch surrounded by water can be noticeably longer. This configuration of an SWD–water layer may have various applications in biology, medicine, and water purification.

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