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NUMERICAL MODEL OF A GASEOUS INDUCTIVE DISCHARGE IN OXYGEN, TAKING INTO ACCOUNT THE COMPLETE SCHEME OF THE VIBRATIONAL KINETICS OF O_2 MOLECULES

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ABSTRACT

In this work, the two-dimensional model of inductively coupled plasma discharge in oxygen was developed. The model includes hydrodynamic equations in drift-diffusion approximation for describing the kinetics of charged (electrons and ions) and neutral plasma particles, Maxwell's equations for electromagnetic fields, and equations for the temperature and neutral gas flow as well as a detailed scheme of plasma-chemical reactions. The model was tested against theoretical and experimental data in a simple cylindrical chamber. The electron density and temperature distributions were obtained over a wide range of powers deposited in the plasma (100–500 W) and compared with literature data. Also, the complete scheme of the vibrational kinetics of O_2 molecules was included in the model. The vibrational distribution function was calculated in low-pressure inductive discharge as well as spatial distributions of plasma parameters (density and temperature of electrons, excited components, neutral gas temperature, etc.) and flows of charged and active neutral particles at the reactor walls.

KEYWORDS

Low-temperature plasma; inductive discharge; oxygen; plasma modelling.

ЧИСЛЕННАЯ МОДЕЛЬ ГАЗОВОГО ИНДУКЦИОННОГО РАЗРЯДА В КИСЛОРОДЕ С УЧЕТОМ ПОЛНОЙ СХЕМЫ КОЛЕБАТЕЛЬНОЙ КИНЕТИКИ МОЛЕКУЛ O_2

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АННОТАЦИЯ

В данной работе разработана двумерная модель индукцинного плазменного разряда в кислороде. Модель включает в себя гидродинамические уравнения в диффузионно-дрейфовом приближении для описания кинетики заряженных (электронов и ионов) и нейтральных частиц в плазме, уравнения Максвелла для вычисления электромагнитных полей, уравнения для расчета температуры и протока нейтрального газа, а также детальную схему плазмохимических реакций. Модель была протестирована на теоретических и экспериментальных данных в простой цилиндрической камере. Получены распределения плотности электронов и температуры в широком диапазоне вкладываемых в плазму мощностей (100–500 Вт) и сопоставлены с литературными данными. Также в модель была включена полная схема колебательной кинетики молекул O_2. Рассчитаны колебательная функция распределения в индукционном разряде низкого давления, а также пространственные распределения параметров плазмы (плотность и температура электронов, возбужденных компонентов, температура нейтрального газа и др.) и потоков заряженных и активных нейтральных частиц на стенки реактора.

КЛЮЧЕВЫЕ СЛОВА

Низкотемпературная плазма; индукционный разряд; кислород; моделирование плазмы.

Introduction

Non-equilibrium low-temperature oxygen plasma has a wide range of applications. The use of such plasma has literally revolutionised many industrial processes such as plasma etching, surface treatment, plasma sterilisation and medicine. The study of vibrational excitation and relaxation in oxygen plasma is a poorly studied area due to the complexity of experimental methods for detecting the vibrational distribution function in oxygen. New experimental data on the distribution of vibrational excitation in stationary and nonstationary discharges in oxygen was recently obtained [1], and this indicates the need to develop more accurate models to describe the relaxation kinetics of vibrational excitation under conditions of significant gas dissociation and to adapt these processes into complete self-consistent models.

The vibrational kinetics of oxygen molecules is usually not treated in global models of plasma discharges. Usually vibration-to-translation (V-T) and vibration-to-vibration (V-V) energy exchanges were taken into account and the corresponding rate coefficients were calculated, while e-V processes were considered by including only the first four vibrational levels. At that time, it was concluded that the vibrational distribution function (VDF) was not significantly populated and it was therefore disregarded in subsequent publications. However, this picture has been challenged by recent experimental findings on a low-pressure pure oxygen discharge excited by an inductively coupled plasma (ICP) source in an industrial scale plasma etch reactor [2, 3] and recent calculations of electron-impact vibrational excitation cross-sections [4, 5]. Thus, further research in this area is necessary and self-consistent models including vibrational kinetics of oxygen molecules under the conditions of various inductively coupled discharge plasma chambers are required.

1. Description of the model

The two-dimensional model used in this work has been described in detail elsewhere [6, 7]. Next, we briefly describe the main points of this model without writing equations for brevity. The plasma density, the electron and ion fluxes onto the electrode, and the electron temperature were found by solving a set of following equations.

1) The continuity equations for the particle densities (electrons, ions, and neutrals).

2) The conservation equation for the particle momentum in drift-diffusion approximation both for ions and electrons.

3) The energy conservation law for electrons, taking into account Maxwellian energy distribution. For the ions, energy conservation law is not solved. In accordance with [8], it is assumed that the ion temperature was constant (on the order of 0.1–0.5 eV) throughout the chamber.

4) The distributions of the electromagnetic fields are described by Maxwell's equations, which are solved in the two-dimensional axisymmetric geometry.

5) To correctly describe the gas temperature distribution, the heat balance equation for neutral gas is solved. Accounting for gas heating is especially important when studying processes in mixtures containing molecular gases [9].

6) In order to take into account the gas flow, the Navier-Stokes equations are included in the model assuming the absence of turbulence and volumetric forces.

7) The constants of electron reactions are calculated using the energy integral of the product of the reaction cross-section, the particle rate, and the energy distribution function. In the present study, the EEDF is assumed to be Maxwellian. The experimental results [10–12] prove the validity of this assumption for O_2 plasma in the pressure range under study (10–20 mTorr). The electron impact and heavy particle reactions with their rate coefficients are listed in Table 1.

Table 1. List of electron impact and heavy particle reactions

Таблица 1. Список электронных и химических реакций

№	Electron impact reactions / Электронные реакции		
	Reaction / Реакция	Energy threshold (eV) / Энергетический порог (эВ)	Reference / Ссылка
1	$e + O_2 => e + O_2$	Упругое / Elastic	[13]
2	$e + O_2 => O^- + O$	–	[13]
3	$e + O_2 => e + O_2(rot)$	0.02	[13]
4	$e + O_2 <=> e + O_2(a1d)$	0.977	[13]
5	$e + O_2 <=> e + O_2(b1s)$	1.627	[13]
6	$e + O_2 <=> e + O_2(res)$	4.5	[13]
7	$e + O_2 => e + O + O$	6	[13]
8	$e + O_2 => e + O + O(1d)$	8.4	[13]
9	$e + O_2 => e + O + O(1s)$	9.97	[13]
10	$e + O_2 => 2e + O_2^+$	12.06	[13]
11	$e + O_2(a1d) => e + O_2(b1s)$	0.5	[14]
12	$e + O_2(a1d) => e + 2O$	5	[13]
13	$e + O_2(a1d) => e + O + O(1d)$	7.59	[13]
14	$e + O_2(b1s) => e + 2O$	4.08	[13]
15	$e + O_2(b1s) => e + O + O(1d)$	6.94	[13]
16	$e + O_2(a1d) => O + O^-$	–	[15]
17	$e + O_2(b1s) => O + O^-$	–	[15]
18	$e + O_2(res) => O + O^-$	–	[13]
19	$e + O(1d) => 2e + O^+$	11.65	[16]
20	$e + O_2(a1d) => 2e + O_2^+$	11.08	[17]
21	$e + O_2(b1s) => 2e + O_2^+$	10.43	[17]
22	$e + O_2 => 2e + O + O^+$	21	[18]
23	$e + O => e + O$	Упругое / Elastic	[16]
24	$e + O <=> e + O(1d)$	1.968	[16]

The end of table 1

Окончание таблицы 1

25	$e + O <=> e + O(1s)$	4.192	[16]
26	$e + O => 2e + O^+$	13.618	[16]
27	$e + O^- => 2e + O$	5.5	[17]
	Heavy particles reactions / Химические реакции		
	Reaction / Реакция	Rate coefficient (m^3/s or m^6/s) / Скорость ($м^3/с$ или $м^6/с$)	Reference / ссылка
28	$e + O_2 + O_2 => O_2^- + O_2$	$1.4\times10^{-41}(300/T_e)\ e^{-600/Te}$	[20]
29	$e + O_2^+ => O + O$	$2\times10^{-13}(300/T_e)$	[20]
30	$e + O_2^+ => O + O(1d)$	$1.95\times10^{-13}(300/T_e)^{0.7}$	[21]
32	$O_2(a1d) + O_2 => 2O_2$	$2.2\times10^{-24}(T_{gas}/300)^{0.8}$	[20]
33	$O_2(a1d) + O => O_2 + O$	7×10^{-22}	[20]
34	$O_2(b1s) + O_2 => 2O_2$	$7.4\times10^{-23}T_{gas}^{0.5}e^{-1104/Tgas}$	[22]
35	$O_2(b1s) + O => O_2 + O$	8×10^{-20}	[23]
36	$O_2(res) + O_2 => 2O_2$	2×10^{-19}	[24]
37	$O(1d) + O_2 => O + O_2$	$6.4\times10^{-18}e^{67/Tgas}$	[25]
38	$O(1d) + O => 2O$	8×10^{-18}	[26]
39	$O(1s) + O_2 => O + O_2$	$4.3\times10^{-18}e^{-850/Tgas}$	[20]
40	$O(1s) + O => 2O$	$5\times10^{-17}e^{-300/Tgas}$	[23]
41	$O + O + O_2 => 2O_2$	$3.34\times10^{-42}T_{gas}^{-1}e^{-170/Tgas}$	[21]
42	$O + O + O => O + O_2$	$3.6\times10^{-44}\ T_{gas}^{-0.63}$	[26]
43	$O^+ + O_2 => O + O_2^+$	$2\times10^{-17}\ (T_{gas}/300)^{-0.5}$	[26]
44	$O^- + O => O_2 + e$	1.9×10^{-16}	[27]
45	$O^- + O_2 => O + O_2^-$	2.5×10^{-20}	[28]
46	$O^- + O^+ => 2O$	2.7×10^{-13}	[29]
47	$O^- + O_2^+ => 3O$	$2.6\times10^{-14}(T_{ion}/300)^{-0.44}$	[24]
48	$O_2^- + O_2^+ => 2O_2$	$4\times10^{-13}(T_{ion}/300)^{-0.5}$	[24]
49	$O_2^- + O^+ => O_2 + O$	$4\times10^{-13}(T_{ion}/300)^{-0.5}$	[24]
50	$O_2^+ + O^- => O_2 + O$	$9.6\times10^{-14}(T_{ion}/300)^{-0.5}$	[21]
51	$O_2(a1d) + O^- => O_2 + O + e$	1.5×10^{-16}	[21]
52	$O_2(b1s) + O^- => O_2 + O + e$	6.9×10^{-16}	[21]
53	$O(1s) + O => O(1d) + O$	$5\times10^{-17}e^{-300/Tgas}$	[23]
54	$O(1d) + O_2 => O_2(b1s) + O$	$2.56\times10^{-17}e^{-67/Tgas}$	[30]
55	$O(1d) + O_2 => O_2(a1d) + O$	1×10^{-18}	[21]
56	$O(1s) + O_2(a1d) => O_2(b1s) + O(1d)$	2.9×10^{-17}	[26]
57	$O(1s) + O_2(a1d) => O_2(res) + O$	1.1×10^{-16}	[26]
58	$O(1s) + O_2(a1d) => 3O$	3.2×10^{-17}	[26]
	Reactions of vibrationally excited molecules O_2 / Реакции колебательно-возбужденных молекул O_2		
59	$e + O_2(v) <=> e + O_2(w)$	Vibrational transition threshold (eV) / Порог колебательного перехода (эВ)	[4]
60	$O_2(v) + O <=> O_2(w) + O$, $(\Delta v=v–w=1–30)$	$k_{v,w}^{(60)}$	[31]
61	$O_2(v) + O_2 <=> O_2(v–1) + O_2$	$k_{v,v-1}^{(61)}$	[32, 33]
62	$O_2(v) + O_2(w–1) <=> O_2(v–1) + O_2(w)$	$k_{v,v-1,w,w-1}^{(62)}$	[33]

The complete scheme of the vibrational kinetics of O_2 molecules includes neutral particles such as unexcited oxygen molecule and atom (O_2, O), electronic excitations of oxygen molecule (O_2(a1b), O_2(b1s), O_2(res)) and atom (O(1s), O(1d)), vibrational excitations of oxygen molecule (O_2(v=1–34)) and charged particles such as positive and negative ions of oxygen molecule and atom (O_2^+, O_2^-, O^+, O^-). Here O_2(res) is the sum of higher level electron excitations of the O_2 molecule. Also, O_2(v=34) includes higher level vibrational excitations of the O_2 molecule. It should be noted that vibrational cross-sections were summarised and normalised to the total vibrational cross-section (available, for example, at [34]) to achieve self-consistency of the resulting cross-sections set.

2. Verification of the model

The model was tested against the available theoretical and experimental data on discharges in oxygen from the work [35]. The calculations were performed in a simple two-dimensional axial symmetric geometry of a cylindrical reactor with a flat coil on the top of the chamber. The cylindrical discharge chamber was 16.2 cm in radius and 10.4 cm in height. The antenna was a flat four-turn coil separated from the discharge by a 1.5 cm thick quartz glass. For more details, please refer to [35]. The inductive discharge was simulated under the following conditions: the frequency was 13.56 MHz, the gas pressure was 10 mTorr, the power applied to the coils was from 100 to 500 W, and the gas flow was 33.5 standard cubic cm per minute (sccm). Part of the calculation results is shown in Fig. 1.

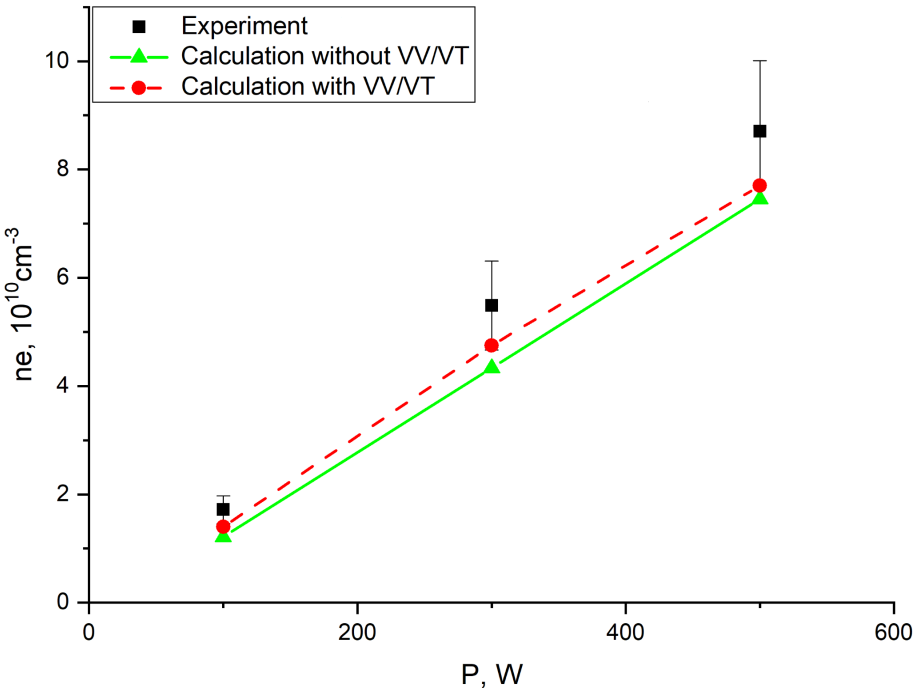

Fig. 1. Electron concentration depending on the discharge power, calculated according to a simplified kinetic scheme and taking into account vibrational kinetics, in comparison with the experiment

Рис. 1. Концентрация электронов в зависимости от мощности разряда, рассчитанная по упрощенной кинетической схеме и с учетом колебательной кинетики, в сравнении с экспериментом

This figure shows the electron concentration measured experimentally in work [35] using the Langmuir probe (black squares) and calculated using the model from this work (lines). All data presented in this work were obtained in the centre of the chamber, according to the position of experimental measurements. As can be seen from the figure, the model without taking into account the vibrational kinetics gives rather good agreement both qualitatively and quantitatively with the experiment within the error. Considering the complete vibrational kinetic scheme will be discussed in the next section.

3. Inclusion of vibrational kinetics in the model

After successful verification of the model without taking into account vibrational kinetics, the next goal of this work was to integrate the full set of reactions associated with VV/VT (Vibration-Vibration and Vibration-Translation) transfer. To do this, in addition to the reactions of VV/VT transfer, it is necessary to add to the kinetic scheme the reactions of vibrational excitation by electron impact. In Table 1 these reactions numbered 59–61. In this work 34 vibrational levels of the O_2 molecule were added, based on previous calculations performed by our group. As mentioned above, all cross sections of vibrational levels [4] were summed and then normalised to the total cross section of vibrational excitation. Then, each section was individually scaled in accordance with the obtained coefficient. In total about 2000 reactions are included in the model with full vibrational kinetics.

After these changes in the model, it was necessary to verify that the plasma characteristics did not vary. As can be seen from Fig. 1, the electron concentration remained practically unchanged (red dotted line), the change in values does not exceed 10%. Thus, the addition of a full set of vibrational kinetics did not affect the description of the main plasma characteristics by the model.

The next task of this work was to obtain the vibrational distribution function (VDF). To do this, a series of calculations was made in the conditions and geometry of the reactor from work [1]. Briefly, a pure oxygen plasma in a cylindrical chamber of 27.5 cm in radius and 10 cm in height is excited by 13.56 MHz power (up to 500 W) through a four-turn planar spiral antenna placed on a top window made of Al_2O_3. All other surfaces are hard anodized aluminium. The measurements were carried out at pressures of 10, 20 mTorr at the centre of the reactor. The results from [1] and calculations from this work are presented in Fig. 2.

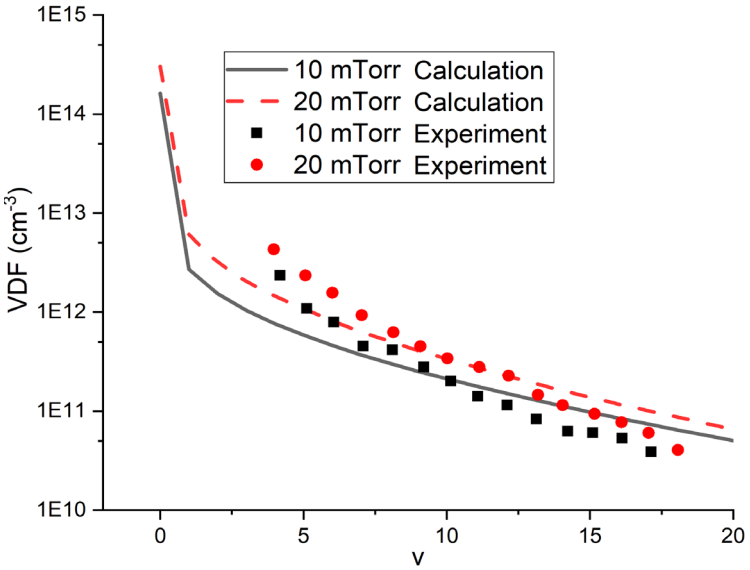

Fig. 2. Vibrational distribution function for two pressures. Experiment [1] and calculation

Рис. 2. Колебательная функция распределения для двух давлений. Эксперимент [1] и расчет

Comparison gives good agreement between experiment and calculations. A flat plateau was obtained according to experimental observations, which is impossible without inclusion of VV/VT reactions in the calculation. Its origin lies in electron impact e-V collisions and not in V-V up-pumping, in contrast to what happens in all other molecular gases known to date [1]. The relaxation of vibrational quanta is mainly due to V-T energy-transfer collisions with O atoms [1]. So the 59–62 reactions are crucial for the shape of VDF in oxygen ICP plasma. Without these processes we could not obtain the experimental shape of VDF.

Conclusions

In this work, a two-dimensional hydrodynamic model of a plasma discharge in oxygen in two cylindrical reactors was constructed and tested. The calculations were carried out at various powers in the coils and pressures. The model showed good agreement with the experimental data. The plasma characteristics presented in this work on the example of the electron density are well described by the model both with and without detailed vibrational kinetics. However, it is impossible to achieve an experimental VDF profile without taking into account the VV/VT processes; therefore, the calculations were carried out taking them into account and the VDF were obtained for two pressures. In the future, the model can be used to obtain fluxes of charged and active neutral particles on the surfaces, as well as for plasma diagnostics, when it is impossible to carry out experimental measurements.

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REFERENCES

1. Annušová A., Marinov D., Booth J.-P., Sirse N., da Silva M. L., Lopez B., Guerra V. Kinetics of highly vibrationally excited $O_2(X)$ molecules in inductively-coupled oxygen plasmas // Plasma Sources Science and Technology. 2018. V. 27, No. 4. Article number 045006. DOI: 10.1088/1361-6595/aab47d.

2. Marinov D., Foucher M., Campbell E., Brouard M., Chabert P., Booth J.-P. High sensitivity ultra-broad-band absorption spectroscopy of inductively coupled chlorine plasma // Plasma Sources Science and Technology. 2016. V. 25, No. 3. Article number 035019. DOI: 10.1088/0963-0252/25/3/035019.

3. Foucher M., Marinov D., Carbone E., Chabert P., Booth J.-P. Highly vibrationally excited O_2 molecules in low-pressure inductively-coupled plasmas detected by high sensitivity ultra-broad-band optical absorption spectroscopy // Plasma Sources Science and Technology. 2015. V. 24, No. 4. Article number 042001. DOI: 10.1088/0963-0252/24/4/042001.

4. Laporta V., Celiberto R., Tennyson J. Resonant vibrational-excitation cross sections and rate constants for low-energy electron scattering by molecular oxygen // Plasma Sources Science and Technology. 2013. V. 22. Article number 025001. DOI: 10.1088/0963-0252/22/2/025001.

5. Laporta V., Celiberto R., Tennyson J. Dissociative electron attachment and electron-impact resonant dissociation of vibrationally excited O_2 molecules // Physical Review A. 2015. V. 91. Article number 012701. DOI: 10.1103/PhysRevA.91.012701.

6. Kropotkin A. N., Voloshin D. G. Simulation of an inductive discharge in argon with the gas flow and inhomogeneous gas temperature // Plasma Physics Reports. 2019. V. 45. P. 786–797. DOI: 10.1134/S1063780X19070055.

7. Kropotkin A. N., Voloshin D. G. ICP argon discharge simulation: the role of ion inertia and additional RF bias // Physics of Plasmas. 2020. V. 27, No. 5. Article number 053507. DOI: 10.1063/5.0003735.

8. National Research Council. Database Needs for Modeling and Simulation of Plasma Processing. Washington, DC: The National Academies Press, 1996. P. 47.

9. Cunge G., Ramos R., Vempaire D., Touzeau M., Neijbauer M., Sadeghi N. Gas temperature measurement in CF_4, SF_6, O_2, Cl_2, and HBr inductively coupled plasmas // Journal of Vacuum Science & Technology A. 2009. V. 27. P. 471–478. DOI: 10.1116/1.3106626.

10. Singh H., Graves D. B. Measurements of the electron energy distribution function in molecular gases in a shielded inductively coupled plasma // Journal of Applied Physics. 2000. V. 88, No. 7. P. 3889–3898. DOI: 10.1063/1.1290450.

11. Hsu C.-C., Nierode M. A., Coburn J. W., Graves D. B. Comparison of model and experiment for Ar, Ar/O_2 and Ar/O_2/Cl_2 inductively coupled plasmas // Journal of Physics D: Applied Physics. 2006. V. 39. Article number 3272. DOI: 10.1088/0022-3727/39/15/009.

12. Seo M. W., Bae M. K., Chung T. H. Comparison of various interpretation methods of the electric probe measurements in inductively coupled Ar and O_2 plasmas // Physics of Plasmas. 2014. V. 21. Article number 023514. DOI: 10.1063/1.4867350.

13. Phelps database. URL: www.lxcat.net/Phelps.

14. Hall R. I., Trajmar S. Scattering of 4.5 eV electrons by ground (X3Σg-) state and metastable (a1Δg) oxygen molecules // Journal of Physics B: Atomic and Molecular Physics. 1975. V. 8. P. L293–L296. DOI: 10.1088/0022-3700/8/12/008.

15. Burrow P. D. Dissociative attachment from the O_2(a1Δg) state // The Journal of Chemical Physics. 1973. V. 59. Article number 4922. DOI: 10.1063/1.1680707.

16. Morgan database. URL: www.lxcat.net.

17. Itikawa Y. Cross sections for electron collisions with oxygen molecules // Journal of Physical and Chemical Reference Data. 2009. V. 38. Article number 1. DOI: 10.1063/1.3025886.

18. Krishnakumar E., Srivastava S. K. Cross-sections for electron impact ionization of O_2 // International Journal of Mass Spectrometry and Ion Processes. 1992. V. 113. P. 1–12. DOI: 10.1016/0168-1176(92)87037-F.

19. Vejby-Christensen L., Kella D., Mathur D., Pedersen H. B., Schmidt H. T., Andersen L. H. Electron-impact detachment from negative ions // Physical Review A. 1996. V. 53. Article number 2371. DOI: 10.1103/PhysRevA.53.2371.

20. Kossyi I. A., Kostinsky A. Yu., Matveyev A. A., Silakov V. P. Kinetic scheme of the non-equilibrium discharge in nitrogen-oxygen mixtures // Plasma Sources Science and Technology. 1992. V. 1. P. 207–220. DOI: 10.1088/0963-0252/1/3/011.

21. Eliasson B., Kogelschatz U. Basic Data for Modelling of Electrical Discharges in Gases: Oxygen. Baden: ABB Asea Brown Boveri, 1986. P. 158,

22. Huang S., Volynets V., Hamilton J. R., Lee S., Song I.-C., Lu S., Tennyson J., Kushner, M. J. Insights to scaling remote plasma sources sustained in NF_3 mixtures // Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films. 2017. V. 35. Article number 031302. DOI: 10.1116/1.4978551.

23. Herron J. T., Green D. S. Chemical kinetics database and predictive schemes for nonthermal humid air plasma chemistry. Part II. Neutral species reactions // Plasma Chemistry and Plasma Processing. 2001. V. 21. P. 459–481. DOI: 10.1023/A:1011082611822.

24. Gudmundsson J. T., Thorsteinsson E. G. Oxygen discharges diluted with argon: dissociation processes // Plasma Sources Science and Technology. 2007. V. 16. Article number 399. DOI: 10.1088/0963-0252/16/2/025.

25. Capitelli M., Ferreira C. M., Gordiets B. F., Osipov A. I. Plasma Kinetics in Atmospheric Gases. Heidelberg: Springer Berlin, 2000.

26.mGordiets B. F., Ferreira C. M., Guerra V. L., Loureiro J. M. A. H., Nahorny J., Pagnon D., Touzeau M., Vialle M. Kinetic model of a low-pressure N_2-O_2 flowing glow discharge // IEEE Transactions on Plasma Science. 1995. V. 23. P. 750–768. DOI: 10.1109/27.467998.

27. Ferguson E. E. Rate constants of thermal energy binary ion-molecule reactions of aeronomic interest // Atomic Data and Nuclear Data Tables. 1973. V. 12. P. 159–178. DOI: 10.1016/0092-640X(73)90017-X.

28. Snuggs R. M., Volz D. J., Gatland I. R., Schummers J. H., Martin D. W., McDani E. W. Ion-molecule reactions between O^- and O_2 at thermal energies and above // Physical Review A. 1971. V. 3. Article number 487. DOI: 10.1103/PhysRevA.3.487.

29. Sato T., Makabe T. A numerical investigation of atomic oxygen density in an inductively coupled plasma in O_2/Ar mixture // Journal of Physics D: Applied Physics. 2008. V. 41. Article number 035211. DOI: 10.1088/0022-3727/41/3/035211.

30. Stafford D. S., Kushner M. J. $O_2(^1\Delta)$ production in He/O_2 mixtures in flowing low pressure plasmas // Journal of Applied Physics. 2004. V. 96. P. 2451–2465. DOI: 10.1063/1.1768615.

31. Esposito F., Armenise I., Capitta G., Capitelli M. O–O_2 state-to-state vibrational relaxation and dissociation rates based on quasiclassical calculations // Chemical Physics. 2008. V. 351. P. 91–98. DOI: 10.1016/j.chemphys.2008.04.004.

32. Coletti C., Billing G. D. Vibrational energy transfer in molecular oxygen collisions // Chemical Physics Letters. 2002. V. 356. P. 14–22. DOI: 10.1016/S0009-2614(02)00279-8.

33. Lino da Silva M., Loureiro J., Guerra V. A multiquantum dataset for vibrational excitation and dissociation in high-temperature O_2–O_2 collisions // Chemical Physics Letters. 2012. V. 531. P. 28–33. DOI: 10.1016/j.cplett.2012.01.074.

34. Raju G. G. Gaseous Electronics: Tables, Atoms, and Molecules. London: Taylor & Francis, 2012. P. 171.

35. Kiehlbauch M. W., Graves D. B. Inductively coupled plasmas in oxygen: Modeling and experiment // Journal of Vacuum Science & Technology A. 2003. V. 21. P. 660–670. DOI: 10.1116/1.1564024.