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Transport Analysis of Neon–Copper Plasma: Power, Elastic/Inelastic Losses, Energy Characteristics and Total Ionization Frequency

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ABSTRACT

Objective: *This study introduces a model and examines the transport parameters of a neon–copper plasma mixture, emphasising energy and power characteristics, along with the effects of both elastic and inelastic power losses.* ***Method:*** *The researchers utilise theoretical and computational methodologies, predominantly employing the Boltzmann equation to examine the distribution of electrons and ions within the plasma, and the equation is solved using numerical methods, which give a detailed look at how collisions affect power losses and help us better understand how energy moves through the plasma.* ***Results:*** *The study examines two principal factors: the diminished electric field (E/N), which varies from 1 to 20 Td, and the influence of fluctuating copper concentrations, ranging from 0.001 to 0.5 mol, on electron-related metrics, including power, elastic and inelastic power losses, and energy distribution, the analysis gives useful information about how these parameters change when the electric field and copper concentration change, and the results also show how elastic and inelastic processes work together and how they affect the plasma's power use and energy properties.* ***Novelty:*** *This study is pertinent to numerous applications, encompassing nanomaterial synthesis, metal surface treatment, plasma discharge technologies, light and laser generation, gas processing and pollutant elimination, and the advancement of sophisticated plasma-based electronic devices, providing a clear picture of how to predict and improve plasma performance in mixed-gas environments by accounting for the effects of electric fields and changing gas concentrations.*

INTRODUCTION

The noble gases (He, Ne, Ar, Kr, Xe, Rn) are positioned in Group 18 of the periodic table. They are characterized by their remarkable chemical inertness, resulting from the complete occupancy of their outer electron shells [1]. This property makes them ideal candidates as a base medium for plasma formation, since noble gases provide a neutral environment that enables the generation of stable and controllable plasma [2]. However, using a noble gas alone can be limiting; therefore, they are often mixed with other elements or gases to achieve tailored plasma properties. Pure plasma may not generate a sufficient number of electrons. For example, when nitrogen (N_2) is added to argon, inelastic collisions increase, leading to a higher density of free electrons [3]. It is therefore natural to investigate composite mixtures that combine a noble gas with a metallic element. Among such mixtures, the neon–copper (Ne–Cu) system has attracted growing interest [4] in advanced research and applications. The motivation for using neon arises from its nature as a medium-mass noble gas, distinguished by its relatively high ionization energy (21.6 eV), which allows it to produce stable plasma under low pressures. It also permits easy electrical discharge, enabling the formation of a uniform glow discharge inside sealed tubes. Moreover, neon exhibits strong spectral emissions in the red–orange region [5], which historically made it the basis for conventional neon lamps. These characteristics make neon a suitable environment for sustaining plasma and assisting in the ionization or excitation of other added elements. Copper, on the other hand, is chosen because of its importance as a metallic element. Copper exhibits a complex electronic structure characterized by multiple energy levels that can be easily excited through collisions with plasma electrons. It also displays strong spectral lines in both the visible and ultraviolet regions, making it an essential element in spectroscopy and laser technologies. Furthermore, its excellent thermal and electrical conductivity enhances its function within plasma systems by facilitating efficient energy and radiation transfer. When copper vapor is introduced into a noble gas plasma such as neon, it forms a unique combination that integrates the stability of the noble gas with the radiative properties of the metal [6]. This mixture offers several important applications, the most notable being the copper vapor laser [7], which represents a key use of the neon–copper plasma system. Recent studies have shown that interactions between laser radiation and copper targets can produce emissions in the soft X-ray region, which have been employed in the development of X-ray microscopes, thereby advancing imaging and diagnostic techniques in physical research [8]. The plasma generated by the neon–copper mixture is also used in material spectroscopy [9]. By analyzing spectral emissions, the properties of various substances can be identified, contributing to the development of new techniques in fields such as chemistry and physics.

RESEARCH METHOD

In this study, the transport parameters of a Neon–Copper plasma mixture were investigated using a theoretical and computational approach. The analysis was based on solving the Boltzmann equation for electrons under steady-state and spatially homogeneous conditions, where the electron energy distribution function (EEDF) plays a central role in determining the transport and power characteristics. The plasma system consisted of Neon (Ne) as a buffer gas with varying mole fractions of Copper (Cu) vapor. The concentration of copper (Cu) was systematically varied from 0.001 to 0.5 mol to investigate the influence of metallic content on the electronic transport properties of the mixture. Furthermore, the effect of changing the reduced electric field was examined within the range of 1 to 20 Townsend (Td). The electron energy distribution function (EEDF) is fundamental to understanding plasma transport properties, as it represents how electron energies are statistically distributed under specific discharge conditions [10]. In the present study, the EEDF was obtained by solving the Boltzmann equation for a mixture of neon and copper atoms, considering both elastic and inelastic collision processes [11]. This function provides essential information about how electrons exchange energy with the background gas and how their energy distribution evolves with changes in the reduced electric field (E/N) [12]. Accurate knowledge of the EEDF allows for the calculation of key parameters such as electron mobility, diffusion coefficients, mean energy, and ionization and excitation rates. Therefore, it serves as a critical link between the microscopic collision cross sections and the macroscopic plasma characteristics, including power dissipation, energy balance, and overall discharge behavior [13]. The derived EEDF was subsequently used to compute transport coefficients and energy loss rates that describe the performance of the Ne–Cu plasma system under different operating conditions [14].

Evaluated Transport Parameters

The following parameters were calculated from the numerical solution of the Boltzmann equation:

1. Power.
2. Elastic power loss.
3. Inelastic power loss.
4. Characteristic Energy.
5. Total ionization frequency.

The values shown in the electronic parameter plots for various concentrations of neon and copper were calculated using the following equations:

1. **Power /N (eV m³/s)**

Energy per unit time absorbed by the electrons from the electric field, calculated from different expressions depending on the field configuration, as follows.

DC electric field with temporal growth (PT) or without growth:

$$(P / N) = (\mu N)(E / N)^2$$

DC electric field with spatial growth (SST):

$$(P / N) = (\mu N)(E / N)^2 \left(\frac{1}{2} + \frac{1}{2}\left(1 - \frac{4\,(DN)((v_{iz} - v_{at})/N)}{(\mu N)^2\,(E / N)^2}\right)^{1/2}\right)$$

AC electric field:

$$(P / N) = (\mu_{Re} N)(E / N)^2$$

DC electric field crossed with magnetic field under angle β:

$$(P / N) = \left((\mu_{Re} N)\sin\beta + (\mu N)\cos\beta\right)(E / N)^2$$

2. **Elastic power loss /N (eV m³/s)**

$$(P_{el} / N) = \sum_{k=elastic} \gamma\, x_k \frac{2m_e}{M_k} \int_0^{\infty} \left[\sigma_k \left(\varepsilon^2 f_0 + \frac{K_B T}{e} \frac{\partial f_0}{\partial \varepsilon}\right)\right] d\varepsilon$$

Total net energy loss rate due to elastic electron-neutral collisions, without electron-ion Coulomb collisions.

3. **Inelastic power loss /N (eV m³/s)**

$$(P_{inel} / N) = \sum_{k=inel} u_k\, x_k \left(y_k^{low}\, k_k - y_k^{up}\, k_k^{inv}\right)$$

Total net energy loss rate due to inelastic collisions, including super-elastic collisions.

4. **Characteristic Energy (eV)**

$$v_{ch} = e\, \frac{De}{\mu e}$$

5. **Total ionization frequency /N (m³/s)**

$$(v_{iz} / N) = \gamma \int_0^{\infty} \sum_{k=ionization} x_k\, \sigma_k\, \varepsilon\, f_0\, d\varepsilon$$

Total ionization frequency, number of electrons created per unit time.

List of symbols

N (m^{-3}) : Total gas particle number density

γ ($C^{1/2}kg^{-1/2}$): Constant coefficient: $\gamma = (2e / m_e)^{1/2}$

ε (eV) : Electron energy

e (C) : Elementary charge

f_0 ($eV^{-3/2}$) : Isotropic part of electron distribution function, corresponding to zeroth-order term of spherical harmonics expansion in velocity space, sometimes called "electron energy probability function" (EEPF) [8].

m_e (kg) : Electron mass

σ_k (m^2) : Cross section of electron-neutral collision process k. For inelastic processes this is the total cross section, for elastic processes the momentum-transfer cross section.

x_k (1) : Fractional particle number density of target gas species of collision process k.

E (V/m) : Electric field

M_k (kg) : Particle mass of target particles of collision process k.

u_k (eV) : Threshold energy of inelastic collision process k.

y_k^{low} (1) : Fractional population of lower quantum state of excitation process k, set to 1 for other collision types.

y_k^{up} (1) : The fractional population of the upper quantum state during the excitation process k is assigned a value of zero for all other types of collisions.

Transport parameters are essential because they link electron–gas collision cross sections with gas discharge phenomena and glow discharge models relevant to gas lasers, lamps, and plasma display panels [15]. A detailed analysis of these parameters over a wide range of electric fields is critical for understanding electron transport behavior in gaseous plasma discharges [16].

RESULTS AND DISCUSSION

Figure 1, illustrates the power as a function of the reduced electric field E/N for a copper–neon gas mixture at various copper concentrations ranging from 0.001 to 0.5 mole. The vertical axis represents the power divided by the particle density N, expressed in units of (eV ·m^3/s), while the horizontal axis shows the reduced electric field E/N, in units of Townsend (Td), for values ranging from 1 to 20 Td.

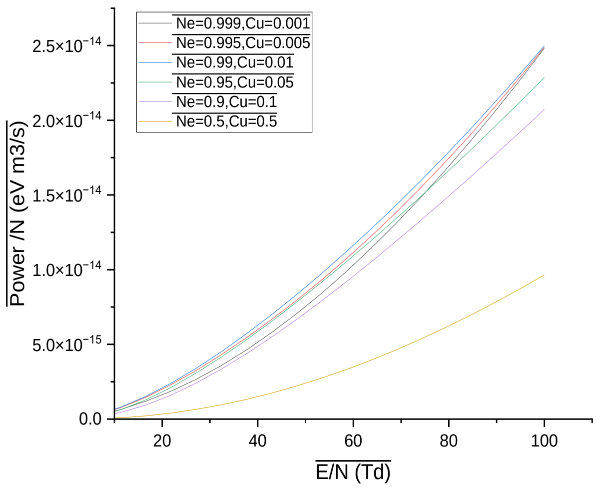

Figure 1. The Power as a function of reduce electric field (E/N), for different concentrations of Cu (0.001- 0.5) mole in Ne-Cu mixture.

1. Influence of reduced electric field on power

The figure (1) clearly shows that increasing the value of the reduced electric field E/N significantly influences the power of the Ne–Cu plasma mixture. This is reflected in the behavior of the curves: at approximately 5 Td, the curves begin to rise in a quasi-exponential manner and continue this trend with further increases in E/N, reaching a peak at around 20 Td. Hence, higher E/N values positively impact power enhancement, which also depends on the concentration of each element in the mixture. This phenomenon is attributed to the ability of free electrons to ionize neon and copper atoms after gaining sufficient energy from the applied high reduced electric field. As the ionization rate increases, more electrons and ions are produced, resulting in lower electrical resistance and higher current both of which contribute to increased power due to their direct relationship. There is a relationship between the density of electrons in the plasma and the number of particles measured [17]. As electrons gain more energy, they accelerate, resulting in an increased frequency of collisions. These collisions mainly involve ionization due to interactions between electrons and atoms, which further raises the number of charged particles in the mixture and improves electrical conductivity [18]. Additionally, these inelastic collisions lead to significant energy loss, resulting in higher power absorption. When atoms return to their ground state after being excited by high-energy electrons at elevated E/N ratios, they emit photons during their transition from higher energy levels. This radiative process adds to the total energy loss from the electrons and, consequently, the overall power absorbed. At lower electric field values, the discharge is weak; however, at higher E/N values, the discharge transforms into glow or even arc discharges. These transitions are associated with a significant increase in power due to the rise in electron density and higher current flow [19].

2. Influence of increasing copper concentration in the mixture on the power

From the Figure 1, it can be observed that as the concentration of copper increases, the power in the neon-copper mixture decreases. The figure shows that the highest curve, which corresponds to a very high concentration of neon, exhibits the maximum power value. This occurs at the composition (Ne = 0.999, Cu = 0.001). In contrast, the lowest curve—shown in a lighter color—corresponds to the highest copper concentration and exhibits the minimum power value, specifically at (Ne = 0.5, Cu = 0.5). This indicates that this particular mixture is the least efficient, as it leads to a reduction in the plasma's ability to absorb and transfer energy. This effect is due to energy losses caused by the introduction of a large number of copper atoms into the mixture. The presence of more copper increases the rate of ineffective collisions, as the electrons become less capable of exciting or ionizing atoms. As a result, the plasma's energy transfer capability is diminished, since copper atoms or ions absorb energy from the electrons, leading to a decrease in overall power [20].

Inelastic Power Loss Modeling

Inelastic power loss, as illustrated in Figure 2, is presented as a function of the reduced electric field E/N for a plasma mixture of copper and neon gas at various copper concentrations ranging from 0.001 to 0.5 mole. The vertical axis represents the inelastic power loss per particle density N, expressed in units of (eV ·m³/s), while the horizontal axis represents the reduced electric field E/N, measured in Townsend (Td), for values ranging from 1 to 20 Td.

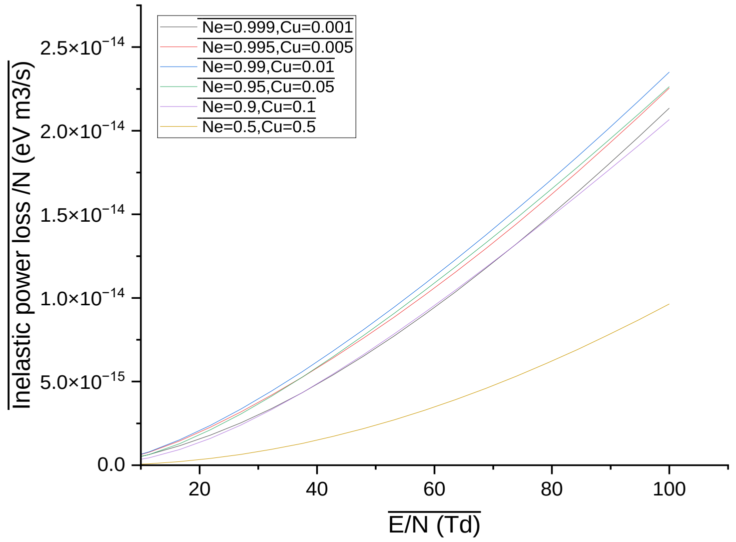

Figure 2. The Inelastic Power Loss as a function of reduce electric field (E/N), for different concentrations of Cu (0.001- 0.5) mole in Ne-Cu mixture.

1. Influence of reduced electric field on inelastic power loss

The Figure 2, shows a clear dependence of inelastic power loss on the reduced electric field E/N in the copper–neon mixture. As E/N increases, the inelastic power loss rises significantly. The curves originate near zero and show a steep increase at around E/N > 5 Td. The curves become significantly more pronounced and inclined, especially at E/N = 15 Td. It is further noted that the curve corresponding to the mixture with a higher copper concentration exhibits lower values compared to the mixture with a reduced copper content. This upward trend persists as E/N increases up to approximately 20 Td.

With increasing E/N, the electrons acquire greater kinetic energy, which results in more frequent inelastic interactions with copper or neon atoms. During such interactions, electrons impart energy to the atoms through various mechanisms, including ionization, excitation, and other radiative transitions. These processes do not contribute to the conduction current; rather, they lead to energy dissipation, classified as inelastic energy loss.

At elevated E/N values, additional mechanisms arise that further amplify inelastic energy dissipation. A prominent example is the heightened likelihood of multiple ionization, which occurs at elevated energy levels. In this case, not only is the first electron removed from the atom, but additional electrons can also be stripped, especially in copper atoms, which have multiple energy levels. As a result, multiply charged ions (such as Cu^{2+} or Cu^{3+}) are formed, a process that requires significantly higher energy input [21].

2. Influence of increasing copper concentration in the mixture on the inelastic power loss

The Figure 2, clearly illustrates the impact of a high copper concentration in the gas mixture on inelastic power loss. It shows a noticeable decrease in inelastic power loss as the copper concentration increases. This trend is observed through the graph lines, where we move from the upper lines corresponding to the lowest copper concentration (Ne = 0.999, Cu = 0.001) to the lower lines, which represent the highest copper concentration (Ne = 0.5, Cu = 0.5). A reduction in inelastic power loss is evident along this transition. This decrease in inelastic power loss can be attributed to the increase in copper concentration, which is accompanied by a corresponding decrease in neon concentration. Neon atoms have a larger and more effective cross-section for inelastic collisions compared to copper. As a result, the reduced number of neon atoms available for electrons to interact with leads to fewer inelastic collisions. Instead, electrons undergo more frequent elastic collisions with copper atoms, causing them to lose kinetic energy more rapidly before reaching the energy threshold necessary to induce effective inelastic collisions [22]. Consequently, the overall inelastic power loss in the neon-copper gas mixture decreases.

Elastic Power Loss Modeling

Elastic power loss is presented as a function of the reduced electric field E/N for a copper–neon gas mixture at various copper concentrations ranging from 0.001 to 0.5 mole, as shown in Figure 3. The vertical axis represents the elastic power loss per particle density N, expressed in (eV ·m^3/s), while the horizontal axis corresponds to the reduced electric field E/N, in Townsend (Td), for values ranging from 1 to 20 Td.

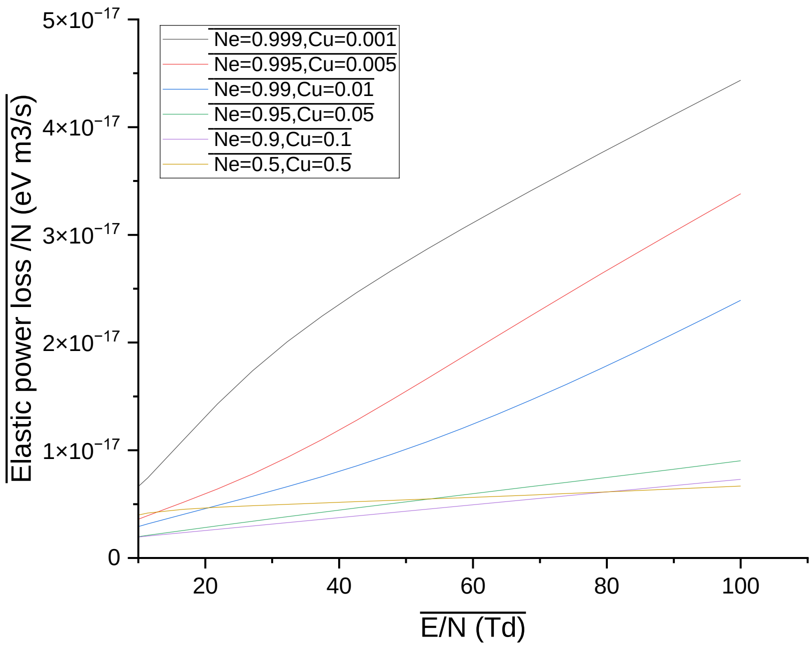

Figure 3. The Elastic Power Loss as a function of reduce electric field (E/N), for different concentrations of Cu (0.001- 0.5) mole in Ne-Cu mixture.

1. Influence of reduced electric field on elastic power loss

The Figure 3, indicates that elastic power loss increases significantly with rising E/N. All curves show a noticeable upward trend after approximately E/N = 2-5 Td; however, the exact point at which this increase begins differs depending on the mixture composition. For mixtures with a higher neon concentration, the curve begins to rise sharply at around E/N > 3 Td, as clearly seen in the pronounced upward bend. On the other hand, the mixture with a higher copper concentration begins to increase at approximately E/N = 2 Td, but unlike the other mixtures, it shows a gradual decrease afterward. Nevertheless, the elastic power loss continues to rise overall as E/N increases up to 20 Td. This behavior is attributed to the fact that electrons acquire greater energy from the high reduced electric field, leading to an increase in collision rates [23]. As the electron velocity increases, the frequency and energy of collisions with neon and copper atoms also increase, leading to significant energy dissipation. At high E/N ratios, the energy distribution does not reach equilibrium, causing a persistent loss of energy and an increase in elastic energy loss. With an increase in the E/N ratio, elastic and inelastic collisions become intertwined. Electrons may gain enough energy to reach the excitation or ionization thresholds, which makes even elastic collisions energetically costly. At high E/N ratios, "hot electrons" emerge. While they represent a small fraction of the total collisions, they significantly increase the elastic energy loss through more intense and frequent collisions. This "non-linear" effect greatly influences the overall behavior of the plasma. Additionally, changes in electron density and plasma polarity also contribute to the unexpected rise in elastic power loss [24].

2. Influence of increasing copper concentration in the mixture on the elastic power loss

It can be observed from the Figure 3, that the value of elastic power loss gradually decreases as the concentration of copper in the neon-copper mixture increases. The figure clearly shows that higher copper concentrations represented by the lower curve corresponding to the values (Ne = 0.999, Cu = 0.001), result in the lowest elastic power loss. In contrast, the highest elastic power loss is clearly seen in the upper curve, corresponding to the values (Ne = 0.5, Cu = 0.5). This indicates that the influence of copper concentration becomes more pronounced at higher E/N values. This behavior can be explained by considering that neon atoms are light, with an approximate atomic mass of 20 u, which makes them more efficient in transferring energy from electrons. This clearly demonstrates the effect of adding neon gas to different mixtures, which alters the insulating properties of the gas mixture [25]. When the number of copper ions increases in the mixture copper having a higher atomic mass of about 63.5 u the presence of these heavier atoms leads to a reduction in the overall energy transfer rate. This occurs due to a decrease in the collision frequency between electrons and heavy ions. Since elastic power loss is directly proportional to the electron-ion collision frequency, any reduction in this frequency causes a corresponding decrease in elastic power loss. Therefore, the increased concentration of copper atoms in the mixture enhances the reduction in energy transfer efficiency from electrons to ions during elastic collisions.

Characteristics Energy Modeling

Figure 4, below illustrates the characteristics energy as a function of the reduced electric field E/N for various concentrations of Cu (0.001–0.5 mole) in the (Cu + Ne) mixture, represented by the colored curves. The horizontal axis represents the reduced electric field E/N in units of Townsend (Td), with selected values ranging from 1 to 20 Td. The vertical axis shows the energy properties measured in electron volts (eV).

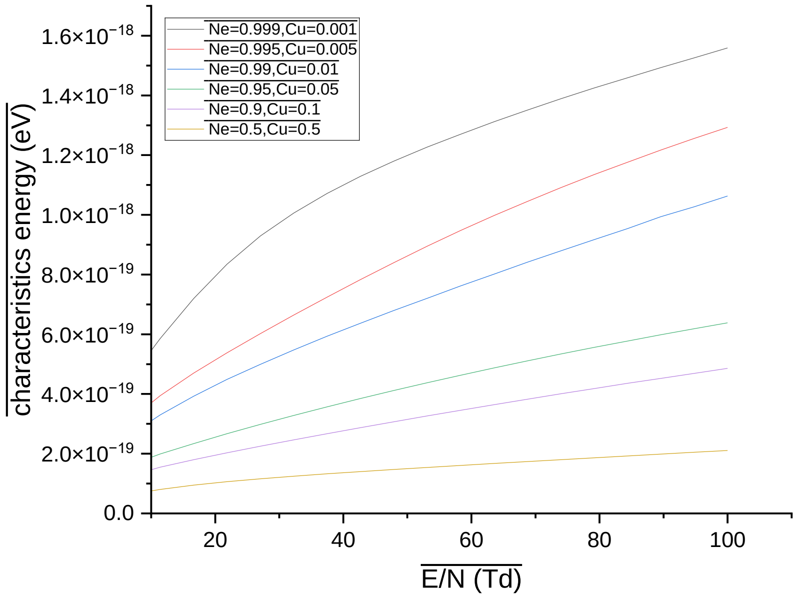

Figure 4. The characteristics energy as a function of reduce electric field (E/N), for different concentrations of Cu (0.001- 0.5) mole in Ne-Cu mixture.

1. Influence of reduced electric field on characteristics energy

Figure 4, illustrates the direct effect of the low electric field (E/N) on the energy characteristic, where an increase in this field leads to an increase in the measured energy characteristic. This behavior is clearly visible in the curves, which display a similar trend: a rapid and significant rise at low values (0–7 Td), followed by a slower and more gradual increase at higher values, as the curves tend to stabilize at approximately 19 Td. This increasing relationship arises because higher E/N ratios improve the efficiency of electron transport through the gas. This enhanced transport reduces the losses resulting from elastic collisions, allowing the system to retain more energy in the form of effective electronic energy. Furthermore, the number of inelastic collisions increases at high E/N values, leading to greater energy storage within the atomic system. In addition, this leads to the generation of more electrons, which increases the total energy transferred. Heavy copper atoms exhibit a decreased capacity to dissipate the energy transferred to electrons as heat under high conditions, which results in higher energy retention within the system. At elevated values, double layers may form due to abrupt changes in electric potential. These layers consist of a positively charged region opposite a negatively charged one. Their formation is caused by an imbalance in the flow of particles (ions and electrons), or when electron energy rises because of the high. Furthermore, a high reduced electric field causes the system to reach ionization saturation, known as ionization saturation, which leads to changes in gas behavior. The gas properties shift from those of a partial insulator to those of a semiconductor. This transition causes a rapid accumulation of high energy within a short time [26].

2. Influence of increasing copper concentration in the mixture on the characteristic's energy

Based on the Figure 4, it can be concluded that the energy properties of the neon–copper mixture decrease as the concentration of copper increases. This is evident at the concentrations (Ne = 0.999, Cu = 0.001), where the energy properties are high due to the very low copper content. In contrast, at the concentrations (Ne = 0.5, Cu = 0.5), a noticeable decline in energy properties is observed as a result of the increased copper concentration in the mixture.

Copper atoms, being heavier and larger than neon atoms, cause undesirable inelastic collisions. These collisions result in significant energy loss in the form of heat rather than contributing to ionization or radiation. Furthermore, since neon has a relatively low ionization energy, its ionization efficiency decreases in the presence of increasing copper content [27]. This leads to a lower number of free electrons and, consequently, a reduction in plasma energy density. Therefore, it can be concluded that the energy characteristics of the neon–copper mixture decline with increasing copper concentration. All these factors collectively contribute to the decline in the energy characteristics of the neon–copper mixture as the copper concentration increases.

Total Ionization Frequency

Figure 5, illustrates the total ionization frequency as a function of the reduced electric field E/N for a copper–neon gas mixture at various copper concentrations, ranging from 0.001 to 0.5 mole. The horizontal axis represents the reduced electric field E/N, measured in Townsend (Td), within the range of 1 to 20 Td. The vertical axis shows the total ionization frequency divided by the particle number density, in units of (m3/s).

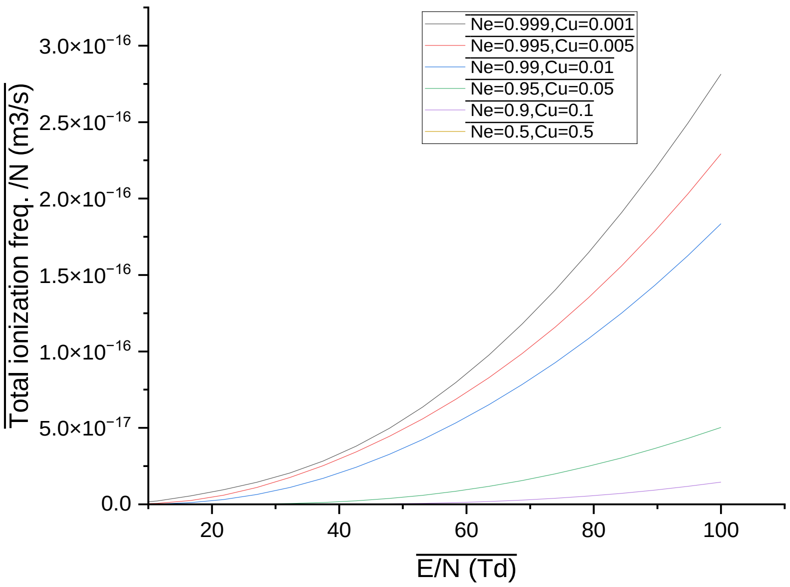

Figure 5. The Total Ionization Frequency as a function of reduce electric field (E/N), for different concentrations of Cu (0.001- 0.5) mole in Ne-Cu mixture.

1. Influence of reduced electric field on total ionization frequency

The total ionization frequency increases with rising values of the reduced electric field E/N, as seen in the Figure 5. Initially, the curves begin at zero, then show a noticeable increase around 10 Td. Beyond this range, particularly at E/N > 13 Td, the ionization frequency increases exponentially, as indicated by the steep upward slope of the curves. This increase occurs because a higher allows free electrons within the gas to gain more energy between collisions. Consequently, these electrons become increasingly effective at ionizing gas atoms or molecules via inelastic interactions, resulting in a larger production of ions, a higher rate of ionization.

At low electric field intensities, a substantial fraction of the electrons' energy is dissipated in non-ionizing interactions, such as elastic collisions and excitation processes. However, at elevated, the electrons acquire enough energy to overcome these intermediate processes and proceed directly to ionization. In low-pressure plasma environments with high, electrons are effectively "heated," enabling them to sustain repeated ionization events with minimal energy loss [28]. This leads to a substantial increase in the total ionization frequency.

2. Influence of increasing copper concentration in the mixture on the total ionization frequency

It can be inferred from the Figure 5, that the total ionization frequency in the neon-copper mixture decreases as the concentration of copper atoms increases. This decrease is evident from the shift in the line position on the graph, which occurs as the proportion of neon decreases and that of copper increases. This effect is clearly illustrated by the yellow line at the bottom, which corresponds to equal concentrations of the two elements (Ne = 0.5, Cu = 0.5). In contrast, the black line at the top represents the state with a high neon concentration and a very low copper concentration (Ne = 0.999, Cu = 0.001), where the total ionization frequency is higher due to the near-complete absence of copper. Increasing the concentration of copper in the mixture reduces ionization efficiency. Unlike neon, copper tends to scatter electrons through non-ionizing collisions, which cause the electrons to lose energy without resulting in ionization. As a consequence, the total ionization frequency decreases. Plasma diagnostics include all the methods and techniques employed to determine the macroscopic and microscopic properties and parameters of plasma, aiming to obtain a clearer and more comprehensive understanding of plasma behavior [29].

CONCLUSION

Fundamental Finding : The study investigated the transport and energy characteristics of Neon–Copper plasma mixtures and found that increasing copper concentration reduces total power along with elastic and inelastic power losses, with mixture curves showing behavior dependent on the reduced electric field to gas concentration ratio (E/N), where higher copper concentrations produce slower-rising curves compared to mixtures with lower copper and higher neon. **Implication:** These results highlight that both electric field strength and copper concentration are key determinants of energy transport in mixed-gas plasma systems, offering a foundation for optimizing plasma performance through adjustments in composition and field conditions. **Limitation :** The study is limited to Neon–Copper mixtures and does not examine other gas combinations, nonlinear plasma behaviors, or external influences such as temperature, pressure variations, or magnetic fields. **Future Research :** Future studies should explore additional gas mixtures, evaluate a wider range of physical parameters, and develop predictive models incorporating dynamic plasma conditions to further improve the optimization of mixed-gas plasma systems.

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