

**Temperature Effect on the Effective Secondary Emission Coefficient for He and Ne Gases**

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**Abstract**

The relation between the effective secondary emission coefficient (ESEC)  $\gamma$  and temperature has been studied for He and Ne atoms. So we are studied the variation of  $\gamma$  with reduced electric field to the gas pressure ( $E/p$ ) between electrodes at different temperature ( $T$ ) for each gas. It has been found that the ESEC increase with ( $E/p$ ) at constant ( $T$ ) and decreases with temperature at constant ( $E$ ).

**Keywords** Temperature, effective secondary emission coefficient, discharge

**Classification** QC717.6-718.8

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## Introduction

The effective secondary emission coefficient  $\gamma$ , which can be define as the number of the secondary electrons yield as a result of positive ions bombarded the cathode surface[1], and it is an important parameter in gas discharge physics[2].

A gas discharge physics is a fascinating area of research and a source of many important applications ranging from plasma lighting to ozone production, and from etching of computer chips to production of solar cells. Gas discharge can be created by applying electric field through a gas which filled the gap between electrodes[3].

A theoretical treatment for ESEC has been developed recently by Nagorny and Drallos[4]. This treatment has been used with more details in this work for calculation of different parameters which can be affected on the ESEC.

## The theoretical consideration

The system containing neutral atoms, ions and electrons can be described by Boltzman's distribution function as,

$$\frac{\partial f_{\alpha}}{\partial t} + \bar{u} \cdot \bar{\nabla}_r f_{\alpha} + \frac{q}{m} (\bar{E} + \bar{u} \times \bar{B}) \cdot \bar{\nabla}_u f_{\alpha} = \left( \frac{\partial f_{\alpha}}{\partial t} \right)_{coll} \dots (1)$$

Where  $f_{\alpha}$  is a distribution function for species  $\alpha$ , which is a function of position  $r$ , velocity  $\bar{u}$  and the time  $t$ .  $q$  and  $m$  are the charge and mass of species  $\alpha$  respectively,  $\bar{E}$  and  $\bar{B}$  are electric and magnetic fields.

In the absence of the magnetic field,  $B=0$ , we rewrite Boltzman's equation for electron in the z-direction in the form

$$\frac{\partial f}{\partial t} + u_z \frac{\partial f}{\partial z} - \frac{e}{m} E_z \frac{\partial f}{\partial u_z} = \left( \frac{\partial f}{\partial t} \right)_{coll} \dots (2)$$

Flat surfaces of anode and cathode with gap distance,  $d$  have been considered and the z-axis is treated normally to the cathode, so that the applied electric field is anti-parallel of the axis. Also we consider the electric field is weak and the density of the noble gas is high in this treatment, therefore the mean free path of emitted electron  $\lambda_e$  is small compare with the distance between electrodes and the kinetic energy that electron gains  $eE\lambda_e$  between collisions is also small compare with its initial kinetic energy ( $eE\lambda_e \ll W$ ).

Because of the symmetry of the problem, one conclude that the gradient of the electrons distribution function is linear with the z-axis. Also the electron distribution function is isotropic at distance from the electrode exceeding a few times of  $\lambda_e$  [4].

In order to solve equation (2), we use for the electron distribution function (EDF), the relation[5]

$$f(u) = f_0(u) + \frac{1}{v} (\bar{u} \cdot \bar{f}_1(u)) \dots (3)$$

Where  $f_0$  is isotropic part and  $f_1$  is anisotropic part. The second term of equation (3) could be written as

$$\frac{1}{u} (\bar{u} \cdot \bar{f}_1(u)) = f_1 \cos \theta \dots (4)$$

$\theta$  is the angle between velocity vector and the z-axis.

The isotropic part and the anisotropic part of EDF associated with each others in the following two equations[5],

$$\frac{\partial f_0}{\partial t} + \frac{u}{3} \frac{\partial f_1}{\partial z} - \frac{e}{m} E_z \frac{1}{3u^2} \frac{\partial}{\partial u} (u^2 f_1) + S_0 = 0 \dots (5)$$

And

$$\frac{\partial f_1}{\partial t} + u \frac{\partial f_0}{\partial z} - \frac{e}{m} E_z \frac{\partial f_0}{\partial u} + S_1 = 0 \dots (6)$$

$$S_0 = -(C_{il}(f_0) + C_{el}(f_0)) \dots (7)$$

$$E = |E_z| = -E_z \dots (8)$$

where  $E$  is the electric field.  $u, e, m$  are the velocity, charge and mass of electron, respectively,  $C_{il}(f_0)$  is an inelastic collision term and  $C_{el}(f_0)$  is the part of electron elastic collision term describing the exchange between electrons and neutral gas atoms.  $S_1$  and  $S_0$  are the terms of collision, for  $S_1$ , we used simple expression [5]

$$S_1 = \nu_{tr} f_1 \dots (9)$$

With

$$\nu_{tr} = N \sigma_{tr} u \dots (10)$$

Here  $N$  is the background gas density,  $\sigma_{tr}$  is the electron-atom momentum transfer cross section and  $\nu_{tr}$  is the frequency of elastic collision between electron and neutral gas. With the condition [5]

$$\nu_{tr} \gg \frac{\partial}{\partial t} \dots (11)$$

By using equation (9) and equation (11), equation (6) is taking the form

$$f_1 = -\frac{1}{\nu_{tr}} \left( u \frac{\partial f_0}{\partial z} - \frac{e}{m} E_z \frac{\partial f_0}{\partial u} \right) \dots (12)$$

This equation gives the anisotropic part  $f_1$  of the EDF by the term of isotropic part  $f_0$ . We

rewrite equation (5) and by using equation (12) in the form

$$\begin{aligned} & \frac{\partial f_0}{\partial t} + \frac{u}{3} \frac{\partial}{\partial z} \left[ -\frac{1}{\nu_{tr}} \left( u \frac{\partial f_0}{\partial z} - \frac{e}{m} E_z \frac{\partial f_0}{\partial u} \right) \right] \\ & - \frac{e}{m} E_z \frac{1}{3u^2} \frac{\partial}{\partial u} \left[ u^2 \left( -\frac{1}{\nu_{tr}} \left( u \frac{\partial f_0}{\partial z} - \frac{e}{m} E_z \frac{\partial f_0}{\partial u} \right) \right) \right] + S_0 = 0 \end{aligned} \dots (13)$$

With some simplification equation (13) is taken the form

$$\begin{aligned} \frac{\partial f_0}{\partial t} = & \frac{1}{3u^2} \left( u \frac{\partial}{\partial z} + \frac{eE}{m} \frac{\partial}{\partial u} \right) \frac{u^2}{\nu_{tr}} \left( u \frac{\partial}{\partial z} + \frac{eE}{m} \frac{\partial}{\partial u} \right) f_0 \\ & + C_{il}(f_0) + C_{el}(f_0) \end{aligned} \dots (14)$$

The electron density is related to the isotropic part of the EDF is defined as [7]

$$n_e = \int f_0 d^3u = 4\pi \int_0^\infty u^2 f_0 du \dots (15)$$

and the electron current density is related to the anisotropic part of the EDF,  $\frac{1}{u} (\bar{u} \cdot \bar{f}_1(u)) = \delta f$ , which can be defined as [7]

$$j_e = -e \int u_z \delta f d^3u \dots (16)$$

Use equation (4) into equation (16), and integrated it result,

$$j_e = \frac{4\pi e}{3} \int_0^\infty u^3 f_1 du \dots (17)$$

To simplify equations (12) and (14), the change of variables  $(z, u)$  into the independent variables  $(z, \varepsilon)$ , can be used

$$\begin{aligned} \frac{\partial f_0(z, \varepsilon)}{\partial t} = & \frac{1}{3u} \frac{\partial}{\partial z} \frac{u^3}{\nu_{tr}} \frac{\partial}{\partial z} f_0(z, \varepsilon) \dots (18) \\ & + C_{il}(f_0) + C_{el}(f_0) \end{aligned}$$

and

$$f_1 = \frac{u}{v_{tr}} \frac{\partial f_0(z, \varepsilon)}{\partial z} \dots (19)$$

Where

$$\varepsilon = \frac{1}{2} mu^2 - eEz \dots (20)$$

Because of the existence of the electric field, we can neglected the elastic collision term ( $C_{el}(f_0 = 0)$ ), and the inelastic collision term is given by [4]

$$C_{il}(f_0) = -v_{il}(u) f_0 \dots (21)$$

The inelastic collision can happen at the certain distance from the cathode  $z_I(W_0)$ , which is given by

$$z_I(W_0) = (W_{ex} - W_0)/eE \dots (22)$$

where  $W_{ex}$  is the excitation energy of neutral atom and  $W_0$  is the electron energy near the cathode. Therefore we need to find the solution of equation (18) at this distance  $z_I(W_0)$ . The stationary solution of equation (18) is given by[4]

$$f_0(z, \varepsilon) = F(z) \delta(\varepsilon - W_0) \dots (23)$$

By using the energy conservation law with the help of equation (20) and using  $W = \frac{1}{2} mv^2$ , then

we can write equation (23) in the form

$$f_0(z, \varepsilon) = F(z) \delta(W - eEz - W_0) \dots (24)$$

by substituting the stationary solution (equation 24), equation (21) and ( $C_{el}(f_0 = 0)$ ) into equation (19), we can write

$$\frac{\partial^2 F}{\partial z^2} = \frac{3v_{tr}}{u^2} v_{il} F \dots (25)$$

In order to use  $v'_{il}$  in the equation (25), instead of  $v_{il}$  we use the approximation  $v'_{il}$  instead of  $v_{il}$  can be used in equation (25) because

$$\left| W_{ex} \frac{\partial f_0(W)}{\partial W} \right|_{W_{ex}} \ll f_0(W_{ex})$$

$$v'_{il} = \frac{\partial v_{il}}{\partial W} \Big|_{W=W_{ex}} = \frac{v_{il}}{W - W_{ex}} \text{ at } W \gg W_{ex}, \text{ or}$$

$$v_{il} = v'_{il}(W_{ex})(W - W_{ex}) \dots (26)$$

where  $v'_{il}$  is the derivative of  $v_{il}$ .

The energy conservation must satisfied when we used the stationary solution, i.e.

$$W = W_0 + eEz \dots (27)$$

From equation (23) we can write

$$W_{ex} - W_0 = eEz_I \dots (28)$$

Where  $z$  is the distance between electron and cathode. From equations (26),(27) and (28), we can write equation (25) at  $W \cong W_{ex}$  in the form,

$$\frac{\partial^2 F}{\partial z^2} = (z - z_I) \frac{3v_{tr} v'_{il}}{u_{ex}^2} eE(z_I) F, \text{ where we use } (u \cong u_{ex}), \text{ or}$$

$$\frac{\partial^2 F}{\partial z^2} = \kappa^3 \xi F \dots (29)$$

Where  $u_{ex}^2 = \frac{2W_{ex}}{m}$ ,  $\xi = (z - z_I)$  and

$$\kappa = \left[ \frac{3v_{tr} v'_{il}}{u_{ex}^2} eE(z_I) \right]^{1/3} \dots (30)$$

equation (29) is an Airy differential equation. The solution in the region  $z \leq z_I$  ( $\xi = z - z_I \leq 0$ ), is[4]

$$F(z \leq z_l) = F(z_l) \left( 1 + C \int_{z_l}^z \frac{v_{tr}}{u^3} dz \right) \dots (31)$$

When we use the stationary solution and using the properties of delta function[8] then equations (15) and (23) give an expression for the electron density,

$$n_e = 2\pi F(z) u \dots (32)$$

and the electron current density could be found from equations (17) and (19),

$$j_e = \frac{2\pi e}{3v_{tr}} u^3 \frac{\partial F(z)}{\partial z} \dots (33)$$

We must use the solution of Airy differential equation at the region  $z \leq z_l$  ( $\xi = z - z_l \leq 0$ ), in equation (31) to apply the boundary condition for the electron current density. The boundary condition of the electron current density at  $z=0$  for small electric fields and isotropic distribution of secondary electrons is given by [9]

$$j_e(W_0) = G(W_0) \gamma_i j_i + en_e u_0 / 4 \dots (34)$$

where  $u_0 = \sqrt{2W_0/m}$  is the electron velocity near the cathode surface,  $j_i$  is the ion current density,  $\gamma_i$  is the secondary emission coefficient for gas in vacuum and  $G(W_0)$  shows what part of the emitted electrons has the initial energy in the range  $(W_0, W_0 + dW_0)$  and satisfies the normalization condition [4]

$$\int_0^{W_{\max}} G(W_0) dW_0 = 1 \dots (35)$$

by applying the solution of Airy differential equation in the region  $z \leq z_l$  ( $\xi = z - z_l \leq 0$ ) equations (32) and (33) could be written in the form

$$n_e = 2\pi v F(z_l) \left( 1 + C \int_0^{z_l} \frac{v_{tr}}{u^3} dz \right) \dots (36)$$

and

$$j_e = -\frac{2\pi e}{3} C F(z_l) \dots (37)$$

using these equations into equation (34) and rewrite the solution for  $F(z_l)$  then

$$F(z_l) = -\frac{3}{2\pi e C} G(W_0) j_i \gamma_i \times \left[ 1 + \frac{3u_0^2}{4C} + \frac{3u_0^2}{4} \int_0^{z_l} \frac{v_{tr}}{u^3} dz \right]^{-1} \dots (38)$$

By using equation (38) into equation (37), one can obtain the ratio  $\frac{j_e}{j_i}$  such as

$$\frac{j_e}{j_i} = G(W_0) \gamma_i \left[ 1 + \frac{3u_0^2}{4C} + \frac{3u_0^2}{4} \int_0^{z_l} \frac{v_{tr}}{u^3} dz \right]^{-1} \dots (39)$$

From the definition of ESEC,  $\gamma = \frac{j_e}{j_i}$ , then  $\gamma$

will be

$$\gamma = G(W_0) \gamma_i \left[ 1 + \frac{3u_0^2}{4C} + \frac{3u_0^2}{4} \int_0^{z_l} \frac{v_{tr}}{u^3} dz \right]^{-1} \dots (40)$$

The quantity  $\frac{1}{C}$  in the second term of right of this equation can be found by solving Airy differential equation in the region  $z \geq z_l$  ( $\xi = z - z_l \geq 0$ ) such as [4]

$$\frac{1}{C} \cong \frac{1}{u_{ex}^2} \left[ \frac{\sigma_{tr}}{\sigma_{il} e E \lambda_{tr}} \right]^{1/3} \dots (41)$$

and

$$\gamma = G(W_o) \gamma_i \left[ 1 + \frac{3}{4} \frac{u_o^2}{u_{ex}^2} \left( \frac{\sigma_{tr}}{\sigma_{il} e E \lambda_{tr}} \right)^{1/3} + \frac{3u_o^2}{4} \int_0^{z_i} \frac{v_{tr}}{u^3} dz \right]^{-1} \dots (42)$$

We can write  $\frac{u_o^2}{u_{ex}^2}$  and  $u^3$  in the forms

$$\frac{u_o^2}{u_{ex}^2} = \frac{W_o}{W_{ex}} \dots (43)$$

and

$$u^3 = u_o^3 \left( 1 + \frac{eEz}{W_o} \right)^{3/2} \dots (44)$$

Use these definition from equations (43) and (44) into equation (42) then,

$$\gamma = G(W_o) \gamma_i \left[ 1 + \frac{3}{4} \frac{W_o}{W_{ex}} \left( \frac{\sigma_{tr}}{\sigma_{il} e E \lambda_{tr}} \right)^{1/3} + \frac{3}{4v_o} \int_0^{z_i} \frac{v_{tr}}{\left( 1 + \frac{eEz}{W_o} \right)^{3/2}} dz \right]^{-1} \dots (45)$$

Now the last term in equation (45) could be simplified to be

$$\frac{3}{4v_o} \int_0^{z_i} \frac{v_{tr}}{\left( 1 + \frac{eEz}{W_o} \right)^{3/2}} dz = \frac{3NW_o}{4eE} \int_{W_o}^{W_{ex}} \frac{\sigma_{tr}(W)}{W} dW,$$

then equation (45) becomes

$$\gamma = G(W_o) \gamma_i \left[ 1 + \frac{3}{4} \frac{W_o}{W_{ex}} \left( \frac{\sigma_{tr}}{\sigma_{il} e E \lambda_{tr}} \right)^{1/3} + \frac{3NW_o}{4eE} \int_{W_o}^{W_{ex}} \frac{\sigma_{tr}(W)}{W} dW \right]^{-1} \dots (46)$$

We can write equation (46) in the form

$$\gamma(W_o, X) = G(W_o) \gamma_i \frac{1}{1 + \phi \left( \frac{\tilde{X}}{X} \right)^{1/3} + \psi(\omega) \left( \frac{\tilde{X}}{X} \right)} \dots (47)$$

Where

$$\omega = \frac{W_o}{W_{ex}} \dots (48)$$

and

$$X = \frac{E}{p} \dots (49)$$

Where p is the gas pressure, and  $\tilde{X}$  is denoted the characteristic electric field reduced to a pressure of 1 Torr,  $\tilde{X} = \frac{W_{ex}}{e\lambda_{tr}(W_{ex})}$ , or we can

write  $\tilde{X}$  in the form

$$\tilde{X} = \frac{W_{ex}}{e} \sigma_{tr}(W_{ex}) \times 3.54 \times 10^{16} \text{ cm}^{-3} \dots (50)$$

The function  $\psi(\omega)$  is

$$\psi(\omega) = \frac{3}{4} \omega \int_0^1 \frac{\sigma_{tr}(W_{ex}y)}{\sigma_{tr}(W_{ex})y} dy \dots (51)$$

And the coefficient  $\phi$  is

$$\phi = \frac{3}{4} \left( \frac{\sigma_{tr}(W_{ex})}{\sigma_{il}(W_{ex})W_{ex}} \right)^{1/3} \dots (52)$$

After integrating over  $W_o$ , ESEC results as a function of reduced electric field as the follow

$$\gamma(X) = \int_0^{W_{max}} \gamma(W_o, X) dW_o \dots (53)$$

We treat equation (47) and equation (53) for He and Ne atoms by considering the function  $G(W_o)$  is fixed for the electron energies less than  $W_{max}$  and zero for electron energies greater than  $W_{max}$ . From normalization condition, we have

$$G(W_o) = \frac{1}{W_{max}} \text{ for } W_o < W_{max} \dots (54)$$

When the distribution of emitted electrons is wide and most of electrons are emitted in the

energy range  $0 \rightarrow W_{ex}$  where the function  $\psi(\omega)$  also has a maximum and changes very little over this energy range. In this case we substitute  $\psi(\omega)$  by its average value which is given by [4]

$$\bar{\psi}(\omega_{max}) = \int_0^{\omega_{max}} \psi(\omega) G(W_{ex} \omega) W_{ex} d\omega \dots (55)$$

Where

$$\omega_{max} = \frac{W_{max}}{W_{ex}} \dots (56)$$

From equations (47), (53) and (55) we get

$$\gamma(X) = \int_0^{\omega_{max}} \frac{G(W_{ex}) \gamma_i}{1 + \omega \phi \left( \frac{\tilde{X}}{X} \right)^{1/3} + \bar{\psi}(\omega_{max}) \left( \frac{\tilde{X}}{X} \right)} d\omega \dots (57)$$

Using equation (54) and integrate, we get

$$\gamma(X) = \frac{\gamma_i}{\omega_{max} \phi \left( \frac{\tilde{X}}{X} \right)^{1/3}} \ln \left[ \frac{1 + \omega_{max} \phi \left( \frac{\tilde{X}}{X} \right)^{1/3} + \bar{\psi}(\omega_{max}) \left( \frac{\tilde{X}}{X} \right)}{1 + \bar{\psi}(\omega_{max}) \left( \frac{\tilde{X}}{X} \right)} \right] \dots (58)$$

using equation (54) into equation (58) we can write

$$\gamma(E/p) = \frac{\gamma_i}{\omega_{max} \phi \left( \frac{\tilde{X}}{X} \right)^{1/3}} \ln \left[ 1 + \frac{\omega_{max} \phi \left( \frac{\tilde{X}}{X} \right)^{1/3}}{\bar{\psi}(\omega_{max}) \left( \frac{\tilde{X}}{X} \right)} \left( \frac{E/p}{\tilde{X}} \right)^{2/3} \right] \dots (59)$$

By using the gases law, equation (59) could be converted as a function of temperature

$$\gamma(T) = \frac{\gamma_i}{\omega_{max} \phi \left( \frac{\tilde{X}}{X} \right)^{1/3}} \left( \frac{E/NK_B}{\tilde{X}} \right)^{1/3} T^{1/3} \ln \left[ 1 + \frac{\omega_{max} \phi \left( \frac{\tilde{X}}{X} \right)^{1/3}}{\bar{\psi}(\omega_{max}) \left( \frac{\tilde{X}}{X} \right)} \left( \frac{E/NK_B}{\tilde{X}} \right)^{2/3} T^{2/3} \right] \dots (60)$$

Where  $T$  is the gas temperature and  $K_B$  is the Boltzman constant.

## Results and discussion

The values of  $\tilde{X}$  and  $\psi(\omega)$  depend on the momentum transfer cross section,  $\sigma_{tr}$ , for the gas. So we take an experimental data for the momentum transfer cross section to a collision of electron with He and Ne atoms [10,11]. We made a fitting for this experimental data to be suitable with our programs.

The coefficient  $\phi$  depends on the momentum transfer cross section and the ionization cross section or energetic distribution of the single differential cross section  $\sigma'_{ii}$ . Also an experimental data for ionization cross section has been used.

Figure (1) illustrated our calculation for the function  $\psi(\omega)$  as a function of  $\omega$  for He and Ne respectively. Our results are comparing with that calculated by [4] and we found a very good agreement.

Figure (2) shows the change in the ratio  $\gamma/\gamma_i$  versus the applied reduce electric field for He and Ne at different temperatures ( $273 K^\circ$ ,  $298 K^\circ$  and  $373 K^\circ$ ) and with maximum electron energy  $W_{max} = 10 eV$ . In this case we are assumed that the temperature is fixed along the time of experiment. From these figures, one could see that  $\gamma$  is increase with increasing  $T$  and the ratio  $E/p$ .

In figure (3) we draw the changing of  $\gamma/\gamma_i$  versus the temperature for He and Ne for different values of the electric field ( $10 v/cm$ ,  $100 v/cm$  and  $1000 v/cm$ ) at maximum electron energy  $W_{max} = 10 eV$ . In this case we are assumed that the applied electric field is fixed along the time of experiment. From these results we conclude that the ESEC decrease with  $T$  and increase with applied electric field.

From figure (1) we conclude that (ESEC).increase with the ratio ( $E/p$ ) at constant temperature while (ESEC) decrease with increasing temperature at applied constant electric field.

Finally our result compare with that calculated by other calculations and give good agreement with it.



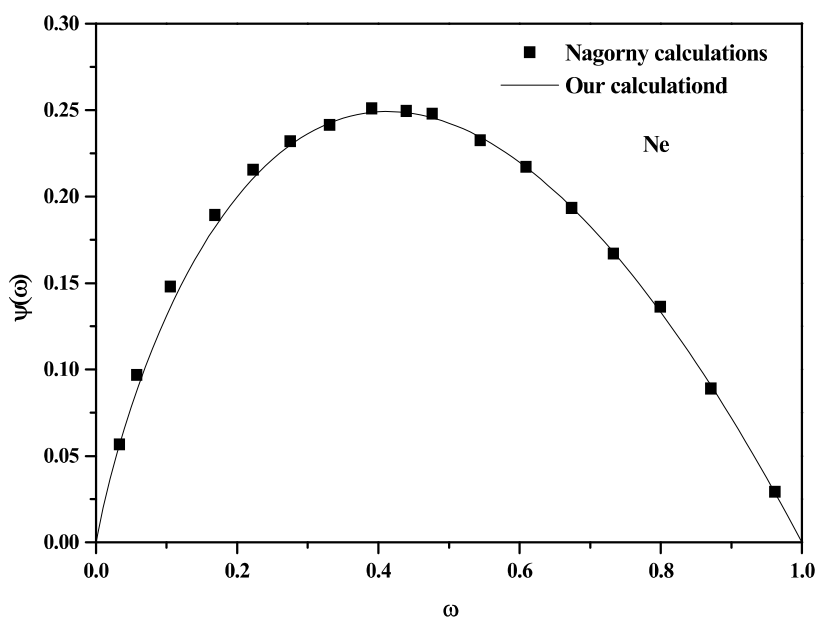
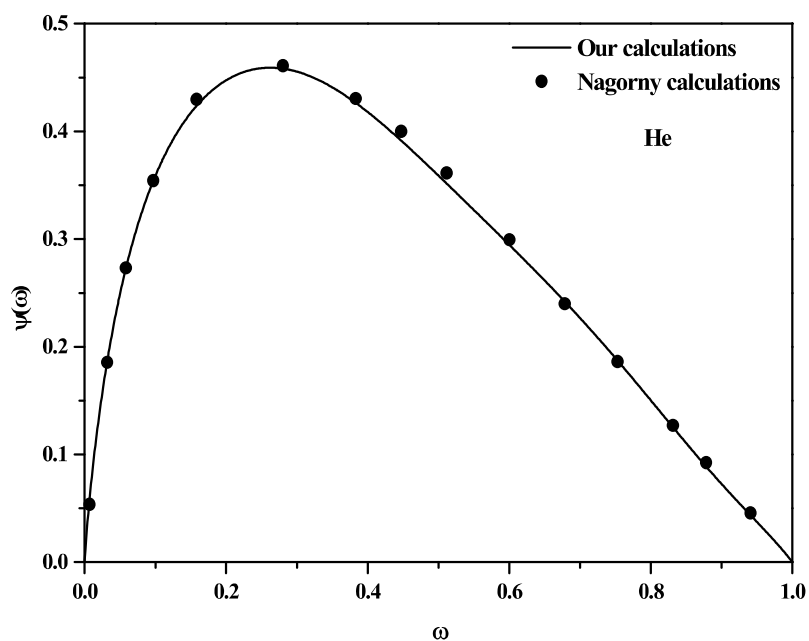


Figure (1): the function  $\psi(\omega)$  as a function  $\omega$  for He and Ne.

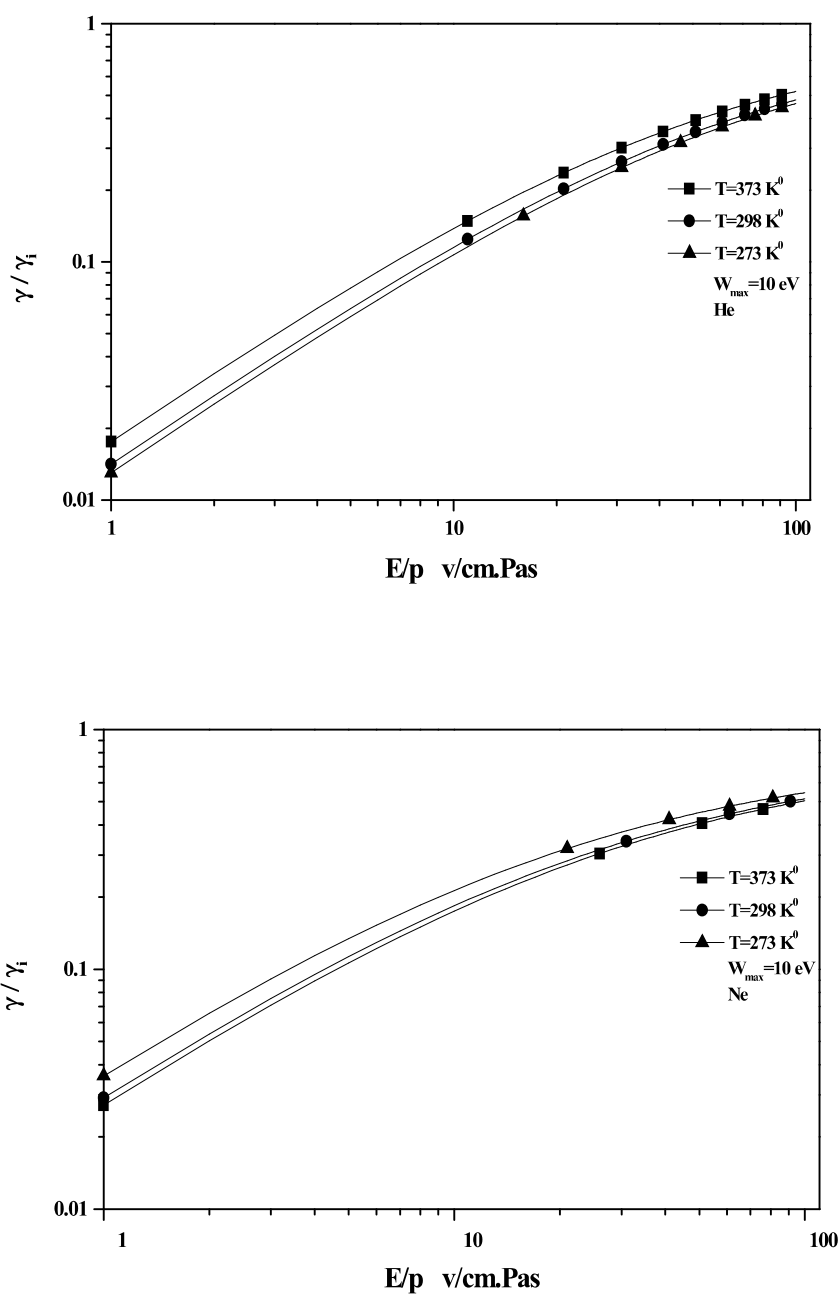


Figure (2):  $\gamma/\gamma_i$  versus the applied electric field reduce to the gas pressure for He and Ne for different temperatures ( $273\text{ K}^\circ$ ,  $298\text{ K}^\circ$  and  $373\text{ K}^\circ$ ) at maximum electron energy  $W_{\text{max}} = 10\text{ eV}$ .

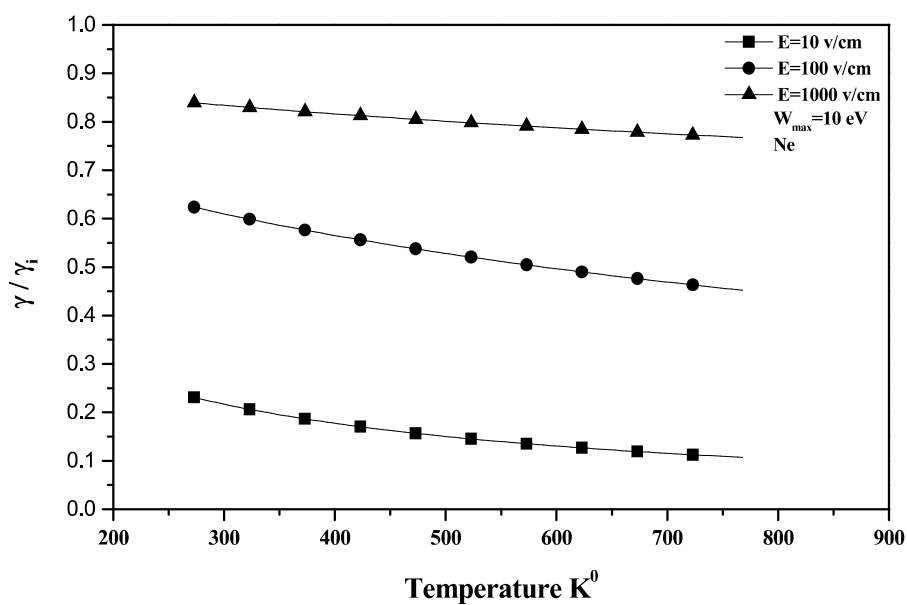
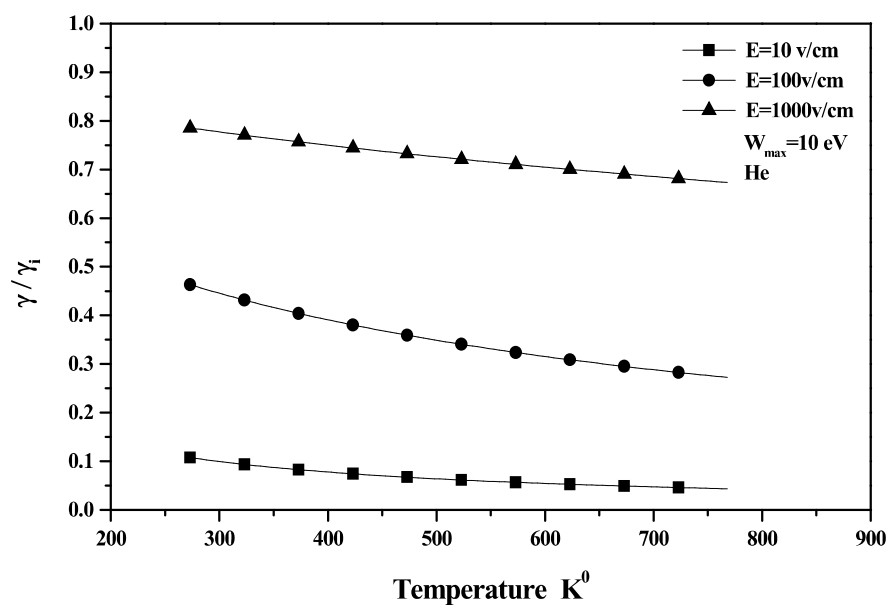


Figure (3):  $\gamma/\gamma_i$  versus the temperature for He and Ne for different values of the electric field (10 v/cm, 100 v/cm and 1000 v/cm) at maximum electron energy  $W_{max} = 10$  eV.

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**تأثير درجة الحرارة على عامل الانبعاث الثانوي المؤثر  
لغازي الهيليوم والنيون**

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**الخلاصة**

تم دراسة العلاقة بين عامل الانبعاث الثانوي المؤثر  $\gamma$  ودرجة الحرارة لغازي الهيليوم والنيون. كذلك تم دراسة تغير  $\gamma$  مع النسبة بين الجهد المسلط بين قطبين وضغط الغاز ( $E/p$ ) عند درجات حرارة مختلفة لكل غاز. وجد بان عامل الانبعاث الثانوي المؤثر يزداد مع النسبة ( $E/p$ ) عند ثبوت درجة الحرارة  $T$  ويتناقص مع زيادة درجة الحرارة عند ثبوت المجال الكهربائي المسلط ( $E$  بين القطبين).

الكلمات المفتاحية: درجة الحرارة , عامل الانبعاث الثانوي المؤثر , التفريغ

\*البحث مستل من أطروحة دكتوراه للباحث الاول