

RESEARCH PAPER

Numerical Investigation Extremely Low-Frequency Plasma Generation and Frequency Effects on Plasma Parameters for Nanotechnology Applications Using COMSOL Multiphysics

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ABSTRACT

The use of low-frequency plasma has become widespread due to its high efficiency in energy coupling. In this study, a numerical analysis of low-frequency plasma generation was conducted using COMSOL Multiphysics software to evaluate the impact of operating frequencies on plasma dynamics and use it to synthesize nanomaterials. Investigating plasma at frequencies of 11 Hz and 15 Hz offers a unique computational advantage: the voltage cycle period is significantly longer than the timescales of electron and ion transport. This allows the fluid model within COMSOL to track the complete expansion and contraction processes of the plasma sheath throughout each cycle, utilizing low-pressure argon gas as the discharge medium. With all other parameters held constant, this work employed low frequencies (11 and 15 Hz) to precisely monitor space-charge transient relaxation processes and sheath dynamics, while also examining electron density, electron thermal conductivity, and magnetic flux. The use of low-frequency plasma enhanced electron heating and ionization processes, resulting in increased electron density and temperature—factors that, in turn, influence nanomaterial formation. Temperature and electron density are fundamental factors in the formation of nanomaterials using plasma. Furthermore, the magnetic flux distribution varied with frequency, thereby affecting the plasma's ability to absorb electromagnetic energy. This study highlights the effectiveness of the "COMSOL Multiphysics" program as a reliable tool for examining and optimizing low-frequency plasma, and confirms that low-frequency plasma is a significant feature for characterizing plasma properties.

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INTRODUCTION

The fourth phase of matter constitutes plasma. Consisting of almost neutral free ions with electrons, it acts collectively via electromagnetic interactions [1]. Thin films formation, treatment of surfaces, nanomaterial and semiconductor technology are just a few of the scientific and industrial fields that have taken an interest in Low-Frequency Plasma because of its capacity to operate at lower pressures and allow precise regulation for the plasma characteristics that result [2]. The discharge chamber is where electromagnetic energy and electrons are mixed when Low-Frequency Plasma excitation was utilized to create plasma. Finding out the electron's density and speed relies heavily on energy absorption methods. Since the rate of energy gain during collisions nor the electrons' response to a changing electric field are both affected by frequency, it's a crucial parameter in Low-Frequency Plasma systems. The plasma's transport characteristics and ionization level are affected by this [3]. A great deal of research shows that Low-Frequency Plasma systems' magnetic and electrical field distributions, electron densities, and velocities can be dramatically changed by tuning the excitation frequency [4]. Systems that rely on magnetic confinement or want to improve energy coupling efficiency may find that Low-Frequency Plasma combined with a magnetic field affects the effective magnetic flux [1]. The complexity of Low-Frequency Plasma systems has made multiphysics numerical modelling an essential tool for their research and understanding. The ability to solve coupled equations describing charge transport with electromagnetic fields in a single numerical framework makes COMSOL Multiphysics software a popular tool for Low-Frequency Plasma modelling [5]. Numerical simulation of low frequency plasma formation in COMSOL Multiphysics is the goal of this research, which aims to investigate the effect the variation in frequency on the density of electrons, electron velocity, and flux magnetic magnitude. The study's results shed light on how frequency affects Low-Frequency Plasma properties, which can

be used to improve the design and operation of plasma systems used in research and industry. Despite the widespread usage of Low-Frequency Plasma in many fields, the vast majority of research to date has focused on systems operating at the industry standard frequency of 13.56 Hz.

Changes to this value within adjacent frequency bands have been the subject of relatively little investigation. Therefore, we still do not completely understand the physical consequences of changing the frequency close to the standard value, namely 13–15 Hz, on the inherent plasma properties. Furthermore, studies of the frequency dependence of the density of electrons and distribution of velocity often fail to account for the simultaneous fluctuations of magnetic flux, which play a crucial role in explaining electron dynamics in Low-Frequency Plasma and energy coupling mechanisms. Additionally, most of the numerical models that have been published either simplify the description of in fields of electricity or split the solution of field equations from charge transport, which limits how well they can portray the real behaviour of plasma as the frequency changes. An innovative approach to solving electromagnetic field equations and charge transport equations is taken advantage of in this research, which uses COMSOL Multiphysics software to perform a multiphysics numerical study. The study examines how changing the excitation frequency from 11 to 15 Hz affects the physical properties of Low-Frequency Plasma, including the density of electrons, electron velocity, and flux magnetic magnitude. Findings from this work, which is one of the first of its kind, can improve operational efficiency and optimize plasma properties for sophisticated industrial applications by providing insights into the consequences of small frequency deviations on Low-Frequency Plasma behavior by systematic numerical analysis.

2. Mathematical Model and Governing Equations Using Low-Frequency Plasma plasma, this research looked at how different operating frequencies affected plasma properties. The plasma within a discharge chamber containing low-pressure argon gas was stimulated by a dual-frequency Low-Frequency Plasma power source operating at 11 Hz and 15 Hz. All other operational parameters, including voltage, gas pressure, and shape, were maintained constant in order to observe the effect of frequency change on plasma behaviour. In the bulk region, plasma was believed to be nearly neutral. The self-consistent electric fields method did account for space-charge effects close to the electrodes, though. The main priorities of the model are electron mobility and energy balance. Low-Frequency Plasma electric field

and frequency have a major effect on them. The frequency-transient investigation's mathematical model is available in the COMSOL Multiphasic user manual [6].

To avoid energy losses, the electron velocity and temperature of the plasma were calculated theoretically to select the optimal conditions for preparing nanomaterials.

In plasma, electron density, electron temperature, and the rate of inter-particle collisions are among the key factors governing nanoparticle size, size distribution, and crystalline structure. Non-thermal plasma provides an environment characterized by high electron energy and relatively low gas temperature, enabling the synthesis of high-purity nanomaterials without the need for high processing temperatures. Recent studies have demonstrated that controlling plasma parameters—such as applied voltage, electrical power, and the working gas—allows for the regulation of nucleation and growth processes, thereby yielding nanomaterials with high surface areas and enhanced electronic and catalytic properties. Furthermore, plasma facilitates the generation of crystalline defects and oxygen vacancies; these features are crucial for optimizing the performance of nanomaterials used in sensors, as well as in optical and catalytic applications.

Increasing the electron temperature elevates the rates of ionization and molecular dissociation within the plasma, thereby promoting the formation of initial nanoparticle nuclei and enhancing the likelihood of their ordered growth. Consequently, investigating fundamental plasma parameters—particularly electron temperature and electron density—is essential for understanding the behavior of the resulting nanomaterials and for optimizing their physical and chemical properties [7].

The continuity equation governs the temporal and spatial evolution of electron density: $\partial n / \partial t + \nabla \cdot \Gamma_e = R_e - (u \cdot \nabla) n_e$, where n_e is the electron density, Γ_e is the electron flux, and R_e is the rate at which ionization processes make electrons. The last term takes into account how convection affects transport. By maintaining a constant number of electrons in the plasma, this equation describes how the density of electrons varies due to Low-Frequency Plasma excitation [8].

The drift-diffusion approximation was used to characterize the electron flux: $\Gamma_e = -(\mu_e E) n_e$

— $D_e \nabla n_e$. The equation is defined in terms of the electron diffusion coefficient D_e , the electric field E , and the electron mobility μ_e . The first term demonstrates the movement of electrons caused by the Low-Frequency Plasma electric field, while the second term depicts the spreading of electrons caused by electron density gradients. Since the Low-Frequency Plasma frequency alters the magnitude and velocity of the electric field—which impacts the efficiency with which electrons move—it has an immediate impact on this equation [9].

To get the temperature of an electron, we must first solve the equation for its energy density: $\partial n / \partial t + \nabla \cdot \Gamma_e + E \cdot \Gamma_e = S_{en} - (u \cdot \nabla) n_e + Q + Q_{genq}$. Here, n_e stands for the electron energy density, Γ_e for the electron energy flux, and S_{en} for energy losses caused by inelastic collisions; The phrase $E \cdot \Gamma_e$, which is very frequency dependent, denotes the transfer of energy from the Low-Frequency Plasma electric field to electrons. Electrons absorb more energy from the oscillating field as the Low-Frequency Plasma increases, leading to a quicker heating process [10].

The electric field is a result of the electrostatic potential: $E = -\nabla V$. Could one utilize Poisson's equation to determine the potential distribution using:

$\nabla \cdot (\epsilon_0 \epsilon_r E) = \rho_q$, where ρ_q is the density of the space charge. Using these equations, we can determine the plasma's electric field in a self-consistent manner. Electron velocities, paths, and energy absorption are all directly modulated by this field. The electric field's temporal behaviour is affected by changes in Low-Frequency Plasma, which in turn affects the depth of field penetration and the creation of plasma sheaths [11].

The equation represents the electron energy distribution function (EEDF). (EEDF) is given by $f(\epsilon) = \phi - 3/2 \beta_1 \exp(-\phi \epsilon \beta_2)$. The variables $\beta_1 \beta_2$ are defined using Gamma functions, and ϕ represents the average electron energy. Ionization and excitation, two energy dependent reactions that are sensitive to changes in Low-Frequency Plasma, can be precisely calculated using this formulation [2].

MATERIALS AND METHODS

In order to determine how operating frequency affects critical plasma parameters, this work statistically analyzed Low-Frequency Plasma with COMSOL Multiphysics. Using the gas pressure

(1 Torr / 133.3 Pa), the sinusoidal AC voltage amplitude ($V = 700V$), the chamber dimensions (15-5 cm), and the inter-electrode gap (5cm),. nozzle length (10cm). The models considered the dispersion of the density of electrons, magnetic field flux, as well as electrons temperature. Two electrodes, one linked to an Low-Frequency Plasma voltage source with the other to ground, were used to construct a cylindrical discharge chamber. Argon gas was selected as the working gas for low-pressure environments. Connecting the Plasma Module to the Low-Frequency Plasma Module allowed us to simulate plasma behaviour. This allows us to simultaneously determine the distribution of electromagnetic fields and the transit of charged particles. The equations that controlled the system were the Low-Frequency Plasma electromagnetic field equations developed by Maxwell and the electron and ion continuity equations. We also determined the distribution of electron temperatures in the plasma by solving the conservation of energy equation. Assuming conducting electrodes and grounded boundaries, we utilised the correct boundary conditions at the walls of the chamber and the electrodes. By keeping the applied voltage, pressure of gas, and chamber shape constant, we ran simulations at two Low-Frequency Plasma —11 Hz and 15 Hz—to see how frequency affected the results. The stability of plasma production and the convergence of plasma

properties were verified by running time-varying simulations. In order to determine the effect of Low-Frequency Plasma.

RESULTS AND DISCUSSION

It is evident from the simulation findings that the plasma properties are frequency dependent. At 11 Hz and 15 Hz, the electron density and temperature spatial distributions are displayed in the figures

Fig. 1. Significant insights into plasma behaviour under low-frequency driving circumstances are provided by the spatial distributions of electron density acquired from COMSOL simulations at two different excitation frequencies (11 Hz and 15 Hz). There is a pattern of spatial oscillations along the vertical axis of the electron density at 11 Hz, with regions of low density alternating with regions of high density. When an oscillating electric field is provided and interacts with the dynamics of charged particles, standing plasma waves are formed, as seen by this distribution. Near the left boundary, the maximum number of electrons is about. the value often reported for similar lowtemperature plasma discharges is $1.2 \times 10^{20} m^{-3}$, as previously stated [8]. Elevated spatial frequency of plasma waves is indicated by an increasing number of oscillations in the electron density profile within the same spatial domain as the excitation frequency approaches

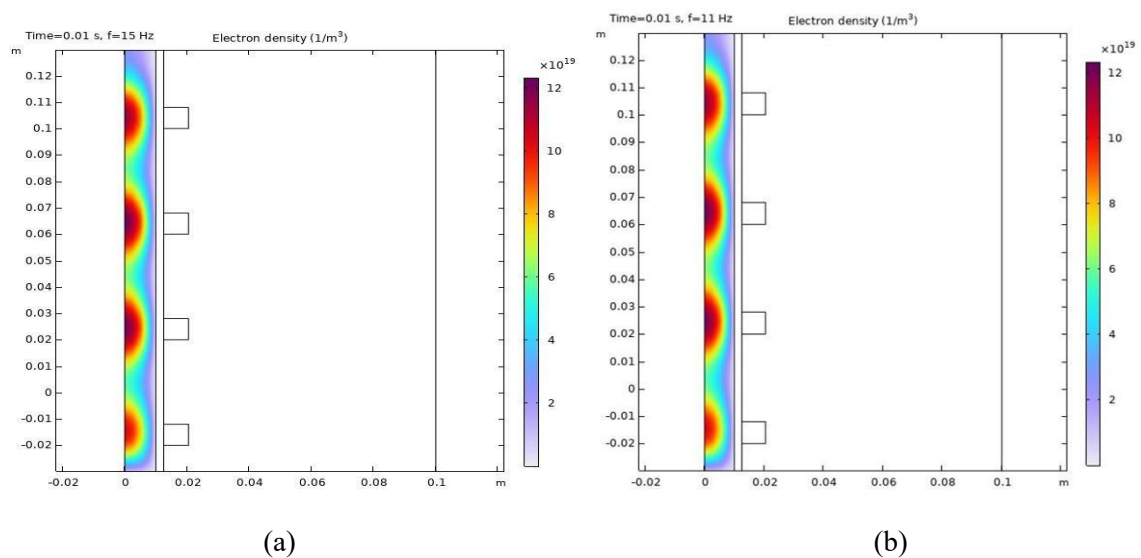


Fig. 1. The set (a, b) For two excitation frequencies, (a) 15 Hz and (b) 11 Hz, the distribution of electron density along the length of the ionization chamber at $t=0.01$ s follows.

15 Hz. This is explained by the fact that driving frequency is directly related to the modes of plasma oscillation. Denser spatial wave patterns are the result of rapid changes over time, which are brought about by higher frequencies. Since the maximum electron density remains constant, the overall ionization balance and energy input of the plasma are unaffected by this little frequency variation.

The current results align with the findings of [9], who demonstrated that increasing the excitation frequency directly influences electron dynamics and ionization rates within the plasma, thereby increasing electron density and enhancing plasma discharge characteristics. [9] noted that frequency variations induce significant changes in electron density and behavior within argon plasma, with the potential to achieve higher plasma densities at elevated frequencies. Furthermore, an increased low-frequency contribution enhances the electron density distribution within the discharge region. These observations are consistent with the current study, which showed improved electron density at 15 Hz compared to 11 Hz. This result is highly significant for nanotechnology applications, as high electron density is associated with increased fluxes of ions and active species—elements

essential for processes such as nano-thin film deposition, atomic-scale etching, and material surface modification, all of which are fundamental to modern nanofabrication technologies.

Fig. 2 heating mechanism, the electron temperature distributions at 11 Hz and 15 Hz display distinct spatial features. A more uniform distribution with broader high-temperature regions characterizes Te at 11 Hz. The prolonged oscillation period was characterised by a great deal of diffusive relaxation, as shown here. In contrast, high-Te regions exhibit a 15-20% improvement in spatial contrast, making them sharper and more concentrated at 15 Hz. This demonstrates a decrease in heat diffusion between cycles. There has been no change in the heating mechanism because at 15 Hz, the peak electron temperatures are just marginally higher (~ 0.1 eV). Increasing the excitation frequency mostly enhances the localization and contrast of electron energy, rather than its size, as seen by this direct comparison. Discharges at 15 Hz are more effective in concentrating energy on the powered electrode, whereas discharges at 11 Hz allow it to disperse more widely. These findings provide a clear method for improving plasma homogeneity and energy deposition in low-frequency capacitive

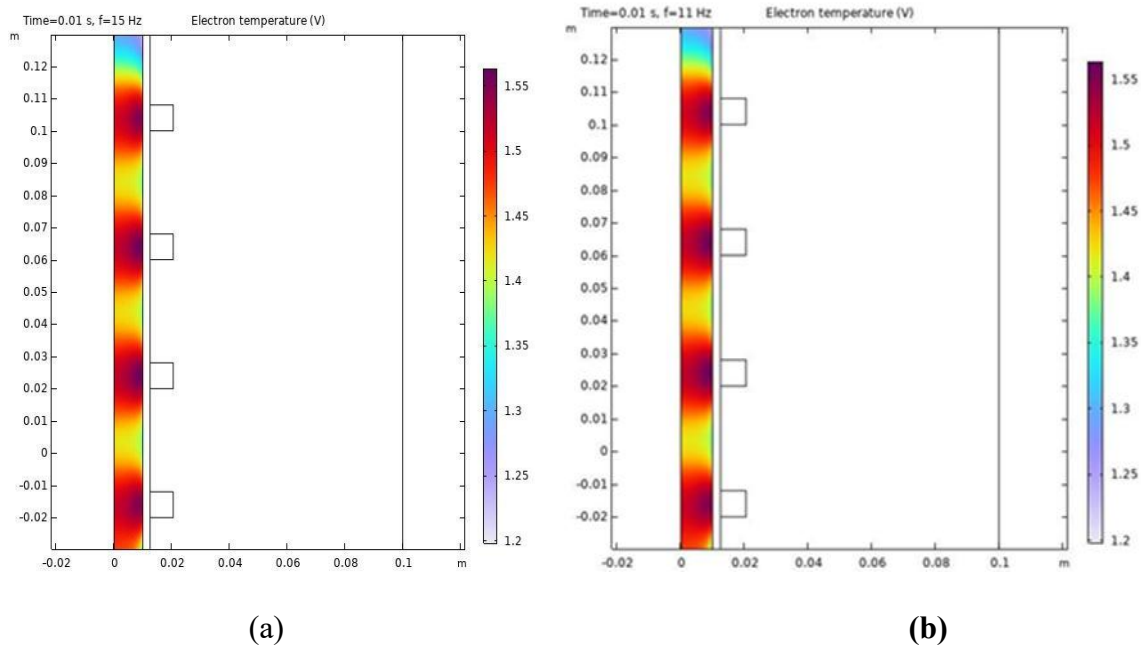


Fig. 2. The electron temperature distribution for two stimulation frequencies (a) 15 Hz and (b) 11 Hz along the ionization chamber's length at $t=0.01$.

discharges by demonstrating that spatial energy may be controlled by changing frequency. The calculated electron temperature values indicate the formation of a non-thermal plasma with sufficient electron energy to drive ionization and

excitation processes without causing excessive gas heating. These conditions are suitable for various nanotechnology applications, particularly the fabrication and processing of heat-sensitive nanomaterials. Among potential nanomaterials,

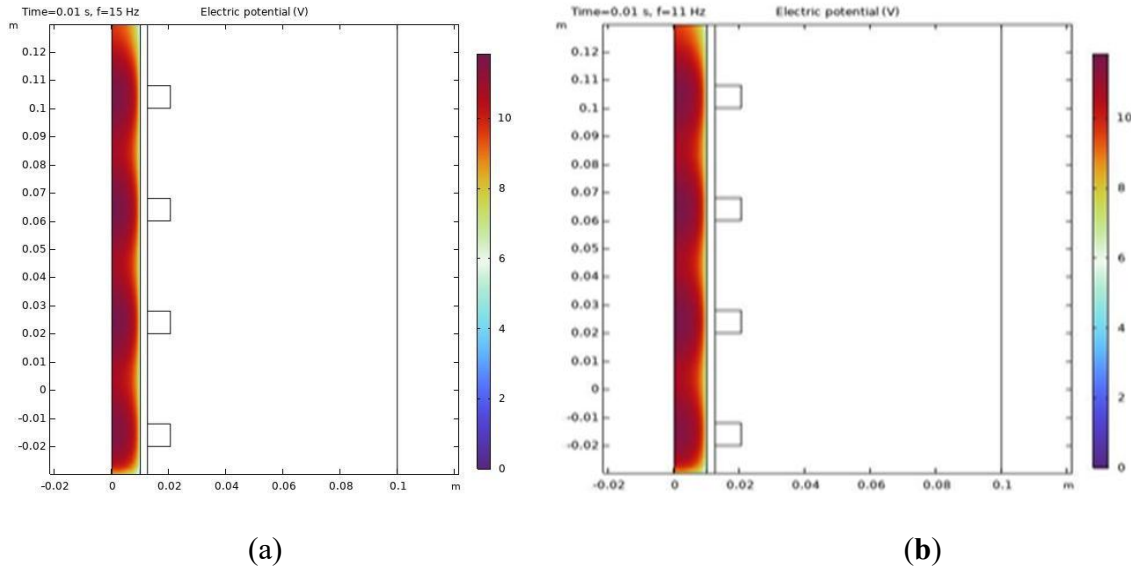


Fig. 3. (a,b) The distribution of electron potential along the length of the ionization chamber at $t=0.01$ s for two excitation frequencies: (a) 15 Hz and (b) 11 Hz.

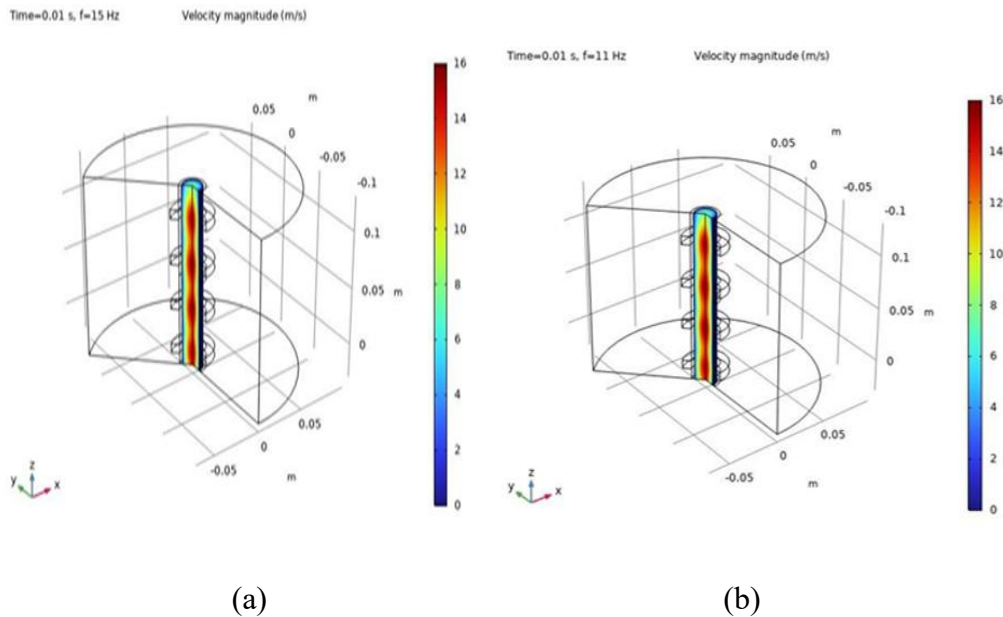


Fig. 4. Shows how the velocity magnitude (m/s) is spread out over the surface (m/s) at $t=0.01$ s for two excitation frequencies: (a) 15 Hz and (b) 11 Hz.

ZnO nanostructures are highly compatible with these operating conditions, given their strong dependence on electron density and temperature during growth, deposition, and surface modification. Furthermore, the generated plasma can be utilized to enhance the properties of carbon nanoparticles, graphene films, and titanium oxide nanostructures, making frequency control an effective tool for tailoring material properties at the nanoscale.

Fig. 3 The electric potential distributions at 11 Hz and 15 Hz maintain an identical sheath-dominated configuration, with over 90% of the applied voltage diminishing near the powered electrode and a quasi-neutral bulk in both instances, thereby validating operation within the collisional Ohmic regime. However, when the frequency is raised to 15 Hz, the voltage drop area gets smaller (about 10% less effective sheath thickness), and the peak electric field gets stronger (about 10–15%). This happens because there is less time for spacecharge relaxation to happen in each cycle. At 11 Hz, the longer oscillation period lets some of the charge move around and smooths out the electric field profile, which makes the sheath wider. At 15 Hz, the shorter period makes this relaxation less effective, which increases the separation of local charges and makes the

field gradient stronger. Maintaining a constant bulk potential is significant since it verifies the persistence of the global plasma state. Hence, the heating mechanism remains unchanged as the frequency increases; what changes is the electric field form and energy deposition in the sheath due to changes in the balance among charge accumulation with relaxation in space and time.

Fig. 4 The maximum velocity magnitude values are mostly found near the left boundary, which is where the dynamic excitation source is located. In the horizontal direction, the velocity magnitude gradually decreases. This is due to viscous damping and energy dissipation mechanisms in the medium. The results show a clear response that depends on frequency. When the excitation frequency goes up from 11 Hz to 15 Hz, the localized velocity magnitude goes up, and the spatial gradient gets steeper. This behavior is due to the higher frequency excitation, which causes the dynamic acceleration to increase. The gradual decline of velocity amplitude indicates the existence of dissipative mechanisms regulating wave propagation within the system. The internal rectangular elements cause local flow and structural field changes, but their effect is not as strong as the effect of the boundary

Fig. 5 The results show that the temperature in

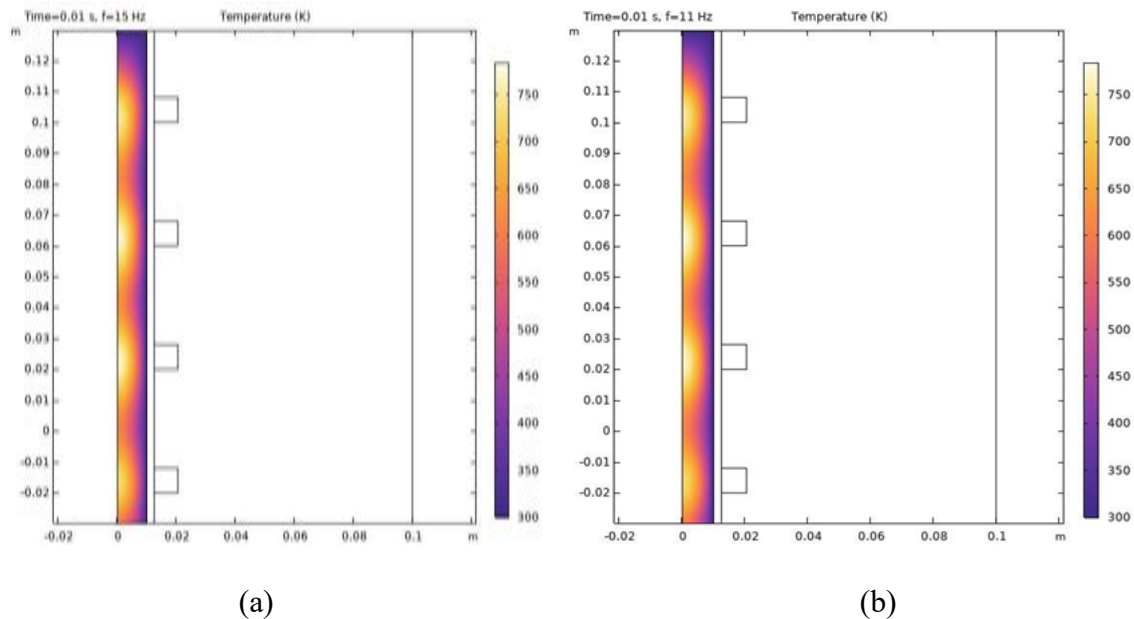


Fig. 5. Shows the distribution of temperature in space. at $t=0.01$ s for two excitation frequencies: (a) 15 Hz and (b) 11 Hz.

space rise is mostly happening near the left edge of the domain, which is where Low-Frequency Plasma excitation is applied. This means that electromagnetic power is absorbed in the area near the electrode or inductive coil, which causes the electrons to heat up quickly, energy to be transferred to the neutral gas through collisions, and a steep thermal gradient to form along the radial direction. Thermal conduction and energy loss through collisions cause the temperature to drop slowly as you move away from the source of

excitation. At 15 Hz, the thermal distribution along the plasma region is more uniform, while at 11 Hz, the heating zones are more concentrated in certain areas. This is because raising the frequency changes how the electric field couples with the plasma, and under certain coupling conditions, the energy transfer to electrons becomes more efficient.

Fig. 6 In both cases, a pattern that looks like wave forms along the vertical direction near the left wall of the channel every so often. However,

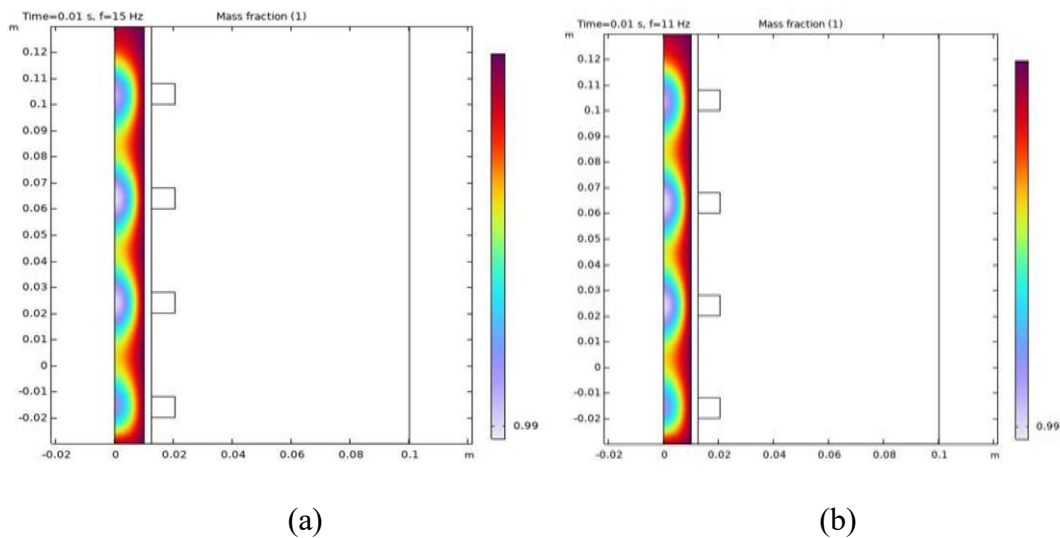


Fig. 6. Presents the Spatial Temperature Distribution at $t=0.01$ s for two excitation frequencies: (a) 15 Hz and (b) 11Hz.

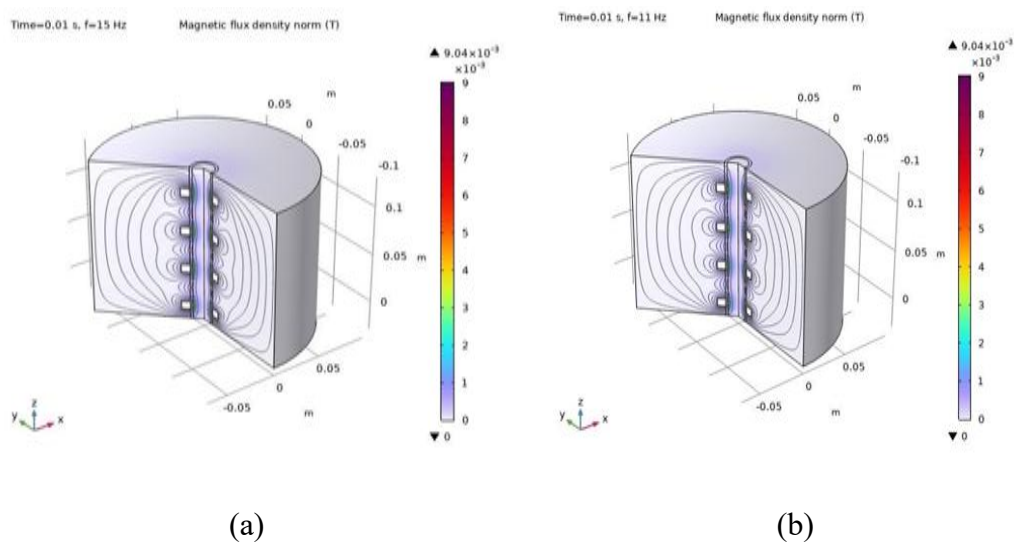


Fig. 7. Presents the magnetic field lines at $t=0.01$ s for two excitation frequencies: (a) 15 Hz and (b) 11 Hz.

when the frequency goes up from 11 Hz to 15 Hz, there are more spatial undulations in the same geometric length. This means that the oscillations have a shorter spatial wavelength. Important things to note are A higher rate of change in the color gradient means that the property variations in the visualization results are steeper. According to the theoretical model of oscillatory flow systems, this behavior is in line with the inverse relationship among spatial wavelength (λ) and frequency (f) as a result of the phase velocity (U) and frequency correlation: $\lambda = U / f$. Consequently, the wave structure shrinks and the pattern's spatial repetition increases as the frequency increases. When it comes to diffusion layer thickness, at $f = 11$ Hz, the gradient region has a wider lateral extension away from the wall, which means that the diffusion layer is thicker at $f = 15$ Hz: On the other hand, the layer that is affected gets thinner and more concentrated near the wall. This phenomenon can be elucidated by the fact that elevating the frequency diminishes the available diffusion time within each half-cycle of the oscillation. This decrease limits the diffusion penetration depth (δ), which is theoretically determined by the relationship: δ is about the same as $\sqrt{D / \omega}$ D is the diffusion coefficient, and ω is the angular frequency ($\omega = 2\pi f$). So, higher frequencies make diffusive effects less deep, which makes the boundary layer next to the wall more confined.

Fig. 7 The closed-loop magnetic field lines are concentrated around the excitation coil and decay toward the plasma bulk. Both the 11 Hz and 15 Hz distributions of the magnetic flux density ("B") have nearly identical global structure. The two instances do not modify the peak magnetic flux density, which is approximately 9.04×10^{-3} T. This proves that the applied current, and not the little shift in frequency, is the primary determinant of the magnetic amplitude. The spatial distribution for the magnetic contours does exhibit a small but consistent fluctuation, though. The field lines at 15 Hz are more compressed and have steeper gradients than the 11 Hz lines near the excitation region. This behaviour can be explained by the process of electromagnetic diffusion in conductive media. In collisional plasmas, where particle collisions are common, the magnetic diffusion equation, derived from Maxwell's equations (the basic equations governing electricity and magnetism), controls the evolution of the magnetic field when the plasma

operates in the Ohmic regime (where standard electrical resistance dominates current flow: $\partial B / \partial t = \eta \nabla^2 B$ where $\eta = 1 / (\mu \sigma)$ [1] represents the magnetic diffusivity. The following is a scaling formula for the characteristic penetration depth (the distance the field travels into the plasma) for timeharmonic (time-varying) excitation: $\delta \sim \sqrt{2 \mu \sigma \omega}$ As the frequency of the oscillating magnetic field increases, the effective penetration depth decreases, as predicted by the inverse square-root dependency on angular frequency (where is the rate of oscillation of the field). A quantifiable reduction in magnetic spreading at 15 Hz is demonstrated by the simulation findings. The theoretical trend $\delta \propto 1 / \sqrt{\omega}$ is satisfied, despite the slight frequency change from 11 Hz to 15 Hz. Rather than a shift to a new regime, the impact is a quantification of field diffusion inside the plasma. Collectively, these results suggest that, rather than adjusting the quantity of the energy input, the spatial diffusion features are mostly affected by frequency changes. Improving local temporal variation is as easy as increasing the frequency slightly. The reason the peak B magnitude remained constant despite an increase in contour compression is because the induced electric fields scale with $\partial B / \partial t$, which means that this could slightly enhance the induced current density close to the source region.

To validate our model, we compare our simulation trends with classic experimental literature on low-frequency gas discharges such as [13]. The simulation accurately captures the experimental hallmarks of low-frequency discharges, and the localized peaks in electron temperature near the electrodes due to ohmic heating.

CONCLUSION

This study presents a detailed analysis of plasma dynamics in a low-frequency, capacitively coupled electrical discharge, focusing on frequency precision through high-resolution COMSOL simulations at 11 Hz and 15 Hz. Although the fundamental discharge mechanism—specifically the collisional Ohmic heating mode—remains constant, the results clearly demonstrate that slight variations in excitation frequency lead to significant changes in spatial distribution and plasma confinement characteristics; these, in turn, influence the plasma intensity used in nanomaterial synthesis, affecting the resulting size

and properties. While fluctuations in peak electron density (approximately $1.2 \times 10^{20} \text{ m}^{-3}$) and maximum electron temperature remain minimal, a distinct spatial compression of plasma structures is evident at higher frequencies, manifested by a shorter spatial wavelength and increased density oscillations. Furthermore, regions of high electron temperature can be identified with greater precision, allowing them to be directed onto the target material to induce nanomaterial formation—where high-temperature electrons bombard the surface, removing the top layer and transforming it into nanomaterials—exhibiting a 15–20% higher spatial variation; additionally, the peak electric field increases by 10–15%, and the sheath layer compresses by approximately 10%. Thermal and concentration layers become thinner due to the reduced diffusion penetration depth. These results demonstrate the potential to effectively utilize the excitation frequency to control spatial energy confinement, the sheath layer, and the wave structure without altering the overall plasma state. Regarding the potential application of this type of plasma for nanomaterial synthesis, the results indicate that the properties of the generated plasma are suitable for producing nanomaterials; furthermore, the size of the produced nanomaterials can be controlled by adjusting plasma parameters. To enhance plasma uniformity and localized energy deposition in low-frequency capacitive discharges, it is recommended to set the frequency at an intermediate level.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

REFERENCES

1. Bogaerts A, Neyts E, Gijbels R, van der Mullen J. Gas discharge plasmas and their applications. *Spectrochimica Acta Part B: Atomic Spectroscopy*. 2002;57(4):609-658.
2. Chen FF. *Introduction to Plasma Physics and Controlled Fusion*. Springer International Publishing; 2016.
3. Chapter 3. COMSOL Multiphysics: Overview and CFD Module. *CFD Module: De Gruyter*; 2015. p. 75-102.
4. Fridman A. *Plasma Chemistry*: Cambridge University Press; 2008 2008/05/05.
5. Hagelaar GJM, Pitchford LC. Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models. *Plasma Sources Sci Technol*. 2005;14(4):722-733.
6. Hazeltine RD, Waelbroeck FL. *The Framework of Plasma Physics*. CRC Press; 2018. <http://dx.doi.org/10.1201/9780429502804>
7. Shah K, Patel J, Kumar S, Pandey R, Maity G, Dubey S. Perspectives on sustainable and efficient routes of nanoparticle synthesis: an exhaustive review on conventional and microplasma-assisted techniques. *Nanoscale*. 2024;16(44):20374-20404.
8. Lieberman MA, Lichtenberg AJ. *Principles of Plasma Discharges and Materials Processing*: Wiley; 2005 2005/01/27.
9. Cao Y, Zhang S, Ma M, Zhang Y. Correction: Cao et al. Fluorinated PEG-PEI Coated Magnetic Nanoparticles for siRNA Delivery and CXCR4 Knockdown. *Nanomaterials* 2022, 12, 1692. *Nanomaterials*. 2024;14(10):830.
10. Yin G, Gao S, Liu Z, Yuan Q. The discharge characteristics of low-pressure capacitively coupled argon plasma with Langmuir probe. *Phys Lett A*. 2022;426:127910.
11. Chapter 11 Bioheat Models Using COMSOL Multiphysics 4.x. *Multiphysics Modeling Using COMSOL®4: De Gruyter*; 2012. p. 489-544.
12. Obiozor CN, Sadiku MNO. Finite elements in electromagnetics for undergraduate curriculum. *Proceedings of Southeastcon '93: IEEE*. p. 4.
13. Coburn JW, Kay E. Positive-ion bombardment of substrates in rf diode glow discharge sputtering. *J Appl Phys*. 1972;43(12):4965-4971.
14. Flamm DL. Frequency effects in plasma etching. *Journal of Vacuum Science and Technology A: Vacuum, Surfaces, and Films*. 1986;4(3):729-738.