RELAXATION OF A CONCENTRATED ELECTRON BEAM IN A DENSE GAS MEDIA

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Abstract

Electron-beam plasma is an object which has a whole series of technological applications. Electron-beam cleaning of exhaust gases of toxic impurities (nitric and sulfur oxides), conversion of silicon tetrachloride ($SiCl_4$) into trichlorosilane ($SiHCl_3$), deposition of silicon films etc. are among of these applications. Development of different technological systems in frame of realization of such projects requires preliminary calculation of different parameters connected with spreading of electron beam in a gas media.

In this paper basic process taking place during relaxation of electron beam with energy up to 100 keV and current up to 100 mA in gas with pressure up to atmospheric are analyzed. On the basis of analysis the computational model of such process is developed and calculations of some modes are conducted for relaxation of beam in air with atmospheric pressure. The calculations are conducted on basis of step-by-step method because the problem is self-consistent. Modeling of electron beam is carried out on the basis of Monte-Carlo method with help of single collisions scheme. Elastic and inelastic collisions are taken into consideration. Taking into account of gas heating by the electron beam is executed at the calculations. Furthermore it is shown, that under pressures of about atmospheric it is necessary to take into consideration influence of magnetic field induced by extraction system. It makes a strong impact on the relaxation pattern. Comparison of acquired results with experimental data is quoted.

PROBLEM STATEMENT

Electron beam in a dense gas

Passing of an electron beam trough a dense gas accompanies with great variety of physical and chemical process. Collisions of beam electrons with gas molecules lead to the beam scattering and energy losses. The spatial widening of the beam happens as a result of interaction between electrons and nuclei of neutral atoms. Inelastic collisions lead to a gas ionization and appearance of slow secondary electrons. An exciting of different gas degrees of freedom also happens. Finally it leads to a gas heating. Changes in a gas temperature lead to changes in constants of elementary processes.

Different plasma-chemical passes in plasma generated by electron beam. They can change a chemical constitution of a gas. The changes in a gas cause the changes in relaxation pattern of an electron beam. Thus the investigated physical problem is self-consistent and interaction between electron beam and gas should be examined in frame of complex model.

Mathematical model

The mathematical model used in this work is based on the modeling of gas flow with help of conversation laws and modeling of electron beam propagation with help of Monte-Carlo method. The simulation is conducted on the basis of calculation of electron beam propagation in a gas with known density distribution function and following calculation of gas flow with known energy-release distribution. This cycle is repeated iteratively.

Since the ionization degree under considered pressures and powers is low then the existence of plasma and neutral particles created in plasma (e.g. nitric oxides, ozone) isn't taken into consideration.

The model of single collisions of Monte-Carlo method is used during simulation of scattering process. In this model each collision, which happens with electron during its penetration into a media, is studied separately. This model requires increasing of calculation volume but it allows efficiently taking into consideration the influence of focusing magnetic field.

The scheme of drawing is similar to that described in works [1, 2]. The processes of elastic scattering of electrons on neutral atoms of gas molecules and inelastic collisions with atomic electrons are taken into consideration during the drawing procedure. Bremsstrahlung is not taken into account, because under initial energy of beam electrons lower than 100 keV, these losses are less than 1% of total losses [1].

The Rutherford cross-section $d\sigma_R$ taking into account the screening effect is used as elastic scattering cross-section:

$$d\sigma = d\sigma_R\left(\frac{1-\cos\theta}{1-\cos\theta+2\eta}\right)^2, \qquad (1)$$

where θ - angle of scattering, η - screening parameter:

$$\eta = 1.7*10^{-5}Z^{2/3}\frac{1-\beta^2}{\beta^2}[1.13+3.76\frac{\alpha^2}{\beta^2}], \qquad (2)$$

α - fine structure constant, β - relativist factor.

Inelastic electron-electron scattering is described by Möller formula:

$$\frac{d\sigma}{dw} = 2\pi r_0^2\frac{(\varepsilon+1)^2}{\varepsilon^2(\varepsilon+2)}[\frac{1}{w^2}-\frac{1}{w(1-w)}\frac{2\varepsilon+1}{(\varepsilon+1)^2}+ +\frac{1}{(1-w)^2}+\frac{\varepsilon^2}{(\varepsilon+1)^2}], \qquad (3)$$

where ε - energy of primary electron, $w\varepsilon$ – transmitted energy in m_0c^2 units, $0 \le w \le 1/2$, r_0 – classical electron radius.

The influence of magnetic field generated by ejection device is taken into consideration during simulation of primary electron trajectory. It is supposed that electron moves under influence of magnetic field in intervals between collisions.

The model of nonviscous compressible liquid is used for simulation of gas flow. The conversations laws for such fluid can be written in the following form:

$$\begin{aligned} &\partial_t \rho + \partial_j(\rho u_j) = 0 \\ &\partial_t(\rho u_i) + \partial_j(\rho u_i u_j) = -\partial_i p \\ &\partial_t(\rho w) + \partial_j(\rho w u_j) + \partial_j(p u_j) = Q - F, \end{aligned} \tag{4}$$

where ρ, u_i and p denotes the density of the gas, the i component of the velocity field and the pressure field respectively, w – is full specific energy of the gas, Q – heating function, F-radiation function.

The system of equations can be completed with help of equation of state for the gas:

$$p = \rho RT, \tag{5}$$

where R - gas constant, T – gas temperature.

Solving of this system of equations is carried out with help of particle-in-cell method suggested in work [3]. Gas heating by electron beam and heat transfer by radiation and gas flow are taking into consideration during calculations.

It is assumed that all energy of primary electrons turns into heat in that place where they lost it. It is conditioned by the fact that secondary electrons, exited atoms and ions have very short free path in a gas with atmospheric pressure (the free path for electron with energy 10 keV in the air with atmospheric pressure is ~$3*10^{-2}$ mm, cell length ~ 1 mm).

The medium is assumed to be optically thin because gas temperature less than 4000 K and typical size of plasma ~ 20 sm.

RESULTS AND DISCUSSION

The electron beam with power up to 10 kW and initial energy up to 100 keV injected into the air with atmospheric pressure has been simulated. The gas mixture is assumed to be composed of 80% of molecular nitrogen and 20% of molecular oxygen during the calculations. The geometry of simulation area, distribution of the magnetic field and initial conditions by pressure and temperature of the gas were set to be as close as possible to real conditions realized at electron-beam ejection systems. The pressure at undisturbed environment– 750 Torr, temperature – 300 K, pressure in first sluice of ejection system ~10 Torr.

The experimental investigations was conducted at electron beam system having the following basic parameters: accelerating voltage – 80..100 kV, beam current – up to 200 mA, beam power – up to 20 kW. The measurements of current of high-energy electrons were conducted with help of high-energy electrons probe which had been developed in Keldysh Research Centre. This kind of probes allows cutting off slow plasma electrons and measuring only high-energetic part of electron current. The scheme of low part of ejection device is presented in Fig. 1.

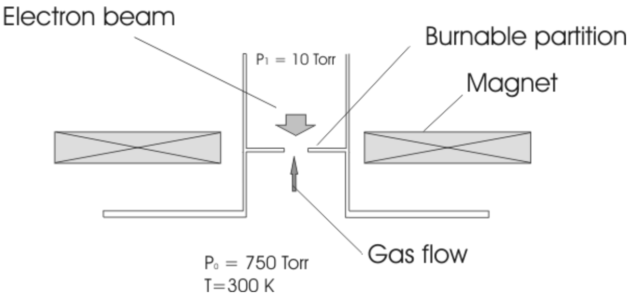

Figure 1: The scheme of the bottom part of ejection device.

The calculations were conducted for different initial energies and powers of electron beam. For example the results of calculation of spatial energy-release distribution are presented in Fig. 2 for electron beam with initial energy 30 keV and current 30 mA.

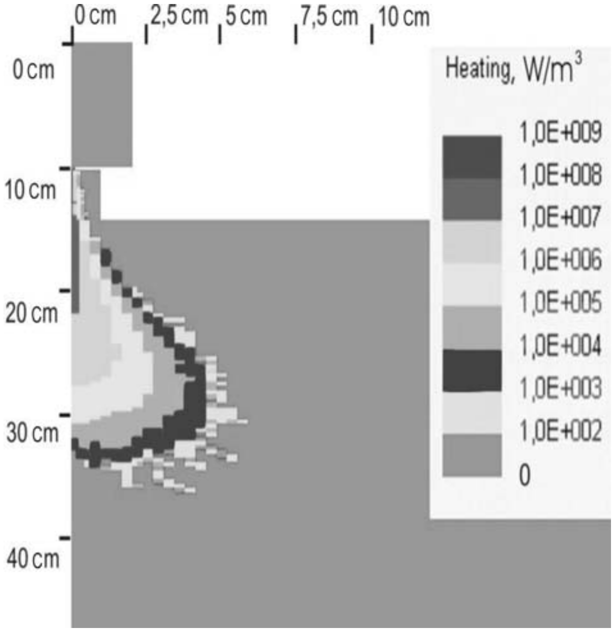

Figure 2: Spatial energy-release distribution for electron beam, E=90 keV, I=30 mA.

The comparison of calculated and experimentally measured radial current density distribution for cross-section located at a distance 9 cm from burnable partition and degradation of current density along the axis of injection are presented in Fig. 2 and 3 respectively. The comparisons are presented for the following regime: accelerating voltage – 90 kV, beam current – 12 mA.

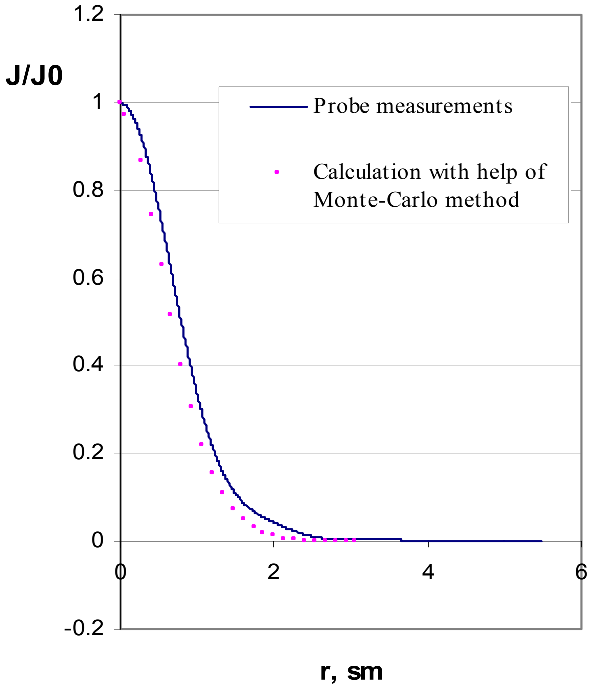

Figure 3: Comparison of calculated and experimental results by radial current density distribution.

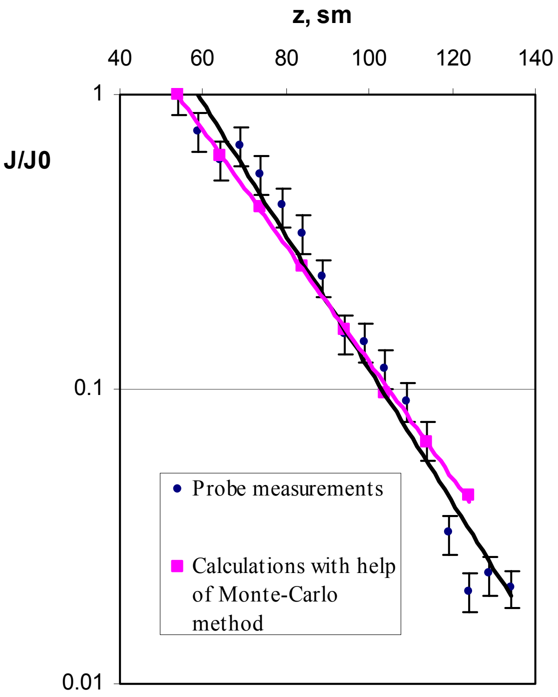

Figure4: Comparison of calculated and experimental results by axial current density degradation.

To carry out comparison of experimentally measured current distributions with calculated ones for larger currents unfortunately impossible because probe can not work under such big thermal flows.

Qualitative comparison of electron beam image obtained during experimental investigations and calculated radiation field is presented in Fig. 5. The electron beam energy is 90 keV, beam current – 30 mA. It was assumed during calculation that electron beam radiate the part of energy constant in space. The focusing of electron beam in the atmosphere by magnetic field of ejection device is well observed on this picture.

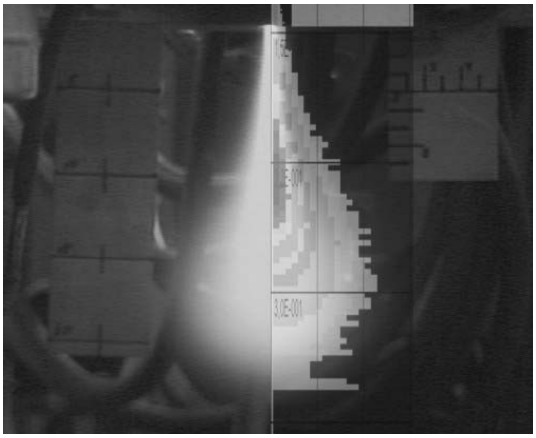

Figure 5: Qualitative comparison of calculated and experimentally observed radiation field for electron beam, E=90 keV, I=30 mA.

CONCLUSION

The mathematical model for relaxation of electron beam with beam energy up to 100 keV and power up to 10 kW in a gas with pressure up to atmospheric is presented.

The calculations of relaxation of electron beam in air atmosphere are conducted in frame of this model for different powers.

The comparison of calculated results with experimental ones is cited. Satisfactory coincidence of experiments with calculations is showed.

REFERENCES

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[3] O.M. Belotserkovskii, U.M. Davydov, “Particle-in-cell method in gas dynamics”, Moscow, 1982 (in Russian).