Characterization of Cold Atmospheric Plasma

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Abstract

In this letter, emission spectroscopy was used to characterize the reactive agents within a cold atmospheric plasma jet structure with the aim to better understand and identify the nature of non-thermal plasma. Cold atmospheric plasma has been used in various medical applications due to the attractive chemistry of the reactive species that are created depending on the source gas being ionized. The reactive species generated have been used in applications such as the sterilization and decontamination of bacteria. While the uses of these reactive species have been exploited by various fields, their nature in cold atmospheric plasma is not extensively understood. Helium plasma was produced by sending helium gas through a dielectric glass tube with a high AC voltage ring electrode on the outside of the tube, ionizing the gas and creating various reactive agents when emitted into ambient air. Emission spectra of the plasma plume at various locations of collision with ambient air were analyzed with SciLDA spectroscopy software in order to characterize the presence of these reactive species. Spectrum characterizations from the different spatial regions of the plume were compared to assess the differences in emission and present reactive species. Analysis of the spectrum under these variables effectively characterizes the nature of cold atmospheric plasma according to the composition of its excited gases. The parameter of gas flow was also modeled with the multi-physics simulator COMSOL with a 3D model of the apparatus to analyze the expected system behavior compared to physical observation. In addition to helium plasma being characterized, oxygen, a helium-oxygen mix, and even ambient air may be put into the system to result in unique plasma properties. The reactive species created in these discharges could have a significant impact on technology processes and on the environment.

Keywords: Cold-Atmospheric Plasma, Emission Spectrum, Reactive Species

1. Introduction

The study of cold atmospheric plasma has many useful bio-medical applications but is not fully understood. Its use has increased due to its exceptional reaction chemistry and intrinsic plasma stability. Helium plasma is most commonly used because of its high metastable energy levels, which act as a “reservoir of energy”, making it ideal for use for plasma processing.[8] Analysis of the emission spectra of helium plasma reveals the presence of the reactive agents that the plasma creates such as reactive oxygen and nitrogen. It is these reactive species that are applied in various fields for their beneficial properties. Better understanding how the species are affected by the parameters of generation will allow further optimization of these species in their respective applications. The distance from the outlet of the glass tube, and thus the exposure distance, is the main parameter studied here.
1.1. background

Plasma is created by applying energy to a gas to ionize it in the same way energy is added to a solid to change its phase to a liquid. When energy is added to a gas, ionization reorganizes the electronic structure of the gas and produces excited species and ions. The main constituents of plasma consist of electrons, ions, and neutrals which are in fundamental and excited states. Overall, plasma is electrically neutral but contains free charges and is electrically conductive because of this structure. Plasma is the most abundant state of matter in the universe because it is the make-up of stars. This type of plasma is created by thermal energy. There is another type of plasma without the need for intense thermal energy called non-thermal plasma. The energy used to create non-thermal plasma almost always comes from electrical energy. A very high oscillating potential difference is required in non-thermal plasma since it influences the behavior of the electrons and ions. The energy of an electric field gives energy to the electrons of the working gas, accelerating them to collide with neighboring neutral particles and excite, and even ionize them. The excited states relax to the ground state by giving off a photon and the result is an emission spectra of the working gas used. This property is used in everyday neon signs, fluorescent bulbs, and plasma ball toys.

1.1.1. cold atmospheric plasma

Non-thermal plasma also has further classifications based on its generation conditions. Cold atmospheric plasma is the ionized gas of a particular element that is generated at atmospheric pressures and produces plasma that is “cold” enough to touch. The term “cold” refers to the generation of the plasma being non-thermal. This also describes the temperature of the accelerated electrons being extremely higher than the heavy particle temperature. The inelastic collisions between electrons and heavy particles cause excitation and ionization. These collisions do not rise the heavy particles temperature and thus the plasma temperature (or gas temperature) is fixed by the heavy particle temperature. Therefore the overall temperature remains within 300K, allowing for application to skin without harm. This chemistry is appealing since it does not require raised gas temperatures. The chemistry of reactive species generated depends on the initial working gas used for the plasma as many different gases will produce unique plasmas. The gas most commonly used is helium because of its high thermal conductivity and has been shown to have antimicrobial effects.

1.1.2. medical benefit

The elements in the ambient air, excited from the plasma electrons, have interesting and useful characteristics. The created reactive species such as oxygen and nitrogen have direct medical benefits, including sterilization of bacteria cells while promoting the growth of mammalian cells. Plasma was found to reduce infection, activate platelets, and enhance fibroblast proliferation without damage to living tissue. The nature of the plasma itself also allows for different types of exposure. If a sample is in direct contact with the plasma it is subject to all agents of the plasma including “heat, charged particles, reactive neutrals, and electromagnetic radiation (such as ultraviolet light).” Charged particles play a significant role in the rupture of the outer membrane of bacterial cells. The electrostatic force accumulated on the outside of the cell membrane could overcome the tensile strength of the membrane and cause it to rupture. On the other hand, samples can be treated indirectly with the plasma solely from the UV radiation by increasing the distance from the plasma plume. At a distance, charged particles do not affect the sample as significantly since they have time to equilibrate before coming into contact. Features of radiation and treatment vary depending on the working gas used and the nature of the plasma produced. These features are continuously being researched for uses such as dentistry, sterilization of materials, burn wound treatment, and oncology. This low temperature solution to decontamination has a multitude of uses in the medical field such as sterilization of surgical instruments, decontamination of biological surfaces, bio compatibility, self-cleaning surfaces, hydrophilicity/hydrophobicity, sterilization of the inside of small-diameter plastic tubes, food decontamination, and antibacterial films.
2. Methodology

2.1. apparatus

As illustrated in the schematic of the apparatus in figure 1, compressed helium flows through vinyl tubing into a glass dielectric tube and is measured with a volumetric flow meter capable of measuring up to 30 Standard Cubic Feet per Hour (scfh). For reference, 1 scfh is approximately 0.5 L/min. A copper electrode surrounds the glass tube and is powered with a high sinusoidal voltage. An oscilloscope fitted with a high voltage probe measures the voltage and frequency of the copper electrode. The ground probe of the high voltage supply is connected to the metal stand that holds up the glass tube where the plasma is generated. The plasma’s emission spectrum is captured with a spectroscopy perpendicular to the flow of plasma which displays the constituent wavelengths vs. their relative amounts to one another on a monitor. The glass tube can be moved such that a different part of the plasma plume can be analyzed at any time.

2.2. acquisition

The plasma emitted into ambient air created a plume of visible light. This plume was put perpendicular to the slit of the spectrometer to collect the light from the plume at different distances from the outlet. The glass tube with the copper electrode and the generated plasma can be seen in figure 2. The light collected at each distance was only a small horizontal “slice” of the plasma plume. The photons the plume emits at that slice are then separated by a grating inside of the spectroscope and are then able to be resolved and graphed by SciLDA software of the spectrometer. The spectrometer was set collect light in the range of 200-600nm.

Figure 1: Schematic of the setup used. High AC voltage, monitored by an oscilloscope, is sent through a copper electrode on the outside of the glass tube. Helium flows through vinyl tubing, monitored by a volumetric flow meter, into the glass tube. The resulting plasma plume is visible and lined up to the slit of the spectrometer. The monitor displays the resulting data of relative counts vs. wavelength.

Figure 2: As helium flows through the glass tube, the electric field created by the copper electrode ionizes and excites the gas. This excitation is visible but very faint.

2.3. variables

The emission spectrum of the plasma was taken at various distances from the outlet of the glass tube to compare the presence of the reactive species relative to other locations. This corresponds to the different degrees of exposure to
the plasma. Emission spectra at the slices 0 cm, 2 cm, 4 cm, and 6 cm from the outlet were taken as seen in figure 3. The other parameters of flow rate, voltage, and frequency were chosen for this experiment to be respectively 13 scfh, 4 kV, and 22 kHz. These parameters were chosen as thus to obtain a visible plasma plume of 5.5 cm long. These specifications were to create a strong visible plume to ensure the light would be captured by the spectrometer. Frequency was chosen by suggestion from previous senior design work with the apparatus such that plasma was sustained. The voltage was able to be varied from 1 kV to 7 kV and analysis of the effects of voltage on the shape of plasma plume revealed that after a certain point, the voltage had adverse effects on the shape, length, and collimation of the plume. These effects were backed by research and a middle ground of 4 kV was chosen for adequate brightness. As for the flow rate, the length of the plume was measured at various flow rates. These flow rates through the 6 mm diameter glass tube were converted to the corresponding Reynolds number. The length of the plasma plume generated at the corresponding Reynolds number is shown in figure 4. The trend of the plume length was backed by research, that increase of the gas flow should increase the plasma plume length until a critical value. Therefore a plume length of 5.5 cm was sustained with the flow rate of 13 scfh. This length was satisfactory to obtain four different slices at 2 cm apart with one slice in the “afterglow” region of the plume. This afterglow region is the point of the plasma plume where the visible light ends, but long lifetime species may emit light in the ultraviolet range.

2.4. element spectra

Every element emits unique wavelengths of light when excited, some of which are in the visible spectrum of 400 nm to 700 nm. To get an idea of what the emission spectra of the plasma would look like, the individual elements present were researched on their distinct emission spectra when excited. The visible wavelengths of the elements present in the working gas, helium, and of the primary elements of ambient air, oxygen and nitrogen, are shown in figure 5. This was constructed to have an idea of what visible wavelengths were going to be present when the helium plasma excited the ambient air as well. Additionally, singly ionized oxygen and nitrogen were included to the expected emission spectra because of previous studies already identifying them as major contributors as well as having beneficial applications.

2.5. simulation
In tangent with the analysis of the emission spectra of the plasma being generated, computer simulation was used with the multi-physics simulation software COMSOL. In this program the gas flow of helium was simulated to analyze the velocity, pressure, and shape of the plume helium creates when emitting from the glass tube. This simulation was compared to the physical apparatus to analyze what difference the plasma had on the expected flow, collimation and length to the physical visible plume. The simulation ran at the same flow rate as the apparatus and is shown side by side in figure 5.

![Figure 4: Top: Emission spectrum of the primary components of air, oxygen and nitrogen, are shown with corresponding wavelength (in nm) in the visible spectrum. Also, a major player in the emission spectra of the plasma being analyzed is singly ionized nitrogen (N⁺) and singly ionized oxygen (O⁺). Bottom: Emission spectrum of helium in the visible spectrum is shown with corresponding wavelength (in nm).](image)

![Figure 5: Physical apparatus above the computer simulation. Simulation was the laminar flow of helium into a reservoir of helium. Simulation and physical apparatus had same volumetric flow of 13 scfh.](image)

3. Results

3.1 emission spectra results

Emission spectra from each slice of the plasma plume were taken and plotted as respective wavelength vs. the relative counts, as seen in figure 6. The emission spectra at each distance from the outlet were shown to have different presence of wavelengths as well as their relative amount to one another. These slices, when compared next to each other, show a similar pattern of peaks with the highest peak being the lowest wavelength. Also, each spectrum only contains five or six peak wavelengths. It was revealed as well that every spectra contained ultraviolet and visible light. Interestingly, the 6 cm slice, or the afterglow region, contained the highest count of visible light despite being the faintest visually. It is worthwhile to note that while a background scan was taken, and subtracted from each obtained spectra, there still contains very small insignificant peaks below the 5 counts line. This “noise” is just a result of the accuracy of the spectrometer used.
3.2 simulation results

Computer Simulation and physical measurements of helium gas flow through a glass tube was done to help characterize the resulting cold atmospheric plasma. When excited plasma collides with ambient air and excites the particles present there, it was unknown whether or not the highest velocity gas would be the most excited. It was hypothesized that the highest velocity gas being emitted would be the most excited and brightest since it could have the highest energy. From comparison of the velocity plot and the visible plasma plume it can be seen that a general shape is shared but with key differences. The brightest section of the plasma does not correspond to the highest velocity of gas flow. This result points at there being more to the most energized section than just having the highest velocity of gas flow. Instead, simulation of the propagation of currents or the effect of electric field should be considered for future work to fully analyze the transfer and density of energy through the plume.

4. Conclusion and Discussion

4.1 emission spectra conclusion

The emission spectra of the slices obtained did not contain as many peaks as hypothesized from the emission spectra of the present elements, especially in the visible range. In addition, the peaks that were obtained were rather broad, covering a range around 10 nm. It was also surprising that each slice did not share any wavelengths since this points to the fact that the reactive species vary by location much more than previously thought. On the other hand, the spectra of each slice shared a very similar pattern and almost seemed as if they were the same data but were “shifted”, pointing to possible external factors. Lastly, the 6 cm slice “afterglow” region had little to no visible light when viewing the plume visually. Yet the emission spectra data of this slice had higher count peaks in the visible range.
range than any other slice. These details hint at a need for a more accurate and sensitive spectroscope to eliminate or confirm these unexpected behaviors.

4.2 simulation conclusion

It was observed in the comparison of the simulation to the physical plume that the brightest section of the plume does not correspond to the highest velocity of gas flow. This result points at there being more to the brightest section than just having the highest velocity of gas flow. It is also worthwhile to note that the computer simulation of gas flow was the flow of helium into ambient helium instead of ambient air (nitrogen and oxygen). The transition of helium into air is an advisable step for comparison of the real world system.

4.3 discussion

The uses of cold atmospheric plasma are being expanded rapidly and are becoming more attractive. It is the opinion of this author that fundamental and complete understanding, of any phenomena, furthers the application exponentially as the uses can be tailored by core manipulation. It is this fact that motivates the author’s characterization of cold atmospheric plasma. Detailed setups are presented for future work. This future work may elect to vary parameters such as voltage inside each slice of the plasma plume, for example. The groundwork has been laid for further development.

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6. References

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