Topic number: 6

PLASMAS IN BUBBLES IN LIQUIDS AND STREAMERS INTERSECTING WITH LIQUIDS

Mark J. Kushner and Natalia Yu Babaeva

University of Michigan, 1301 Beale Ave., Ann Arbor, MI 48109-2122 USA

mjkush@umich.edu, nbabaeva@umich.edu

The production of plasmas in or on liquids, particularly in the context of electrical breakdown, often involves a gas-liquid interface.[1] For example, the propagation of streamers through liquids may require the initial production of plasma in bubbles of a few to tens of microns in size inside in which the E/N is larger by the ratio of the liquid-to-gas density. In many applications, plasmas are intentionally generated inside bubbles in liquids to produce reactive species which then diffuse through the gas-liquid interface. To some degree, plasmas in bubbles in liquids (PBL) have similar characteristics to dielectric-barrier-discharges – the gas-liquid interface represents a discontinuity in dielectric constant, ε, and conductivity, σ, which results in electric field enhancement and charging. These conditions are made somewhat more complex by the curvature of the gas-liquid surface and on longer time-scales the deformation of that interface by electrical and mechanical forces. The intersection of atmospheric pressure streamers with gas-liquid interfaces have similar properties as PBLs.

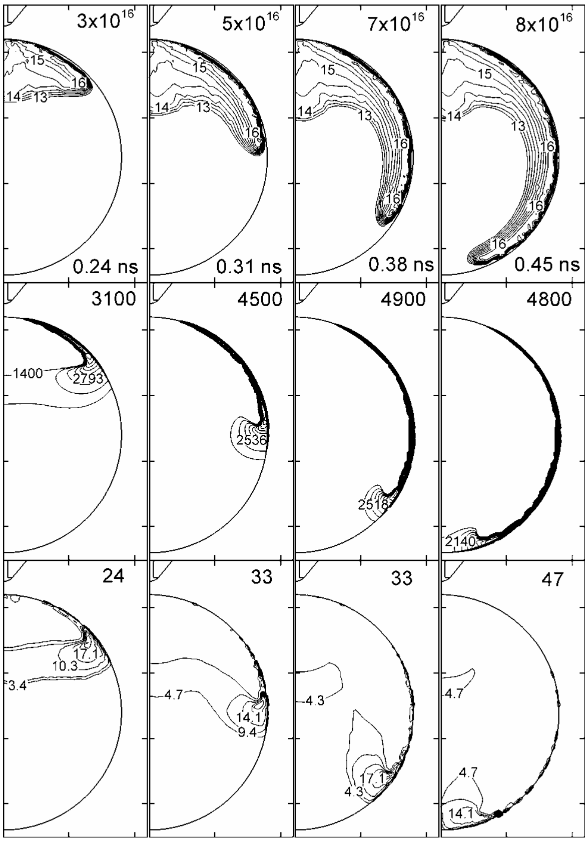

Fig 1. Surface-hugging streamer developing in a bubble of humid air 900 μm in radius immersed in water with conductivity $\sigma = 10^{-7}$ S/cm. Frames are shown over 0.2 ns. (Upper row) Contours of electron number density (cm^{-3}). The labels denote the values of $\log_{10}$ over 4 decades. (Middle row) Reduced electric field in Td (Bottom row) Electron temperature in eV. Maximum values are shown at top right-hand side of each frame.

In this paper, properties of PBLs and of streamers intersecting with liquids will be discussed based on results of computer simulations.[2] The model used in this investigation is *nonPDPSIM*, a 2-dimensional plasma hydrodynamics model in which the densities and momenta of charged and neutral particles are solved coincident with Poisson's equation and radiation transport. Liquids are computationally treated in the same manner as plasma with an appropriate density dependent polarization to provide the liquid density permittivity. Electron and ion impact, and transport processes are allowed in the liquid. An unstructured mesh enables resolution of small bubbles within the liquid. As a first approximation, gas phase electron impact cross sections are used for liquid water, with additional reactions added for the rapid solvation of electrons.

The basic properties of PBLs are determined in large part by the ratio of ε and σ between the gas and liquid, and the ratio of bubble size to the streamer width, α Small ratios of ε and large values of α tend to produce plasmas that propagate through the volume of the bubble. Increasing ratios of ε and decreasing values of α tend to produce plasmas that propagate along the surface of the bubble. These surface hugging streamers have large electric field enhancement at their leading edges, which produce large electron temperatures and so large rates of production of radicals. For example, electron density, electric field and electron temperatures for a streamer developing in a bubble immersed in water ($\varepsilon/\varepsilon_0$=80) are shown in Fig. 1.

One of the proposed mechanisms for electrical breakdown in liquids is the sequential linking of PBLs. For example, the large E/N produced in the bubble compared to the adjoining liquid enables more rapid breakdown and charging of inner surfaces. If the PBLs are in favorable alignment, the inter-bubble electric field enhancement may provide a mechanism for propagating the streamer through the liquid. This process is enhanced if UV/VUV radiation from adjacent bubbles can provide seed electrons.

The intersection of streamers with liquids share many of the properties of PBLs, phenomena that depend in large part on the ε and σ of the liquid. Many of the applications of streamers intersecting with liquids are in the context of plasma treatment of biological tissue or wounds wherein the liquid coats the tissue, or is contained within cells. In this case the intersection of streamers additionally can produce electric fields within the underlying tissue. The values of these electric fields, as large as 100s kV/cm, are above the threshold for breakdown for atmospheric pressure gas bubbles or gas filled vacuoles. As such, it may be possible to produce plasmas within tissues.

Reference

[1] P. Bruggeman and C. Leys, J. Phys. D **42,** 053001 (2009).
[2] N. Yu. Babaeva and M. J. Kushner, J. Phys. D **42**, 132003 (2009).