Atmospheric plasma jet for surface treatment of biomaterials

Mahmood Nasser, Ban AlMandalawi and Layla Nasser
Department of Physics, University of Bahrain, PO Box 32038, Bahrain
E-mail: snasser@uob.edu.bh
Keywords: sterilization, biomaterial, atmospheric plasma jet, E. coli

Abstract
A direct current (DC) powered low-temperature atmospheric pressure plasma (LTAPP) jet device was built and used to sterilize Escherichia coli (E. coli) bacteria. The plasma jet’s general properties, such as length and temperature, were first tested and found to be strongly related to the plasma jet’s operational flow mode (laminar or turbulent flow). The optical emission spectra of various gas mixtures were measured to confirm the presence of active radicals, which is critical for sterilization success. Pure helium gas or a combination of helium with a small percentage of oxygen (6.25%) was found to have the highest intensities of bactericidal species such as atomic oxygen (O) and hydroxide (OH). These mixtures were then used to treat E. coli bacteria previously grown in a Petri dish. Sterilization was accomplished by repeatedly treating the bacteria for 10 s for 5–10 rounds for short periods. The best results were obtained when the bacteria had enough time to rest between rounds.

1. Introduction
Several biomedical applications of plasmas have already been identified, including bacterial decontamination of medical equipment, air, and biological warfare, coating of implants with bio-compatible layers, and surface modification of substrates for cell culture. These techniques have been the subject of extensive research [1–4]. The goal of this treatment is controlled tissue removal, devitalization, and hemostasis. Since modern plasma sources have become more compatible with biomedical, the field of applications is rapidly expanding, and many novel medical techniques are developing. Plasmas are expected to be used for tissue disinfection and the induction of specific cellular reactions [4].

The plasma needle was the first plasma-generating device used to treat biomedical tissues. The needle generates non-thermal and non-uniform plasma at atmospheric pressure, typically driven by radio-frequency (RF) in the 10–13 MHz range. The needle’s body is primarily made up of a small metal wire that serves as the needle’s tip and is surrounded by a dielectric cylindrical tube. A larger tube is placed on top of the dielectric cylinder, through which the used gas, typically helium with possible additions of oxygen or air, is pumped. The metal part of the needle is connected to an amplifier, and a matching network is used to match the source’s impedance to that of the load [5]. The plasma needle requires very little power to operate. It can generate low-temperature atmospheric pressure plasma (LTAPP), making it suitable for sterilization, biomedical tissue applications, and other clinical operations. According to numerous studies, it has demonstrated outstanding potential and satisfactory non-destructive results [6–8].

In this work, we characterize a new configuration of the plasma jet by describing its electrical setup luminosity and length of the jet. The design of the LTAPP was made to improve the ease of working and allow the treatment of large-sized objects. The jet has a plasma plume that varies in size depending on the applied voltage and gas flow, making it more suitable for significant area coverage than the needle. Still, it also has a disadvantage when the operation requires a precise and localized application. The plasma jet operates at a wide range of driving frequencies, from direct current (DC) to microwave sources, and it also employs noble gas mixtures such as helium and argon. We will use the DC to drive two electrodes plasma jet with a high-voltage low-power supply [6]. The effect of the applied voltage and the gas flow rate on the luminosity and length of the jet will be studied.
9. Optical emission spectral measurements will be represented to identify the plasma species and focus on the most recent advancement in the plasma treatment of living tissues.

2. Experimental configuration and methodology

This study used two plasma jet devices, as shown in figures 1(a) and (b). The anode is represented by a longer and narrower aluminum tube inside a cylindrical glass tube, while the cathode is made of copper and is placed outside the glass near the glass nozzle. The cathode in the first device is a small cylindrical tube that fits around the glass tube. In contrast, the cathode in the second device is copper foil, and the cathode in both devices is covered with an insulating fabric tape to prevent arc discharge. Here the plasma jet generator is based on Dielectric Barrier Discharge (DBD) where a DC voltage applied to the gas medium via the electrodes exceeds the breakdown voltage for the gas, a discharge is then ignited, and plasma is exhausted into the open air as a jet. Pure helium (He) is used to operate the plasma jet, and pure oxygen (O₂) creates various gas mixtures. A dual gas flow controller (controls each gas flow rate; this is where the flow rates are adjusted, and the gases are mixed to feed the plasma jet. A DC high-power supply generates and controls the applied voltage on the jet. A PicoScope2202 digital oscilloscope and a PeakTech high voltage probe are used to capture the current and discharge voltage waveforms. The electrical discharge current is measured using a 100 Ω shunt resistor.

The first device (figure 1(a)) was initially used to investigate the general properties of the jet. However, it was eventually replaced with the second one (figure 1(b)) for optical emission spectral measurements. It had larger inner diameters, resulting in larger jets and thus more apparent optical spectra. Each one’s effect was evaluated...
separately. This study aimed to determine the ideal length for a plasma jet to operate at, considering the jet’s length, stability, and comfort when touched. The length of the jet was measured with a Vernier scale, as shown in figure 2. It’s worth noting that the measured length refers to the furthest distance from the target that the plasma can discharge to, as opposed to other studies in which the jet is photographed and measured as it operates in the ambient air, rather than setting a target and measuring it manually or with the help of a camera. Though manual measurement may provide less precise measurements, we chose it because the primary application for such a device is to operate on living tissues. Thus, a sufficient distance between the nozzle and the tissue must be maintained. It ensures that the discharge is safe and painless on the skin, especially in sensitive areas containing complex and intense nerve systems.

Figure 3 shows the temporal evolution of discharge voltage and discharge current at a flow rate of 7 l min$^{-1}$. As can be seen from figure 3, the generated glow discharge has an almost constant current and voltage, unlike the self-oscillated mode discharge in which breakdowns will initiate every time when the electric field near the high voltage electrode reaches the threshold value. The voltage-current waveforms of He plasma and the other mixtures are comparable since all the work is carried out in stable discharge; just the typical waveforms of He plasma are shown in figure 3.

The Reynolds number was calculated to study how the flow mode changes and affects the plasma jet to understand the measured results. The Reynolds number, denoted $\text{Re}$, is often used to predict whether a fluid’s flow mode is laminar, turbulent, or at a transitioning stage in between. The flow mode is laminar for low Reynolds numbers, while high Reynolds numbers relate to a turbulent flow. The terms ‘low’ and ‘high’ are compared to a critical Reynolds number, denoted $\text{Re}_c$, marking the transition between laminar and turbulent modes [10]. Though general values for the critical Reynolds numbers are assigned for several scenarios, the actual value of $\text{Re}_c$ differs for each problem since the Reynolds number is highly dependent on the geometry of the problem and other parameters of interest. The Reynolds number can be expressed using the following parameters in the case of a fluid moving through a cylindrical pipe [10].
where \( V \) (m/s) is the fluid’s velocity, \( D \) (m) is the pipe’s diameter, \( \nu \) (m\(^2\)/s) is the kinematic viscosity, \( Q \) (m\(^3\)/s) is the volumetric flow rate of the fluid, and \( A \) (m\(^2\)) is pipe’s cross-sectional area. Using equation (1), the Reynolds number was calculated at each flow rate to study how the flow mode affects the plasma jet. The inner diameter of the nozzle was measured with a Vernier scale to be \( D = 4.55 \pm 0.05 \) mm, and the kinematic viscosity was estimated to be \( \nu = (1.1 \pm 0.1) \times 10^{-4} \) m\(^2\)/s\(^{-1}\) [11]. The volumetric flow rate was obtained through the following conversion:

\[
Q = \frac{f}{6 \times 10^4}
\]

where \( f \) is the gas flow rate set in the laboratory in units of l/min.

To ensure that the plasma jet can be used safely on living tissues, the temperature of the plasma jet generated by the first jet device was measured using a fibreoptic thermometer (Luxtron R 812 monitor). The fibreoptic was a few millimeters below the glass nozzle, and it was fixed in place to ensure that the temperature was measured at the exact location.

The optical emission spectra of the plasma jet were measured to identify the existing species, a common method previously used for plasma generating devices [12]. The measurements were taken in the 350–1050 nm wavelength range, with a spectral resolution of 0.5 nm on the spectrometer (VIS-NIR Smart CCD Based Spectrometer). The spectra were then viewed using the BWSpec software on a laptop connected to the spectrometer. Several steps were taken to improve the spectra’s quality. The plasma jet device was switched to the second device (figure 1). (b) because it produces a larger jet, the measuring probe was positioned perpendicularly beneath the plasma jet to eliminate the possibility of measuring light from nearby external sources. The OES measurements were taken for jets operating with different gas mixtures. The operating gas mixtures and integration time were fixed during these measurements, while the applied voltage and gas flow rate alternated. The water mist was added to the flowing helium through a nebulizer cup in the case of a helium/water mixture. As the input gas flow rate increases, so do the total mass of the output particles [13]. The volumetric flow rate of the liquid can be calculated by measuring the weight difference of the liquid in the nebulizer cup and the duration of the process; however, studies have shown that the liquid flow is most significant at the start of the nebulization process and decreases with time due to cooling by evaporation [14].

It is aimed to achieve sterilization through the chemical reactions that are driven by the active radicals produced in the plasma. These chemically active molecules can initiate apoptosis, a process also known as programmed cell death, as it is a natural and controlled process of cell death, unlike necrosis, which is the cell death caused by external damage and leads to inflammatory reactions [6].

For testing the jet’s sterilization ability, \textit{Escherichia coli} MM294 bacteria (\textit{E. coli}) was grown in agar-filled-Petri dishes in different concentrations. It was hit with the plasma jet and monitored to see its growth. Two sets, each made of 4 Petri dishes, were prepared and treated with the plasma. Various parameters, operation, and incubation conditions were tested to understand how the varying parameters affect the sterilization process.
After treatment and incubation, the untreated areas will have a foggy white color of the bacterial colonies, while the sterilized spots will show a relatively darker agar color \[8, 15\]. Pictures of the Petri dishes were taken using a smartphone camera and a 1600X USB digital microscope.

3. Results and discussion

3.1. The jet length

Figure 4 shows the length of the jet as a function of the He flow rate at power \( P = 50 \text{ mW} \). At flow rates less than \( 5.0 \text{ l min}^{-1} \), the discharge was uncomfortable to bear on the tip of the finger, and arcing occurred. Starting at a flow of \( 6.5 \text{ l min}^{-1} \), the jet was curved when no target was positioned nearby but straightened when the tip was brought below it. The curvature reduces at a flow of \( 8.0 \text{ l min}^{-1} \) as the flow becomes strong enough to overcome the external airflow. As we increase the flow, the discharges remain straight regardless of the target’s presence. It discharges in pulses rather than a continuous glowing discharge, and at flows greater than \( 10.0 \text{ l min}^{-1} \), arcing starts to occur again. At low flow rates, the gas flow is laminar, and hence mixing between the flowing gas and ambient air is minimal. During this phase, an increase in the gas velocity will reduce the air concentration within the jet, causing it to expand, since the discharge occurs in the nearly pure flow of He, and thus it is limited by the air diffusion, which has a more significant effect when the velocity is lower. In our experimental setup, the jet runs in a laminar flow between \( 6.5–7.5 \text{ l min}^{-1} \). After the jet length reaches its maximum, the jet flow changes from a laminar to a turbulent mode as the flow increases. During the transition, the boundary layer separating the gas flow from ambient air is scattered, enabling the air to mingle with the flowing gas \[16\]. One can also observe how the form of the jet changes from a plume or a bullet shape when the flow is laminar to a cylindrical glow when the flow mode becomes turbulent \[17, 18\]. This mixing leads to a decrease in the jet’s length and influences the jet’s temperature, which will be detailed in the next section. The length decrease continues during the transition phase until the length reaches a minimum when the flow becomes entirely turbulent, which is shown, in our instance, at the flow rates range between \( 7.5–9.0 \text{ l min}^{-1} \). From a flow rate of \( 9.0 \text{ l min}^{-1} \) and beyond, the gas flow is turbulent, and the quantity of air mixed with the gas saturates, resulting in a length increment as the gas flow rises, as we can observe for flow rates between \( 9.0–10.0 \text{ l min}^{-1} \).

The Reynolds number is computed at each flow rate using equation (1), and the results are given in table 1 to validate the transition in flow modes. Table 1 shows that the crucial Reynolds number is within a few hundred. However, the standard value employed in most engineering applications is between 2000–2300 \[16\]. Also, it has been established that, for a fluid traveling in a cylindrical pipe, \( \text{Re} \) is \( \sim 1760 \), which is still around 5 times larger than the values reported in our situation \[19\]. Similar observations have been observed for plasma jets and micro-jets, which employ helium as a working gas, where \( \text{Re} \) values are roughly 3–4 times less than in a cylindrical pipe. A couple of explanations are suggested for this significant reduction in \( \text{Re} \), one of them being the buoyancy effect. The other is related to the dynamic viscosity (and thus, the kinematic viscosity \( \nu \)) and how it may be affected by the temperature and the collisions between multiple species in the plasma. Since the flow mode explains the relation between the jet’s length and the gas flow, one can expect that various parameters may change the jet’s behavior as the flow differs. Indeed, it was shown that the length of an argon jet responds...
differently to the varying flow rate, and even if the same gas is used, the maximum jet length varies depending on the applied voltage [9, 18].

Figure 5 shows the length of the jet as a function of the applied voltage where the He flow rate is fixed at 7.5 l min$^{-1}$. At 5.9 kV, the discharge could be felt like a bit of impact on the fingertip, but, at lower voltages, the jet becomes extremely short and uncomfortable. As the applied voltage increases, the discharge stabilizes and becomes painless until a voltage value of 9.5 kV. With a further increase in voltage, the discharge became unstable and began to pulse again. It can be noticed from figure 5 that as the applied voltage increases, the jet length increases as well; this is simply due to the high energy given to the particles by the electric field, which gains power with increasing the applied voltage [20]. This monotonic increase has been observed in various prior publications, but these studies do not reveal a peak in the jet length, as shown in figure 5. The peak may be a consequence of the decrease of metastable helium atoms as the voltage rises. This monotonic increase has been observed in various prior publications [9, 21].

It has been shown that the intensity of N$_2^+$ is substantially higher near the tip of the plasma jet compared to its intensity closer to the nozzle or other species at the jet tip; that is because it is excited by metastable He atoms that have a relatively long lifetime (2 μs) and are neutral, and thus they can flow farther along with the flowing He gas. However, the density of metastable He atoms drops when the voltage rises, as shown in figure 5. Thus it is considered that, in sequence, this reduction reduces the intensity of N$_2^+$, which is the primary atom near the tip of the discharge. Consequently, the jet seems shorter. This may be evaluated via measuring the intensity of metastable He at the end of the jet, as done in, or by utilizing the optical emission spectral lines of N$_2^+$ as a function of voltage at the tip of the jet [22, 23].

### 3.2. The jet temperature

Figure 6 shows the measured temperatures of the plasma jet at an applied voltage $V = 7.8$ kV and power $P = 50$ mW. The air temperature data reveal small fluctuations around an average value of 296.9 K, which may be

![Figure 5. Length of the plasma discharge as a function of applied voltage at a flow rate of 7.5 l min$^{-1}$.](image)

| Flow rate ± 0.5 l min$^{-1}$ | $Re$ ± $\Delta Re$ | $\Delta Re$ | Flow mode |
|-----------------------------|---------------------|-----------|-----------|
| 6.5                         | 280 ± 30            | 30        | Laminar   |
| 7.0                         | 300 ± 30            | 30        | Laminar   |
| 7.5                         | 320 ± 40            | 40        | Laminar   |
| 8.0                         | 340 ± 40            | 40        | Transition|
| 8.5                         | 360 ± 40            | 40        | Transition|
| 9.0                         | 380 ± 40            | 40        | Turbulent |
| 9.5                         | 400 ± 40            | 40        | Turbulent |
| 10                          | 424 ± 44            | 44        | Turbulent |
attributable to the strong air stream from the laboratory’s cooling system. After 4.5 min, the helium gas was allowed to flow. We can see how the temperature rises as the gas flow get substantially more robust than the initial airflow, so the temperature variations become more unstable. However, after the plasma jet was switched on, the temperature reduced abruptly from 297.9 K to 296.8 K, and it continued to fall throughout the monitoring time. It is also evident from figure 6 that the variations are most miniature when the plasma jet is functioning, with an average value of 296.7 K.

This decrease is again tied to the jet’s operating mode. As shown in table 1, at a flow of 8.5 l min$^{-1}$, the plasma jet is at a late stage of transitioning from laminar to turbulent flow mode. At the same time, the applied voltage remains at 7.8 kV. Thus due to the mixing eddies in the turbulent flow, the species of high temperature present in the jet are continuously mixed with the relatively cold ambient air, which decreases the temperature sufficiently. This process is known as turbulent cooling, and it has been seen in plasma jets earlier [15, 17]. As this cooling effect is related to the jet’s operational mode, it is expected that lowering the flow rate to a point where the flow is laminar should reduce the cooling or perhaps even result in a slight temperature increment. However, the temperature remains in a range that qualifies the jet for medical applications [24, 25].

Although it has been proven that the temperature is undoubtedly adequate for operation on live tissues, as stated in prior research, more investigations on the jet’s temperature may be done. The flow rate may be varied to evaluate the cooling efficiency at various speeds and in different operating modes [26]. Also, the fiber optic may be positioned at multiple positions around or inside the jet to examine how the temperature fluctuates. It has been proven that the temperature gradient along the jet’s axis (i.e., the $z$-axis if cylindrical coordinates are employed since they fit the jet’s form) also relies on the operating mode. The gradient of a turbulent jet is more robust than that of a laminar jet [17, 27]. Within a small distance of a few millimeters, the temperature of a turbulent jet can drop from hundreds of Celsius degrees to almost room temperature. In contrast, the temperature of a laminar jet remains in the same order of magnitude. Thus, if the fiber optic were set very close to the glass nozzle, the measured temperature would be much higher than the given values [15].

### 3.3. Optical emission spectroscopy (OES)

The optical emission measurements yielded intriguing findings for the varied gas combinations tested. First, pure helium was evaluated on its own within an applied voltage range of 0.5–8.6 kV, and an optical spectrum corresponding to 7.4 kV is selected and displayed in figure 7 in blue, as it delivered the maximum relative intensity from the tested voltage range. The primary spectra observed were He, O, $N_2^+$, $N_2$, OH$^-$, and H$\alpha$ [8, 18, 22]. The same peaks appeared in the spectra, regardless of the applied voltage. However, the intensities varied, sometimes drastically, as the voltages changed, indicating that the types of species in the jet are not changing; however, the amounts of each are highly dependent on the applied voltage. Roughly, the peaks of a particular spectrum tend to rise and decrease. In the specific example of pure He, a significant shift in the intensities occurred when the voltage was reduced from 6.2 kV to 6.0 kV. However, comparable variances of 0.2 kV in the applied voltage revealed no indication of such extreme changes at other values of V. Though the difference is relatively slight; it demonstrates the necessity of giving the various species with the proper amount…

![Figure 6. Temperature as a function of time. The discharge voltage was 7.8 kV.](image-url)
of energy that optimizes their interaction (i.e., the energy at which their cross-sections maxima) with other particle or objects.

Along with pure helium, the mixture of 6.25% of oxygen with helium also showed a rich spectrum with high intensities, which is shown in figure 7 in red, and it also is the spectrum of highest intensities for that mixture; however, it is obtained at 7.8 kV within a range of 3.0–8.0 kV, which is expected to be at a higher voltage than He, as the additional amount of oxygen requires more energy to be ionized.

The remaining gas mixes resulted in substantially lower relative intensities and fewer species variations, as illustrated in figure 8. These voltages again give the highest intensities, and they are 7.8 kV, 7.0 kV, and 7.5 kV, corresponding to the He/O mixture (He flow = 7.5 l min⁻¹, O₂ flow = 1.0 l min⁻¹ | P ~ 50 mW), He/H₂O (He flow = 7.0 l min⁻¹ | P ~ 20 mW) and He/H₂O (He flow = 10.0 l min⁻¹ | P ~ 50 mW), respectively, whereas in the case of He/H₂O mixture (set at 7.8 kV) of varying He flow, the flow rate that gave the highest intensities was He: 10 l min⁻¹ (P ~ 50 mW). The intensities alter as the helium flow rate rises in the He/H₂O combination as predicted, owing to the increase of water mist transported by the strong He flows from the nebulizer, which takes more energy to ionize. The same applies to lowering the quantity of oxygen in the He/O combination, which resulted in a substantial fall in relative intensities.

After investigating the spectra of these mixes, it is reasonable to assert that the pure helium and helium/oxygen mixtures are the best for sterilization. They provide substantially more significant amounts of bactericidal species like O and OH⁻ at similar voltages. In addition to understanding the existing species, these spectra may also be utilized to determine how particles interact in the plasma based on the degree of shift the spectral lines experience. This explains why various studies report different values for the spectral wavelength, which also varied from the values found in this experiment and other works in the literature [18–21].

3.4. Treatment of E. coli bacteria

Figure 9 shows Petri dish images at several periods after treatment, written in white at the top-left corner of each picture. The dish is held against a light source to show the treated areas more clearly in the first picture from the left. Notice the change of the 4th spot with time, circled in read in each photo. It is clear from this series of images that the plasma initially formed avoid, but it was covered by the bacteria again as time passed. It is clear from figure 9 that sterilization was achieved successfully, which showed signs of sterilization just 12 h after treatment, particularly in spots 5–10. However, a closer look reveals that spots 6–8 have slightly bigger areas than spots 5 and 9–10.

Out of the treated spots, spot 7, which shows the largest treated area, had the best balance between treatment time and resting time between each round, as it had a total treatment time of 70 s during all 7 rounds, and there were relatively long resting periods before and after each round of operation of the plasma jet on it, as it comes in the middle of the range of successfully treated spots, 5–10. This observation raises questions and provides grounds for future investigations on optimizing treatment and rest periods between operational rounds on bacteria. A possible reason behind this may be linked to the time required for the radicals provided by the plasma.
to interact with the bacterial cells. If the minimum (threshold) time required is not met, sterilization does not occur, as seen in the first few spots. On the other hand, if a load of radical species is provided frequently, only part of the radicals will be able to interact with cells, while the remaining may interact with other undesired atoms or molecules, especially since the extremists are very active.

Figure 8. Optical emission spectra of various gas mixtures when the peaks reach an optimum in each combination at different voltages. (a) He/O and He/H₂O mixtures are shown in (b) different He/H₂O mixtures.

Figure 9. Images of Petri dish at several periods after being treated by plasma.
The spots on dish 2 showed signs of sterilized regions just 12 h after treatment. Spot 4 also showed a small dark void at the time, indicating that agar was visible and sterilization occurred. However, this void was covered again with the foggy white substance that is the bacteria as time passed, which can be seen in the middle 2 images of figure 9, until it was covered entirely after 31 h as if this spot was not affected by the plasma initially. This raises an important question: was the bacteria in this spot killed or just detached for a while? As suggested, detached bacteria were able to move back after hours of plasma treatment [7]. The detachment was also shown to have a much higher possibility of occurrence than apoptotic cell death. The latter requires specific conditions that are not easily achieved compared to cell detachment. Though it is more probable that if the remaining 6 spots were sterilized, spot 4 would have been sterilized.

Though apoptosis is the desired outcome from this study, verifying the ability of the plasma jet to detach cells can also be an asset for various medical applications that require the removal of living and healthy tissues from damaged tissues needing treatment of removal, compared to traditional methods which depend on necrotic treatments and thus result in damaged and inflated cells [7].

Since sterilization was successful, it is appropriate to discuss how the bacteria were killed. For example, we would like to know if the death here is necrotic or apoptotic. As a start, the conditions under which the treatment was done can be examined. The plasma jet temperature was verified to be low and near room temperature, and it was again touched without any harm or sensing of heat. Also, the applied voltage was chosen to be 7.5 kV to reduce the chances of heating while trying to produce maximum amounts of radicals. In addition, the discharge-to-arc transition was very seldom and did not reach the bacteria. Moreover, it has been shown that the lowest denaturation temperature of E. coli is \( \sim 320.2 \) K, far from the operating jet’s temperature. Another process that may lead to necrotic death is desiccation, which depends on the gas flow rate. For this reason, the flow rate was chosen to be 7.5 l min\(^{-1}\) to reduce the chances of necrosis by desiccation [28]. Another reason that leads to the belief that apoptosis occurred is the OES measurements that verified the presence of radicals known to be bactericidal, mainly O and OH\(^{-}\), which have been repeatedly confirmed to kill bacteria [7, 8]. And although the current was not measured during sterilization trials, previous measurements in earlier tests regarding the characterizations of the jet were in the order of several micro Amperes, meaning that, even if such a current value is multiplied by the applied voltage of 7.5 kV, the power outcome is still somewhat below the threshold power to achieve necrosis, which is about 300 mW [7].

### 4. Conclusions

An LTAPP jet device was built and investigated in this work to test its ability to sterilize bacteria. A dc power source powered the plasma jet, which was fed with various gas mixtures, primarily pure helium (He) and a mixture of helium and oxygen (O\(_2\)). The length of the jet and its relationship to the applied voltage and gas flow rate were investigated first. The length increases monotonically with applied voltage up to a certain point, after which it starts to decrease as the voltage increases. This is related to generating various metastable helium atoms at multiple energies and how their existence is linked to ionizing plasma species like N\(_2^+\).

The relationship between the gas flow rate and the operation mode of the flowing gas was somewhat more complicated (i.e., whether it is laminar or turbulent). The length of the jet increased in both modes, though the increase was faster in the laminar mode; however, the length of the jet decreased with increasing flow rate during the transitioning stage in between. The cause of this effect is unclear, though many studies suggest that mixing between the flowing gas and ambient air is to blame. When it comes to the temperature of the jet, it was discovered that the operating plasma has a temperature similar to that of the room. The temperature was slightly lower than room temperature when the jet was operating. Because the jet was in turbulent mode, this is due to the turbulent cooling effect.

To identify the plasma species, optical emission spectral measurements were performed. Pure helium and a mixture of He/O, in which oxygen makes up 6.25% of the gas, were found to have the highest intensities and widest variety of species, particularly bactericidal spices like O and OH\(^{-}\). These mixtures were then used to sterilize bacteria grown in a petri dish, including Escherichia coli (E. coli). Several factors influenced the sterilization process, including bacteria concentration, the gas mixture used, treatment method and duration, incubation conditions, and distance from the glass nozzle. Sterilization of 1:2 diluted E. coli bacteria was achieved in several trials when short treatment periods of 10 s were repeated several times (3–10 times). It was best when the bacteria were allowed to rest for short periods between each jet application.

### Acknowledgments

The authors would like to thank Mr. Hassan Yousif for his technical assistance in aiding with the creation of the experimental setup.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Mahmood Nasser  https://orcid.org/0000-0003-3190-8663

References

[1] Laroussi M 2002 IEEE Trans. Plasma Sci. 30 1409–15
[2] Radu I, Bartnikas R and Wertheimer M R 2003 J. Phys. D: Appl. Phys. 36 1284–91
[3] Moisan M, Barbeau I, Moreau S, Pelletier I, Tabrizian M and Yahia I H 2001 Int. J. Pharmuc. 226 1–21
[4] MacDonald D E, Betts F, Stannick M, Doty S and Boskey A I. 2001 J. Biomed. Mater. Res. 54 480–90
[5] Kieft I E, Laan E P V D and Stoffels. E 2004 New J. Phys. 6 149–149
[6] Lee H W et al 2011 J. Phys. D: Appl. Phys. 44 053001
[7] Stoffels E et al 2006 Plasma Sources Sci. Technol. 15 S169–149
[8] De M. Magrina et al 2012 Journal of Physics: Conf. Series vol 3701 (Bristol) (IOP Publishing) p 012011
[9] Novopashin S and Muriel A 2002 J. Exp. Theor. Phys. 95 262–5
[10] White F M and Corfield I 2006 Viscous Fluid Flow vol 3 (New York: McGraw- Hill)
[11] Xiong Q et al 2010 Phys. Plasmas 17 043506
[12] Dean H et al 1996 Chest 110 498–505
[13] Dennis J H 2003 Practical Handbook of Nebulizer Therapy 1st edn (London: CRC Press)
[14] Kolb J F et al 2008 Appl. Phys. Lett. 92 241501
[15] Jin D J, Uhm H S and Cho G 2013 Phys. Plasmas 20 083513
[16] Mohamed A-H, Kolb J F and Schoenbach K H 2010 The European Physical Journal D 60 517–22
[17] Basher A H and Mohamed A-H 2018 J. Appl. Phys. 123 193302
[18] Heesoo J et al 2011 Plasma Processes Polym. 8 535–41
[19] Almarshi I Q M 2019 AIP Adv. 9 105020
[20] Nan J et al 2011 J. Appl. Phys. 109 093305
[21] Joh H M et al 2014 IEEE Trans. Plasma Sci. 42 3656–67
[22] Ihor K et al 2020 J. Phys. D: Appl. Phys. 53 185201
[23] Jógi I et al 2020 Contrib. Plasma Phys. 60 e201900127
[24] Cheng Y-C et al 2017 Plasma Sources Polym. 14 1600235
[25] Pei X et al 2011 IEEE Trans. Plasma Sci. 39 2276–7
[26] Wenxia P et al 2002 Plasma Chem. Plasma Process. 22 271–83
[27] Mackey B M et al 1991 Microbiology 137 2361–74

J. Phys. Commun. 6 (2022) 105005  M Nasser et al

IOP Publishing