Calculation of Effective Molecules Collision Frequency and Cross-Sectional Ratio for Electromagnetic Discharge in Various Gases Mixtures

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Abstract

Estimation of gases quantities in gases mixture in plasma were accomplished at 300K. Each mixture has an effective value of the molecular collision frequency, electro-ions collision frequency and collision cross-sectional ratio. The computational and experimental results are correlated. In this work, the concept of separate control ion energy and ion flux by the two frequencies works generally well for the investigated discharge setup. The high frequency mainly determines ion flux and radical formation in the mixture discharges while ion energies are strongly influenced by the low frequency. Deviations from an ideally separated control of ion flux and energy are caused by influences on discharge parameters and interaction between the two frequencies since the radio frequency (RF) power sources are coupled to each other in the current setup.

Keywords: atomic and molecular transport data, molecular collisions, Boltzmann distribution, kinetic temperature, interaction of radio waves.

Introduction

For two media and low RF waves an interaction of two electromagnetic waves is observed in the ionosphere when one of them is sufficiently strong. The readable transfer of modulation is from the strong wave to the carrier of the weaker wave when strong wave amplitude is moderated. Ionosphere cross-modulation theory indicates that if the interfering waves, observed the main energy of electron increases in the region of the ionosphere, this will lead to changes in the collision frequency of electron. The required modification is the presence of the observed disturbing wave if the absorption of an electromagnetic wave in the region of ionosphere is determined by collision frequency of the electron in the region. According to the effect of earth's magnetic field the theory extended to transfer modulation at radio frequencies corresponding to the gyro-frequency of the electrons was predicted which has been observed experimentally [1-7]. In gaseous discharge plasma, controllable laboratory experiments of interaction between microwaves are simultaneously propagated. The aim of this work is to verify the experimental data with the theoretical values to study the collision processes for different percentages of Ar-He-N_2 and Ar-H_2 mixtures.

Theoretical Formulation

Assume the mechanism of energy absorption in case of wave interaction phenomena in gaseous discharge plasmas mentioned above for an isotropic medium is the electric field, E, has a time dependence, yield

$$P_L = \int_V \frac{|E'_\circ|^2}{2} \sigma_r dV \quad \text{.......................................(1)}$$

where P_L refers to the total dissipated power rate $E \sim E_0^1 e^{iwt}$, σ_r refers to the real part of the complex conductivity, σ; for a medium containing free electrons in a gas of heavier molecules and ions gives [3].

$$\sigma = \sigma_{real} + i\sigma_{imag} = \frac{n_e e^2}{m}\left[\frac{\nu - i\omega}{\omega^2 + \nu^2}\right] \quad \text{............(2)}$$

were n_e represents the electron number density, e and m are the electronic charge and mass, respectively. ν represents the effective electron collision frequency. In an ionized gas according to the Maxwell distribution of electron velocities, the complex conductivity σ is [2, 4, 5,6]

$$\sigma = 1.504\frac{e^2 n_e}{m}\left[\int_0^\infty \frac{\nu(u)u^4 e^{-u^2} du}{\omega^2 + \nu^2(u)} - i\omega\int_0^\infty \frac{u^4 e^{-u^2} du}{\omega^2 + \nu^2(u)}\right]$$
$$\text{..............................(3)}$$

Where

$$u = (m/2KT_e)^{\frac{1}{2}}\upsilon \quad ....(4)$$

u is the electron energy, K is the Boltzmann constant, T_e is the gas temperature and υ is the electron velocity. Using the condition $\nu^2 << \omega^2$ for the high-frequency case and from equations 2 and 3 the effective electron collision frequency ν is:

$$\nu = 1.504\int_0^\infty \nu(u)u^4 e^{-u^2}du \quad ....(5)$$

at $\nu^2 << \omega^2$, equation1 becomes:

$$P_I = \frac{1}{2}\frac{e^2}{m}\frac{\nu}{\omega^2}|E'_\circ|^2 \quad ....(6)$$

The power balance of the average electron is [8]:

$$P_I = dQ_e/dt + G\nu(Q_e - Q_m) \quad ....(7)$$

where P_I the energy per unit time, G is an energy loss factor, Q_e and Q_m is the mean agitation energies of the electron and molecules respectively. In different concentrations of argon-helium-nitrogen mixtures and argon-hydrogen mixtures and electrons with energies below ~2eV, this is a good approximation for the probability of collision of electrons with the molecules is independent of velocity. From Eq. (5) the effective electron-molecules collision frequency yields [8]:

$$\nu_m = \frac{4}{3}q_m n_m \bar{\upsilon} \quad ....(8)$$

where $q_m = 2.15\times10^7 \times E/N \big/ [V_d \times (D/\mu)^{1/2}]$ and q_m refers to the effective cross sectional area of the molecules. n_m is the molecular density, N is the total gas density, V_d is the electron drift velocity, D/μ is the diffusion coefficient to the electron mobility ratio, E/N is the ratio of the applied electric field to the gas number density and $\bar{\upsilon}$ is:

$$\bar{\upsilon} = (8KT_e/\pi m)^{\frac{1}{2}} \quad ....(9)$$

Where

$$e<u> = KT_e \quad .... (10)$$

Calculation of ν_{ei}

The effective electron collision frequency (ν_{ei}) with charged particles of the plasma is theoretically calculated using the following equation [8]:

$$\nu_{ei} = A\frac{n_i}{T_e^{\frac{3}{2}}}\ell n\left[\frac{B}{n_i^{0.5}}T_e\left(\frac{2T_eT_i}{T_e+T_i}\right)^{0.5}\right] \quad .... (11)$$

Here A and B are constants, T_i is the ion temperature, n_i is the number of ions per cubic centimeter. In this work, we consider $n_i = n_e$.

Decaying Plasma

The relation for the rate of energy loss and gain for the average electron is given by Eq(7) which involves both electron-molecule and electron-ion collisions. For isothermal electrical discharge plasma this requires that $Q_e = Q_m$ where $Q_m = \frac{3}{2}KT_g$

at $T_g = T_e$ hence:

$$Q_e = \frac{3}{2}KT_e \quad .... (12)$$

Substituting equation 6 and 12 into equation 7 yields:

$$dQ_e/dt = d\left(\frac{3}{2}KT_e\right)\Big/dt = K\frac{3}{2}dT_e/dt$$
$$= P_I - G\nu(Q_e - Q_m)$$
$$= \frac{1}{2}\frac{e^2(E')^2}{m\omega^2}(\nu_{ei} + \nu_{em})$$
$$-\left[G_m\nu_m(Q_e - Q_m) + G_i\nu_i(Q_e - Q_i)\right] \quad .... (13)$$

Where $\nu = \nu_{ei} + \nu_{em}$ is the total electron collision frequency .... (14)
$G = G_i + G_m$ is the total loss energy factor, G_i has the significance for electron-ion collision as shown below:

$$\lambda = G(1 - Q_m / Q_e) \quad (15)$$

and

$$G_m = 2m / M \quad (16)$$

Where M refers to the mass of the molecule, Q_i refers to the ionic mean energy and was considered equal to $Q_m = Q_\circ$ at all times. The difference $(Q_e - Q_\circ)$ is of the order of zero, which is:

$$Q_e - Q_\circ \Rightarrow 0 \quad (17)$$

Substitute equation 17 into equation 13 yields:

$$\frac{dT_e}{dt} = \frac{e^2 (E')^2}{3K\, m\omega^2} (\nu_{ei} + \nu_{em}) \quad (18)$$

This mean that at t = 0, dT_e/dt is due directly to $(\nu_{ei} + \nu_{em})$ and $(E')^2$ .where fore the rate of change of collisions frequency as a function of time, is as given below:

$$d\nu_{em} / dt = \frac{2}{3} q_m N_m (8K / \pi m)^{\frac{1}{2}} T_e^{-\frac{1}{2}}\, dT_e/dt \quad (19)$$

and as well as ν_{ei}

$$d\nu_{ei}/dt = -\frac{3}{2} A n_i T_e^{-5/2} \left\{ \ell n \left[B T_e n_i^{-1/2} \left(2T_e T_i / (T_e + T_i)^{-1} \right)^{\frac{1}{2}} \right] - 1/3 T_e / (T_e + T_i)^{-1} \right\} dT_e/dt \quad (20)$$

Experimental values of ν_{ei}

With $A = 3.6$ and $B = 3.7 \times 10^3$, $n_i = n_e$, $T_e = T_i$ and by substituting these experimental values into equation 11 yields [9] :

$$\nu_{ei} = 3.6 n_i T_e^{-3/2} \ell n [3.7 \times 10^3 n_i^{-0.5} T_e^{3/2}] \quad (21)$$

Calculation of q_i

An effective cross section area q_i for collision of electrons with ions, may be defined as [7-15]:

$$\nu_{ei} = \frac{4}{3} q_i n_i \bar{\nu} \quad (22)$$

where:

$$q_i = \frac{3}{2} \frac{\Gamma^{ee}}{u^2} \quad (23)$$

$$\Gamma^{ee} = e^2 / 24\pi\varepsilon_\circ^2 \ell n(\Lambda) \quad (24)$$

$$u = (m / 2KT)^{1/2} \upsilon \quad (25)$$

$$\upsilon = \nu_m / N q_m \quad (26)$$

$$\Lambda = 6.2 \times 10^{13} \times 2\pi \times \langle u \rangle^{1.5} / \omega \quad (27)$$

$$\omega = 2\pi\nu \quad (28)$$

$$\nu = 1.495 \times 10^8 \times 1 / V_d \quad (29)$$

where $\varepsilon_\circ$ refers to the permittivity of free space, e $= 8.854 \times 10^{-12}$ F m^{-1}, $\ell n(\Lambda)$ refers to the coulomb logarithm, $\langle u \rangle$ refers to the electron average energy, ω refers to the radial frequency and V_d refers to the electron drift velocity. There points up the importance of electron-ion collisions, even in plasmas with low degrees of ionization.

Theoretical values of ν_{ei}

The experimental results for electron-ion collisions, as stated in equation 21 compared with theoretical works is applicable to experimental conditions. The theoretical prediction of Burckhardt, Elwert and Unsold is given by [8]:

$$\nu_{ei} = 2.25\, n_i \times T_e^{-3/2}\, \ell n\, [8.4 \times 10^3 \times T_e^{-3/2} \times n_i^{1/2}] \quad (30)$$

Transport Equation Solution

The behavior of electron interactions with gas molecules are governed by the distribution in space, energy and time of the electrons in the pure gas and/or in a mixture of gases. The prediction of the distribution function can be done by solving the electron transport equation. The general form of the transport equation may be written as [13, 14]:

$$\frac{\partial f}{\partial t}+v.\nabla_r f+a.\nabla v\ f$$
$$=\sum_j \iint [f(v^`,r,t)F_j(v_j^`,r,t)-f(v,r,t)F_j(v_j,r,t)]$$
$$\times v_{rj}\sigma_j(\theta,v_{rj})d\Omega_j dv_j \qquad (31)$$

Where $\partial f/\partial t$ defines that $f(v^`,r,t)$ changes with time at fixed values of v and r.

$v.\nabla_r f$ represents the charged particles in the vicinity of r, $a.\nabla v\ f$ represents the motion of the charged particles. F_j represents the loss of electrons by collisions in v ,and $F_j^`$ represents the gain of electrons by collision around v . $a=eE/m$ refers to the acceleration of charged particle , F_j is the velocity distribution function of the neutral species j, v , v_j are the velocity of charged particles and the velocity of neutral species j respectively, $v_{rj}=|v-v_j|$ refers to the relative velocity of charged particle with respect to the neutral species of gas J, $\sigma_j(\theta,v_{rj})$ refers to the differential microscopic cross section of the interacting charged particles with neutral species J, $d\Omega_j$ refers to the element of solid angle.

Theoretical Evaluations

When numerically solved the transport Eq.(11), as pointed out in equation 31 gives transport coefficients, such as, electric field E, drift velocity V_d , the ratio of the coefficient diffusion to the electron mobility D/μ, electron average energy $<u>$ and electron mobility μ as shown in tables1- 4 respectively. These parameters were substituted in the calculated equations.

Results and Discussion

The value of effective collision frequency is measured for mixtures of Ar(10%)- He(45%)-N_2(45%), Ar(80%)-He(10%)-N_2(10%), Ar(5%)- H_2(95%) and Ar(95%)-H_2(5%) ν_{em}, ν_{it}, dν_{em}/dt and dν_{ei} /dt. These result were obtained from isothermal plasma at room temperature (300 K). The result, as illustrated in Fig.(1), shows the electron density and electron collision frequency as calculated from equation 8 regardless of electron–ion collision (ν_{ei}/ν_{em} <<1). The effective electron molecular frequency depends on total number density as Ar(10%)-He(45%)-N_2(45%) and Ar(90%)-He(10%)-N_2(10%) mixtures but in Ar(5%)-H_2(95%) and Ar(95%)-H_2(5%) mixtures it depends on density as frequency was found to increase with number of density. The rate of electron-molecular frequency and the electron-ion frequency with time dv_{em}/dt, dv_{ei}/dt were reduced with low total collision frequency as shown in Figs. (2) and (3). On the other hand when collision frequency is equal to zero frequency rates is independent for all mixtures. This result was obtained from equation 19 and 20. The result of the electron-ion collision V_{ei} as a function of electron density is shown in Fig.(4) which indicates a linear dependence on electron density $n_e=n_i$. When v_{ei} is to follow the form by equation 21. To assign a value to B constant under logarithm will be difficult, because large changes in B influence the slope of v_{ei}against n_0. Also Fig.(a) shows that experimental values can be determined from electron-ion frequency v_{ei}as illustrated in equation 30 and drawn in Fig.(4) against electron density-from the above result. It shows a relation between experiment and theoretical results [6]. Finally Fig.(5) shows that electron-ion frequency dependence on gas total number density is linear as calculated from equation 22 for different gaseous mixture.

11. Conclusions

1. The magnitudes of effective electron molecule collision frequencies V_{em} in a mixture of Ar(10%)-He(45%)-N_2(45%), Ar(90%)-He(5%)-N_2(5%),Ar(5%)-H_2(95%) and Ar(95%)-H_2(5%)at room temperature (~300°k) plasma are (3.320×10^7-1.6780×10^8)s^1, (2.689×10^7-1.255×10^8)s^1, ($1.162\times10^7 3.7330\times10^7$) s^{-1} and (2.157×10^7-1.130×10^8)s^{-1} respectively. According to the above for these experiments equations 5 and 8 the effective cross sectional area of the above mixtures for electrons having average energies (0.11074-1.00852) eV, (0.37355-1.45179) eV, (0.04405-0.22271) eV, and (0.05765-0.81091) eV respectively, may be calculated by the equation,

$q_m=2.15\times10^7$ $E/N/(V_d\sqrt{D/\mu})$ to be$(1.10108499\times10^{-15}-1.843\times10^{-17})cm^2$, $(2.444\times10^{-16}-5.788\times10^{-18})$ cm^2, $(1.700\times10^{-14}-2.422\times10^{-16})$ cm^2, and $(2.876\times10^{-15}-4.015\times10^{-17})cm^2$ respectively.

2. A magnitude of the effective electron-ions collision frequency ν_{ei} for the isothermal plasma at room temperature have been found using equation 22for the above mixtures which are equal to $(4.47470928\times10^9-1.898\times10^{11})$ s^{-1}, $(5.424\times10^9-3.309\times10^{11})$ s^{-1}, $(2.135\times10^8-1.249\times10^{10})s^{-1}$, and $(1.9946\times10^9-7.035\times10^{10})$ s^{-1} respectively.
3. The values of the effective cross-sectional area for electron-ion collisions q_i in the above mixtures are equal to $(1.483\times10^{-13}-2.085\times10^{-14})$, $(4.929\times10^{-14}-1.525\times10^{-14})$ cm^2, $(3.124\times10^{-13}-8.109\times10^{-14})$ cm^2, and $(2.658\times10^{-13}-2.498\times10^{-14})cm^2$ respectively at constant temperature.
4. The ratio q_i/q_m of the effective cross sections for electrons in case of electron-ion and electron-molecule collisions for the above mixtures are calculated and equal to $(134.748-1.131\times10^3)$ s^{-1}, $(201.679-2.635\times10^3)$ s^{-1}, (18.372-334.794) and $(92.417-622.188)s^{-1}$ respectively.
5. The above defined condition indicates the importance of electron-ion collisions, even in plasmas with low degrees of ionization.
6. The mixtures parameters are obtained and compared with available experimental results for electron-ion collisions, as in equation 21 with the theoretical work as in equation 30. The best and almost exact agreement with work of Ref. [7]

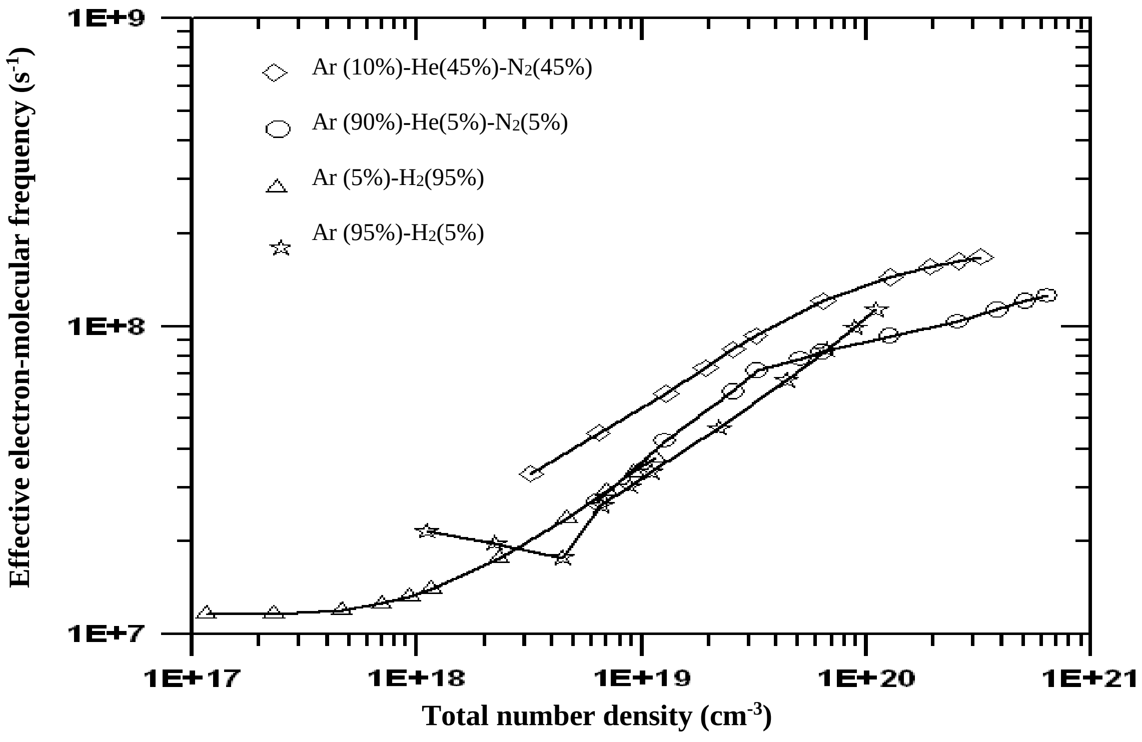

Fig. (1) The effective electron-molecular frequency, ν_{em} against the gas total number density, N in different mixtures.

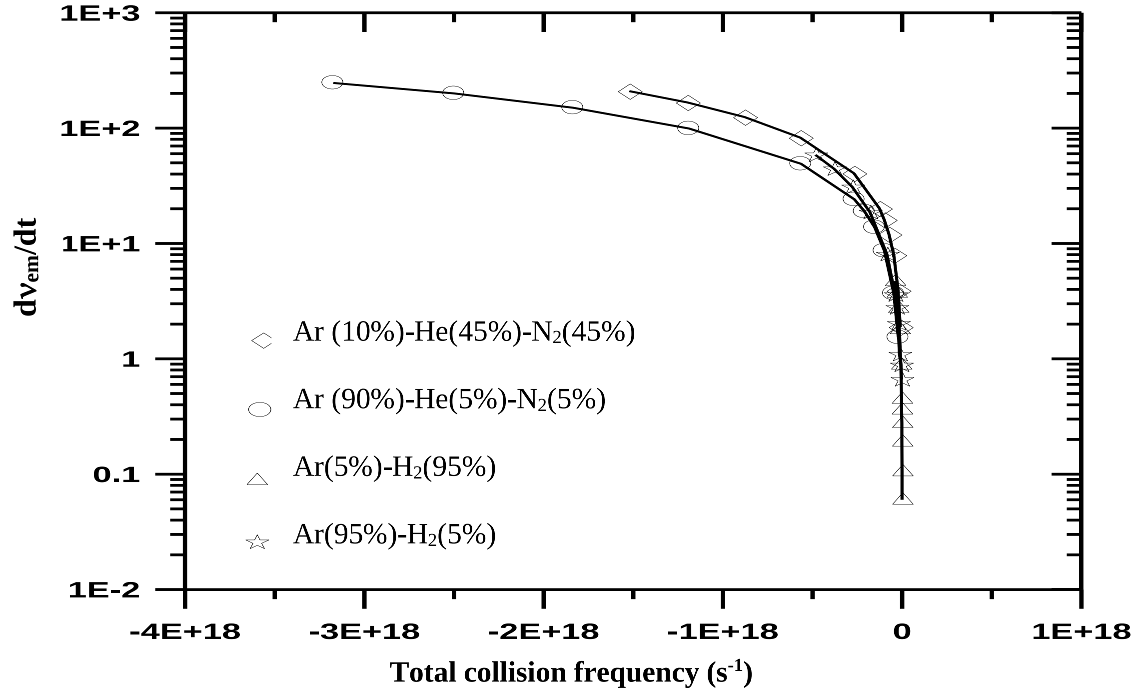

Fig. (2) The rate of change the electron-molecular frequency with time, $d\nu_{em}/dt$ against the total collision frequency, ν in different mixtures.

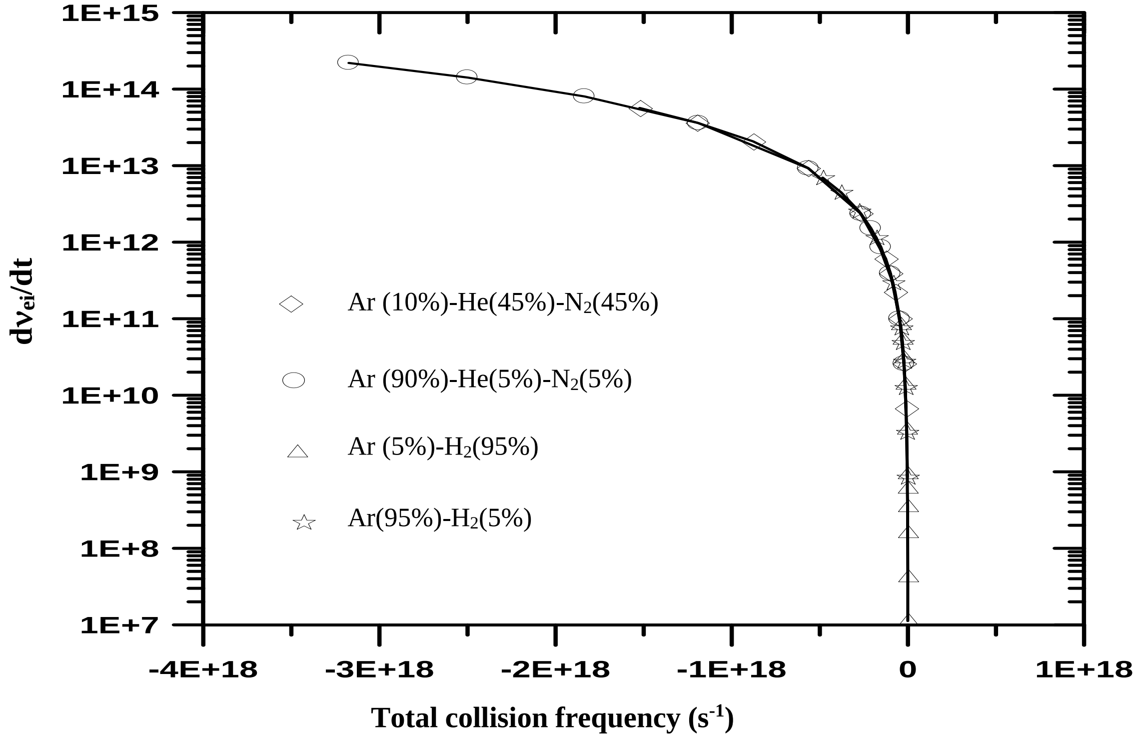

Fig. (3) The rate of change of the electron-ion frequency with time, $d\nu_{ei}/dt$ against the total collision frequency, ν in different mixtures.

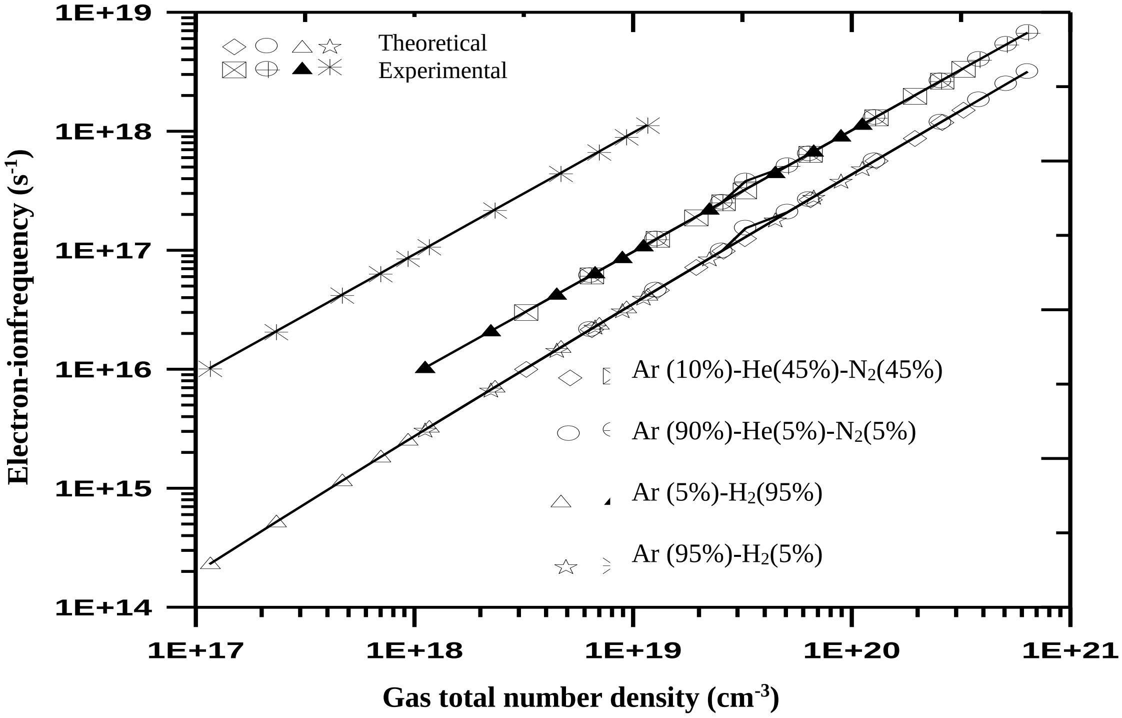

Fig. (4) The electron-ion frequency , ν_{ei} as a function of the gas total number density, N for experimental and the theoretical data in different mixtures.

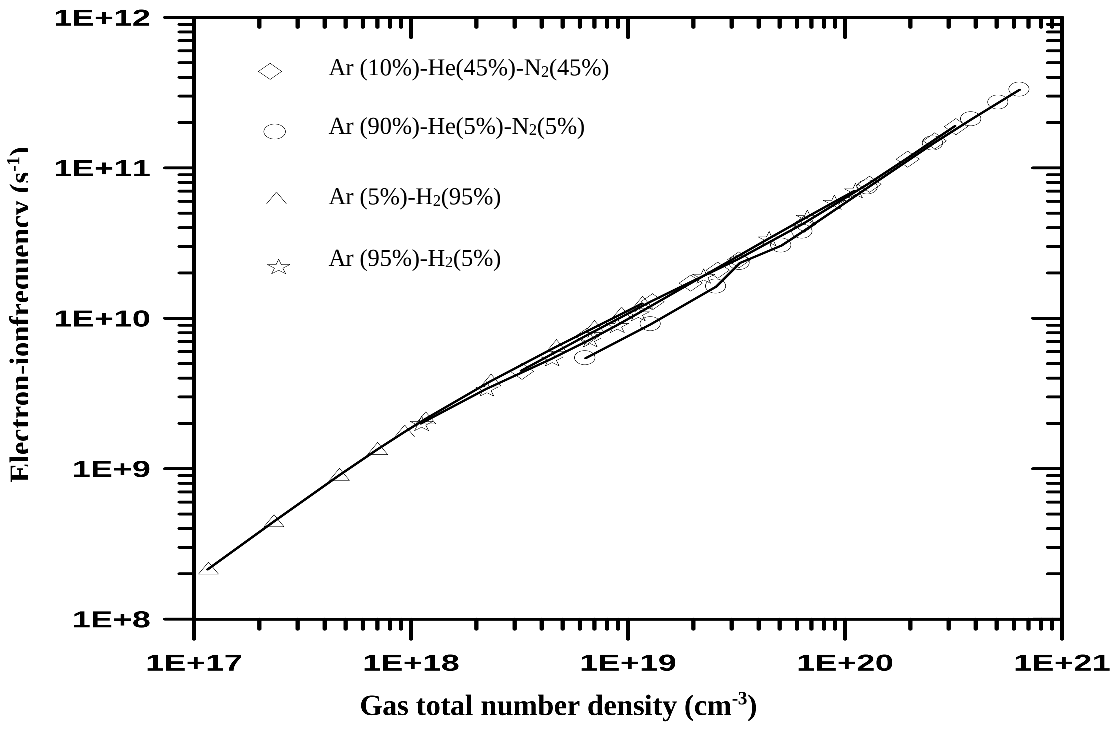

Fig. (5) The electron-ion frequency ,ν_{ei} against the gas total number Density, N in different mixtures.

Table (1)
The calculated electron diffusion motion parameters for Argon (10%)-Helium (45%)-Nitrogen (45%).

E V cm^{-1}	V_d Cm 5^{-1} ×10^5	D/μ Ev	<u> (eV)	μ cm^2/V.sec
6.426	1.324	.087	.11074	20610.77
12.851	1.927	.133	.16471	14994.13
25.703	2.890	.199	.25028	11242.15
38.545	3.600	.264	.33556	9338.387
51.406	4.182	.327	.41699	8136.229
64.257	4.705	.386	.48879	7321.584
128.514	7.061	.597	.71133	5494.023
257.028	11.322	.803	.88236	4404.835
385.542	15.395	.903	.94881	3993.001
514.056	19.388	.963	.98433	3771.554
642.57	23.289	1.003	1.00852	3624.391

Table (2)
The calculated electron diffusion motion parameters for Argon (90%)-Helium (5%)-Nitrogen (5%) mixture.

E V cm^{-1}	V_d Cm 5^{-1} ×10^5	D/μ eV	<u> (eV)	μ cm^2/V.sec
12.760	3.081	.326	.37355	24144.02
25.520	3.677	.551	.56170	14410.29
51.040	4.837	.818	.75098	9477.230
76.560	6.051	.966	.84573	7904.180
102.079	7.296	1.058	.90095	7147.368
127.590	8.568	1.119	.93613	6714.874
255.198	15.032	1.255	1.01688	5890.370
510.396	27.002	1.368	1.11348	5290.533
765.594	37.947	1.438	1.23010	4956.540
1020.79	49.143	1.470	1.34983	4814.239
1275.99	60.980	1.484	1.45179	4778.952

Table (3)
The calculated electron diffusion motion parameters for Argon (95%)- Hydrogen (5%) mixture.

E V cm^{-1}	V_d Cm 5^{-1} ×10^5	D/μ eV	<u> (eV)	μ cm^2/V.sec
2.213	.799	.035	.05765	36082.5
4.426	1.698	.059	.09186	38372.11
8.852	2.894	.181	.16482	32693.6
13.279	3.456	.173	.21846	26028.4
17.705	3.868	.218	.25709	21845.4
22.131	4.250	.253	.28673	19206.0
44.262	5.855	.373	.38615	13228.4
88.524	7.937	.537	.52138	8965.7
132.786	9.356	.666	.62894	7045.9
177.048	10.485	.775	.72310	5922.2
221.310	11.475	.871	.81091	5176.9

Table (4)
The calculated electron diffusion motion parameters for Argon (5%)- Hydrogen (95%) mixture.

E V cm^{-1}	V_d Cm 5^{-1} ×10^5	D/μ eV	<u> (eV)	μ cm^2/V.sec
.232	.146	.030	.04405	6355.5
.463	.290	.031	.4461	62639.2
.926	.560	.033	.04667	60432.2
1.389	.798	.035	.04970	57453.1
1.852	1.004	.038	.05331	54253.0
2.315	1.184	.041	.05727	51162.5
4.63	1.837	.059	.0842	39677.5
9.26	2.651	.095	.11971	28633.2
13.89	3.228	.127	.15808	23239.0
18.52	3.706	.157	.19276	20011.9
32.15	4.150	.183	.22271	17927.2

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الخلاصة

تم في هذا العمل حل معادلة الانتقال عددياً لأمزجة غازية مختلفة بعد تعرضها لمجال كهربائي وذلك لحساب مصلحات انتقال الاليكترون وهي:

تردد التصادم الفعال لأليكترون–جزئية ν_{em}, تردد التصادم الفعال لأليكترون – أيون ν_{ei}, المقطع العرضي الفعال التصادمات اليكترون – أيون q_i ونسبة المقاطع العرضية لتصادم اليكترون ايون وجزئية q_i/q_m.

أظهرت هذه النتائج التي تم الحصول عليها تطابقاً بين القيم النظرية والعملية المنشورة.