ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 4, Issue 9, March 2015

Comparison study of electron beam skirt behavior in Environmental Electron Microscope

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Abstract*— This work concerns the comparison of the results of electron scattering by gas in an Environmental Scanning Electronic Microscope (ESEM). For this, we have developed a Monte Carlo simulation model based on the monitoring of the behavior of electrons in the gas. Water vapor and helium were chosen to validate the results by changing the gas pressure and the energy of the electrons. The results obtained on the evolution of the skirt lateral expansion by Monte Carlo simulation are consistent compared to the theoretical Rs commonly used in literature (Reimer and Smith-Schumacher).

***Keywords*— interaction gas-electrons, Low-vacuum, Monte Carlo simulation, skirt.**

I. INTRODUCTION

Conventional Electron Microscopy (CSEM) is based on the electron-matter interactions. It allows the production of high resolution images of the sample surface with fields of depths greater than the optical microscopy. In Low-vacuum mode conditions with Environmental Scanning Electron Microscopy (ESEM), the key problem for images of the almost same quality as those obtained in High-vacuum mode (CSEM) is the detection of emitted electrons. To better predict the experimental results and guidance in a useful way the conduct of experiments, modeling step is required. The goal is to provide the fullest possible understanding of the phenomena of interaction gas-electrons. In other words, it is possible to validate our simulation results for the radius of the Skirt with the expressions values published in the literature and commonly used [1, 2]. It should be noted that the primary electron beam is divided into two fractions after interaction with the atoms / molecules of the gas [3], 1) a non-scattered beam, which keeps the same diameter and the same distribution pattern as the probe primary electronics. 2) A scattered beam consisting of primary electrons whose trajectory is deviated by gas atoms (or molecules), and called the beam skirt (Rs). The scattered electrons give characteristic lines and background noise corresponding to their impact points on the sample surface. Accordingly, X-rays produced by the electrons of "skirt" are difficult to distinguish from those produced by the unscattered primary electron beam. This affects the results of the X-ray microanalysis by changing the signal to noise ratio of EDS in the ESEM. So it is of paramount importance to know the magnitude and extent of the skirt in order to predict the best resolution may be reached under some given experimental parameters. A number of articles have been published on the study of the problems encountered by the skirt phenomenon which can significantly alter the results of the X-ray microanalysis and image quality [4, 5, 6, 7, 8, 9]. Common concern of most studies published earlier on the subject was essentially measure the amplitude of the beam (skirt) and how to evaluate its impact on the analyzes [10, 11], in focusing mainly to the phenomenon of interaction between the atoms / molecules of the gas and the primary electron beam.

In this work, we study the distribution of electrons in the two gases by a Monte Carlo method in a wide range of pressure and incident electron energy as used in an electron microscope Environmental. Results will be compared with the values obtained by expressions commonly used in the literature (Reimer and Smith-Schumacher).

II. THEORETICAL BACKGROUND

A. Monte Carlo simulation

In our case, it is proposed to use the Monte Carlo method to study the behaviour of the incident electrons in the gas, simulating each collision, and then follow all elastic and inelastic electrons until they leave the gas reaching the surface of the material.

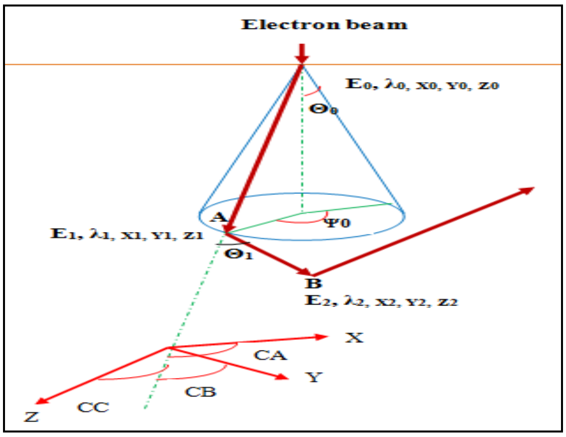

Fig. 1: coordinate system for the Monte Carlo simulation.

Considering a primary electron beam of initial kinetic energy E, r(x, y, z) coordinates and direction d (u, v, w). The initial coordinates of the electron at the entrance are chosen such that: x0=0, y0=0, z0=0. Once the electron interacts with the target at point A, it changes direction and goes into the volume of gas while selling part of its energy. If the electron undergoes interaction at point B

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after travelling the path Sn, the coordinates of point B are calculated relative to those of A (Fig. 1) is given by [12] :

$$\begin{cases} x_n = x_{n-1} + S_n \\ y_n = y_{n-1} + S_n \\ z_n = z_{n-1} + S_n \end{cases} \quad ($$

Factors CA, CB and CC are the direction vectors cosine:

$$\begin{cases} CA = C_x \cos\theta + V_1 V_3 + C_y V_2 \\ CB = C_y \cos\theta + V_4 (C_z V_1 - C_x \\ CC = C_z \cos\theta + V_2 V_3 - C_y V_1 \end{cases} \quad ($$

With:

$$\begin{cases} V_1 = AM * \sin\theta \quad ; \quad V_2 = AN * AM * \sin\theta \\ V_3 = \cos\psi \quad ; \quad V_4 = \sin\psi \\ AN = -\left(\frac{C_x}{C_z}\right); \quad AM = \frac{1}{\sqrt{1 + AN^2}} \end{cases}$$

The mean free path that defines the distance between two successive scattering events can also make the difference between solid and gaseous targets. In the gas, the mean free path λ for an energy E defined by Danilatos [13], is given by the following equation:

$$\lambda = \frac{K_b\, T}{P\, \sigma_T} \quad (m) \qquad (3)$$

Where is the total scattering cross-section in meter (m²) which varies with the electron energy, the Boltzmann constant (J/K), T the absolute temperature of the gas in Kelvin (°K) and P the pressure in Pascal (Pa).

Several experimental and theoretical studies have been dedicated to calculate the cross section of the solid target atoms [14, 15, 16, 17]; but much less for atoms/molecules of gas targets [18, 19]. Only a few experimental attempts dedicated to the study of the total cross section σT of the gas have been reported in the literature including the gases used in the ESEM. Unfortunately, the results of these experiments are not always concordant [13], [20, 22, 23, 24]. The values of the total scattering cross-section for the various types of gas are derived from the work of Danilatos [19]. The movement of electrons after the shock is sampled according to energy loss distribution functions and angular deviation specific to the sampled interaction. Studies by Joy and Luo [25] suggest that the expression Bethe was dissatisfied at low energies. They proposed a modified form of the relationship Bethe [26]. This formula reflects the average energy loss dE per unit length ds. This expression is valid for the whole energy range.

$$\frac{dE}{ds} = -78500 \left(\frac{\rho Z}{AE}\right) Log\left(\frac{1.166E}{J} + 1\right) \quad \left(\frac{keV}{cm}\right) \qquad (4)$$

Where is the density of the target, A atomic weight of the target, E is the energy of the electron in keV, and J is the mean ionization energy in keV. The latter is given by Berger and Seltzer [14]:

$$J = \left[9.76Z + \frac{58.5}{Z^{0.19}}\right] 10^{-3} \quad (keV) \quad si \quad Z > 13 \qquad (5)$$

$$J = 0.015Z \quad (keV) \quad si \quad Z \le 13 \qquad (6)$$

The new direction of the electron after nth collision is defined by two angles (θ, Ψ): The calculation of these two angles can predict the direction that will take the electron.

For elastic collisions, angular elastic deflection is given by the screened elastic Rutherford scattering, θ is the scattering angle plane, that is to say the angle between the direction of the incident electron and the direction distributed (Fig. 1). Thus a ratio obtained from the probability distributions of Newbury [12]:

$$\cos\theta = 1 - \frac{2\, \alpha\, RND}{1 + \alpha - RND} \qquad (7)$$

Where RND is a random number drawn automatically by computer and is the screening factor are given by the relationship [27]:

$$\alpha = 0.00343 \, \frac{Z^{0.67}}{E} \qquad (8)$$

For inelastic scattering event, the new direction is derived from [28]:

$$\sin^2\theta = \frac{dE}{E} \qquad (9)$$

Where dE is the energy loss of ionizing collisions.

Is the azimuthal scattering angle (0 and 360°) determined in the plane perpendicular to the electron direction (Fig. 1) is then obtained by simple selection of a random number RND.

$$\Psi = 2\, \pi\, RND \qquad (10)$$

B. The skirt

Following the release of the gas, the redistribution of electrons around the primary beam forms what is called the skirt. Various terms have been proposed to calculate the radius of the skirt (Rs). Among these equations, we find that proposed by Reimer [1]; and Smith-Schumacher [2] where all the main experimental parameters (E, P, L, Z) are used from a simple analytical model:

- The formula described by Reimer [1] and adapted by Danilatos [13]:

$$R_s = \frac{364\, Z}{E} \left(\frac{P}{T}\right)^{0.5} L^{\frac{3}{2}} \quad (m) \qquad (11)$$

Where L has the length of the path of the electron in the gas (working distance) in (m); P is the pressure (Pa); T is the temperature expressed in Kelvin (° K), Z is the atomic number of the gas, the energy E is expressed in (eV).

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 4, Issue 9, March 2015

- Smith-Schumacher [2]:

$$R_s = \frac{793.2}{\beta^2(E+E_0)}\left[\frac{Z(Z+1)}{T}\, ln\left(\frac{192\beta}{Z^{\frac{1}{3}}}\right)\right]^{0.5} L^{\frac{3}{2}} \quad (m)\ (12)$$

With

$$\beta = \left[1 - \frac{1}{(1+\frac{E}{E_0})^2}\right]^{0.5}$$

E0=511keV: initial energy of the electron at rest.

Note that the approximation of the scattered electrons 90% was chosen to calculate the skirt radius width to compare Monte Carlo simulation results with the two formulas (11) and (12).

III. RESULTS AND DISCUSSION

In order to assess the consequences of the use of gas in the ESEM and the effects skirt on the interaction volume, it is necessary to study the variations of the skirt in a wide range of operating parameters ESEM including energy and pressure. Under these conditions, the pressure plays a role, which is the evacuation of the charges of the surface of the sample and the amplification of the signal emitted by the sample. The increase in this parameter amplifies the electron scattering phenomenon (Fig. 2). In addition, the acceleration voltage is indirectly involved. When the acceleration voltage increases, the fraction of the scattered electrons is decreased (Fig. 3) in agreement with previous study. In order to make comparison, two gases are used such as helium and water vapor with a pressure range (1 Pa to 665Pa) and energy range (5 keV to 30 keV).

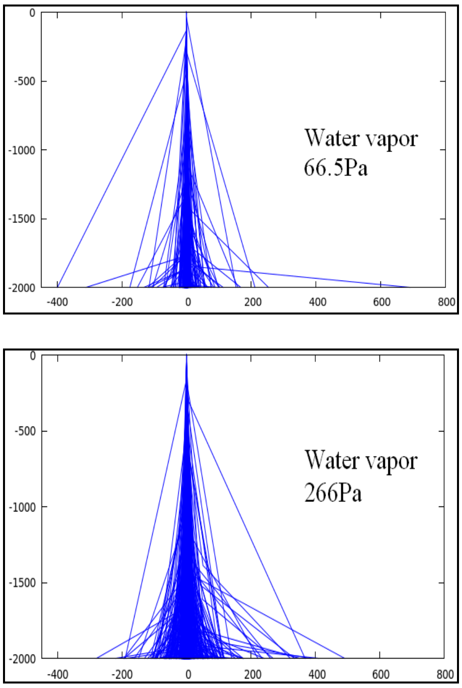


Fig. 2: Comparison of skirt (water vapor) for two pressure values (66.5 and 266Pa), and an energy of 5 keV and a working distance of 2mm.

In the figure 2 are showed the variation of the skirt according to the pressure (266Pa and 66.5), assuming that the primary electron beam passes through a thickness of 2 mm of gas (water vapor) and energy of 5keV. We can see as expected, skirt simulated by Monte Carlo expanded quite considerably with increasing pressure in agreement with theoretical predictions and experimental [3], [29].

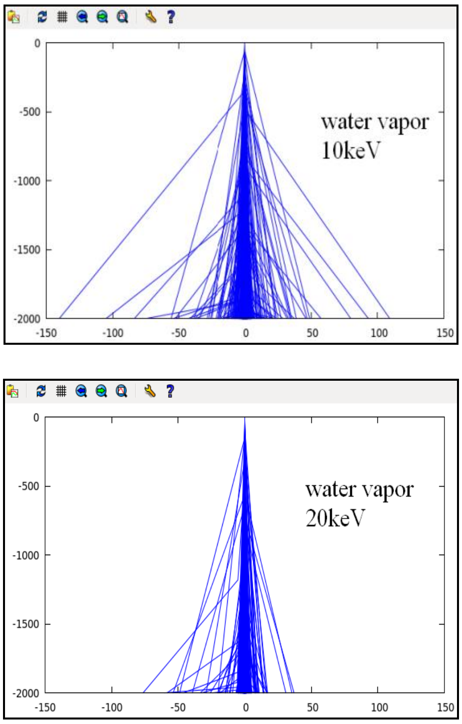
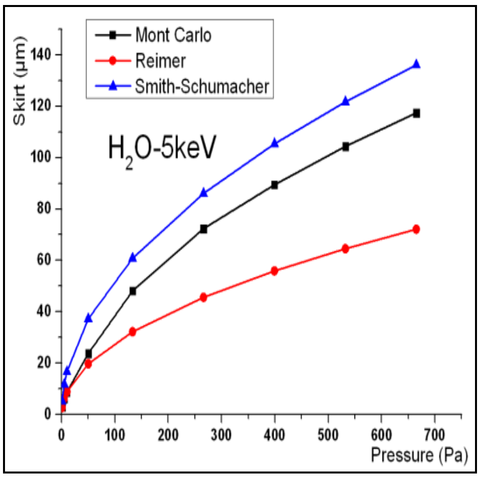


Fig. 3: Comparison of skirt in the gas (water vapor) for two energy values (10 and 20 keV) with a pressure of 133Pa, and a working distance of 2mm.

Figure 3. Shows the variation of skirt when the electron beam energy increases between 10 keV and 20 keV for a given pressure P = 133 Pa, and a working distance of 2mm. Thus one can see a reduction in the width of skirt with increasing energy in agreement with theoretical predictions



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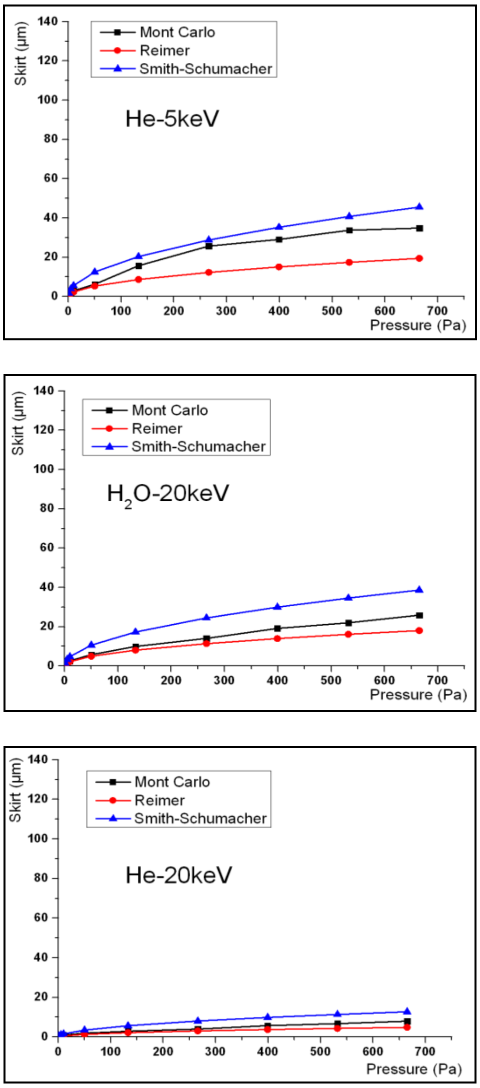

Fig. 4: Variation of the skirt according to the pressure under water vapor and helium environment with energy values of E= 5keV and 20keV, and a working distance of L= 2mm.

Figure 4. Shows another comparison between our calculation model and the results of theoretical calculations based on the pressure. It can be seen that increasing the skirt with pressure is lower by the relationship Reimer, followed by skirt calculated by Monte Carlo simulation and then by the skirt Smith-Schumacher. In particular, it appears that most of the gas pressure increases, the radius of skirt increases. Note also that enlargement appears great for Smith-Schumacher as Monte Carlo and Reimer for large pressure values. We interpret the increase skirt rays to be due to a phenomenon of enlargement of the electron beam. However, with helium as environmental setting, it appears that the skirt thus produced is low and little disturbance analysis on the ESEM. It can be concluded that the use of water vapor and helium with different pressure range of 1-665 Pa for an energy range (5KeV and 20KeV) give better skirt radius results with the Monte Carlo method in agreement with previous experimental results.

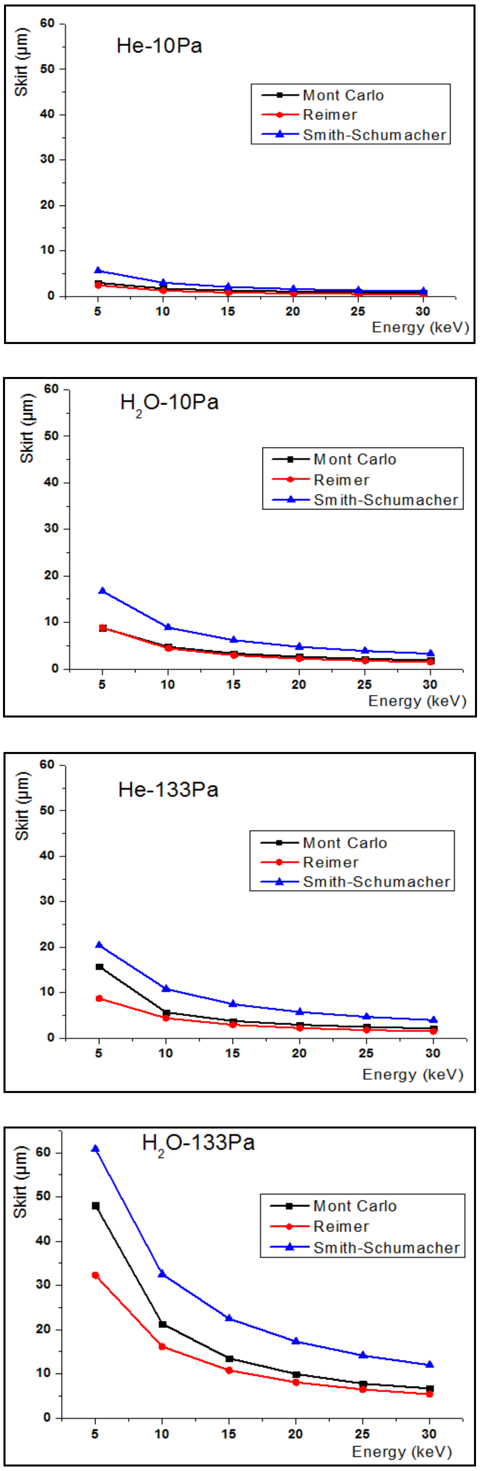

Fig. 5: Variation of the skirt according to electron bean energy under water vapor and helium environment with pressure values of P=10Pa, 133Pa, and a working distance of L= 2 mm.

Another important parameter that influences the skirt is the energy of the incident beam. More energy increases, the scattering of electrons is low [ref]. Figure 5 shows the variation of the skirt according to the electron energy. We find that the radius of the skirt decreases as the energy primary electron beam is increased regardless of the pressure (10 and 133Pa presented as an example) .We note that the radius of the skirt calculated by Reimer is lower followed by the Monte Carlo simulation and Smith-Schumacher. We note a good agreement between the results of theoretical calculations and Monte Carlo simulation across the spectrum of energy. The values obtained by Monte Carlo simulation are between those obtained by the expressions of Reimer and Smith-Schumacher. This shows the validity of the model we have proposed.

IV. CONCLUSION

In this work we presented a comparative study of electron scattering results in a gaseous environment as is the case in an Environmental Scanning Electron Microscope. The results obtained by the Monte Carlo model were compared with values from expressions radius skirt (Reimer and Smith-Schumacher). This study shows the good correlation between the proposed model and expressions of the skirt in both high and low energy. Future objective is to open a new research approach based on the combination between the interaction of electrons with the gas molecules and the interactions of electrons with the atoms of the material by Monte Carlo simulation to better assess the impact of gas on the ESEM imaging and analysis.

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