Electron Transport and Discharge Behavior in Cryogenic He-N_2 Mixtures: Boltzmann Equation Analysis

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ABSTRACT

For the first time, electron swarm parameters (electron drift velocity, mean energy, reduced diffusion coefficient, reduced electron mobility, and ionization coefficient) were calculated in cryogenic binary He–N_2 mixtures containing 1%, 4%, 8%, 15%, and 20% of Nitrogen (N_2) at a low temperature of 77 K, and a pressure of 1 MPa, over a wide range of reduced electric field strength E/N=1-200 Td (1Td=10^{-17} V cm^2), with E being the electric field strength in (Vcm^{-1}), and N the gas number density in (particle cm^{-3}). These swarm parameters were analyzed using a two-term expansion of the Boltzmann equation, along with electron collision cross sections for Helium (He) atoms and Nitrogen (N_2) molecules. For pure He, the obtained results are in good agreement with previously reported experimental and theoretical findings. Furthermore, the influence of the reduced field strength E/N was examined, demonstrating that even a small concentration of N_2 significantly affects the Electron Energy Distribution Function (EEDF) and swarm parameters. The present results will be helpful for high-energy physics detectors, cryogenic tracking systems, low-temperature plasmas, high-voltage insulation systems, gas discharge, and superconducting technologies.

Keywords-He atom; N_2 molecule; transport parameters; Boltzmann equation; superconductor; low-temperature; ionization; distribution function; cross-sections

I. INTRODUCTION

Superconductors, identified in 1911, exhibit no resistance at their critical temperatures. These materials are divided into Low-Temperature Superconductors (LTS), with critical temperatures below 30 K, and High-Temperature Superconductors (HTS), discovered in 1986, with critical temperatures starting at 35 K. LTS and HTS are both significant in plasma physics. LTS are non-equilibrium plasmas (Te>>Tg) where electrons are energetic, but the bulk gas remains relatively cold. LTS are widely used in surface processing, environmental protection, biomedical applications, semiconductor manufacturing, and cryogenic plasma studies of electron kinetics, such as Electron Energy Distribution Function (EEDF) and transport coefficients, using the Boltzmann equation. HTS plasmas are those where electrons and heavy particles are in thermal equilibrium (Te ≈ Tg). Typically, at very high temperatures, they are governed by the thermal plasma theory and fluid models rather than kinetic models. This is important in high-energy physics and plasma physics. HTS are widely employed for studying transport coefficients, radiation, and thermodynamic properties, fusion research, arc discharges, metallurgy and material processing, and astrophysical plasmas. Superconducting applications commonly use Nitrogen (N_2), with a critical temperature range of 66-77 K, and Helium (He), with a range of 1.2-4.2 K for cooling [1]. Liquid N_2 and gaseous He are standard cryogenic media often used for HTS power applications, as N_2 has the property of high heat capacity and high dielectric strength. As for gaseous He, its wide working temperature range, low dielectric strength, and decreased asphyxiation peril make it extremely important [2, 3].

Generally, N_2 is a non-polar gas, with a boiling point of 77 K, colorless, odorless, non-flammable, tasteless, non-poisonous, slightly soluble in water, and its breakdown voltage is 32.9 (kV/cm bar). However, He has unique properties with a low boiling point of 4.21 K, high thermal conductivity, and is colorless; it is used in many applications. Besides its pure form, N_2 is also utilized in gas mixtures with SF_6, O_2, and CO_2 for industrial purposes [4-6]. The dielectric strength, EEDF, and key electron transport parameters, including the reduced ionization coefficient, attachment coefficient, effective ionization coefficient, and critical reduced electric field in both binary He-H_2 and ternary He-H_2-N_2 gaseous cryogenic mixtures, have been calculated using the Boltzmann equation analysis over a wide range of temperatures (50–80 K) and pressures 2 MPa relevant to HTS applications [7]. Authors in [8] used the Monte Carlo method to calculate the electron transport coefficients in N_2, N_2-He, and N_2-Ar mixtures, considering anisotropic inelastic electron scattering and the partitioning of residual energy after ionization collisions based on experimental results.

The electron transport coefficient in a pure N_2 molecule was obtained using both theoretical and experimental methods. A good agreement of the calculated and measured parameters was found in [9]. The experimental determination of transport coefficients in gases is not easy; thus, theoretical calculation is the preferred method. Furthermore, the Monte Carlo Simulation Method has been used to calculate electron mobility, transverse diffusion coefficient, and ionization coefficient in methane [10].

The electron transport parameters, dielectric breakdown properties, and EEDF in SF_6-CO_2 mixtures with different concentrations in the E/N range of 50–1000 Td were calculated by two-term spherical harmonic expansion of the Boltzmann equation [11].

The purpose of the current study is to provide the distribution function and electron swarm coefficients in He and its mixtures with N_2 for the first time. The Boltzmann equation was used for these calculations at a low temperature of 77 K in the reduced electric field strength E/N range covering 1 Td to 200 Td, where E is an applied d.c electric field, and N is the natural number density. Reduced field strength (E/N) is a key control parameter in plasma physics because it directly determines how electrons gain and lose energy during collisions. It also controls ionization and electrical breakdown, ensures plasma stability and non-equilibrium conditions, and enables a precise study of transport and kinetic properties. The drift characteristics in the He-N_2 mixture are important to understand the discharge plasmas.

The study of cryogenic He–N_2 mixtures at 77 K advances low-pressure and weakly ionized plasma physics by improving the understanding of electron kinetics and transport under non-equilibrium conditions. At this low temperature, collision dynamics, energy loss processes, and vibrational excitations of N_2 significantly influence the EEDF and the related transport coefficients. This provides more accurate data for validating Boltzmann equation solutions. As a result, the present study enhances theoretical models and supports more reliable predictions of plasma behavior in cold, weakly ionized gas mixtures, which are significant for both fundamental research and practical applications.

II. BOLTZMANN EQUATION

The general form of the Boltzmann equation for the spherically symmetric part of the distribution function $f_o(\varepsilon)$ without the effect of second kind collisions can be written as [12]:

$$\frac{E^2}{M}\frac{d}{\varepsilon}\left(\frac{u}{NQ_m^T(\varepsilon)}\frac{df_o(\varepsilon)}{f\varepsilon}\right)+\frac{2m}{M}\frac{d}{d\varepsilon}\left(\varepsilon^2NQ_m^T(\varepsilon)\right)+\frac{2mK_BT_g}{Me}\frac{d}{d\varepsilon}\left(\varepsilon^2NQ_m^T(\varepsilon)\frac{df_o(\varepsilon)}{d\varepsilon}\right)+\sum_j(\varepsilon+\varepsilon_j)f_o(\varepsilon+\varepsilon_j)NQ_j\left(\varepsilon+\varepsilon_j\right)-\varepsilon f_o(\varepsilon)N_j\sum_j Q_j(\varepsilon) \quad (1)$$

where m is the mass of the electron, T_g is the absolute temperature, K_B is the Boltzmann constant, M is the mass of a molecule, N is the number of molecules per cm^3, E is the electric field strength, $Q_m(\varepsilon)$ is the total effective momentum transfer cross-section, $Q_J(\varepsilon)$ is the inelastic cross-sections, ε is the energy of the electron, and ε_j is the excitation energy of the jth excitation state in (eV). The distribution function is normalized by (2):

$$\int_0^\infty \sqrt{\varepsilon}f_o(\varepsilon)d\varepsilon=1 \quad (2)$$

The swarm coefficients were computed using sets of elastic and inelastic cross-sections derived from the EEDF. For gas mixtures, the electron drift velocity (v_d), density-diffusion coefficient (ND), reduced electron mobility (μN), electron mean energy <ε>, and electron temperature can be written as [13, 14]:

$$v_d=-\frac{\gamma E}{3N}\int_0^\infty\frac{\varepsilon}{\sum_k\delta_kQ_{m,mix}^T(\varepsilon)}\frac{\partial f_0(\varepsilon)}{\partial\varepsilon}d\varepsilon \quad (3)$$

$$ND=-\frac{\gamma}{3}\int_0^\infty\frac{\varepsilon}{\sum_k\delta_kQ_{m,mix}^T(\varepsilon)}f_o(\varepsilon)d\varepsilon \quad (4)$$

$$\mu=\frac{v_d}{E} \quad (5)$$

$$\langle\varepsilon\rangle=\int_0^\infty\varepsilon^{3/2}f_0(\varepsilon)d\varepsilon \quad (6)$$

$$T_e=\frac{2}{3}\langle\varepsilon\rangle \quad (7)$$

where $\delta_k=N_k/N$ is the percentage of molecules of species k, $\gamma=(2e/m)^{1/2}$ and $Q_m^T(\varepsilon)$ are the "total effective momentum transfer cross-section", given by:

$$Q_m^T(\varepsilon)=Q_m(\varepsilon)+Q_i(\varepsilon)+\sum_J Q_{ex}(\varepsilon) \quad (8)$$

where $Q_m(\varepsilon)$, $Q_i(\varepsilon)$, and $Q_{ex}(\varepsilon)$ are the momentum transfer, ionization, and excitation (vibration, electronic) cross sections, respectively. For a gas mixture, to determine the associated cross-section sets, the total cross-sections of the ternary mixture are calculated by multiplying the collision cross-sections of the component gases by their respective percentages in the mixture:

$$Q_{m,mix}^T(\varepsilon)=\sum_n K_nQ_m^T(\varepsilon) \quad (9)$$

where K_n is the percentage of gas in the mixtures [15]. For the binary He-N_2 mixture, the momentum transfer cross section is computed using:

$$Q_{m,mix}^T=K_{He}Q_{m,He}+K_{N_2}Q_{N_2} \quad (10)$$

The reduced ionization coefficients are given by [16]:

$$\frac{\alpha}{N}=\frac{\gamma}{v_d}\int_I^\infty\sum_k\delta_k\,Q_i(\varepsilon)\,f_0(\varepsilon)\varepsilon d\varepsilon \quad (11)$$

where $Q_i(\varepsilon)$ are the ionization cross sections, and I denotes the ionization energy (threshold), which is 15.8 eV for He and 15.6 eV for N_2.

III. CROSS SECTION

In this investigation, electron collision cross-sections are essential for calculating the EEDF and electron swarm parameters in cryogenic He–N_2 mixtures. In this study, four types of cross-section data were used for N_2 molecules: momentum transfer, vibrational excitation, electronic excitation, and ionization, with a threshold energy of 15.6 eV [17, 18]. For He atoms, the momentum transfer cross-section [19], the ionization cross-section [18] with a threshold energy of 15.8 eV, and the electronic excitation cross-sections [20] were used as the initial datasets.

IV. RESULTS AND DISCUSSION

In this research, electron collision cross-section datasets for N_2 and He were utilized to derive the EEDF and drift characteristics, with cross-section energies extending to 100 eV. Using the Boltzmann equation method, the electron swarm characteristics in different He-N_2 gas mixtures have been examined from 1 Td to 200 Td. Equation (1) was numerically solved using experimentally measured cross-section data of He and N_2 for processes such as vibration and electronic excitation, and ionization caused by electron impacts. The normalized EEDF and electron swarm parameters in pure N_2 and He are calculated using the two-term approximation of the Boltzmann equation in dc uniform fields in the range 1–200 Td, at a pressure of 1 MPa and a temperature of 77 K. For both gases, the momentum transfer cross-sections are greater than the inelastic cross-sections. This is a necessary condition for the two-term approximation solution of the Boltzmann equation to be valid [14]. The EEDF is one of the most important parameters for gas discharge phenomena and is used for calculating electron swarm parameters.

Figures 1 and 2 display the relationship between the EEDF and electron energy for various reduced electric field strengths (E/N) for pure N_2 and He, respectively. The EEDF is highly sensitive to changes in E /N, with higher E/N values causing the EEDF curves to extend toward higher energy ranges. The distribution function is normalized according to (2).

At low electron energy, the shape of the energy distribution function depends on the momentum transfer cross-sections. For N_2, when the electron energy ≤ 1.7 eV, and for He when the electron energies ≤3 eV, the EEDF decreases as the reduced electric field strength E/N increases. The tail of the distribution decreases, and only a small number of electrons have energies greater than the ionization potential. For the lowest value of E/N≤ 1Td, the electron energy is thermal. The ionization degree $(ne/N) > (Q(\varepsilon)/10^{-13})\,\varepsilon^2$ [where, ε is energy (eV) and $Q(\varepsilon)$ is collision cross-section (cm²), ne is electron density, N is neutral gas density] can be of the order of 10^{-3}–10^{-4}, which is sufficient for the distribution to become Maxwellian, indicated by the straight line with a slope of $(-1/K_BT_g)$. In this case, the ionization degree is very small, and the He atoms and N_2 molecules are in the ground state. When the electron energy is greater than 1.7 eV and 3 eV for N_2 and He, respectively, the EEDF increases with increasing E/N, then the electrons gain higher kinetic energy, and the tail extends to energies above the ionization potential; the distribution is non-Maxwellian. As E/N increases, the degree of ionization increases, and then the number of particles with energies higher than the excitation energy increases. Consequently, the energy tends to spread due to collisions.

Since the EEDF is the basis for understanding electron parameters, Figure 3 demonstrates the influence of N_2 proportion on the EEDF of He-N_2 mixtures at a reduced electric field strength (E/N) of 10 Td, at a temperature of 70 K, and a pressure of 1 MPa. Compared with pure He gas, due to the relatively larger vibration excitation cross section and ionization cross section of N_2 molecules, it can be found that for electrons with energy lower than 3 eV, even a small percentage of N_2 (1%) significantly affects the EEDF. As a result of N_2 dominating the mixture, the electron population at lower energies increases with the addition of N_2. Whereas for electrons with energy higher than 3 eV, the tendency reverses, since ionization of gas molecules requires relatively high energy and increasing the N_2 fraction leads to a reduction in the proportion of the high-energy electron population. This reduction is attributed to the predominance of N_2 molecules, which dissipate electron energy through multiple processes, such as rotational and vibrational excitations, more effectively than He atoms. The increase in N_2 content in the mixed gas will also reduce the ionization rate of the mixed gas, which is also beneficial for improving the dielectric breakdown performance.

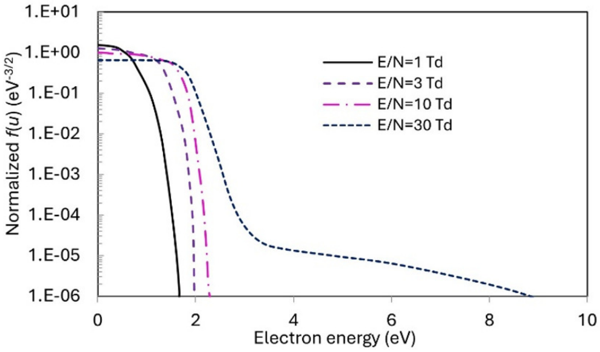

Fig. 1. EEDF for N_2 at different reduced field strengths E/N.

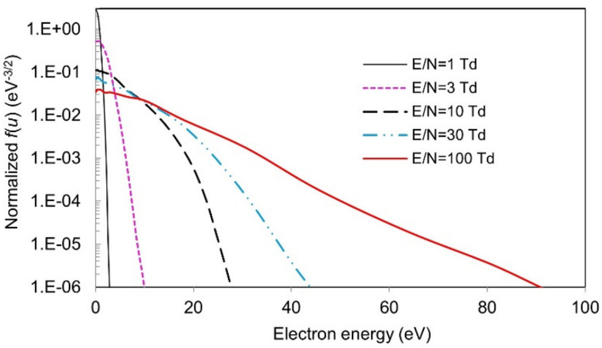

Fig. 2. EEDF for He at different reduced field strengths E/N.

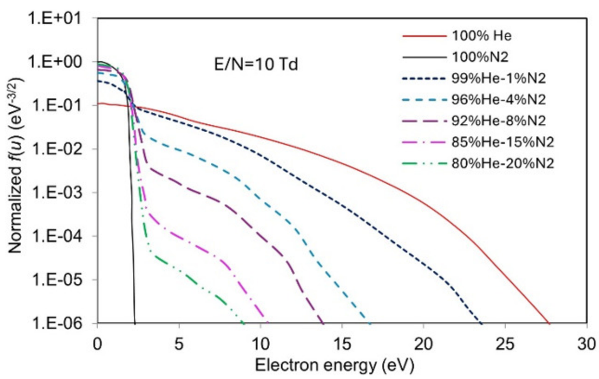

Fig. 3. EEDF for He-N_2 mixtures at E/N= 10 Td.

Cryogenic He–N_2 mixture studies (around 77 K) are more difficult than room-temperature plasma investigations, making theoretical modeling more informative for understanding weakly ionized plasmas. At cryogenic temperatures, collision frequency increases due to higher gas density, and electron energy loss mechanisms change significantly, strongly affecting the EEDF. Figure 4 displays the variation of mean electron energy in He-N_2 mixtures as a function of the reduced electric field E/N, demonstrating an increase in electron mean energy with rising E/N. For pure N_2, the current calculation is consistent with the experimental data [15]. The mean electron energy was determined for pure N_2 and He, as well as for mixtures with 1%, 4%, 8%, 15%, and 20% N_2 content. At low temperatures (e.g., cryogenic conditions), the decrease in mean energy with increasing N_2 is strong and noticeable. Figure 5 illustrates that at a fixed value of E/N= 50 Td, the mean energy decreases with increasing N_2 content. The observed decrease in the mean electron energy with increasing N_2 concentration is primarily due to the inelastic collision (vibrational and electronic excitation) of N_2 molecules. The electrons continuously transfer energy into these modes. Increasing the N_2 fraction increases the probability that electrons collide with N_2 rather than He, which acts as a strong energy loss mechanism. These processes remove energy from electrons even at relatively low energies (vibrational excitation thresholds), leading to a suppression of the high-energy tail of the EEDF. Consequently, the overall distribution shifts toward lower energies, resulting in a reduced mean electron energy. In monoatomic He atoms, electrons mostly lose energy through elastic collisions, allowing electrons to continuously gain energy from the applied electric field and maintaining a relatively high energy distribution function. This behavior is well described by two-term expansion solutions of the Boltzmann equation, where the steady-state electron energy is determined by a balance between the energy gain from the electric field and the energy losses through collisions. The N_2 molecules in binary He-N_2 mixtures increase the collision frequency and inelastic energy loss rate, thereby reducing the electron mean energy.

Equation (7) can be used to determine the electron temperature (T_e) in He-N_2 mixes based on the computed EEDFs. Figure 6 depicts the variation of T_e as a function of the reduced electric field (E/N) for different N_2 concentrations. It is observed that the electron temperature decreases with increasing N_2 content, while the T_e value for pure He has the highest values across the entire E/N range. This reduction is attributed to enhanced inelastic collisions in N_2, particularly vibrational excitation, which dissipate electron energy. In He–N_2 mixtures, the difference in T_e between various compositions becomes more noticeable around E/N ≈ 4 Td (approximately 0.6 eV), and continues to increase at higher electric fields. The electron temperature remains nearly constant at low fields (E/N ≤ 10 Td), where the energy gain from the electric field is limited, and increases at higher fields (E/N > 10 Td) as electrons gain more energy. The variation of T_e with E/N shows a nonlinear behavior for pure He, pure N_2, and their mixtures. This nonlinearity arises from the changing balance between energy gain and energy loss mechanisms, with N_2 playing a dominant role due to its large vibrational excitation cross sections.

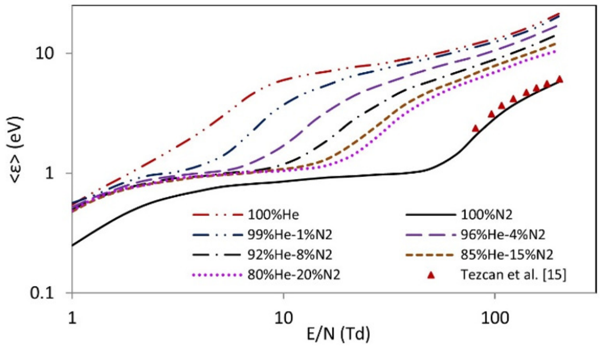

Fig. 4. Mean electron energy for He-N_2 mixtures.

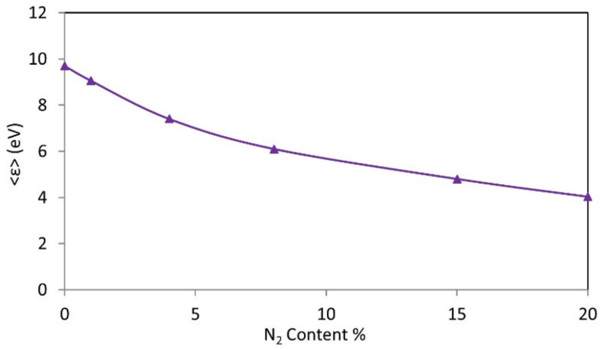

Fig. 5. Relation between mean energy and N_2 content at E/N=50 Td.

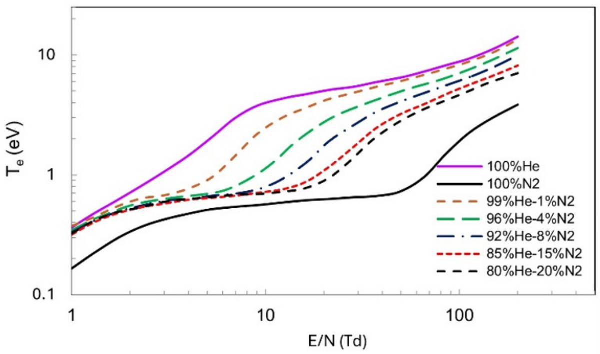

Fig. 6. Electron temperature for He-N_2 mixtures.

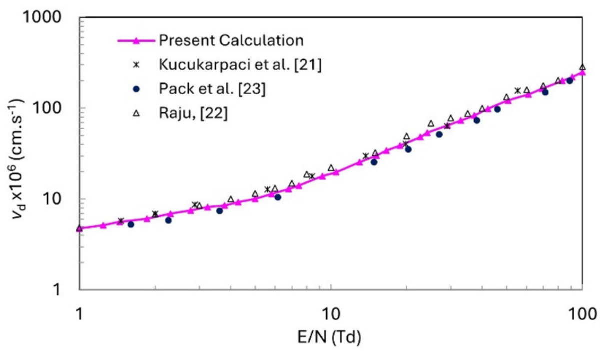

Fig. 7. Electron drift velocity in pure He.

The credibility of the two-term Boltzmann equation solution is reinforced by comparing the calculated electron drift velocity and the reduced ionization coefficient obtained in this study with prior experimental and theoretical findings. Figure 7 presents the calculated drift velocity for He, aligning well with experimental results [21] and theoretical predictions [22]. The experimental data of [23] are consistently lower than the current findings, with the discrepancy expanding to around 9% for E/N values greater than 6 Td.

Figure 8(a) shows variations in the electron drift velocity in He-N_2 mixtures over a reduced electric field strength range of 1-200 Td at 77 K. The drift velocities of 1%, 4%, 8%, 15%, and 20% N_2 in binary mixtures lie between those of pure He and N_2. The drift velocities increase with an increasing E/N but decrease with an increase in the mixture's N_2 content. For comparison with N_2, the current study is in good agreement with the theoretical results [15] and the experimental values [24, 25] across the entire E/N range. Figure 8(b) illustrates the electron drift velocity in a 50% He-50% N_2 mixture, as calculated in the present paper, and compares it with the theoretical Monte Carlo simulation results [8] and the experimental data of [26] for E/N≤61 Td. The obtained results are lower than those inferred from the double shutter tube experiment, and in agreement with the Monte Carlo simulation for the range 1≤E/N≤61 Td.

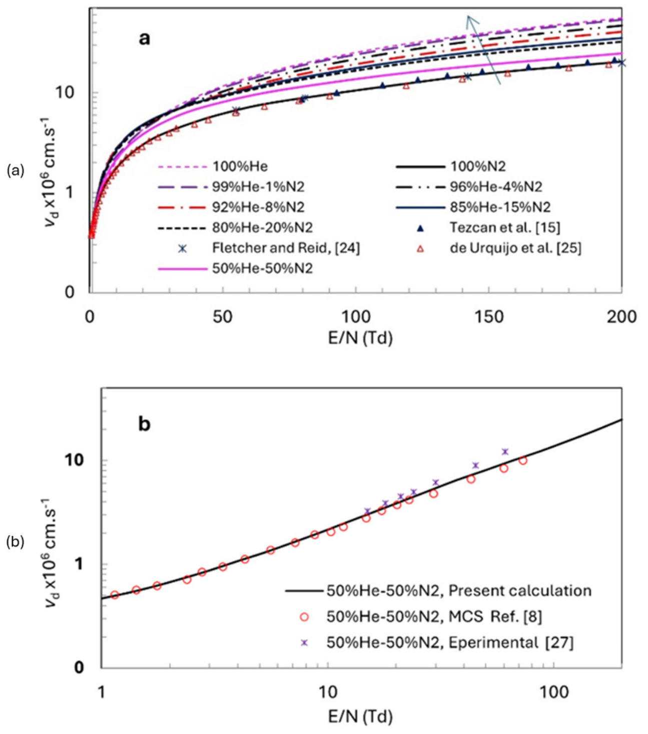

Fig. 8. Electron drift velocity for He-N_2 mixtures.

Figure 9 shows how electron mobility varies with the reduced electric field for pure He, pure N_2, and various He-N_2 gas mixtures. Mobility decreases with increasing E/N up to 10 Td, and then demonstrates a slight increase or flattening at higher E/N for He and its mixtures. Pure He shows higher mobility across the entire range than pure N_2. As N_2 concentration increases (from 1% to 20%), mobility decreases. The μN curves for the mixtures lie between those of the pure gases for E/N≥25 Td; across all values of E/N, pure N_2 has the lowest mobility. He has higher electron mobility due to lower electron cross-sections. Adding N_2 increases inelastic collisions and reduces mobility.

The reduced diffusion coefficients (*ND*) for pure He and He-N_2 mixes as a function of the E/N ratio are displayed in Figure 10. The relationship between the reduced diffusion coefficient and the reduced electric field strength E/N grows exponentially; the curves exhibit the same behavior across all increases in N_2 concentration. It is evident that at a fixed value of E/N, when the amount of N_2 increases, the reduced diffusion coefficients rapidly drop. There are two explanations for the changes in *ND*: First, the composition affects the effective collision frequency values for the momentum transfer in He and N_2 in (4). Second, the addition of the buffer gas N_2 alters the EEDF, which is the primary cause of the most notable changes.

The density-normalized reduced ionization coefficients (*α/N*) calculated using (11) in the work for He and N_2 gas mixtures with 1%, 4%, 8%, 15%, and 20% N_2 as a function of the reduced electric field strength (E/N) are shown in Figure 11. The results indicate that *α/N* increases with increasing E/N. Moreover, it can be observed that at a given value of E/N, the reduced ionization coefficients decrease with the increasing N_2 content in the cryogenic binary mixture. The reasons for the changes in α/N are: First, the effective collision frequencies for the momentum transfer in He and N_2 are different, and are weighted in (3) as the composition changes. Second, the most significant changes arise from the modifications on the EEDF with the addition of N_2 as a buffer gas due to higher inelastic cross-sections (vibration and electronic). For comparison, the present calculation using the Boltzmann equation is in excellent alignment with the experimental results for pure N_2 [25]. The dependable experimental data of this parameter for pure He at a temperature of 77 K [1] are compared with those of He. It is observed that the experimental values are slightly higher than the obtained values. Finally, the electron transport coefficients in such gas mixtures are largely influenced by the effects of inelastic collisions of N_2.

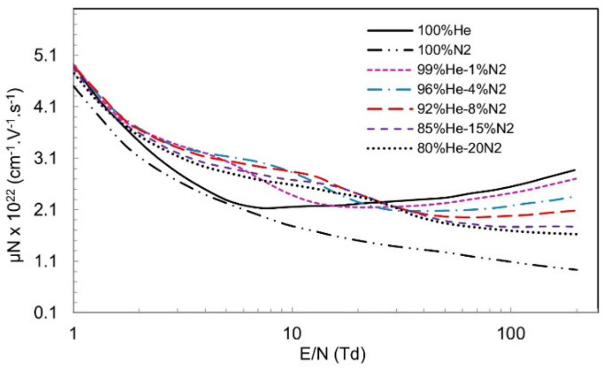

Fig. 9. Reduced electron mobility for He-N_2 mixtures.

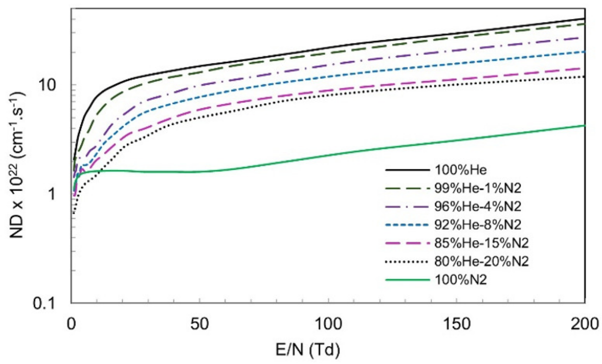

Fig. 10. Reduced diffusion coefficient for He-N_2 mixtures.

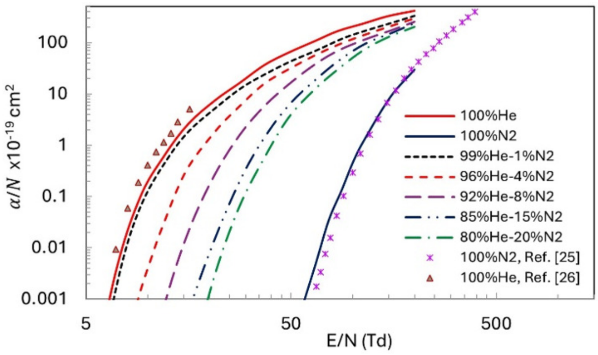

Fig. 11. Reduced ionization coefficient for He-N_2 mixtures.

V. CONCLUSION

Based on electron collision cross section sets for Helium (He) atoms and Nitrogen (N_2) molecules, kinetic analysis, electron transport properties, and gas discharge characteristics in cryogenic He–N_2 mixtures at a temperature of 77 K have been carried out using the two-term solution of the Boltzmann equation. The reduced electric fields (E/N) range covered was 1-200 Td (1 Td=10^{-17} V·cm²), including the evaluation of key swarm parameters such as electron drift velocity, diffusion coefficients, electron temperature, mean electron energy, electron mobility, and ionization coefficient. In comparison, the present calculations for pure He and N_2 agree with the values of prior research. The current study provides new insights into the behavior of electron swarm parameters in binary mixtures under cryogenic conditions for the first time. The results demonstrate that gas composition plays a significant role in determining electron transport behavior. Pure He exhibits high mean electron energy due to its limited inelastic collision cross sections. In contrast, the addition of N_2 significantly alters electron transport through enhanced inelastic collisions due to vibrational and rotational excitation processes, which act as energy loss mechanisms and substantially modify the tail of the Electron Energy Distribution Function (EEDF) to the lower energy region. This leads to a reduction in mean electron energy, electron temperature, drift velocity, and ionization coefficients in cryogenic He–N_2 mixtures. The effect of N_2 on the He-N_2 mixture leads to a noticeable shift in the effective ionization coefficient and breakdown conditions toward higher reduced electric fields. The nonlinear dependence of electron temperature and transport coefficients on the reduced electric field strength (E/N) further highlights the complex interaction between the energy gain and collisional losses in cryogenic He-N_2 mixtures. From a physical and application perspective, these results are highly relevant for the design and operation of cryogenic systems, particularly in superconducting power applications, dielectric strength, electrical breakdown, semiconductor manufacturing, plasma processing, insulation systems, and cryogenic discharge devices.

Overall, this work contributes to advancing the understanding of electron kinetics in cryogenic gas mixtures and provides a reliable theoretical benchmark for future experimental and computational studies of He–N_2 plasmas.

DECLARATION OF COMPETING INTERESTS

The author declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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DATA AVAILABILITY

All data and materials that support the findings of this study are included within the article. Further information is available upon request.

REFERENCES

[1] C. Park, "Dielectric Properties of Cryogenic Gases," Ph.D. dissertation, School of Electrical and Computer Engineering, Georgia, 2018.

[2] C. Park, S. Pamidi, and L. Graber, "Evaluating the dielectric strength of helium-nitrogen gas mixtures by plasma parameter measurements," *Physics of Plasmas*, vol. 25, no. 4, Apr. 2018, Art. no. 043520, https://doi.org/10.1063/1.5023057.

[3] P. Węgierek, M. Lech, D. Kostyła, and C. Kozak, "Study on the Effect of Helium on the Dielectric Strength of Medium-Voltage Vacuum Interrupters," *Energies*, vol. 14, no. 13, 2021, Art. no. 3742, https://doi.org/10.3390/en14133742.

[4] X. Li, H. Zhao, and S. Jia, "Dielectric breakdown properties of SF_6–N_2 mixtures in the temperature range 300–3000 K," *Journal of Physics D: Applied Physics*, vol. 45, no. 44, 2012, Art. no. 445202, https://doi.org/10.1088/0022-3727/45/44/445202.

[5] N. M. B. Sham, N. Z. Zahid, M. S. Kamarudin, N. A. M. Jamail, and R. Abd-Rahman, "Breakdown Characteristic of N_2-CO_2 Gas Mixtures under AC and DC Test Voltages," *Journal of Physics: Conference Series*, vol. 1874, no. 1, 2021, Art. no. 012027, https://doi.org/10.1088/1742-6596/1874/1/012027.

[6] H. Zhao and H. Lin, "Dielectric breakdown properties of N_2–O_2 mixtures by considering electron detachments from negative ions," *Physics of Plasmas*, vol. 23, no. 7, July 2016, Art. no. 073505, https://doi.org/10.1063/1.4956466.

[7] C. Park, L. Graber, and S. Pamidi, "The dielectric properties of gaseous cryogen mixtures of He, H_2, Ne, and N_2 in a temperature range of 50–80 K at pressures up to 2.0 MPa," *Journal of Applied Physics*, vol. 121, no. 8, Feb. 2017, Art. no. 083304, https://doi.org/10.1063/1.4976565.

[8] S. Kawaguchi, K. Takahashi, and K. Satoh, "Electron collision cross section set for N_2 and electron transport in N_2, N_2/He, and N_2/Ar," *Plasma Sources Science and Technology*, vol. 30, no. 3, March 2021, Art. no. 035010, https://doi.org/10.1088/1361-6595/abe1d4.

[9] A. V. Phelps and L. C. Pitchford, "Anisotropic scattering of electrons by N_2 and its effect on electron transport," *Physical Review A*, vol. 31, no. 5, pp. 2932–2949, May 1985, https://doi.org/10.1103/PhysRevA.31.2932.

[10] A. Gadoum and D. Benyoucef, "Monte Carlo Modeling and Simulation of Electron Dynamics in Low Temperature Methane Gas," *Engineering, Technology & Applied Science Research*, vol. 14, no. 6, pp. 18153–18159, Dec. 2024, https://doi.org/10.48084/etasr.8712.

[11] R. Zhang, L. Wang, J. Liu, and Z. Lian, "Numerical simulation of breakdown properties and streamer development processes in SF_6/CO_2 mixed gas," *AIP Advances*, vol. 12, no. 1, Jan. 2022, Art. no. 015003, https://doi.org/10.1063/5.0076343.

[12] L. S. Frost and A. V. Phelps, "Rotational Excitation and Momentum Transfer Cross Sections for Electrons in H_2 and N_2 from Transport Coefficients," *Physical Review*, vol. 127, no. 5, pp. 1621–1633, Sept. 1962, https://doi.org/10.1103/PhysRev.127.1621.

[13] G. J. M. Hagelaar and L. C. Pitchford, "Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models," *Plasma Sources Science and Technology*, vol. 14, no. 4, Oct. 2005, Art. no. 722, https://doi.org/10.1088/0963-0252/14/4/011.

[14] K. Smith and R. M. Thomson, *Computer modeling of gas lasers*, 1st ed., USA, New York: Plenum Press, 1978.

[15] S. S. Tezcan, H. Duzkaya, S. Dincer, and M. S. Dincer, "Electron Swarm Parameters in Methane-Nitrogen Mixtures," *Acta Physica Polonica A*, vol. 135, no. 3, pp. 495–500, 2019, https://doi.org/10.12693/APhysP ol A.135.495.

[16] L. Láska, K. Mašek, J. Krása, and V. Peřina, "Dielectric properties of SF6 mixtures containing oxygen and other gases," *Czechoslovak Journal of Physics B*, vol. 34, no. 10, pp. 1038–1047, Oct. 1984, https://doi.org/10.1007/BF01590097.

[17] A. G. Engelhardt, A. V. Phelps, and C. G. Risk, "Determination of Momentum Transfer and Inelastic Collision Cross Sections for Electrons in Nitrogen Using Transport Coefficients," *Physical Review*, vol. 135, no. 6A, pp. A1566–A1574, Sept. 1964, https://doi.org/10.1103/PhysRev.135.A1566.

[18] D. Rapp and P. Englander‐Golden, "Total Cross Sections for Ionization and Attachment in Gases by Electron Impact. I. Positive Ionization," *The Journal of Chemical Physics*, vol. 43, no. 5, pp. 1464‐1479, Sept. 1965, https://doi.org/10.1063/1.1696957.

[19] L. S. Frost and A. V. Phelps, "Momentum-Transfer Cross Sections for Slow Electrons in He, Ar, Kr, and Xe from Transport Coefficients," *Physical Review*, vol. 136, no. 6A, pp. A1538–A1545, Dec. 1964, https://doi.org/10.1103/PhysRev.136.A1538.

[20] A. Chutjian and D. C. Cartwright, "Electron-impact excitation of electronic states in argon at incident energies between 16 and 100 eV," *Physical Review A*, vol. 23, no. 5, pp. 2178–2193, May 1981, https://doi.org/10.1103/PhysRevA.23.2178.

[21] H. N. Kucukarpaci, H. T. Saelee, and J. Lucas, "Electron swarm parameters in helium and neon," *Journal of Physics D: Applied Physics*, vol. 14, no. 1, 1981, Art. no 9, https://doi.org/10.1088/0022-3727/14/1/004.

[22] G. G. Raju, *Gaseous Electronics: Tables, Atoms, and Molecules*, 1st ed, UK: CRC Press, 2018.

[23] J. L. Pack, R. E. Voshall, A. V. Phelps, and L. E. Kline, "Longitudinal electron diffusion coefficients in gases: Noble gases," *Journal of Applied Physics*, vol. 71, no. 11, pp. 5363–5371, June 1992, https://doi.org/10.1063/1.350555.

[24] J. Fletcher and I. D. Reid, "The transport parameters of an electron swarm in nitrogen at elevated E/N," *Journal of Physics D: Applied Physics*, vol. 13, no. 12, Sept. 1980, Art. no. 2275, https://doi.org/10.1088/0022-3727/13/12/013.

[25] J. de Urquijo *et al*., "Assessment of the self-consistency of electron-THF cross sections using electron swarm techniques: Mixtures of THF–Ar and THF–N2," *The Journal of Chemical Physics*, vol. 151, no. 5, Aug. 2019, Art. no. 054309, https://doi.org/10.1063/1.5108619.

[26] S. Takeda and Y. Nakamura, "Electron Swarm Parameters in N_2, He, and in their Muxtures (I. Measurement)," *IEEJ Transactions on Fundamentals and Materials*, vol. 102, no. 9, pp. 491‐498, 1982, https://doi.org/10.1541/ieejfms1972.102.491.