THE PLASMA CONNECTION

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Atmospheric Pressure Low Temperature Plasma Sources

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Most industrial plasmas (ionized gases) have traditionally been generated at low pressure where the air in a containment vessel is evacuated and replaced by gas mixtures that are selected for specific applications (see Figure 1). Under low pressure the electrons and ions that form the plasma do not collide too often with each other or with the atoms/molecules of the working gas. Uniform plasmas can be easily generated, which are used for various applications including the fabrication of semiconductor devices with tiny features that can be as small as a few nanometers (a few millionth of a millimeter). However, if one wants to generate a similar plasma but at atmospheric pressure one would quickly realize that 1.) It is extremely difficult to keep the plasma at a reasonably low temperature (a temperature at which the plasma does not burn the items it touches), and 2.) It is as difficult to achieve volumetric uniformity (same plasma all over). This situation changed starting around the early 1990s when a few scientists figured out methods to overcome these difficulties. This educational brief introduces the reader to the two main plasma sources that satisfy the three requirements of a.) low temperature, b.) atmospheric pressure, and c.) relatively good plasma uniformity. Working at atmospheric pressure eliminates the need for vacuum equipment, which simplifies operations and drastically reduces costs. Working at low temperature allows the application of plasma to heat sensitive materials including plastics and even animal tissues. Having good uniformity allows for similar effects all over the surface of the material under plasma treatment. These plasma devices are sometimes referred to as cold plasma sources. They are today used for the modification of surface properties, to make VUV lamps, for ozone generation, in biomedicine, in agricultural applications, and others.

Fig. 1 Image of a low pressure plasma. The plasma is contained inside a vacuum chamber where working gas is introduced.

The Dielectric Barrier Discharge (DBD)

The DBD was conceived more than 160 years ago and was initially used mainly to generate ozone, O3. Ozone was then used to decontaminate water supplies. The DBD is made of two metal electrodes that are covered by a dielectric (non-conducting material). The electrodes are separated by a small gap where the operating gas is introduced. To generate the plasma an AC (alternating current) high voltage is applied to the electrodes. The plasma generated by the DBD is not uniform, with thin filaments appearing randomly. In the late 1980s and early 1990s researchers reported that by using the DBD with noble gases (such as helium) and applying the right range of frequencies and electrode gap, uniform, diffuse and volumetric low temperature plasmas can be generated at atmospheric pressure. This was a game changer and soon enough research activities intensified to improve the performance of the DBD.

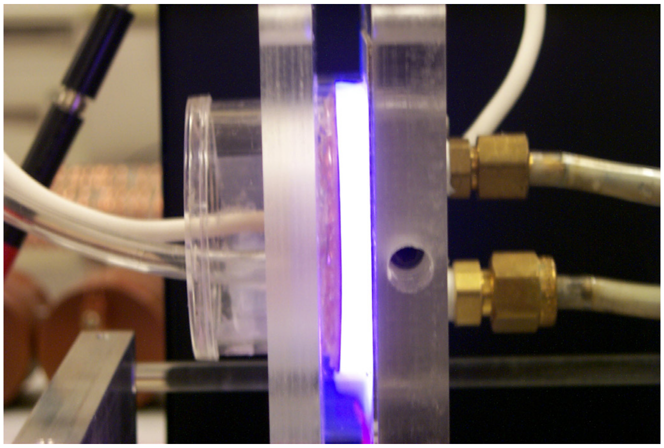

Fig. 2 Image dieletric barrier discharge driven by short pulses of electricity. Gas: Helium.

First, methods to produce diffuse plasmas with various gases and gas mixtures were developed. Second, the operating frequency range was extended all the way to DC (direct current) by devices like the resistive barrier discharge (RBD) where the dielectric was replaced by a high resistivity film. And finally, instead of using sinusoidal voltages, researchers started using short pulses of electricity (pulse duration as short or shorter than a millionth of a second). These pulses energize the electrons in the plasmas but not the ions or the neutral atoms. This way the plasma becomes more energized without any rise in the gas temperature (See Figure 2).

Low Temperature Plasma Jets

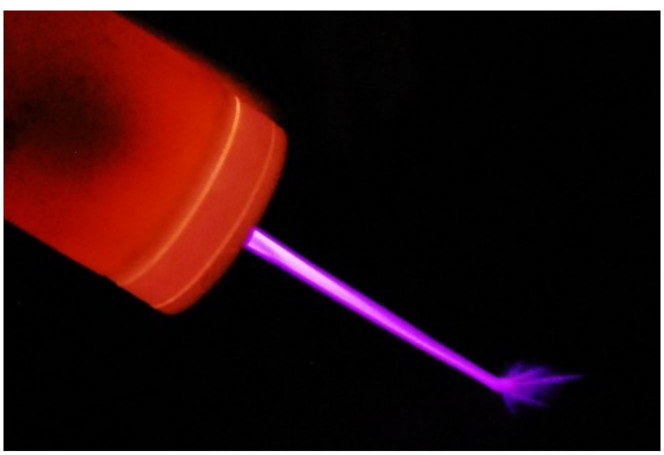

Fig. 2 Image of the plasma pencil in operation.

Plasma jets have been around for many decades but most of them generated high temperature plasmas (few hundreds to thousands of degrees). As such they were not suitable for applications that require relatively low temperatures (below 100 degrees), including biomedical applications. In the early 2000s researchers came up with new designs that could meet the low temperature requirement, these are known as low temperature atmospheric pressure plasma jets (APPJs). APPJs are a class of plasma sources that can generate stable thin plumes of cold plasma outside the confinement of electrodes and into the surrounding environment. Because the plasma propagates away from the high voltage region the plasma is electrically safe (does not cause electrical shock). Figure 3 shows an image of an APPJ, known as the "plasma pencil" which was one of the first cold plasma jets developed specifically for medical applications. It is of note to mention here that investigators discovered that the plasma plume is not continuous as it appears to the naked eye, but it is in fact made of fast propagating discrete plasma packets known as "plasma bullets".

Fig. 4 Plasma jet driven by a piezoelectric transformer. Photo courtesy Dr. Claire Tendero

APPJs have been used extensively in biomedical applications (dentistry, wound healing, cancer treatment, etc.) because of their unique properties of 1.) delivering the plasma to the target (cells, tissues, etc.) without using the target as a counter electrode, 2.) they can be accurately aimed at specific locations for local treatment. 3.) they can be portable and handheld. Recently researchers made them even more practical by using batteries or piezoelectric transformers to supply the electricity to these devices. Figure 4 shows an image of a plasma jet driven by piezoelectricity.

Suggested Reading

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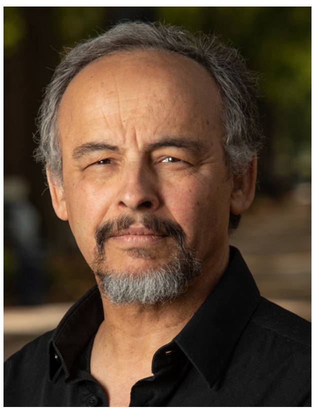
2. M. Laroussi and T. Akan "Arc-free Atmospheric Pressure Cold Plasma Jets: A Review", *Plasma Process. Polym.*, Vol.4, No. 9, pp.777-788, (2007).

3. X. Lu, S. Reuter, M. Laroussi, and D. Liu. Non-equilibrium Atmospheric Pressure Plasma Jets: Fundamentals, Diagnostics, and Medical Applications. CRC Press, Boca Raton, (2019). ISBN 978-1-4987-4363-1.

4. M. Laroussi, X. Lu, and M. Keidar, "Perspective: The Physics, Diagnostics, and Applications of Atmospheric Pressure Low Temperature Plasma Sources Used in Plasma Medicine", *J. Appl. Phys.* 122, 020901 (2017).

5. R. Brandenburg, "Dielectric barrier discharges: progress on plasma sources and on the understanding of regimes and single filaments" *Plasma Sources Sci. Technol.* 26, 053001, (2017).



ABOUT THE AUTHOR

Dr. Mounir Laroussi is a Professor at the Electrical & Computer Engineering Department of Old Dominion University (ODU) and is the Director of ODU's Plasma Engineering & Medicine Institute (PEMI). Dr. Laroussi's research interests are in the physics and applications of non-equilibrium gaseous discharges including the biomedical applications of low temperature plasma (LTP). He designed and developed numerous novel LTP devices such as the resistive barrier discharge (RBD) and the plasma pencil. Dr. Laroussi conducted the first pioneering experiments on the use of low temperature atmospheric pressure plasmas for biomedical applications and contributed to the establishment of the interdisciplinary field of "Plasma Medicine". For his scientific achievements in the field of low temperature plasmas and their biomedical applications he was elevated to the grade of Fellow by IEEE in 2009 and was awarded the 2012 IEEE-NPSS Merit Award.