An Investigative Study on the Electron Energy Distribution Function and Electron Transport Coefficients in SF_6 – Ne Gas Mixtures

Bushra J. Hussein , M. K. Jassim

Department of Physics – College of Education for Pure Science (Ibn Al-Haitham) - University of Baghdad

Abstract

The program (EEDF) is employed to solve Boltzmann equation to study the electron energy distribution function EEDF and the transport coefficients of pure sulfur hexafluoride gas and its mixtures with Neon gas. In this paper it is focused on the effect of various concentrations of the gas mixtures on the EEDF and the corresponding transport coefficients. The results are graphically presented and discussed in order to exhibit the differences among the various mixtures on the EEDF and the transport coefficients. In this sense, it is found that each mixture has an individual influence on EEDF and the transport coefficients.

Keywords: (EEDF) program, EEDF, Boltzmann equation, SF_6 – Ne mixture, transport coefficients

دراسة تحقيقية بشأن دالة توزيع طاقة ومعاملات النقل الإلكترونات

في مخاليط غاز SF_6– Ne

د.بشرى جودة حسين   د.مصطفى كامل جاسم

قسم الفيزياء/ كلية التربية للعلوم الصرفة (أبن الهيثم)/جامعة بغداد

الملخص

وظف برنامج (EEDF) لحل معادلة بولتزمان لدراسة دالة توزيع طاقة الإلكترونات EEDF ومعاملات النقل لغاز سادس فلوريد الكبريت النقي ومخاليط منه مع غاز النيون. البحث الحالي يركز على دراسة تأثير تراكيز مختلفة من خليط الغاز على EEDF ومعاملات النقل المقابلة. عرضت

النتائج بيانيا ونوقشت من أجل إظهار الاختلافات بين المخاليط على EEDF ومعاملات النقل. ووجد أن كل خليط له تأثير منفرد على EEDF وعلى معاملات النقل.

الكلمات المفتاحية: برنامج (EEDF) ، دالة توزيع طاقة الإلكترونات EEDF ، معادلة بولتزمان ، خليط غاز سادس فلوريد الكبريت – النيون ، معاملات النقل

Introduction

It is well known that the inert gases when mixed with certain gases are of a certain important in some applications such as plasma technology, and electrical discharge. As the inert gases are monoatomic and its atoms have closed – shell structure, the electron collisions with inert gas atoms is an ideal case of the processes of the electron – atom collision [1]. The inelastic collisions are insignificant compared to elastic collisions on the distribution function [2]. The electron energy distribution function EEDF is essential in plasma modeling because it is important to compute the reaction rates [3-4]. There are many functions that describe the EEDF such as Druyvesteyn, Maxwellian, and solution of the Boltzmann equation [5-6]. The transport coefficients can be derived from EEDF which is affected by the choice of the function used. It is known for high – voltage equipment the use of sulfur hexafluoride SF_6 as an insulation medium for a large scale [7]. Although, the transport properties of the mixtures of SF_6 with Ne have been studied for the previous couple decades [8], the numerical solutions corresponding to the rapid development of computers lead to the appearance of some creative scientific software package that treat the problems so friendly and give a suitable and highly appreciate of accuracy of the problem. One of these programs is (EEDF) which solve numerically the Boltzmann equation for the EEDF in low ionized plasma of a mixture of gases in an electric field by the two – term approximation [9]. While the physical properties of the plasma can be mainly defined by electron velocity distribution function, the statistical behavior of electrons and its transport properties are directly ruled by the electron energy distribution function EEDF. To obtain the EEDF one can solve the Boltzmann equation. The balance of the electron collision losses with electrons gain due the acceleration of electric field determines the EEDF. Therefore the EEDF is essential to understand the transport properties of both pure and gas mixtures in plasma discharge for example. This paper theoretically investigates the influence of SF_6 gas concentration in SF_6 – Ne mixtures on the electron transport properties. The EEDF and the corresponding transport properties are obtained by solving Boltzmann equation using (EEDF) software package program. Further, the study includes the investigation the effect of reduced electric field E/N on the electron transport coefficients.

The Numerical Solution of (EEDF) Code

The program (EEDF), described in [9] is used for calculation of EEDF and the electron transport parameters by solving the Boltzmann equation. The Boltzmann equation describes the evolution of the distribution function in phase space. The Boltzmann equation can be written as[5]:

$$u^{1/2} f_0(u)(dn_e/dt) = I_{\mathrm{E}}(u) + I_{\mathrm{el}}(u) + I_{\mathrm{in}}(u) + I_{\mathrm{ee}}(u) \qquad (1)$$

where u is electron energy, $f_0(u)$ is the isotropic part of the function, $I_{\mathrm{E}}(u)$ describes the electrons heating in the electric field, and $I_{\mathrm{el}}(u)$, $I_{\mathrm{in}}(u)$ and $I_{\mathrm{ee}}(u)$ characterize the elastic, inelastic and electron – electron collisions. The term dn_e/dt represents the conservation of the electron density

$$dn_e/dt = n_e(\bar{\nu}_{\mathrm{i}} - \nu_{\mathrm{att}} - \nu_{\mathrm{rec}}) \qquad (2)$$

where $\bar{\nu}_{\mathrm{i}}$,ν_{att}, ν_{rec} are expressed in terms of suitable integrals of $f_0(u)$. They are the frequencies of ionization, attachment and recombination, respectively. Iterative method is used to solve Boltzmann equation numerically. The code solves Boltzmann equation starting with equation (2) which then substituted in the equation (1) in order to calculate $(dn_e/dt)^n$ value. The code is restricted by criterion value to end the iterations procedure and the function f_0^{n+1} is counted as a solution. Finally, by setting the distribution function, some of the plasma characteristics are calculated. These equations are used to calculate
The mean electron energy

$$\bar{u} = \int_0^\infty u^{3/2} f_0(u) du \qquad (3)$$

The electron mobility

$$\mu_e = -\frac{1}{3}\frac{2e}{m}\int_0^\infty \frac{u^{3/2}}{v_m(u)}\frac{\partial f_0}{\partial u} du \qquad (4)$$

where v_m represents the electron momentum – transfer collision frequency.
The drift velocity

$$W_e = -\frac{E}{3}\frac{2e}{m}\int_0^\infty \frac{u^{3/2}}{v_m(u)}\frac{\partial f_0}{\partial u} du \qquad (5)$$

The electron diffusion coefficient

$$D_e = \frac{1}{3}\frac{2}{m}\int_0^\infty \frac{u^{3/2}}{v_m(u)} f_0 du \qquad (6)$$

The characteristics energy

$$\mu_{\text{ch}} = e\,\frac{D_e}{\mu_e} \qquad (7)$$

Results and Discussion

Figure (1) shows the electron distribution function EEDF vs. mean electron energy for various values of reduced electric field *E*/*N* where *E* is the electric field and *N* the gas density in pure SF_6 in a unit of TD ($1\ \text{TD} = 10^{-17}\ \text{Vcm}^2$). The outcome of curves in the figure is due to usage of constant electron concentration is $1 \times 10^{16}\ \text{cm}^{-3}$ and constant pressure is $760\ \text{torr}$ in the calculations. The figure shows that as the mean electron energy increases the EEDF decreased for fixed *E*/*N*. At lower mean electron energy, the lower value of reduced field *E*/*N* gives higher value of EEDF, nevertheless as the mean electron energy increases the decreasing of EEDF is fast for lower *E*/*N* compared to the higher values. It is evident that the width of EEDFs for various *E*/*N* is being large for higher *E*/*N*. The higher band of larger E/N is due to the higher value of the electric field which heats the electrons and therefore increases the energy of cold electrons. In turn, this will affect the electron transport coefficients.

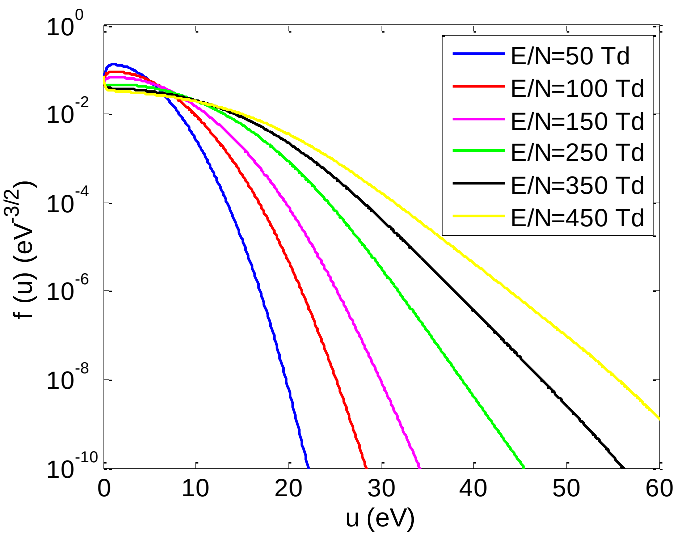


Figure (1): EEDF versus mean electron energy for different values of reduced electric fields *E*/*N* in pure SF_6

One of the main parameters that affected by concentration's variation of SF_6 is the mean electron energy. Figure (2) shows this effect for a fixed value of reduced field. In this figure we can observe that the mean electron energy decreases with increase the SF_6 content in the mixtures. The reason for this behavior is due to the variation of the EEDF of the each individual mixture.

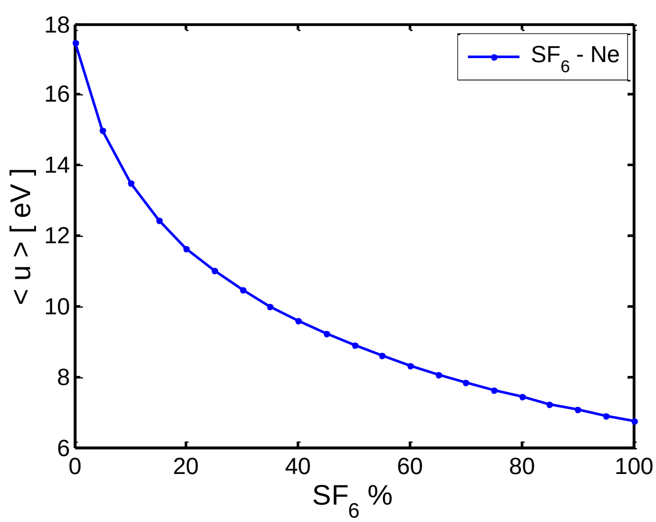


Figure (2): Mean electron energy versus SF_6 content for SF_6 – Ne mixture, the electron concentration is $1 \times 10^{16}\ \mathrm{cm}^{-3}$, the pressure is 760 torr and $\mathrm{E/N} = 200\ \mathrm{Td}$

Whenever we change the ratios of the mixture of SF_6 and Ne gas, the relation of EEDF with mean electron energy will be independent distributed for a fixed value of E/N as shown in figure (3). The pure SF_6 has higher EEDF at lower mean electron energy compared to its mixtures with Ne. However, at mean electron energy $\lesssim$ 14 eV the EEDF shifted to the right towards increasing values of EEDF as the SF_6 concentration is decreased.

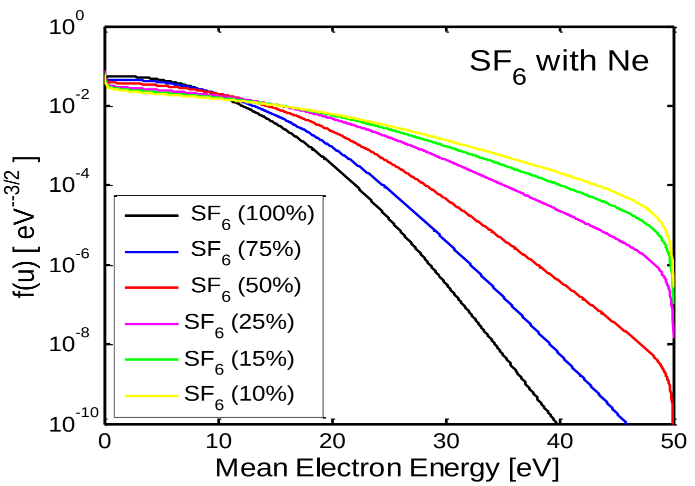
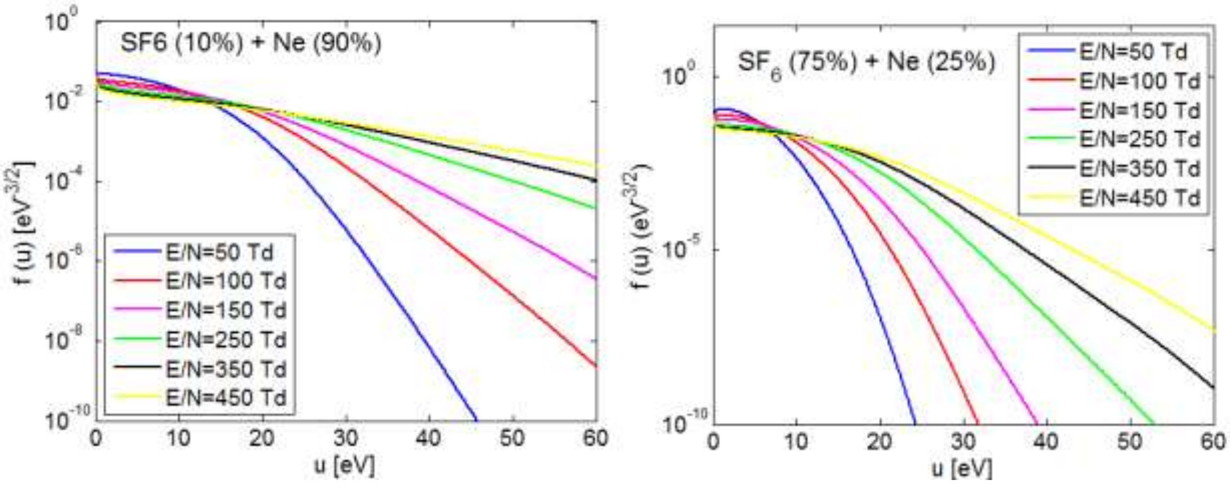


Figure (3): EEDF of SF_6 – Ne mixtures versus mean electron energy, $E/N = 200$ Td

Figure (4) indicates the relation of electron energy distribution as a function of mean electron energy for some certain values of E/N from in two different mixtures that are SF_6 (10%) – Ne (90%) as shown in figure (4a) and in SF_6 (75%) – Ne (25%) as in figure (4b). Clearly, as the mean electron energy increases the EEDFs are shifted to right as the reduced electric field increased. The shift of EEDFs is higher in the case of SF_6 (10%) – Ne (90%) compared with the concentration SF_6 (75%) – Ne (25%). This means that lower concentrations of SF_6 in the mixture leads to raise the profile of EEDF of the mixture.



(a) (b)

Figure (4): (a) Electron energy distribution functions vs. mean electron energy of SF_6 (10%) – Ne (90%) mixture for different values of *E*/*N*. (b) The electron energy distribution function versus mean electron energy of SF_6 (75%) – Ne (25%) mixture.

The effect of reduced field on mean electron energy for some concentrations is plotted in figure (5). The range of *E*/*N* used in the calculations is 10 – 500 Td. In this figure, we note that as *E*/*N* increases the mean electron energy is nonlinearly increased. The relation depends on the concentration of SF_6 gas in the mixture. The pure SF_6 gives lower curve and as the SF_6 gas decreases the curves begin to rise up in the direction of increased mean electron energy. In other words, the curves are raised up as the percentage concentration of buffer gas increased in the mixtures. The literature is in good convention with this fact.

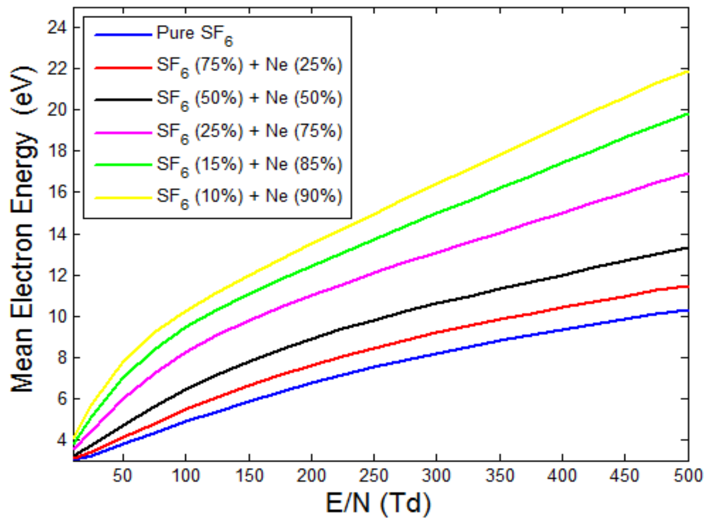


Figure (5): Mean electron energy versus reduced field *E*/*N* of SF_6 and its mixture with Ne

Figure (6) expresses the relation between the reduced field and the characteristic energy for the same mixtures used above. As the *E*/*N* increased the characteristic energy increased. The increasing of the buffer Ne gas in the mixture leads to rise the curve up, however, the curve of higher concentration of the buffer gas differently increases compared to the other curves of lower concentration at higher reduced field.

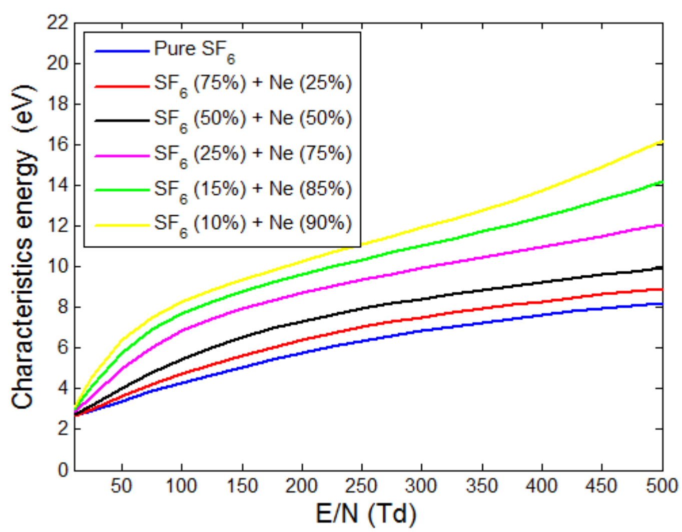


Figure (6): The characteristic energy versus reduced field *E*/*N* of SF_6 and its mixture with Ne.

Figure (7) denotes the relation between electron diffusion coefficients with the reduced electric field. The electron diffusion coefficient increases gradually as the E/N increased. Mixing Ne gas with SF_6 yields higher curves, respect to the pure SF_6, depending on the percentages of ratios of both gases. A lower ratios of SF_6 in the mixture gives higher curves.

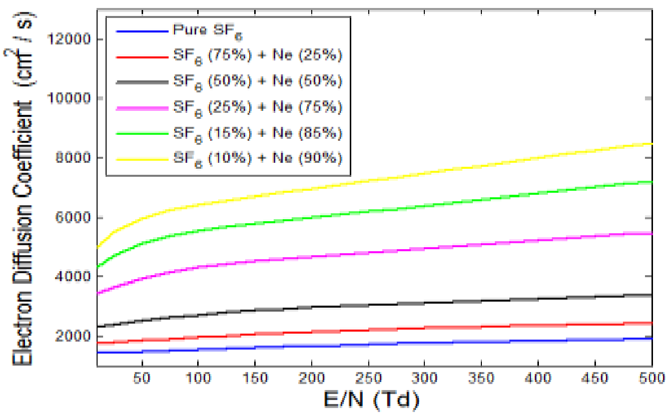


Figure (7): Electron diffusion coefficient vs. reduced field of SF_6 and its mixture with Ne, the electron concentration is 1×10^{16} cm^{-3}, and the pressure is 760 torr .

Figure (8) shows the dependence of the drift velocity on the reduced field for various values of ratios of SF_6 and Ne. The drift velocity increases as E/N increased for the pure SF_6 and its mixture with Ne. Higher concentration of buffer Ne gas in the mixture gives higher drift velocity. In spite of that, one can note that at higher E/N and for the ratio of SF_6 (10%) – Ne (90%) the slowly nonlinear increasing compared to other ratios. The drift velocity results due to opposite movements of both electrons and ions respect to the electric field.

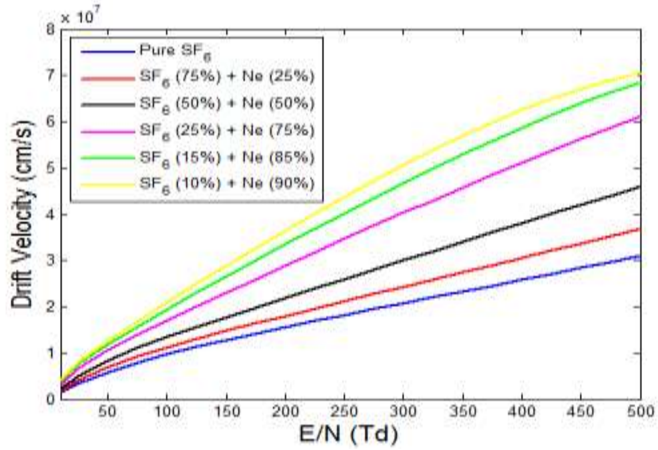


Figure (8): The drift velocity versus reduced field of SF_6 and its mixture with Ne.

Figure (9) shows the electron mobility versus *E*/*N* for different percentages concentration of SF_6 in the mixture. The electron energy loss due to the collisions between electrons and the neutral the electron mobility is inversely exponential proportional with *E*/*N*. As SF_6 decreases in the gas mixture, the curve of mobility vs. reduced electric field is raised.

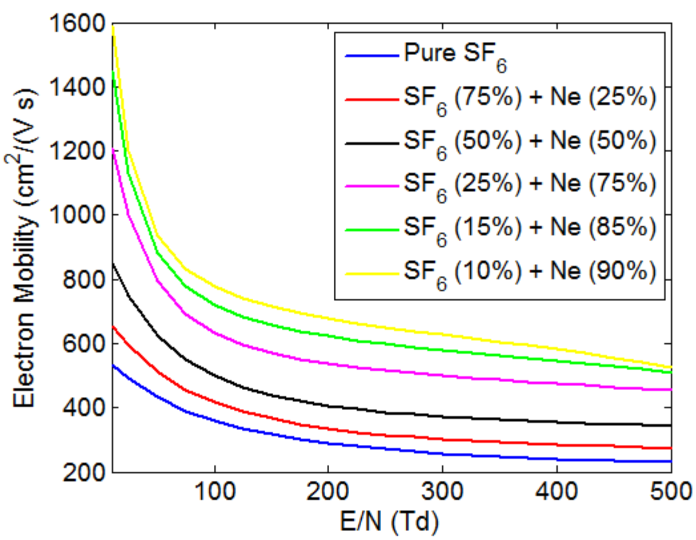


Figure (9): The electron mobility versus reduced field of SF_6 and its mixture with Ne.

Conclusion

In this study, we use (EEDF) software program to solve Boltzmann equation to obtain the electron energy distribution function and the transport coefficients of SF_6 – Ne gas. Results show that the relation between the mean electron energy of SF_6 – Ne and the concentration of SF_6 in mixtures is exponentially decreasing as SF_6 content is increased. Furthermore, there is an intensive reliance of EEDF on E/N as SF_6 – Ne gas mixture is varied. The EEDF shifts towards increasing of mean electron energy according to the increasing of E/ N. Decreasing SF_6 content in the gas mixture leads to raise the EEDF curves versus reduced field. The mean electron energy and reduced electric field have increased nonlinearly relationship. Analogous behavior between the characteristic energy versus reduced electric field for the various mixtures is distinguished. However, the behavior for higher concentration of Ne in the mixture and at higher reduced field is different compared to other curves of characteristic energy versus reduced electric field. The electron diffusion coefficient versus reduced field has linear relation for various concentrations of SF_6 and Ne, however at lower values of reduced field this relationship does not apply. Finally, the curve of the drift velocity is bending down at lower concentration of SF_6 content in gas mixture.

References

1. D. M. Xiao, L. L. Zhu and X. G. Li, "Electron transport coefficients in SF_6 and xenon gas mixtures", J. Phys. D: Appl. Phys. 33, L145–L147, (2000).
2. N. R. Pereira, K. G. Whitney, "Non – Maxwellian electron – energy distribution due inelastic collisions in z – pinch plasma", Physical Review A, V. (38), N (1), (1988)
3. V. Demidov, C. DeJoseph, Jr., A. Kudryavtsev, "Nonlocal Effects in a Bounded Afterglow Plasma With Fast Electrons", IEEE Transactions on plasma science, V. (34), N. (3), (2006)
4. E. Meeks, P. Ho, "Handbook of Advanced Plasma Processing Techniques", Springer Berlin Heidelberg, (2000)
5. A. Boogaard, "Plasma-enhanced Chemical Vapor Deposition of silicon dioxide", PhD thesis, University of Twente, Netherlands, (2011)
6. N. J. Behlman, "Electron energy distribution measurements in the plume region of a low current hollow cathode", M.Sc. thesis, Worcester Polytechnic Institute, USA, (2009)
7. M. J. Pinheiro, J. Loureiro, "Effective ionization coefficients and electron drift velocities in gas mixtures of SF6 with He, Xe, CO_2 and N_2 From Boltzmann analysis", APPLIED PHYSICS J. Phys. D: Appl. Phys. 35, 3077–3084, (2002)
8. Xiao D. M., Liu H. L. and Chen Y. Z., "Electron swarm parameters in SF_6/Ne mixtures determined by swarm experiment", J. Appl. Phys. V (86) 6611–2, (1999)
9. Dyatko N.A., Kochetov I.V., Napartovich A.P. Sukharev A.G. , EEDF: the software package for calculations of the electron energy distribution function in gas mixtures. http://www.Ixcat.laplace.univ-tlse.fr/software/EEDF/