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Investigation of the Electron Coefficients of (Ar, He, N_2, O_2) Gases in the Ionosphere

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Abstract:

In this study, the electron coefficients; Mean energy < ε >, Mobility (μN) and Drift velocity (Vd) of different gases Ar, He, N_2 and O_2 in the ionosphere have been calculated using BOLSIG+ program to check the solution results of Boltzmann equation results, and effect of reduced electric field (E/N) on electronic coefficients. The electric field has been specified in the limited range 1-100 Td. The gases were in the ionosphere layer at an altitude frame 50-2000 km. Furthermore, the mean energy and drift velocity steadily increased with increases in the electric field, while mobility was reduced. It turns out that there is a significant and obvious decrease in mobility as a result of inelastic collisions and in addition little energy gained by the reduced electric field. A clear mathematical model was obtained to find out the electronic coefficient values without a simulation program (BOLSIG +). In addition, this model shows a strong correlation between the current work and the electronic transaction values calculated through the BOLSIG+ program.

Keywords: Boltzmann equation, Drift velocity, Electron mobility, Gas discharge, Ionosphere, Mean energy.

Introduction:

Plasma is a quasi-neutral gas composed of positively and negatively charged particles that collide or ionize with neutral particles [1-2]. There are different applications of plasma such as solar cells, optical reagents, biomedical, optoelectronic devices and Ozone generation by micro plasma [3-6]. The ionosphere layer in the upper atmosphere is a primary source of a real ionization neutral particles plasma [7-8]. The ionosphere is made up of different layers due to the different wavelengths in the sun's ultraviolet spectrum [9]. During the day, the solar flux and electron density increase in the ionosphere. This allows the diffusion of higher frequencies for long distances, but at night, when the solar flux is low, radio energy is absorbed very little and lower frequencies are propagated stronger [10]. The word "Discharge" refers to any passage of electric field within an ionized gas and emits energy in the form of light [11]. Emphasis was placed on how O_2 in the mixture would affect the resolved transport data and derive the transport properties that should be incorporated into the flow and discharge fluid model by considering the range (E/n): 0.01-1000 Td [12]. Electron transfer properties of a helium-xenon mixture at a reduced electric field E/N ~15 Td were calculated [13]. The kinetic properties of electron drift in argon at reduced electric fields E/N = (1-100) Td were investigated [14]. BOLSIG+ was used to calculate the electronic coefficients and collapse voltage gradient for the environment of the planetary System, as well as solve the Boltzmann equation [15]. The ionosphere's layers differ due to different wavelengths in the sun's ultraviolet spectrum [9]. Earth's ionosphere is made up of three parts: D (50-90) km, E (90-150) km, and F (150-500 km)[12]. During day time, The F layer is divided into D regions (50-90) km, E region (90-150) km, and F region (150-500) km [16]. During the day, the F layer is frequently divided into sub-layers known as F1 (150-250) km and F2 (250-500) km, which are then combined into a single layer at night. The F region is thicker than the E region and more ionized, with maximum electron density in the 200–

400 km range. The atomic species O+ and O predominate in this region [17].

At an altitude of 60-300 km, ionization results from the absorption of solar energy by neutral gases, the most important of which is atomic oxygen (O, ionized to O+). Hydrogen (H, to H+) and nitrogen monoxide (NO, to NO+) are two other gases that can be ionized. As altitude decreases towards the Earth's surface, solar radiation encounters an increasing number of neutral atmospheric particles, resulting in increased absorption while decreasing radiation intensity. This results in a layer of maximum ionization, which typically occurs at altitudes between 200 and 400 km [18].

BOLSIG + is an excellent application for solving the Boltzmann equation for electrons in a gas with low ionization in regular electric fields, which is seen in a majority of cold plasma when the energy distribution of electrons is calculated by an equilibrium between acceleration in the electric field, momentum, and power loss in collisions of gas molecules. BOLSIG+ solves the electron Boltzmann equation for field equilibrium with a homogeneous electric field and density, no boundaries, and a steady state [19]. The aim of this paper is to estimate the mathematical model that aptly depicts the activity of electronic coefficients by varying the reduced electric field.

Calculation and Methods:

Boltzmann Equation

Equation. 1 explains the characteristics of ions in gases by the phase space functional form f (r, c, t)[20-21].

$$\frac{\partial f}{\partial t} + C.\frac{\partial f}{\partial r} + \frac{\partial E}{m}.\frac{\partial f}{\partial c} = -J\,(f, f_0) \qquad 1$$

Where e, m, t, r, c are the electron's charge, electron's mass, time, position and velocity coordinate respectively. The electric field is assumed spatially homogeneous with magnitude E. J(f, f_0) indicating the change rate for f because they collide with uncharged particles only[12].

Transport coefficients

It is the process of transporting charged particles in a gas. The mathematical expressions used for calculating the output parameters are BOLSIG +, and they are somewhat clear with some additional brief explanations. As well as getting to know the mathematical symbols. It should be noted that all transfer coefficients are multiplied or divided by the product of BOLSIG + with N (total gas number density). This coefficient resulted in a reduction independent of N. All units are with SI units[20].

Mean energy

The mean energy of electrons is field-dependent, and the value of the energy of the "mean" electron corresponds to energy gains compensated for by losses [22].

$$< \varepsilon >= \int \int_0^{\infty} \varepsilon^{\frac{3}{2}} f d\varepsilon \qquad 2$$

Where: $\boldsymbol{\varepsilon}$: Electron mean energy at eV.

Mobility *N

It indicates the velocity of the electron in the plasma and depends on the velocity of drift and decreases with the increase in collisions due to the electron losing its energy upon collision [23].

$$(\mu N) = -\frac{\gamma}{3}\int_0^{\infty} \frac{\varepsilon}{\varrho} \frac{\partial f_0}{\partial \varepsilon}\, d\varepsilon \qquad 3$$

Where: μ at (1/m/V/s): Mobility of electron, N : Number of particles, γ: constant coefficient, = (2e/me)1/2, me in kg: Electron mass, f_0: electron energy probability function" (EEPF), ϱ in m^2: Effective total momentum-transfer cross section, including super elastics and electron-ion Coulomb collisions, if activated. In the case of PT growth model, including also effects of creation or loss

Drift velocity

Drift velocity Vd is the greatest electronic transport parameter used to describe the behavior of electrons in gas, this parameter is determined by the type of gas and the value of the electric field reducer E / N [21], which is an important parameter in the swarm, as it is useful for controlling energy and used as well to describe the conductivity of a weakly ionized gas [24].

$$Vd = \mu E \qquad 4$$

Where: E: Electric field at Td

Influence of reduced electric field on mean energy

From Fig.1, (E/N) affects obviously on $< \varepsilon >$ of electrons for different gases He, N_2, O_2 and Ar, because the reduced electric field affects the cross-sectional area, there is an increase in mean energy with an increase in E/N, and as a result, the rate of elastic and inelastic collisions increases, resulting in an increase in E/N [18]. In other words, the mean energy increases as the reduced electric field increases due to elastic collisions and electrons gaining energy due to the electric field. We can also see from the figure that the He element has the highest mean energy value due to the effect of the higher elastic collisions, whereas this effect is less for N element, as the mean energy values are less than possible.

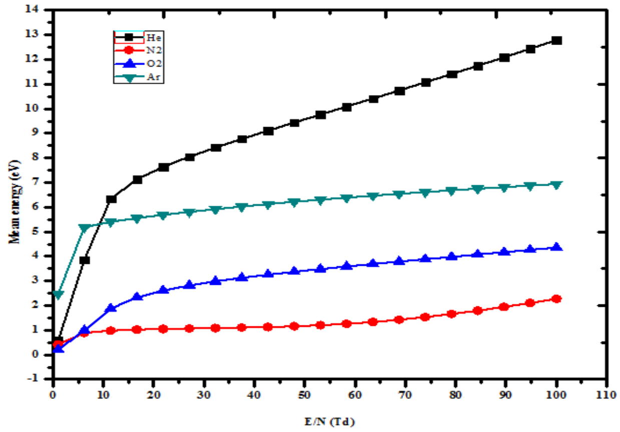


Figure 1. The relationship between the mean energy and increase electric field (E/N) for different gases He, N_2, O_2 and Ar in Earth's ionosphere.

Mean energy modeling

Fig. 2, depicts a high fitting/matching ratio between the original data (utilizing Bolsig+ program) and our simulation model (utilizing Origin program) that indicates the general behavior of the mean energy for Ar gas in the Earth's ionosphere with increasing electric field (E/N).

This relationship is described by Equation 5 with values of the constants and percentage of highest match mentioned in Table. 1:

$$< \varepsilon >= Z_1 e^{((-E/N)/t_1)} + Z_2 e^{((-E/N)/t_1)} + I_0 \qquad 5$$

Where, E/N= (1-100) Td

Table 1. Show the relationship between constants Z_1, Z_2, I_0, t_1 and t_2 and the mean energy <ε> for Ar gas, where represented by Eq. 5.

<ε> (eV) for Ar			
Adj.R-Square	99.997 %		
Z_1	-2.79454	t_1	94.46225
Z_2	-4.95459	t_2	1.61524
I_0	7.89981		

According to Fig.2, a high fitting/matching ratio between the original data (utilizing Bolsig+ program) and our simulation model (utilizing Origin program) indicates the general behavior of the mean energy for He, N_2 and O_2 gases in the Earth's ionosphere with increasing electric field (E/N)

This relationship is described by Eq. 6 with values of constants and the percentage of the highest match mentioned in Table. 2:

$$< \varepsilon >= B_0 + B_1\left(\frac{E}{N}\right) + B_2\left(\frac{E}{N}\right)^2 + B_3\left(\frac{E}{N}\right)^3 + B_4\left(\frac{E}{N}\right)^4 + B_5\left(\frac{E}{N}\right)^5 \qquad 6$$

Table 2. Show the relationship between constants B_0, B_1, B_2, B_3, B_4 and B_5 and the mean energy <ε>, for He, N_2 and O_2 gases, where represented by Eq. 6.

	<ε> (eV) for He	<ε> (eV) for N_2	<ε> (eV) for O_2
Adj.R-Square	99.69 %	99.69 %	99.843 %
B_0	-0.12002	0.39227	-0.06551
B_1	0.82134	0.0845	0.23076
B_2	-0.03187	-0.00374	-0.00709
B_3	6.13×10^{-4}	7.41×10^{-5}	1.16×10^{-4}
B_4	-5.4×10^{-6}	-6.47×10^{-7}	-9.36×10^{-7}
B_5	1.85×10^{-8}	2.14×10^{-9}	2.9×10^{-9}

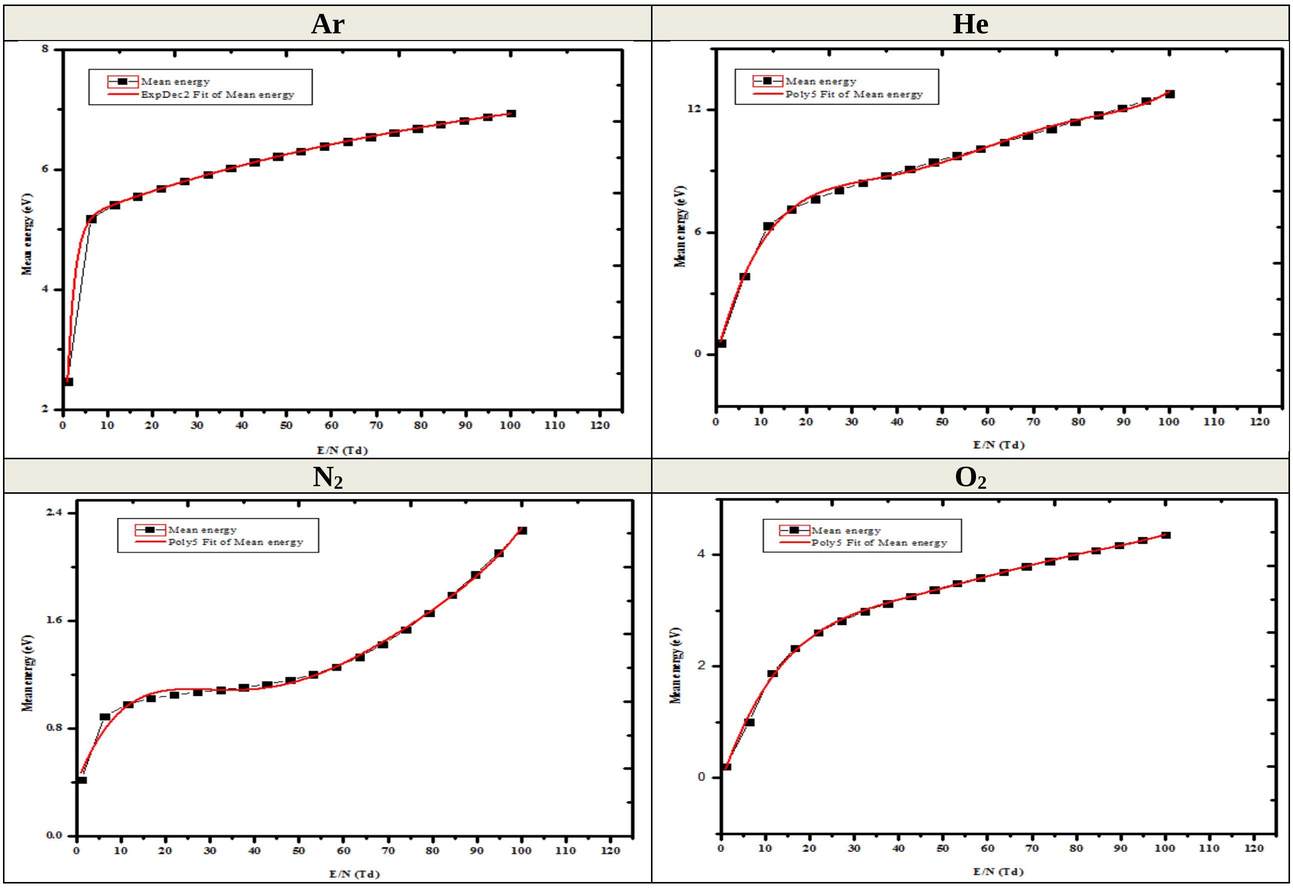


Figure 2. Estimated/simulated data (using mathematical model) of the mean energy <ε> for Ar, He, N_2 and O_2 gases.

Influence of reduced electric field on mobility

Fig. 3, shows that the electron mobility is inversely proportional to the electric field. We observed that the mobility is low at 0-10 Td, due to the energy loss of electrons in the elastic collisions, but the decrease in mobility from 10-100 Td, is very negligible due to the inelastic collisions[25].

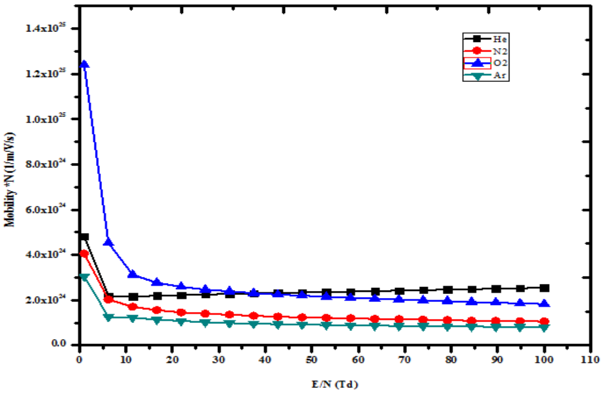


Figure 3. The relationship between the electron mobility and increase electric field (E/N) for different gases He, N_2, O_2 and Ar in Earth's ionosphere.

Mobility modeling

According to Fig. 3, a high fitting/matching ratio between the original data (utilizing Bolsig+ program) and our simulation model (utilizing Origin program) indicates the general behavior of the electron mobility for Ar, N_2 and O_2 gases in the Earth's ionosphere with increasing electric field (E/N).

This relationship is described by Eq. 7 with values of constants and percentage of highest match mentioned in Table. 3:

$$\mu N = F_2 + (F_1 - F_2)/\left(1 + \left(\frac{E/N}{X_0}\right)^P\right) \qquad 7$$

Table 3. Show the relationship between constants (F_1, F_2, X_0 and P) and the electron mobility (μN) for Ar, N_2, O_2 gases, where represented by Eq. 7.

	μN (1/m/V/s) for Ar	μN (1/m/V/s) for N_2	μN (1/m/V/s) for O_2
Adj.R-Square	99.008 %	99.008 %	99.898 %
F_1	1.37×10^{27}	3.75×10^{26}	2.88×10^{25}
F_2	7.47×10^{23}	7.71×10^{23}	1.71×10^{24}
X_0	9.07×10^{-5}	9.71×10^{-5}	0.63246
P	0.687	0.51195	0.95899

According to Fig.3, a high fitting/matching ratio between the original data (utilizing Bolsig+ program) and our simulation model (utilizing Origin program) indicates the general behavior of the electron mobility for He gas in the Earth's ionosphere with increasing electric field (E/N).

This relationship is described by Eq. 8, with values of constants and percentage of highest match mentioned in Table. 4:

$$\mu N = G_1 + (G_2 - G_1)\left[\frac{n}{1 + 10^{\left(u_1 - \left(\frac{E}{N}\right)\right)C_1}} + \frac{1-n}{1 + 10^{\left(u_2 - \left(\frac{E}{N}\right)\right)C_2}}\right] \quad 8$$

Table 4. Show the relationship between constants G_1, G_2, u_1, u_2, C_1, C_2 and n and the electron mobility μN for He gas, where represented by Eq. 8.

	μN (1/m/V/s) for He		
Adj.R-Square	99.98%		
G_1	-6.8×10^{24}	u_1	-0.1034
G_2	1.3×10^{25}	u_2	-426.35
C_1	-0.392	C_2	0.00196
N	0.494		

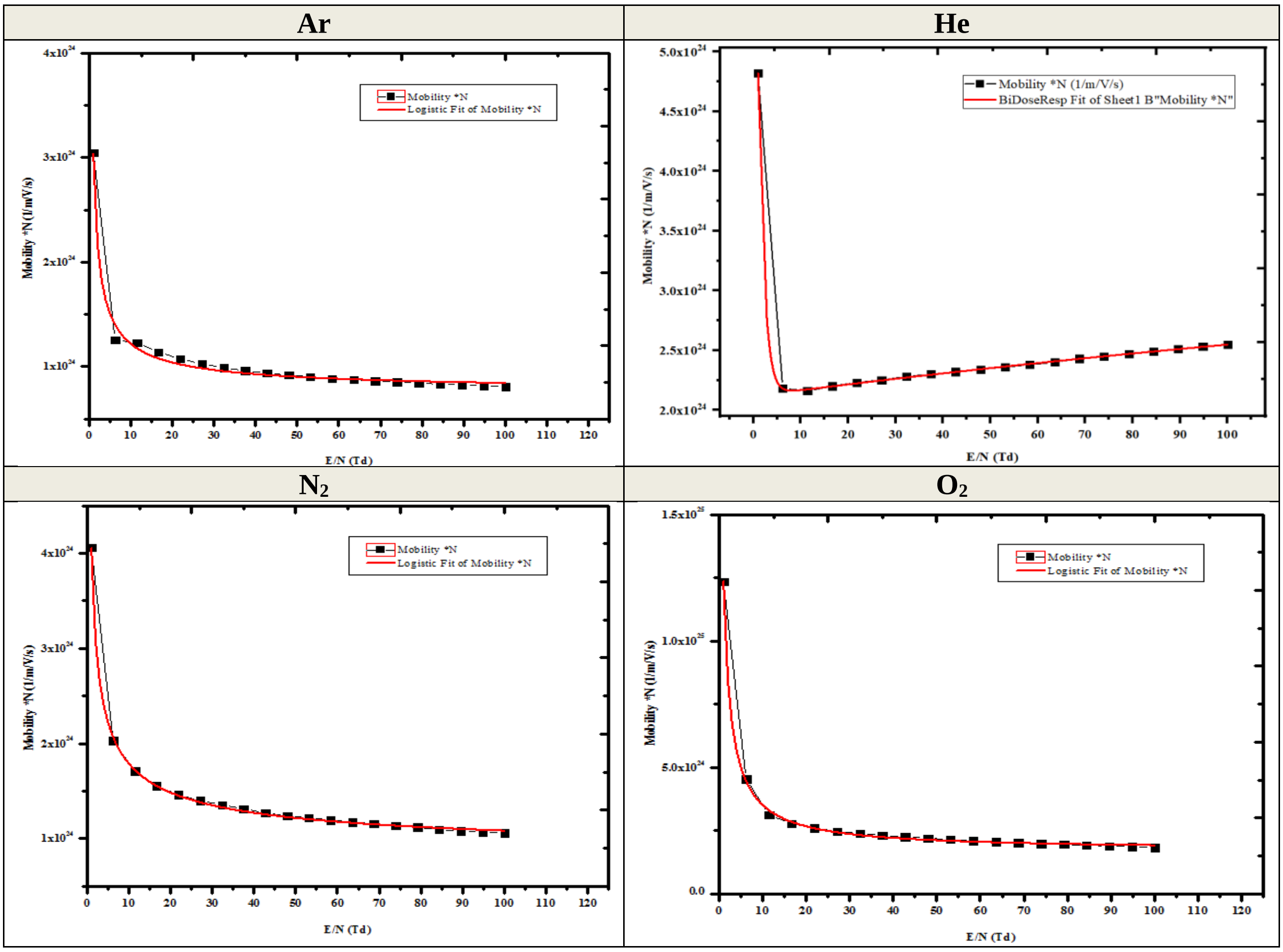


Figure 4. Estimated/simulated data (using mathematical model) of the electron mobility (μN) for Ar, He, N_2 and O_2 gases.

Influence of electric field on drift velocity

The drift velocities increase as a function of E/N, and at lower E/N, the increase is linear. It is also observed that the drift velocity is lower because the elastic collision cross section is large. Because energy depends on the cross-sectional area of the elastic collision, this effect is also caused by the loss of energy caused by ionization and excitement in gases [26]. Fig.5, shows the increasing drift velocity as the electric field increases, where we note that the drift velocity is high at 5 and 20 Td, which is due to elastic collisions, but the drift velocity from 20-100 Td, the increase is progressively due to the inelastic collision. In this figure, we notice that the drift velocity values increase significantly by increasing in (E/N), due to the high impact of elastic collisions as a result of electrons gaining energy. We observed that the He element has the highest drift velocity value at 45- 100 Td due to the effect of higher elastic collisions, whereas this effect is less for Ar because the drift velocity values are less than possible.

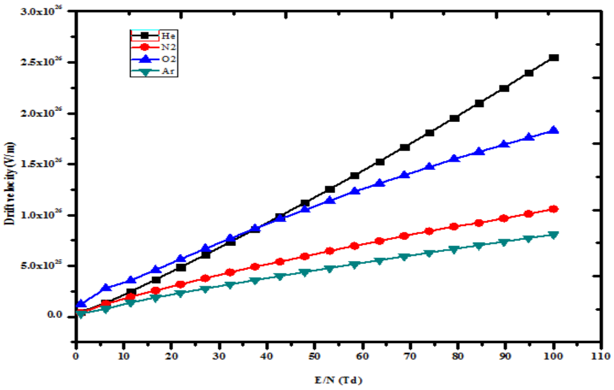


Figure 5. The relationship between the drift velocity and increase electric field (E/N) for different gases He, N_2, O_2 and Ar in Earth's ionosphere.

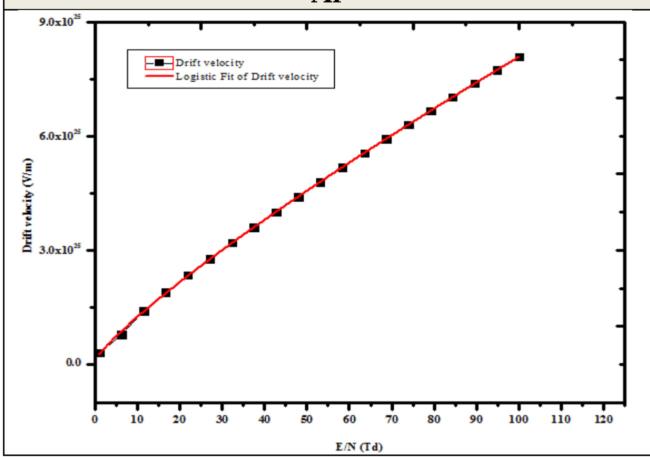
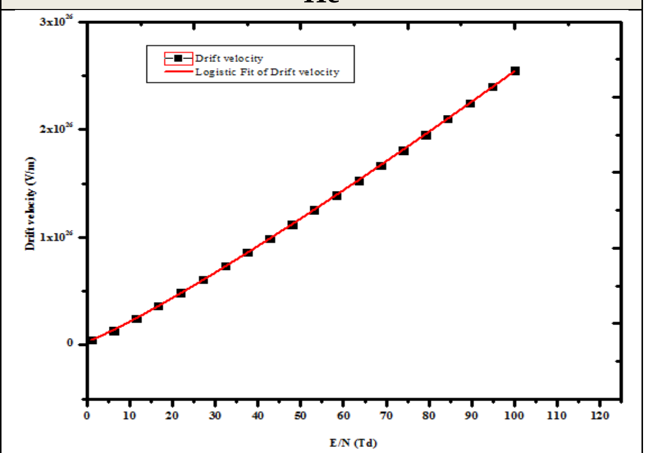
Drift velocity modeling

According to Fig. 6, a high fitting/matching ratio between the original data (utilizing Bolsig+ program) and our simulation model (utilizing Origin program) indicates the general behavior of the electron mobility for Ar, N_2, O_2 gases in the Earth's ionosphere with an increasing electric field (E/N). This relationship is described by Eq. 9, with values of constants and the percentage of the highest match mentioned in Table. 5:

$$Vd = I_2 + (I_1 - I_2)/(1 + (\frac{E/N}{Q_0})^R) \qquad 9$$

Table 5. Show the relationship between constants I_1, I_2, Q_0 and R and the drift velocity (Vd) for Ar, N_2, O_2 and He gases, where represented by Eq. 9.

	Vd (V/m) for Ar	Vd (V/m) for N_2	Vd (V/m) for O_2	Vd (V/m) for He
Adj.R-Square	99.987 %	99.991 %	99.97 %	99.996 %
I_1	1.046×10^{24}	2.13×10^{24}	1.15×10^{25}	3.62×10^{24}
I_2	6.65×10^{27}	9.12×10^{26}	7.39×10^{26}	6.86×10^{30}
Q_0	18328.3	1052.2	320.73	801481.3
R	0.846	0.87	1.006	1.136

Ar	He
	

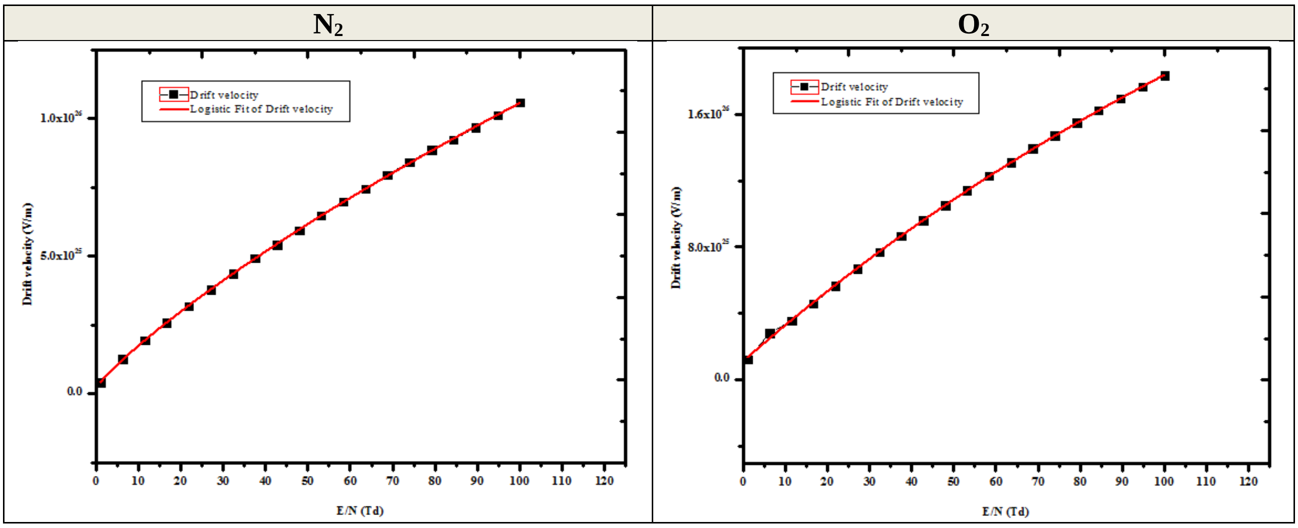


Figure 6. Estimated/simulated data (using mathematical model) of Drift velocity (Vd) for Ar, He, N_2 and O_2 gases.

Conclusion:

This study has proved the value of electronic coefficients shifted due to the change in cross-sectional area as the electric field increased. There was a positive relationship between (E/N) and the electronic transport coefficients (mean energy and drift velocity) for Ar, He, N_2 and O_2 gases. A negative correlation between (E/N) and electrons' mobility was explained for all gases. The correlation between drift velocity and the reduced electric field is linear. Logistic and polynomial functions in this research showed a higher matching than other functions.

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Authors' declaration:

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are mine ours. Besides, the Figures and images, which are not mine ours, have been given the permission for re-publication attached with the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee in University of Baghdad.

Authors' contributions statement:

A. F. A. conceived of the presented idea. All authors contributed to the computational procedure. A. A. T. wrote the manuscript with support from A. F. A. (Supervisor of the results of this work). All authors discussed the results and contributed to the final manuscript.

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التحقق من المعاملات الالكترونية لغازات (Ar، He، N_2، O_2) في طبقة الأيونوسفير الالكترونية

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الخلاصة:

في هذه الدراسة; تم حساب معاملات الإلكترون و متوسط الطاقة <ε >، والتحريكية (μN) وسرعة الانجراف (Vd) لغازات مختلفة Ar، He،N_2، O_2 في الغلاف الأيوني باستخدام برنامج BOLSIG + للتحقق من حل نتائج معادلة بولتزمان ، وتأثير المجال الكهربائي المنخفض (E / N) على المعاملات الإلكترونية. تم اختيار المجال الكهربائي في المدى المحدود 1-100 Td. كانت الغازات في طبقة الأيونوسفير على ارتفاع 50-2000 كم. ازداد متوسط الطاقة وسرعة الانجراف بشكل طردي مع زيادة المجال الكهربائي، بينما انخفضت التحركية. هناك انخفاض كبير وواضح في التنقل نتيجة للتصادمات غير المرنة، وزيادة قليلة في الطاقة بسبب المجال الكهربائي المنخفض. تم الحصول على نموذج رياضي واضح لمعرفة قيم المعامل الإلكتروني بدون برنامج محاكاة (+ BOLSIG) بالإضافة إلى ذلك، أظهر هذا النموذج ارتباطًا قويًا بين العمل الحالي وقيم المعاملات الإلكترونية المحسوبة بواسطة برنامج + BOLSIG

الكلمات المفتاحية: معادلة بولتزمان، سرعة الانجراف، تحركية الإلكترون، تفريغ الغاز، الأيونوسفير، متوسط الطاقة.