UDC 533.9

KINETIC PROCESSES IN A PLASMA OF BARRIER DISCHARGE ON ATMOSPHERIC AIR: INFLUENCE OF WATER VAPOR ON BIOLOGICAL ACTIVITY OF GENERATED MEDIUM

V.Yu. Bazhenov[1], A.V. Ryabtsev[1], I.A. Soloshenko[1], V.A. Khomich[1], V.V. Tsiolko[1], A.I. Shchedrin[1], A. I. Kuzmichev[2], V.I. Kryzhanovsky[2], I. L. Mihno[3].

[1]Institute of Physics NAS of Ukraine, pr. Nauki 46, 03022, Kiev, Ukraine, tsiolko@iop.kiev.ua
[2]National Technical University of Ukraine "Kiev Polytechnical Institute", pr. Peremogy 37, KPI-2230, 03056, Kiev, Ukraine
[3] Institute of Epidemiology and Infective Diseases, st. Protasov Yar 4, 03038, Kiev, Ukraine

Abstract

In the present paper theoretical and experimental investigations of the water vapor influence on the biological activity of the medium generated by barrier discharge on atmospheric air were performed. Numerical calculation of the component composition of the particles generated by barrier discharge in dry and moisture air shown that moistening the air on the one hand results in the ozone concentration reduction, but on the other hand it results in increase of the concentration of the such biologically active particle as N_2O_4 and formation of the new active particles – molecules of hydrogen peroxide H_2O_2, nitric HNO_3 and nitrous HNO_2 acids, and HO_2NO_2 radicals in the discharge. Experiments on the spores processing have shown that moistening of air leads to increase of the biological activity of the medium generated by barrier discharge. On basis of experiments and theoretical calculation one can insists that the rise of the medium activity is connected with generation of the hydric particles H_2O_2, HNO_3, HNO_2 and HO_2NO_2.

1. Introduction

In the last ten years gas discharge plasma attains more and more wide applications in biology and medicine at creation of biomaterials and membranes with pre-defined features (biocompatibility, clot resistance, lowered friction, etc.) and, as well, at cold sterilization of articles made of thermolabile materials. In modern medical practice the cold sterilization of a wide variety of heat-sensitive instruments and materials is mainly performed by means of toxic gases – pure ethylene oxide or its mixture with fluorochlorocarbons. This sterilization technique requires long (up to 24 hours) aeration process and, which is most important, creates serious threat both for servicing personnel health and for the environment. Currently one of the most serious alternatives of gaseous sterilization consists in the use of gas discharge plasma as sterilizing agent. Main advantage of plasma technique is given by fact that plasma, as chemically active medium, is formed in result of excitation, dissociation and ionization of any gaseous or vaporous substance, including non-toxic ones (even inert gases). Whereas a low pressure plasma sterilizers already have been commercially available since early 1990's [1], the great attention to developing of the low temperature sterilizers using atmospheric pressure discharges, which are more attractive due to absence of a vacuum system, has been paid at the past years [2-4]. However, solving this problem is complicated by the fact that up to now complete investigations of barrier discharge plasma, first of all, that of component composition of active particles, are not accomplished. Present paper is devoted to the theoretical studies of the component composition of the particles, which are generated by the barrier discharge in dry and moisture ambient air, and to experimental investigation of the sterilization efficacy of the barrier discharge depending on air moisture.

1. Numerical simulation of air plasma composition and discussion

According to [4] and the experiments described below, in the sterilization by air barrier discharge, besides of ozone, others active particles play role as well. In order to understand, what active particles are, and to find the plasma component content, we modeled barrier discharge in air under conditions close to experimental ones. Modeling of the plasma component content was performed separately for each of two parts of working chamber – the discharge gap of barrier discharge and sterilizing chamber itself, where processed items were placed.

At calculation of the plasma component content and the concentrations of molecules and radicals formed immediately in barrier discharge, kinetic equations were used:

$$\frac{dN_i}{dt} = S_{ei} + \sum_j k_j N_j + \sum_{j,l} k_{jl} N_j N_l + ... \qquad (1)$$

Here N_i are concentrations of molecules and radicals,; k_j, k_{jl} are rate constants of molecular processes; S_{ei} is rate of forming the products of electron-molecular reactions, which was calculated from the following equation:

$$S_{ei} = \frac{W}{V}\frac{1}{\varepsilon_{ei}}\frac{W_{ei}}{\sum_j W_{ej} + \sum_j W_j}. \qquad (2)$$

Here W is power introduced into barrier discharge; V is discharge chamber volume; W_{ej} is specific power spent to electron-molecular process on non-elastic scattering with threshold energy ε_{ej}:

$$W_{ei} = \sqrt{\frac{2q}{m}} n_e N_i \varepsilon_{ei} \int_0^\infty \varepsilon Q_{ei}(\varepsilon) f(\varepsilon) d\varepsilon, \qquad (3)$$

where $q = 1.602 \cdot 10^{-12}$ erg/eV; m and n_e are electron mass and concentration, respectively; Q_{ei} is cross section of respective non-elastic process; $f(\varepsilon)$ is electron energy distribution function (it was calculated from Boltzman equation [5]).

W_i is specific power spent for the gas heating:

$$W_i = \frac{2m}{M_i}\sqrt{\frac{2q}{m}} n_e N_i \int_0^\infty \varepsilon^2 Q_i(\varepsilon) f(\varepsilon) d\varepsilon , \qquad (4)$$

where M_i is mass of respective kind of molecules; Q_i is transport cross section of scattering.

Electron energy distribution function and specific powers W_{ei} и W_i are strongly dependent on electric field value in microscopic chaotically moving current channels in the discharge gap. Since electric field in current channels changes in space and time in random way and in rather wide ranges, mean field value was used in the calculations. As it is shown in [6], where barrier discharge in air at atmospheric pressure was studied, mean electric field value in current channels comprises $E = 20$ kV/cm.

At solving equations (1) more than 100 elementary processes were taken in consideration (see Table 1). (In the absence of the experimental data in the literature the cross sections of non-elastic scattering of electrons on some molecules were calculated by Thompson-Gryzinski formulas [13, 14])

Calculation of the concentrations of atoms, molecules and radicals in sterilizing chamber was also performed on basis of equations (1), but with substitution of S_{ei} by $S_i = \frac{N_i(\tau)}{\tau}\frac{V}{V_S}$, where τ is time of the gas pumping through barrier discharge; $N_i(\tau)$ is concentration of mixture components in the discharge for the time point τ; V_S is sterilizing chamber volume. Electron and ion processes in sterilizing chamber were not taken into account due to absence of charged plasma particles in it.

Equations (1) were solved together with Boltzman equation by means of numeric methods analogous to [5].

In Figs.1,2 component contents of the mixture in sterilizing chamber in dry air (water vapor is absent) for various times τ of pumping through barrier discharge ($\tau = \frac{V}{Sv}$, where S is cross section of the discharge chamber, v is pumping rate) are given. The first figure corresponds to $\tau = 0.1$ s; the second one – to higher pumping rate, when it is possible to neglect the destruction by electrons of the products of plasma-chemical reactions in the discharge chamber. Dark strips correspond to concentrations of the mixture components after 30 minutes of the discharge operation; light strips represent maximum achievable values of the densities during mentioned time period. The largest values are reached by O_3 and N_2O_5 concentrations. As one can see from the figures, the densities of particular mixture components in sterilizing chamber possess rather strong dependence on pumping rate. At that, concentrations of certain components increase, whereas concentrations of other ones decrease with variation of pumping rate. With the decrease of pumping rate, amount of nitrogen-containing molecules decreases, however, ozone density grows up. It is due to fact that at low pumping rate of the mixture through the discharge gap essential decomposition of nitrogen-containing molecules occurs due to dissociation by electron hits. And, in turn, it results in the growth of ozone concentration via the sequence of chain reactions.

In Figs. 3,4 component contents are presented for the mixture in sterilizing chamber in case of moistened air (H_2O concentration corresponds to partial pressure of saturated water vapor) for two given above rates of pumping through the discharge chamber.

It is clearly seen from comparison of Figs. 3 and 4 with Figs. 1 and 2 that moistening the air results in the following effects:

1. Ozone concentration decreases significantly, at that its dependence on pumping rate changes to opposite one – increase of pumping rate results in increase of O_3 concentration.
2. N_2O_2 concentration increases by factor of several orders of magnitude at low pumping rate, and it exhibits small variation at high pumping rate.
2. Efficient generation of H_2O_2, HNO_3, HNO_2, HO_2NO_2 molecules occurs, at that their concentrations can essentially overcome ozone concentration.

3. Experimental set-up and results

The experimental set-up was described in detail in [4]. It consists of a glass work chamber with volume 7 liters, an electrode unit, holders for samples to be sterilized, gas and electric power supply systems. The electrode unit was placed in the center of the chamber. Gases (air, O_2, N_2, Ar) with different humidity (RH) were supplied into the electrode unit, and chemically active particles generated by discharges were directed to the samples. A gas flow was varied in the range of 0.5 – 10.0 l/min. Barrier discharge was created with pulsed power supply. The pulse duration was about 10 μsec at the pulse rates were up to 10 kHz. Specific power normalized to volume of the discharge gap of barrier discharge comprised $W_d = 2 \div 4$ W/cm^3. The whole working chamber volume was spatially split into two parts – central one, where the plasma generation occurred, and sterilizing one, where processed articles were placed. Ratio of volume of the discharge gap to that of sterilizing chamber comprised about $3 \cdot 10^{-3}$. The holders surrounded the electrode unit, and the mean distance from the discharge zone to the samples was about 10 cm.

Polished stainless steel strips inoculated with 10^6 spores *Bac. Stearothermophilus* ATCC 7953 (the surface spore density $\geq 0{,}5 \cdot 10^6$ sp/cm^2) were used as bio-indicators (BI).

After the processing the samples were treated by the standard method used in microbiology, and then the number of surviving bacteria was determined by using the pour-plate method.

The data for sterilization by barrier discharge are given in Figs.5, 6. As one can see from Fig.5, the least efficiency of the sterilization is in the cases of nitrogen and argon. In the case of dry gases the most efficient processing is observed in oxygen (due to the highest ozone concentration). Oxygen moistening results in decrease of ozone concentration, however, efficiency of the sterilization practically is not changed at that. This fact gives an evidence that sterilizing action of ozone is enhanced at presence of moisture in the chamber. At the same time, moistening the air (which is also accompanied by the decrease of ozone concentration) results in essential diminishing of the number of survived spores. As it will be shown below, this effect is most likely due to fact that, in addition to ozone, other chemically active particles participating in the sterilization are also created – first of all, they are hydrogen peroxide, nitrogen oxides, nitric and nitrous acids.

Fig.6 exhibits the survival curves (that is, dependencies of the number of survived spores on the processing time) obtained at sterilization with the use of barrier discharge in dry and moistened air. One can see from the figure that during initial several minutes the number of survived spores decreases significantly with time (practically with the same "speed" for dry and moistened air), and in subsequent the decrease of the number of survived spores occurs much more slowly. Difference in biological activity of the active media generated by barrier discharge in dry and wet air is exhibited especially at the second stage – the number of survived spores in case of wet air is essentially lower.

Since experimental conditions correspond to those given in Figs. 1 and 3, it follows from their comparison that observed increase of the sterilization efficiency at air moistening is due to generation of biologically active particles – hydrogen peroxide H_2O_2, nitric HNO_3 and nitrous HNO_2 acids, HO_2NO_2 radicals and the growth of N_2O and N_2O_5 concentrations.

Thus, as it follows from theoretical calculations and the experiment, by means of variations of pumping rate one can control concentrations of biologically active particles in wide range and, consequently, optimize the process of sterilization of medical instruments.

4. Acknowledgements.

This work was supported in part by grants # 57, #57C of Science and Technology Center of Ukraine.

1. J.H.Young//'New Sterilization Technologies", Chapter 26 in *Sterilization technology for the Health Care Facility,* M.eichert and J.H.Young, Editors, Aspen Publishers, Gaithersburg, MD, ISBN 0-8342-0838-5, pp.228-235, 1997.
2 T.C.Montie, K.Kelly-Wintenderg, J.R.Roth // IEEE Trans. Plasma Sci., **28** (2000), pp. 41-50.
3 M.Laroussi, I.Alexeff and W.L.Kang // IEEE Trans. Plasma Sci., **28** (2000), pp. 184-188.
4 V.A.Khomich, I.A.Soloshenko, V.V.Tsiolko, et al // Contributed papers of International Symposium on High Pressure, Low Temperature Plasma Chemistry (HAKONE VII), Volume 2, Greifswald, Germany, September 10-13, 2000, pp. 402-406.
5 I.A.Soloshenko, V.V.Tsiolko, V.A.Khomich et al // Plasma Physics Report, **26** (2000), pp. 792-800.
6 D.Braun, V.Gibalov, G.Pietsch // Plasma Sources Sci.Technol., **1** (1992), pp. 166-174.
7 Young Sun Mok, Sung Won Ham, and In-Sik Nam // IEEE Transactions on Plasma Science, v.26, N.5 (1998) pp.1566-1574.

8 A.R.Ravishankara, P.H.Wine and J.M.Nicovich // J.Chem.Phys. v.78 (1983) pp.6629-6639.

9 A. A.Turnipseed, G. L.Vaghjiani, T. Gierczak, J. E.Thompson, and A.R.Ravishankara // J.Chem.Phys. v.95 (1991) pp.3244-3251.

10 G. L.Vaghjiani and A.R.Ravishankara // J.Chem.Phys. v.92 (1990) pp.996-1003.

11 I.A.Kossyj, A.Yu.Kostinskij, A.A.Matveev, V.P.Silakov // Proceedings of the Institute of General Physics, v.47, (1994), pp.37-57, in Russian.

12 A. C.Gentile, M. J. Kushner // J.Appl.Phys. v.78 (1995) pp.2074-085.

13 M. Gryzinski// *Phys. Rev*., vol.138, no.2A, (1965), pp.322-335.

14 M. Gryzinski// *Phys. Rev*, vol.138, no.2A, (1965), pp.336-358.

Figure captions

Fig.1. Component content of the particles in sterilizing chamber at barrier discharge operation in dry air (0% RH) for pumping time through the discharge gap $\tau = 0.1$ s (gas flow 1 l/min).

Fig.2. Component content of the particles in sterilizing chamber at barrier discharge operation in dry air (0% RH) for pumping time through the discharge gap $\tau = 0$ s.

Fig.3. Component content of the particles in sterilizing chamber at barrier discharge operation in moistened air (100% RH) for pumping time through the discharge gap $\tau = 0.1$ s (gas flow 1 l/min).

Fig.4. Component content of the particles in sterilizing chamber at barrier discharge operation in moistened air (100% RH) for pumping time through the discharge gap $\tau = 0$ s.

Fig.5. Comparison of sterilizing ability of barrier discharge in various dry (45% RH) and moistened (90% RH) gases by suppression of the number of survived spores *Bac. stearothermophilus* at metal strips. Initial bacterial loading $8 \cdot 10^5$ spores. Sterilization time is 60 min; gas flow is 1 l/min, $W_d = 2$ W/cc; ozone concentration is shown for oxygen and air.

Fig.6. Survival curves for spores *Bac. steraothermophilus* at metal strips obtained by colony count method at sterilization by barrier discharge in dry (45% RH)(curve 1) and moistened (90% RH) (curve 2) air. Initial bacterial loading $8 \cdot 10^5$ spores. Gas flow is 1 l/min, $W_d = 2$ W/cm^{-3}.

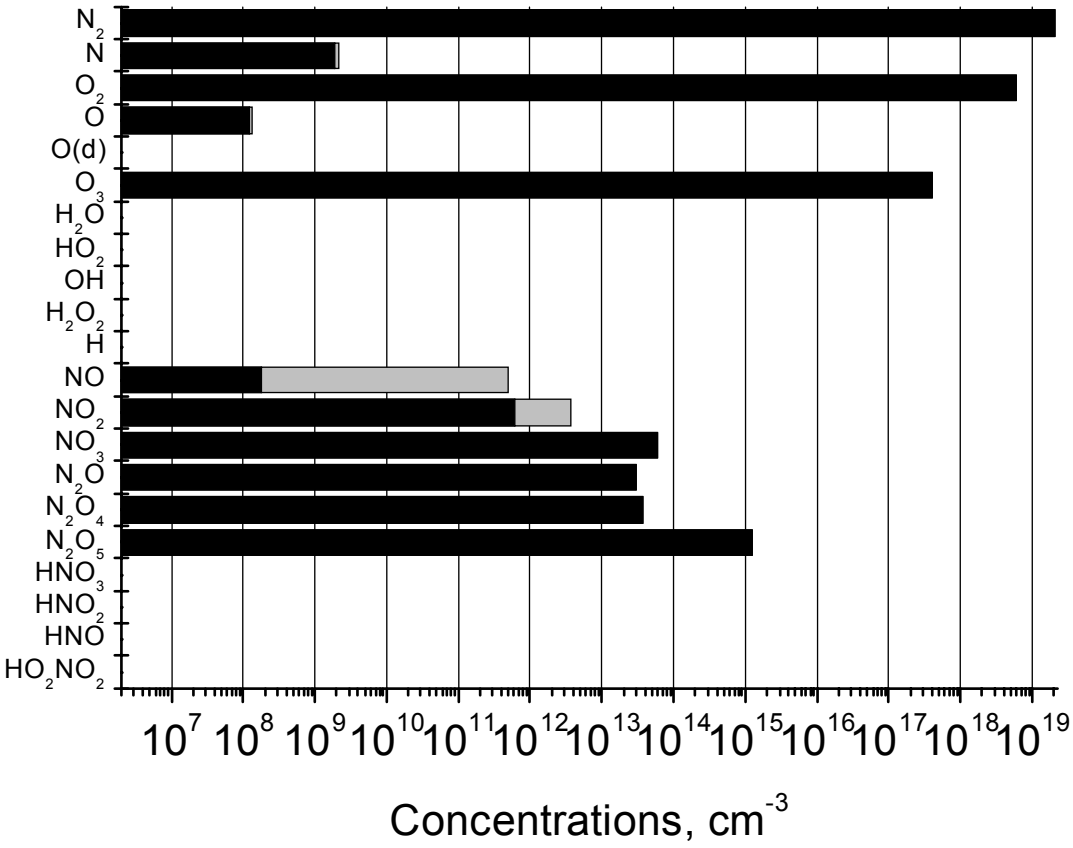
N2
N
O2
O
O(d)
O3
H2O
HO2
OH
H2O2
H
NO
NO2
NO3
N2O
N2O4
N2O5
HNO3
HNO2
HNO
HO2NO2
10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19
Concentrations, cm^-3

FIG.1

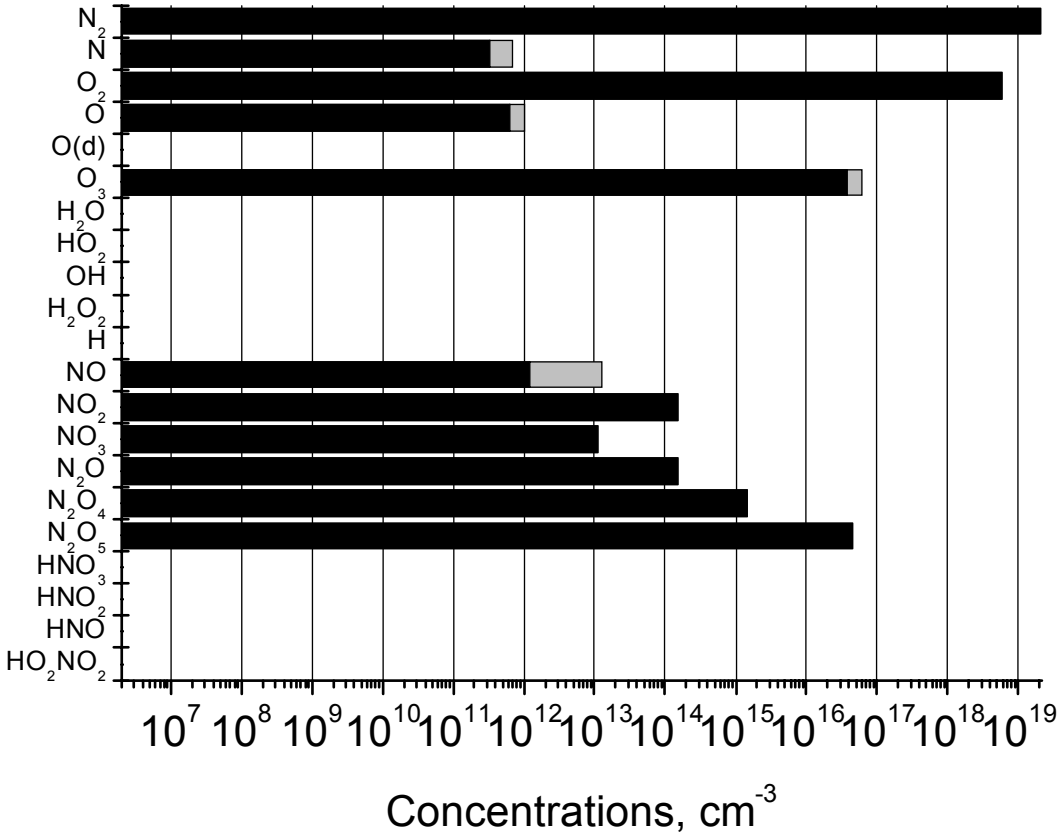
N2
N
O2
O
O(d)
O3
H2O
HO2
OH
H2O2
H
NO
NO2
NO3
N2O
N2O4
N2O5
HNO3
HNO2
HNO
HO2NO2
10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19
Concentrations, cm^-3

FIG.2

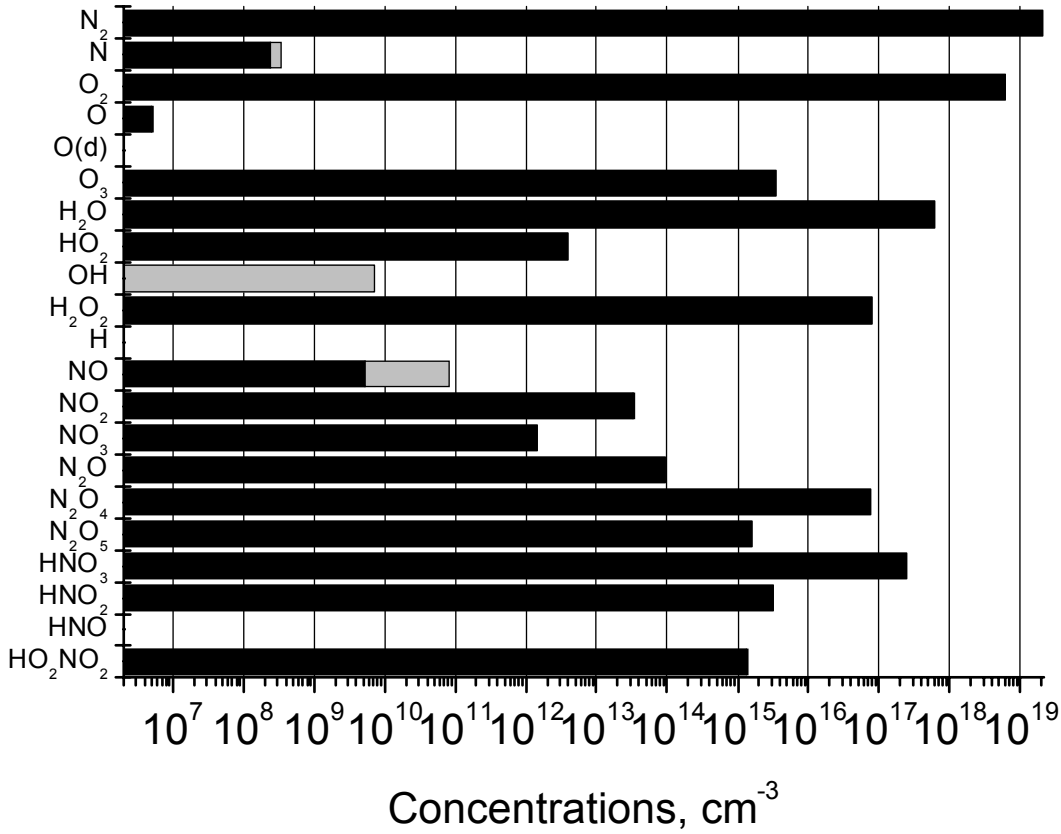
N2
N
O2
O
O(d)
O3
H2O
HO2
OH
H2O2
H
NO
NO2
NO3
N2O
N2O4
N2O5
HNO3
HNO2
HNO
HO2NO2
10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19
Concentrations, cm^-3

FIG.3

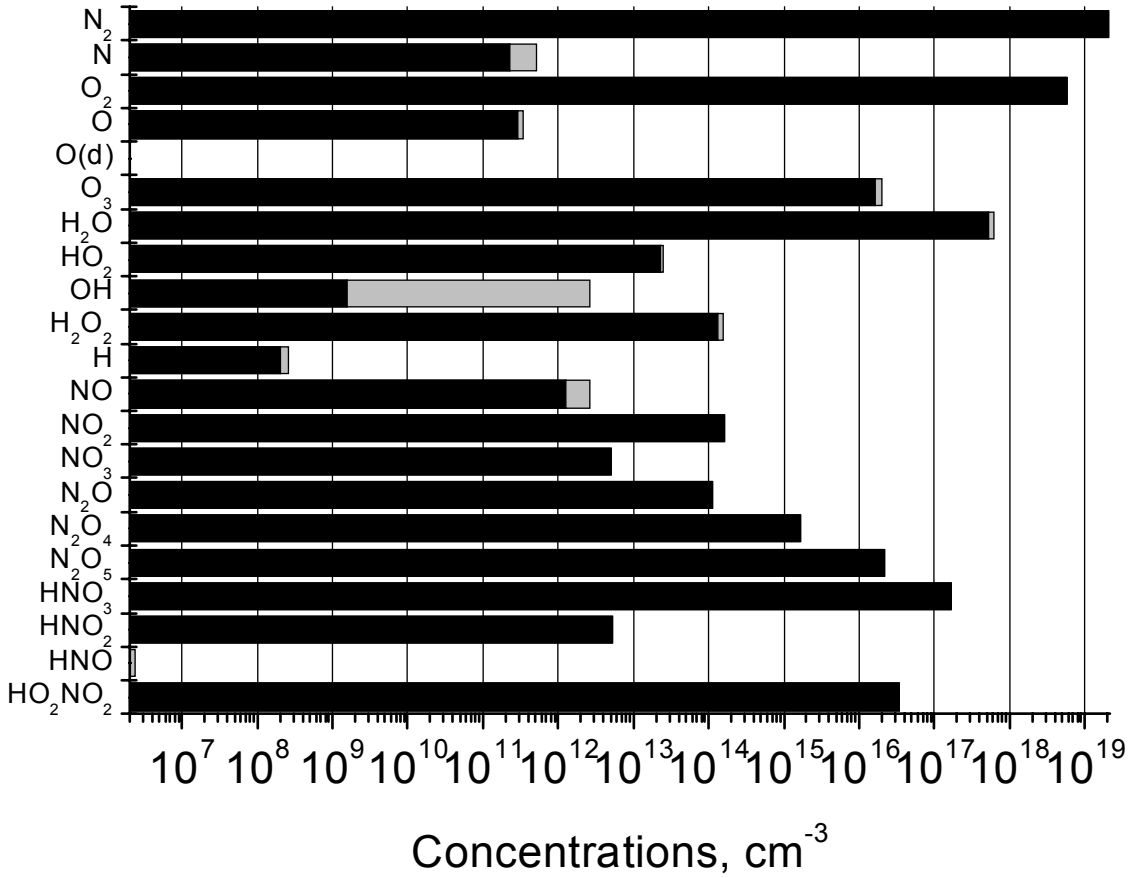
N2
N
O2
O
O(d)
O3
H2O
HO2
OH
H2O2
H
NO
NO2
NO3
N2O
N2O4
N2O5
HNO3
HNO2
HNO
HO2NO2
10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19
Concentrations, cm^-3

FIG.4

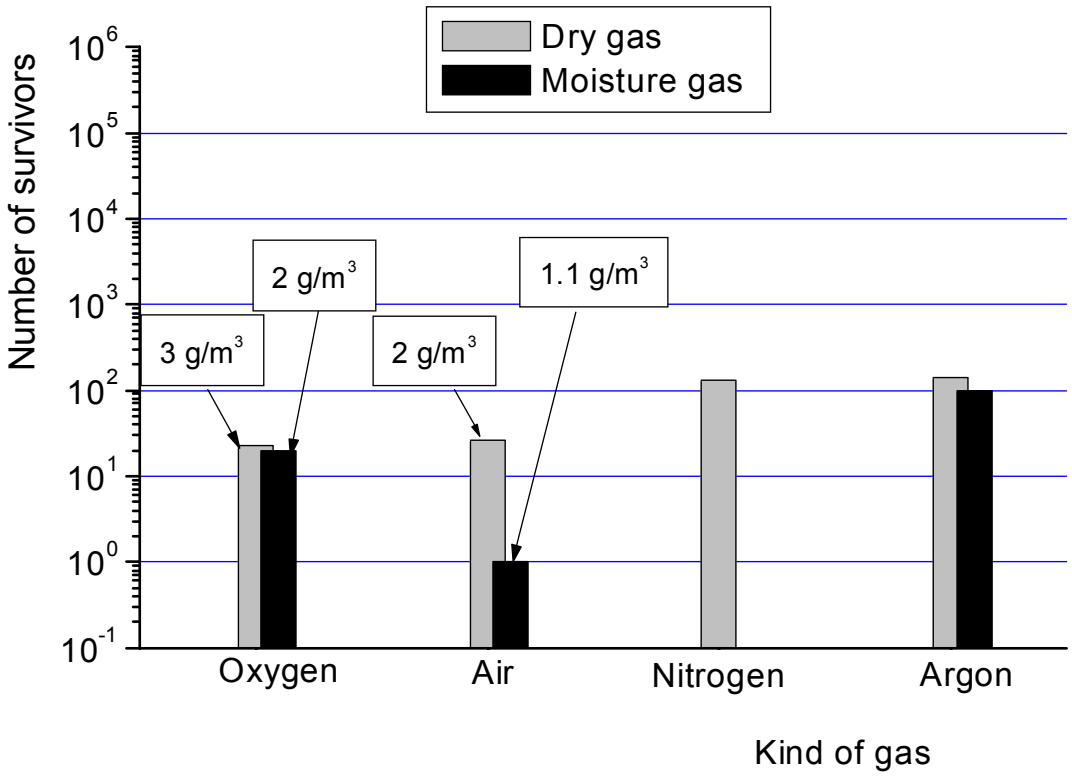
Dry gas
Moisture gas
Number of survivors
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
3 g/m^3
2 g/m^3
2 g/m^3
1.1 g/m^3
Oxygen
Air
Nitrogen
Argon
Kind of gas

Fig.5.

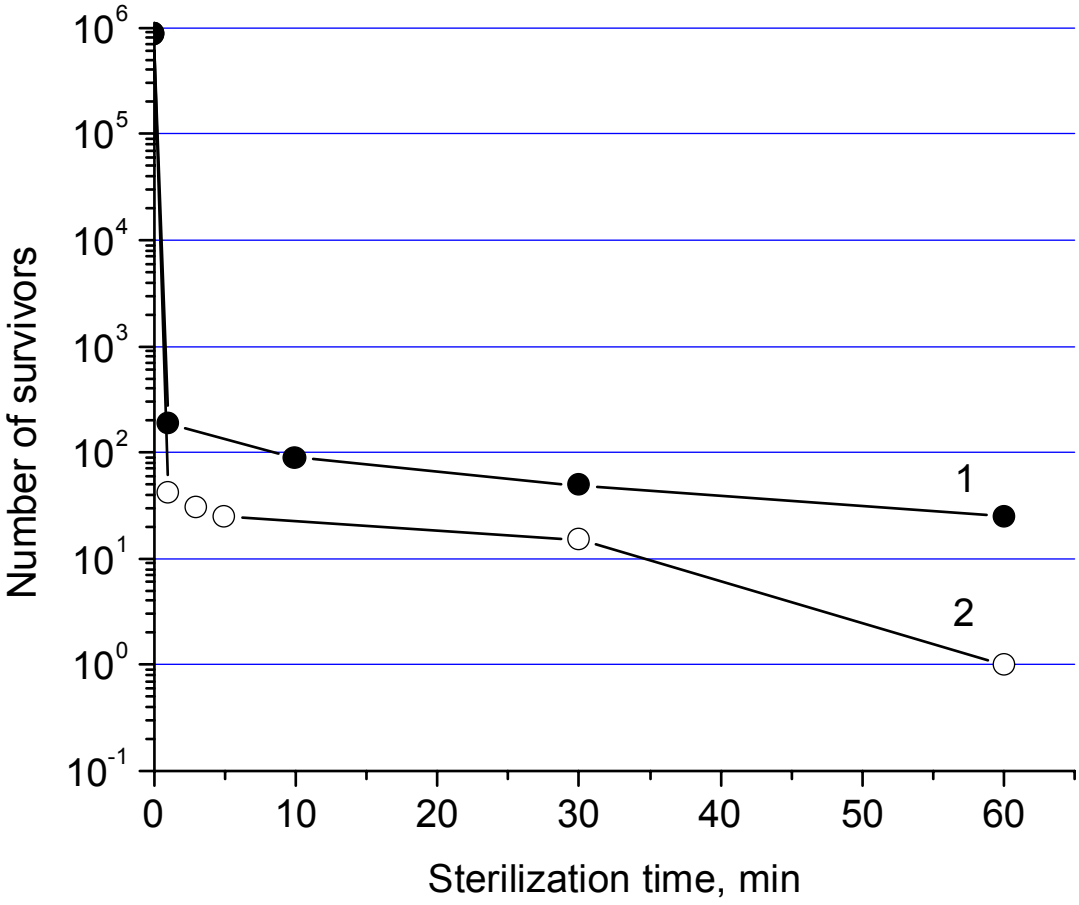
Number of survivors
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
0
10
20
30
40
50
60
Sterilization time, min
1
2

Fig.6.

Table 1.

№	Reactions		reference
1	$H_2O + e \rightarrow OH + H + e$	$1.66/n_e$	*
2	$O_2 + e \rightarrow O + O + e$	$7.5\cdot10^{-2}/n_e$	*
3	$O_2 + e \rightarrow O + O(d) + e$	$2.5\cdot10^{-2}/n_e$	*
4	$N_2 + e \rightarrow N + N + e$	$5.5\cdot10^{-3}/n_e$	*
5	$O(d) + H_2O \rightarrow OH + OH$	$2.2\cdot10^{-10}$	6
6	$O(d) + N_2 \rightarrow O + N_2$	$2.6\cdot10^{-11}$	6
7	$O(d) + O_2 \rightarrow O + O_2$	$3.8\cdot10^{-11}$	6
8	$O(d) + H_2O \rightarrow O + H_2O$	$1.2\cdot10^{-11}$	6
9	$N + HO_2 \rightarrow NO + OH$	$2.2\cdot10^{-11}$	6
10	$NO_3 + OH \rightarrow NO_2 + {}_{HO2}$	$2.3\cdot10^{-11}$	6
11	$OH + OH + M \rightarrow H_2O_2 + M$	$6.5\cdot10^{-31}\ (300/T)^{0.7}$	6
12	$OH + O_3 \rightarrow HO_2 + O_2$	$1.3\cdot10^{-12}\ e^{-956/T} + 2.3\cdot10^{-11}\ e^{110/T}$	6
13	$OH + HO_2 \rightarrow H_2O + O_2$	$4.8\cdot10^{-11}\ e^{250/T}$	6
14	$O + HO_2 \rightarrow OH + O_2$	$2.9\cdot10^{-11}\ e^{200/T}$	6
15	$H + O_3 \rightarrow OH + O_2$	$1.4\cdot10^{-10}\ e^{-480/T}$	6
16	$H + HO_2 \rightarrow OH + OH$	$3.0\cdot10^{-10}\ e^{-500/T}$	6
17	$H + OH + M \rightarrow H_2O + M$	$1.1\cdot10^{-23}\ T^{-2.6}$	6
18	$OH + OH \rightarrow H_2O + O$	$1.0\cdot10^{-11}\ e^{-500/T}$	6
19	$OH + H_2O_2 \rightarrow H_2O + HO_2$	$1.2\cdot10^{-11}\ e^{-270/T} + 8.0\cdot10^{-12}\ e^{2060/T}$	6
20	$O + O + M \rightarrow O_2 + M$	$2.76\cdot10^{-31}/T$	6
21	$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$	$2.2\cdot10^{-13}\ e^{600/T}$	6
22	$HO_2 + HO_2 + M \rightarrow H_2O_2 + O_2 + M$	$1.9\cdot10^{-33}\ e^{980/T}$	6
23	$N + N + M \rightarrow N_2 + M$	$8.3\cdot10^{-34}\ e^{500/T}$	6
24	$O + H_2O_2 \rightarrow OH + HO_2$	$1.45\cdot10^{-15}$	7
25	$O + H_2O_2 \rightarrow H_2O + O_2$	$1.45\cdot10^{-15}$	7
26	$O(d) + O_3 \rightarrow O + O + O_2$	$2.33\cdot10^{-10}$	8
27	$O(d) + O_3 \rightarrow O_2 + O_2$	$2.33\cdot10^{-10}$	8
28	$H + HO_2 \rightarrow H_2O_2$	$9\cdot10^{-11}$	9
29	$N + O_3 \rightarrow NO + O_2$	$2\cdot10^{-16}$	10
30	$N + NO_2 \rightarrow N_2 + O_2$	$7\cdot10^{-13}$	10
31	$N + NO_2 \rightarrow N_2 + O + O$	$9.1\cdot10^{-13}$	10
32	$O + O_3 \rightarrow O_2 + O_2$	$2\cdot10^{-11}\ e^{2300/T}$	10
33	$O + NO_3 \rightarrow O_2 + NO_2$	$1\cdot10^{-11}$	10
34	$NO_3 + NO_3 \rightarrow O_2 + NO_2 + NO_2$	$2.3\cdot10^{-13}\ e^{-1600/T}$	10
35	$N + OH \rightarrow NO + H$	$3.8\cdot10^{-11}\ e^{85/T}$	11
36	$N + O_2 \rightarrow NO + O$	$4.4\cdot10^{-12}\ e^{-3220/T}$	7
37	$N + O + M \rightarrow NO + M$	$5.46\cdot10^{-33}\ e^{155/T}$	7
38	$NO + H + M \rightarrow HNO + M$	$3.4\cdot10^{-32}$	7
39	$NO + HO_2 \rightarrow HNO + O_2$	$9.1\cdot10^{-19}\ e^{2819/T}$	7
40	$NO + HO_2 + M \rightarrow HNO_3 + M$	$5.6\cdot10^{-33}$	7
41	$NO + HO_2 \rightarrow NO_2 + OH$	$3.7\cdot10^{-12}\ e^{240/T}$	7
42	$NO + N \rightarrow N_2 + O$	$3.1\cdot10^{-11}$	7
43	$NO + NO_3 \rightarrow NO_2 + NO_2$	$1.6\cdot10^{-11}\ e^{150/T}$	7
44	$NO + O + N_2 \rightarrow NO_2 + N_2$	$9.1\cdot10^{-28}\ T^{-1.6}$	7
45	$NO + O_3 \rightarrow NO_2 + O_2$	$2.0\cdot10^{-12}\ e^{-14400/T}$	7

46	$NO + OH + M \rightarrow HNO_2 + M$	$7.4\cdot10^{-31} (T/300)^{-2.4}$	7
47	$NO_2 + HO_2 + M \rightarrow HO_2NO_2$	$1.5\cdot10^{-31} (T/300)^{-3.2}$	7
48	$NO_2 + N \rightarrow N_2O + O$	$2.4\cdot10^{-12}$	7
49	$NO_2 + N \rightarrow NO + NO$	$6.0\cdot10^{-13}$	7
50	$NO_2 + NO_2 + M \rightarrow N_2O_4 + M$	$1.4\cdot10^{-33} (T/300)^{-3.8}$	7
51	$NO_2 + NO_3 + M \rightarrow N_2O_5 + M$	$2.7\cdot10^{-30}(T/300)^{-3.4}$	7
52	$NO_2 + O \rightarrow NO + O_2$	$6.5\cdot10^{-12} e^{120/T}$	7
53	$NO_2 + O_3 \rightarrow NO + O_2 + O_2$	$1.0\cdot10^{-18}$	7
54	$NO_2 + O + M \rightarrow NO_3 + M$	$9.0\cdot10^{-32}(T/300)^{-2.0}$	7
55	$NO_2 + O_3 \rightarrow NO_3 + O_2$	$1.2\cdot10^{-13} e^{-2450/T}$	7
56	$NO_2 + OH + M \rightarrow HNO_3 + M$	$2.2\cdot10^{-30} (T/300)^{-2.9}$	7
57	$N_2O_5 + M \rightarrow NO_3 + NO_2 + M$	$8.8\cdot10^{-6} e^{-9700/T}$	7
58	$N_2O_5 + H_2O \rightarrow HNO_3 + HNO_3$	$5.0\cdot10^{-21}$	7
59	$HNO + O_2 \rightarrow NO + HO_2$	$5.25\cdot10^{-12} e^{-1510/T}$	7
60	$HNO_2 + OH \rightarrow NO_2 + H_2O$	$1.8\cdot10^{-11} e^{-39-/T}$	7
61	$HNO_3 + OH \rightarrow NO_3 + H_2O$	$1.5\cdot10^{-14} e^{650/T}$	7
62	$HNO_3 + NO \rightarrow HNO_2 + NO$	$7.37\cdot10^{-21}$	7
63	$HO_2NO_2 + M \rightarrow HO_2 + NO_2 + M$	$5.0\cdot10^{-6} e^{-10000/T}$	7
64	$O + O_2 + M \rightarrow O_3 + M$	$6.2\cdot10^{-34} (T/300)^{-2.0}$	7
65	$O + OH \rightarrow O_2 + H$	$2.3\cdot10^{-11} e^{110/T}$	7
66	$H + O_2 + M \rightarrow HO_2 + M$	$4.8\cdot10^{-32}$	7
67	$H + OH + M \rightarrow H_2O + M$	$8.6\cdot10^{-31}$	7
68	$O_3 + e \rightarrow O_2 + O + e$	$7.3\cdot10^{-3}/n_e$	*
69	$N_2O + e \rightarrow N_2 + O + e$	$1.68\cdot10^{-2}/n_e$	*
70	$NO_2 + e \rightarrow NO + O + e$	$7.5\cdot10^{-2}/n_e$	*
71	$N_2O_4 + e \rightarrow NO_2 + NO_2 + e$	$2.5\cdot10^{-2}/n_e$	*
72	$N_2O_5 + e \rightarrow NO_2 + NO_3 + e$	$2.5\cdot10^{-2}/n_e$	*

* - rates were calculated with the use of electron energy distribution function.

КІНЕТИЧНІ ПРОЦЕСИ В ПЛАЗМІ БАР'ЄРНОГО РОЗРЯДУ НА АТМОСФЕРНОМУ ПОВІТРІ: ВПЛИВ ПАРІВ ВОДИ НА БІОЛОГІЧНУ АКТИВНІСТЬ СЕРЕДОВИЩА

В.Ю.Баженов, А.В.Рябцев, І.О.Солошенко, В.О.Хомич, В.В.Ціолко, А.І.Щедрін, А.І.Кузьмичов, В.І.Крижановський, І.Л.Михно.

Резюме

Робота присвячена теоретичному та експериментальному дослідженню впливу парів води на біологічну активність середовища, що генерується бар'єрним розрядом на атмосферному повітрі. Числове моделювання компонентного складу часток, які генеруються бар'єрним розрядом в сухому та вологому повітрі, показало, що зволоження повітря з одного боку приводить до зменьшення концентрації озону, а з другого - до збільшення концентрації таких біологічно активних часток як N_2O_4 та `появи нових активних часток - молекул перекису водню H_2O_2, азотної (HNO_3) та азотистої (HNO_2) кислот, радикалів HO_2NO_2. Експерименти по обробці спор показали, що зволоженння повітря приводить до підвищення біологічної активності середовища, яке генерується бар'єрним розрядом. На підставі експериментів та теоретичних розрахунків можна стверджувати, що збільшення активності середовища пов'язане з генерацією водневміщуючих часток H_2O_2, HNO_3, HNO_2 та HO_2NO_2.

КИНЕТИЧЕСКИЕ ПРОЦЕССЫ В ПЛАЗМЕ БАРЬЕРНОГО РАЗРЯДА НА АТМОСФЕРНОМ ВОЗДУХЕ: ВЛИЯНИЕ ПАРОВ ВОДЫ НА БИОЛОГИЧЕСКУЮ АКТИВНОСТЬ ГЕНЕРИРУЕМОЙ СРЕДЫ

В.Ю. Баженов, А.В.Рябцев, И.А.Солошенко, В.А.Хомич, В.В.Циолко, А.И.Щедрин, А.И.Кузьмичев, В.И. Крыжановский, И.Л.Михно.

Резюме

Работа посвящена теоретическому и экспериментальному исследованию влияния паров воды на биологическую активность среды генерируемой барьерным разрядом на атмосферном воздухе. Численное моделирование компонентного состава частиц, которые генерируются барьерным разрядом на сухом и влажном воздухе показало, что увлажнение воздуха с одной стороны приводит к уменьшению концентрации озона, а с другой – к увеличению концентрации такой биологически активной частицы как N_2O_4 и появлению новых активных частиц - молекул перекиси водорода H_2O_2, азотной HNO_3 та азотистой HNO_2 кислот, радикалов HO_2NO_2. Эксперименты по обработке спор показали, что увлажнение воздуха приводит к повышению биологической активности среды генерируемой барьерным разрядом. На основе экспериментов и теоретических расчетов можно утверждать, что увеличение активности среды связано с генерацией водородосодержащих частиц H_2O_2, HNO_3, HNO_2 и HO_2NO_2.