Capacitive coupled RF discharge: modelling at the local and not local statement of the problem

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Abstract. The models provided in the research paper describe a capacitive coupled radio-frequency discharge in argon between two parallel plate electrodes, one of which is grounded, and the other is connected to the high-frequency capacitive generator. Herein we review various approaches to simulate a high-frequency capacitive discharge depending on modelled pressure rates. The model of a high-frequency capacitive discharge under low pressure is simulated in non-local approximation, and under high pressure is simulated in local approximation and is sensitive to dimers and molecular ions. We provide calculation data with respect to different pressures and make comparative analysis of data provided by other authors in particular, analysis of data obtained with real experiment.

1. Introduction
The among the discharges applied to treat materials, significant part is assigned to capacitive coupled radio-frequency (CCRF) discharges [1-6]. CCRF-discharges differ under different pressures as by various values of discharge characteristics and by the mechanisms of internal processes. Nowadays the models of HFC-discharges of middle and low pressures are studied in details [5]. Recently the interest to CCRF-discharges of low pressure has increased due to emerged possibility to treat natural materials because of low atom temperature in such discharges, as well as interest to CCRF-discharges atmosphere pressure. Experimental calculation methods, which complement each other, are used to tie internal and external parameters of the discharge [7-11].

The models provided in this research paper describe a capacitive coupled radio-frequency discharge in argon between two parallel plate electrodes, one of which is grounded, and the other is connected to the high-frequency capacitive generator providing that distance between the electrodes is less than dimensions of the electrodes themselves. Under such conditions the electrical field is close to the potential one and the discharge is uniform along the electrodes, what allows using one-dimensional model [5]. Due to use of one dimensional model, we can review kinetics of the discharge with respect to diffusive drift approximation [12-13]. Comparison of time and distance needed for electron to lose the energy obtained from the field and dimensions of computational space revealed that the local and non-local approximations shall be used for modelling of CCRF-discharges under high and low pressures [3, 14].
2. Setting a problem in non-local approximation

The this section devoted to the pressure range from 13.3 Pa to 133 Pa describes the self-consistent mathematical model of CCRF-discharge in non-local approximation under low pressure in argon. This model includes process factors occurred under electron impacts, which are taken with account of electron-electron collision depending on electron temperature and ionization rate [15].

Provided herein model of CCRF-discharge under low pressure includes time-dependent equation of balances for electron gas, metastable atoms, atomic ions, Poisson’s equation for potential of electrical field, time-dependent equation of electronic energy balance, as well steady state equation of thermal conductivity of atomic-ion gas at average parameters. At that here is used the simplified diagram of argon atom, where 4 lowest approximate electronically excited states are replaced with uniform rate resulted with efficient mixing due to their electronic impact [16]. The model includes plasma chemical reactions

\[ \text{Ar}^+ + e \rightarrow \text{Ar} + e; \quad \text{Ar}^* + \text{Ar}^* \rightarrow \text{Ar} + \text{Ar} + 2e; \quad \text{Ar}^* + e \rightarrow \text{Ar} + 2e; \quad \text{Ar} + e \rightarrow \text{Ar}^* + e; \quad \text{Ar}^* \rightarrow \text{Ar} + h_v; \quad \text{Ar}^* + \text{Ar} \rightarrow 2\text{Ar}; \quad \text{Ar}^* + e \rightarrow \text{Ar} + e. \]

Velocity factors of the corresponding reactions are described in the work papers [17-23].

In order to solve the nonlinear system of boundary value problems and initial boundary value problems described herein, we used the approximation method, which is based on preliminary finite dimensional approximation of the problem using difference scheme including further use of iteration process applied for its implementation [24]. Moreover, the research papers [25-29] are devoted to the methods to solve nonlinear problems of continuum mechanics as well describe-layer iteration methods including methods lowering nonlinearity to a lower layer [25-29].

3. Calculation data

The calculation data of CCRF-discharge in plasmatron, which has electron spacing 22 mm, pressure \( P=13.3 \text{ Pa} \), applied voltage rate \( V_a=65 \text{ V} \) qualitatively coincide with the data of the research paper [30], however, ion concentration has specific bell-bottom shape with maximum located in the center of the discharge \( \approx 10^{15} \text{ m}^{-3} \), while the experiments show value [30] \( \approx 7 \cdot 10^{14} \text{ m}^{-3} \).

Electron temperature reaches its maximum level, per the period 3 eV, at near-electrode layers, and maximum value at the center of the discharge was 2.5 eV. However, gas temperature stayed almost permanent: 305 K.

According to the research paper [30] the following temperature range was fixed under voltage \( V_a=65 \text{ V} \) and pressure \( P=13.3 \text{ Pa} \): maximum - 3.4 eV, minimum 1.7 eV providing that inaccuracy is 20%. As well the researchers made calculations under the pressure 133 Pa. Comparison of calculation data revealed that the distance, when an electron lose its energy under pressure 133 Pa decreased significantly (see Fig. 1 and Fig. 2).

![Figure 1](image1.png)  **Figure 1.** Change of electron temperature in time under pressure 13.3 Pa  

![Figure 2](image2.png)  **Figure 2.** Change of electron temperature under pressure 13.3 Pa (Maximum value per the period is given at each point of interelectrode distance)
4. Setting a problem in local approximation
The research paper [31] shows dependency of concentration ratio of atomic and molecular ions depending on gas temperature in CCRF-discharges. Owing to nonuniform distribution of gas temperature in interelectrode spacing, the provided self-consistent model of CCRF-discharge under high pressure includes time-dependent equation of balance for electron gas, metastable atoms, molecular and atomic ions, Poisson’s equation for potential of electrical field, steady state equation of thermal conductivity of atomic-ion gas under boundary conditions of heat exchange, which is calculated according to average parameters, and kinetic reactions include added: \( \text{Ar}^*+\text{Ar}^* \rightarrow \text{Ar}^2 + e; \)
\( 2\text{Ar}^*+\text{Ar}^* \rightarrow \text{Ar}^2 + \text{Ar}^+ + e; \)
\( \text{Ar}_2^+ + e \rightarrow \text{Ar} + \text{Ar} + \text{Ar}^+; \)
\( \text{Ar}_2^+ + e \rightarrow \text{Ar}^* + \text{Ar}^* + e; \)
\( \text{Ar}_2^* + e \rightarrow \text{Ar} + \text{Ar} + \text{Ar}^+; \)
\( \text{Ar}_2^* \rightarrow 2\text{Ar} + h\nu; \)
\( \text{Ar}^* + 2\text{Ar} \rightarrow \text{Ar}_2^* + \text{Ar}; \)
\( \text{Ar}_2^* + \text{Ar}^* \rightarrow e + \text{Ar} + \text{Ar}_2^+; \)
\( e + \text{Ar}_2^* \rightarrow 2\text{Ar}^* + e; \)
\( \text{Ar}^* + 2\text{Ar} \rightarrow 3\text{Ar} + h\nu; \)
\( \text{Ar}_2^* + \text{Ar}^* \rightarrow 2\text{Ar} + \text{Ar}^+ + \text{Ar}^*. \)
Velocity factors of the processes being the subject for electron impact depend on local value of provided electrical field and ionization rate with account of electron-electron collision [15].

5. Calculation data
The work paper [20] states that electron density available from experiments is \( 5 \times 10^{11} \) sm\(^{-3} \) under atmosphere pressure and interelectrode distance – 2mm, according to the calculation data provided at the same work paper, density of electrons and ions approximately is \( \approx 7 \times 10^{11} \) sm\(^{-3} \). Calculations made for our model under the similar conditions revealed that concentration maximum is \( \approx 3.9 \times 10^{11} \) sm\(^{-3} \) (Fig. 3).

![Figure 3](image)

Figure 3. Distribution of average value per the period of charged-particle concentration

6. Conclusion
This research paper describes the self-consistent mathematical model of CCRF-discharge in local approximation under low pressure and non-local approximation under high pressure. Velocity factors of the processes being the subject for electron impact are taken with account of electron-electron collision as well as with account of space variations of gas temperature. The researches have developed the software package, which allows counting parameters of a CCRF-discharge under low pressure in non-local approximation. They performed qualitative and quantitative comparison of numerical calculation data with the data provided by other authors, particularly, with the results of real experiments.

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