# Escape factors for electrons in neon and helium

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The results are presented of Monte Carlo simulations of back-diffusion of electrons in neon and helium, both for reflecting and non-reflecting cathode surfaces. The estimates of the escape factors, based on analytical expressions, are also given.

## 1. Introduction

An appropriate boundary condition describing electron balance at the cathode surface is of fundamental importance to fluid modeling of gas discharges. This boundary condition is conventionally formulated in terms of the escape factor. Various approaches have been applied to evaluation of escape factors [1]. Recently, escape factors for argon have been obtained by means of Monte Carlo simulation [2] of back-diffusion of electrons to the cathode. Analytical expressions have been derived [3] that allow one to estimate escape factors in atomic plasma under conditions where dominating electron energy losses are due to inelastic collisions electron-atom. The estimates [3] for argon agree with results of Monte Carlo simulations [2], both for non-reflecting and reflecting cathodes, and both for monoenergetic and Maxwellian energy distributions of emitted electrons.

In this work, the results are presented of Monte Carlo simulations (MCS) of back-diffusion of electrons in neon and helium, performed using the code from [2]. The estimates of the escape factors in neon and helium, based on analytical expressions, are also given and compared to MCS results.

## 2. The models

Calculations of escape factors $f_{es}$ with Monte Carlo code [2] have been made using the sets of electron-atom collision cross sections for neon [4] and for helium [5]. Both sets were based on the data [5-7] which were completed by adding excitation cross sections and extrapolating the available cross sections to higher energies. However, for moderate energies that are covered here the cross section sets should be fully compatible with the recommended cross sections of A.V. Phelps [5]. In particular the cross section sets were tested to reproduce the low energy electron transport data.

As for the Monte Carlo code, it is a null collision code for dc fields [8] that has all the features required to model both the relaxed hydrodynamic properties and the non-hydrodynamic development close to electrodes. The code has been applied to model electron transport in argon [9], nitrogen [10], neon, xenon [11] and many other gases and has been also used to derive the cross sections for electron excitation. The code has been tested extensively against other codes and numerical techniques and was found to produce the transport data limited in accuracy only by the accuracy of the cross sections and statistical scatter. When the code was modified to calculate escape (back diffusion) coefficients a special care was taken to include reflection from the cathode and realistic initial conditions at the cathode.

It was found that results are very sensitive to the choice of the initial energy and its distribution. When the initial energy distribution is broad there is a large number of electrons with energies close to zero and they cannot return to the cathode. The dependence of the escape factor on the initial (monoenergetic) energy is quite nonlinear and thus for low mean initial energies the results are quite sensitive to the choice of distribution.

Analytical estimates of the escape factors have been obtained with interpolation [3] between $f_{es}$ values in weak electric fields, at $\theta \ll 1$, and the limiting value (unity) in strong fields, at $\theta \gg 1$, of the kind

$$f_{es} = A\theta / (1 + A\theta). \qquad (1)$$

Here $\theta = eE\lambda_e/\varepsilon_0$ is the ratio of the work of the electric field $E$ over the electron mean free path $\lambda_e$ to the average energy $\varepsilon_0$ with which an electron is emitted. Calculation of $f_{es}$ at $\theta \ll 1$ (that is, of the product $A\theta$) was performed by means of solving the kinetic equation for the isotropic part of the electron distribution function, for conditions when the electron energy losses in elastic electron-atom collisions are negligibly small. These conditions correspond to the region

$$\theta \gg (2m/M)^{1/2}\varepsilon_{ex}/\varepsilon_0, \qquad (2)$$

where $m$ and $M$ are the masses of electrons and atoms, respectively, and $\varepsilon_{ex}$ is the excitation energy of the atom. Note that inequality $\theta \ll 1$ may be valid simultaneously with (2) if the emitted electron energy $\varepsilon_0$ is not too small:

$$\varepsilon_0 \gg (2m/M)^{1/2}\varepsilon_{ex}\,. \qquad (3)$$

Inequality (2) limits the range of electric fields, where the obtained estimates of $f_{es}$ are applicable, from below.

A general expression for $f_{es} = A\theta$ at $\theta \ll 1$ can be found in [3]. In particular cases of monoenergetic and Maxwellian energy distributions of emitted electrons this expression reduces, respectively, to

$$A\theta = \frac{4eE}{3n\varepsilon_0 \int\limits_{\varepsilon_0}^{\varepsilon_{ex}} d\varepsilon\, Q_m(\varepsilon)/\varepsilon} \qquad (4)$$

and

$$A\theta = \frac{4eE}{3p}\int\limits_0^{\varepsilon_{ex}/kT} e^{-x}dx \Big/ \int\limits_{kTx}^{\varepsilon_{ex}} d\varepsilon\, Q_m(\varepsilon)/\varepsilon\,, \qquad (5)$$

where $n$ and $p$ are the gas number density and pressure, $T$ is the temperature of emitted electrons, $Q_m(\varepsilon)$ is the transport electron-atom collision cross section, depending on the kinetic electron energy $\varepsilon$.

To account for the effect of reflection of electrons by the cathode surface, an approximate expression has been suggested [3]:

$$f_{es}^{(R)} = f_{es}\,[1+R(1-f_{es})], \qquad (6)$$

where $f_{es}^{(R)}$ is the escape factor for the surface with the reflection coefficient $R$ and $f_{es}$ is the escape factor without reflection.

### 3. Results and discussion

Both Monte Carlo simulations and estimates, using expressions (4)-(6), of escape factors in neon and helium have been made for monoenergetic and Maxwellian energy distributions of emitted electrons with energies 0.2 and 0.6 eV, for two values of the reflection coefficient $R$, 0 and 0.6 (the latter value is typical for metals, e.g., [12]).

In figures 1 – 3 the escape factors are given for monoenergetic distribution of emitted electrons in neon and helium. The estimates are shown in the regions of reduced fields $E/n$ > 5 Td (for Ne) and 40 Td (for He), corresponding to the ranges of validity of inequality (2).

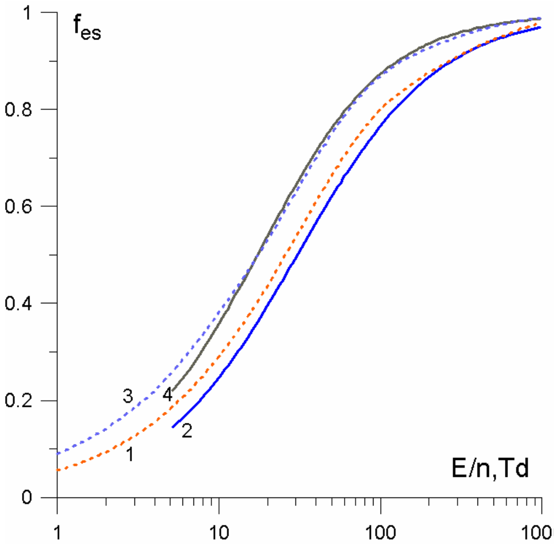

Figure 1. The escape factor in neon for mono-energetic distribution of emitted electrons at $\varepsilon_0$ = 0.6 eV. Dotted – Monte Carlo, solid – estimates. 1,2 – $R$ = 0; 3,4 – $R$ = 0.6.

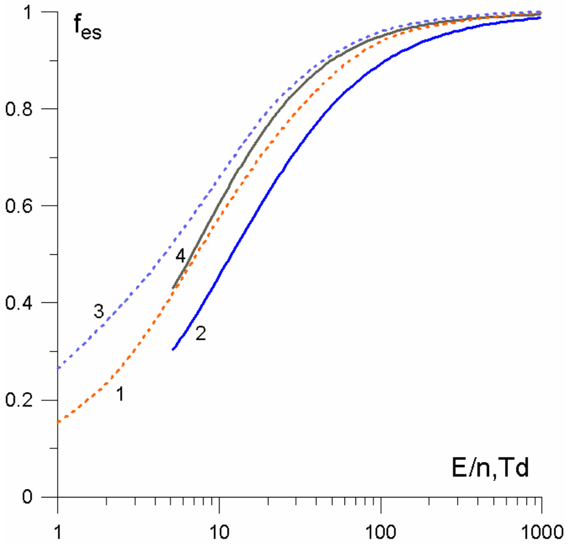

Figure 2. The escape factor in neon for mono-energetic distribution of emitted electrons at $\varepsilon_0$ = 0.2 eV. Dotted – Monte Carlo, solid – estimates. 1,2 – $R$ = 0; 3,4 – $R$ = 0.6.

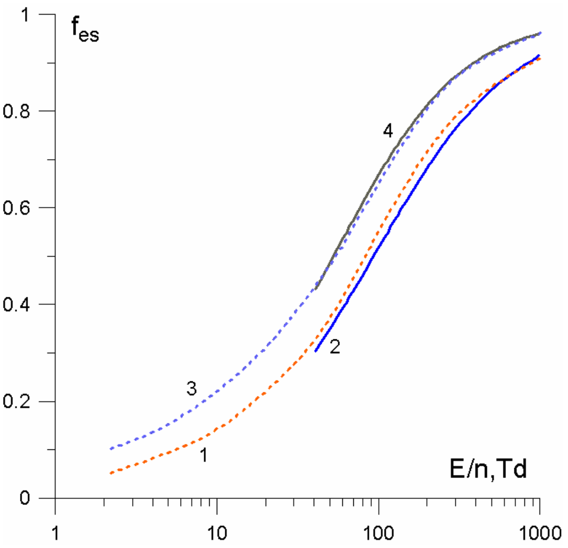

Figure 3. The escape factor in helium for mono-energetic distribution of emitted electrons at $\varepsilon_0$ = 0.6 eV. Dotted – Monte Carlo, solid – estimates. 1,2 – $R$ = 0; 3,4 – $R$ = 0.6.

It is seen that estimates agree with the results of Monte Carlo simulation for $\varepsilon_0$ = 0.6 eV; for lower energy, 0.2 eV, estimates give too small $f_{es}$ values. The reason is, evidently, in an increase, with decreasing $\varepsilon_0$, of the role of electron energy losses in elastic collisions. Note that inequality (3) for He at $\varepsilon_0$ = 0.2 eV is not valid, that is, the effect of electron energy losses in elastic collisions cannot be neglected in the whole electric field range.

Evaluation, by means of Eq. (6), of the effect of reflection agrees with Monte Carlo results both for neon and helium.

In figures 4 and 5 the escape factors in neon and helium at non-reflecting cathodes are presented, for monoenergetic and Maxwellian distributions of emitted electrons, with the same mean energy, $\varepsilon_0$ = 0.6 eV. It is seen that the difference between estimates and Monte Carlo results for Maxwellian distribution is greater than for the monoenergetic one. The reason is the presence of emitted electrons with low energies in the Maxwellian distribution. Electron energy losses in elastic collisions are more substantial for these electrons.

## 3. Conclusion

The escape factors for electrons in neon and helium are evaluated analytically under conditions where dominating electron energy losses are due to inelastic electron-atom collisions, which is the case at sufficiently high values of the reduced electric field in the near-cathode region. An independent evaluation of the escape factors was performed by means of the Monte Carlo simulations. It is found that the analytical results in the range of their applicability are accurate enough. An approximate analytical account of reflection of electrons by the cathode surface is in a reasonable agreement with the results of Monte Carlo simulations.

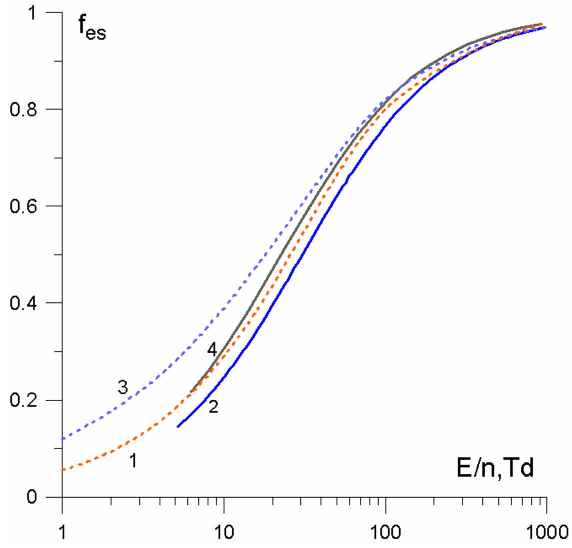

Figure 4. The escape factor in neon for mono-energetic (1,2) and Maxwellian (3,4) distributions of emitted electrons at $\varepsilon_0$ = 0.6 eV and $R$ = 0. Dotted – Monte Carlo, solid – estimates.

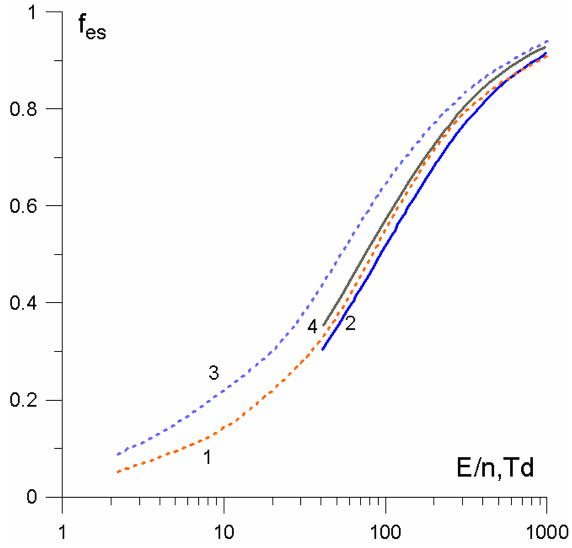

Figure 5. The escape factor in helium for mono-energetic (1,2) and Maxwellian (3,4) distributions of emitted electrons at $\varepsilon_0$ = 0.6 eV and $R$ = 0. Dotted – Monte Carlo, solid – estimates.

## 4. Acknowledgment

The work was supported in part by the project *NumeLiTe* of the 5th Framework programme ENERGIE of the EC, by the project POCTI/FIS/60526/2004 of FCT and FEDER, by the MNZZS project 1478, and by project 155 of Serbian Academy of Sciences.

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