8-1-2002

Simple, compact source for low-temperature air plasmas

D. P. Sheehan
University of San Diego, dsheehan@sandiego.edu

J. Lawson
University of San Diego

M. Sosa
University of San Diego

R. A. Long
University of California, San Diego

Simple, compact source for low-temperature air plasmas

D. P. Sheehan,[a] J. Lawson, and M. Sosa
Physics Department, University of San Diego, San Diego, California 92110

R. A. Long
Scripps Institute of Oceanography, UCSD, La Jolla, California

(Received 14 August 2001; accepted for publication 8 May 2002)

A simple, compact source of low-temperature, spatially and temporally uniform air plasma using a Telsa induction coil driver is described. The low-power ionization discharge plasma is localized (2 cm×0.5 cm×0.1 cm) and essentially free of arc channels. A Teflon coated rolling cylindrical electrode and dielectric coated ground plate are essential to the source's operation and allow flat test samples to be readily exposed to the plasma. The plasma is a copious source of ozone and nitrogen oxides. Its effects on various microbes are discussed.
[DOI: 10.1063/1.1491027]

I. INTRODUCTION

Air plasmas—plasmas generated at atmospheric pressures and compositions—have a variety of industrial, technological, and research applications, including surface and materials processing, electrostatic precipitation of pollutants, pasteurization and sterilization, welding, electrical power control, transient antennae, EMP simulation, hypersonic aerodynamics, lightning, and dusty plasmas. Methods for generating them are multifold, ranging from ac/dc electrical breakdown, radio and microwave breakdown, ultraviolet photoionization, nuclear radiation, particle beams, and high intensity lasers.[1–3]

This Note describes a simple, inexpensive, compact source for low-temperature air plasmas that can be built from a standard laboratory Tesla coil and suitably fashioned electrodes. Unlike the Telsa coil discharge itself, which is characterized by a highly localized, hot, filamentary discharge, the plasma described here extends over hundreds of times greater volume and has a higher degree of spatial and temporal uniformity, lacks the transient arc current channels, and is much cooler, thereby making it suitable for many nondestructive applications. Formally, it may be characterized as an ionization discharge that can be modified to take on some characteristics of a brush discharge. This source is also a copious source of ozone and nitrogen oxides that might be useful for sterilization or chemical bleaching of heat sensitive surfaces.

The typical laboratory Tesla coil is a high-frequency, high-voltage induction coil ($f \leqslant 10^7$ Hz with significant 60 Hz ac ripple; $V \leqslant 10^5$ V). In typical applications its discharge is confined to one or more crooked, threadlike current channels between its sharp-tipped metallic electrode and a ground surface. Temperatures in the current channel can approach $T \simeq 10^5$ K and local heat loads are sufficient to denature most organics and to melt some common metals. These current channels are usually too narrow and erratic in shape to be useful as a well-controlled air plasma source.

Our investigations indicate that these shortcomings can be ameliorated and the high-voltage, high-frequency aspects of the Tesla coil can be exploited by suitable design of electrodes, paying attention to shape, surface smoothness, and composition. Electrode shape and surface smoothness are critical because air breakdown occurs where the local electric field exceeds atmospheric dielectric strength ($10-30 \times 10^3$ V/cm) and this can lead quickly to the formation of localized current channels, such as for arc and brush discharges. For equipotential surfaces (e.g., metal electrodes) the largest electric fields occur where the geometric radius of curvature is smallest, i.e., near sharp edges and surface imperfections. Laboratory Tesla coils have sharped-tipped electrodes for this reason; they act as initiation points for the discharge.

In order to broaden the current channel and suppress arcs created by a standard Tesla coil electrode, we experimentally investigated several alternate electrode geometries. These were fabricated from thick aluminum plate and rod. The test shapes were (i) square (2.5 cm×2.5 cm), (ii) circle ($r = 1.25$ cm), (iii) small radius of curvature cylinder ($L = 4$ cm, $r = 0.65$ cm), and (iv) large radius of curvature cylinder ($L = 4$ cm, $r = 1.9$ cm). (See Fig. 1.) For the former two electrodes, the surface plane was oriented parallel to a planar ground electrode, while for the latter two the cylindrical axis was oriented parallel to the ground plane. For all electrode geometries the discharge area was increased significantly over that of the standard Tesla coil, allowing a more uniform, widespread, and arc-free plasma volume. However, particularly for cases (i) and (ii), the electrodes' relatively sharp surfaces edges still acted as sources for arcing. Predictably, of the two cylinders, the large radius cylinder gave the smoothest continuous discharge and became the electrode of choice. It generated a relatively broad plasma region (4 cm ×0.5 cm) with a diffuse purple glow at the area of closest proximity between the cylinder and ground plane, interspersed with numerous (~100) small, short, straight current channels.

[a]Electronic mail: dsheehan@sandiego.edu

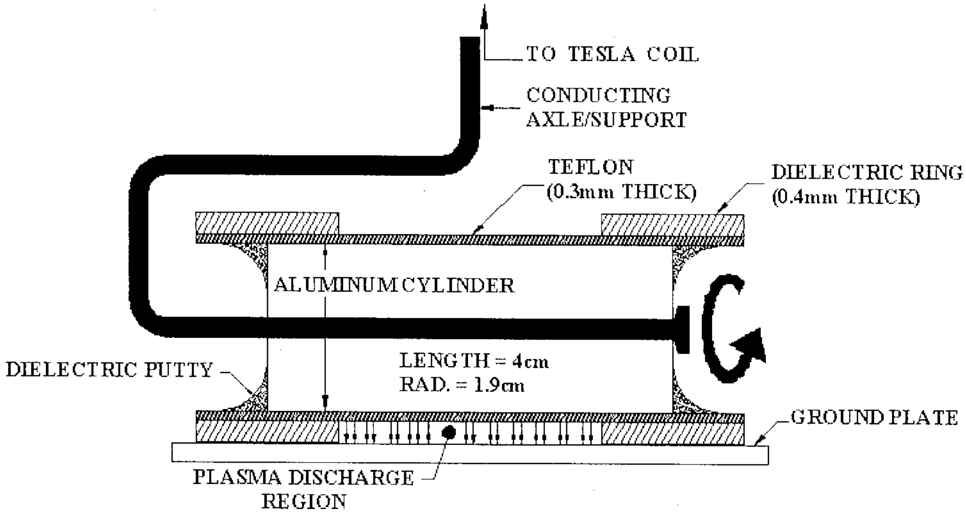

FIG. 1. Schematic of cold plasma device.

The ground electrode consisted of an (36 cm$\times$16 cm $\times$0.25 cm thick) aluminum plate attached by a solid ground wire directly to the ground prong of the Tesla coil power line. The plate was anchored on a (43 cm$\times$28 cm$\times$3.5 cm thick) electrically insulating dielectric plate so as to electrically isolate the high-voltage coil and electrodes from other electrically sensitive systems (e.g., instruments, computers, and experiments). The ground plate is of equal importance to the primary electrode in establishing a smooth, uniform plasma.

An electrode's surface smoothness significantly affected the nature of the plasma. Three surface types were investigated: (a) bare metal (polished), (b) cotton felt, and (c) Teflon. Bare metal surfaces, regardless of how well polished, tends to have small surface irregularities at which large electric fields develop and at which electrical arcing is initiated. As a result, the discharges from all bare metal electrodes, regardless of geometry, produced strong multifilamentary (brush) discharges and relatively nonuniform plasmas. Still, they tended to be more uniform and reproducible than the standard Tesla coil electrode. Taking the multifilimentary concept to an extreme, cotton felt was tested as an overlay for the bare metal. (Felt has been used successfully in plasma electrodes elsewhere.) Here the idea is to create a surface with numerous and uniformly spaced thread electrodes from which multiple current channels should purposefully arise. In theory, these multiple arcs will blend into a smooth volume plasma. In practice, this prediction was partially realized, but again, predominant, localized current channels developed. Ultimately, the high local power densities (and perhaps, ozone) quickly degraded the felt.

The best surface type was found to be a thin wrap of electrical tape directly over the bare metal surface of the large cylindrical electrode, followed by a thin veneer (0.3 mm thick) of Teflon sheet (Fig. 1). The plasma discharge through the tape and teflon showed a high degree of spatial and temporal uniformity and smaller and fewer current channels than the other surface types. It is hypothesized that the electron current does not pass directly from the Teflon/metal electrode to ground—as it does for the bare metal case—but, instead, diffuses through the tape/Teflon combination, and, therefore, charges are more uniformly distributed on the outer Teflon, current-emitting surface. Also, these dielectric layers appear to act a large scale resistor, which effectively steps down the voltage over which the discharge occurs, thereby making it less violent and capricious. The plasma quality was further improved (arcing further suppressed) by fixing a thin flat plastic coating (0.1 mm thick) over the grounding plate; a standard acetate overhead projector slide sufficed.

The cylindrical teflon veneer was extended beyond the ends of the cylindrical electrode ($\sim$1 cm) as a sort of cylindrical awning to supress arcs which otherwise develop at the sharp edges of the cylinder ends. Around each end of the cylinder end was also added a thin ring of electrical tape (width$=$2 cm, differential radius $\sim$0.4 mm). These rings had dual purposes. First, they electrically insulated the cylinder ends, further supressing arcs. Second, they slightly raised the central section of the cylinder off the ground plate electrode so that a plasma could form there and spread out in the resultant 2 cm wide, 0.4 mm deep gap between the cylinder and ground plate. With this arrangement, flat test samples could be inserted into this gap between the electrode and the ground plate and there exposed to the plasma.

An axial hole was drilled along the length of the aluminum cylinder and a steel rod inserted as an axle. This was attached, via a cylindrical metal sleave, to the standard electrode of the Tesla coil. In this way, the Teflon-coated metal cylindrical electrode could be rolled across the ground plate electrode, exposing the flat surface in the gap—and thin flat samples on the grounding plate—to a 2 cm$\times$0.5 cm wide uniform air plasma, nearly free of arcs.

To summarize, the optimized air plasma source consists of a laboratory grade Tesla coil (120 V ac input, 40–50 kV output; high-frequency $f\sim3-4$ MHz with 60 Hz ripple, and adjustable current, $I\leqslant0.1$ A), a Teflon/tape covered cylindrical aluminum electrode ($L=4$ cm, $r=1.9$ cm) which rolls freely over a thin dielectric-covered planar grounding plate. The maximum electrical power consumed by the source is about 10 W. The usable plasma volume is roughly 2 cm $\times$0.5 cm$\times\sim$0.1 cm. Electrodes do not sensibly heat. The plasma density can be varied continuously by adjusting the

Tesla coil current voltage controls. The plasma meets the conditions of an ionization discharge.

Ozone and nitrogen oxides production within the discharge region were measured quantitatively by inserting thin glass Dräger tubes directly into the discharge volume during device operation. Using suction from a hypodermic, gas was sucked from within the discharge region through Dräger tubes calibrated specifically for ozone (O_3) and nitrogen oxides (NO and NO_2). Based on multiple measurements, the average ozone concentration in the discharge (during medium discharge mode) was found to be 360 ppm ± 40 ppm, and the average combined nitrogen oxide concentration was found to be 13 ppm ± 3 ppm. These data suggest that the gaseous products of the plasma, alone could have significant antimicrobial action.

This plasma is relatively cool and free of hot arcs. For instance, tissue paper can be exposed to it without damaging it; in contrast, a standard Tesla discharge ignites paper instantly. This plasma is a copious source of ozone, as evidenced both by its strong, acrid odor, and also by its observed rapid bleaching of organic pigments and chlorophyllic organisms put in its proximity.

II. APPLICATIONS

This plasma source was originally designed to study the effects of plasmas on microbes, in particular, to test the hypothesis by Mendis[4] that the documented sterilizing properties of plasmas are caused by electrostatic disruption of their cell membranes. Based on estimates of the tensile strength of cell membranes, Mendis showed that the electrostatic stress (pressure P) induced on their surfaces by electrostatic charging in plasmas ($P \sim \propto \sigma^2$, where σ is surface charge density) is sufficient to disrupt cell membranes, particularly for Gram-negative bacteria. Bacteria are well known to acquire and maintain electronic charges in their natural states and this can be important to their survival. Here we investigated how they respond to too much of a good thing.

Strains of marine bacteria (Alteromonas spp. and Vibrio spp.) and marine diatoms (Thalassiosira weissflogii and Chaetoceros spp.) were individually concentrated on thin micropore filters of various compositions (paper, silica, polycarbonate, and alumina). Filters were then exposed to various intensities of the air plasma for various durations (0.5–30 s). Filters with bacterial strains were stained with SybrGreen[5] and examined under an epifluorscence microscope. Diatoms were observed by autofluorescence of chlorophyl. It was found that for even brief exposures to moderate air plasmas, the diatoms were severely altered; virtually all of their chlorophyl was destroyed. It is not known whether this destruction is due to the electrical action of the plasma, but perhaps more likely, it is due to the bleaching effects of ozone and nitrogen oxides. Some evidence of membrane disruption was found, but results were inconclusive. These studies are continuing.

ACKNOWLEDGMENTS

The authors thank Dr. F. Azam of Scripps Institute of Oceanography and M. Rosenberg and D. A. Mendis of U.C. San Diego for stimulating conversations and technical assistance. This work was supported by DOE Grant No. ER54544.

[1] E. Nasser, *Fundamental of Gaseous Ionization and Plasma Electronics* (Wiley, New York, 1971).
[2] F. Llewellyn-Jones, *Ionization Avalanches and Breakdown* (Metheuen, London, 1967).
[3] G. Francis, *Ionization Phenomena in Gases* (Academic, New York, 1960).
[4] D. A. Mendis, M. Rosenberg, and F. Azam, IEEE Trans. Plasma Sci. **28**, 1304 (2000).
[5] R. J. Noble and J. A. Fuhrman, Aquatic Microbial Ecology **14**, 113 (1998).