



**EFRE
2020**

7th International Congress on
**ENERGY FLUXES AND
RADIATION EFFECTS**
ONLINE
September 14-26, 2020. Tomsk, Russia



21st International Symposium on
High Current Electronics

S5-P-025004

About the Role of Ozone in Air Purification From Vapors of Volatile Organic Compounds by Pulsed Discharges*

Igor E. Filatov, Victor V. Uvarin and Dmitrii L. Kuznetsov

Institute of Electrophysics, Ural Branch of the Russian Academy of Sciences

106 Amundsen Str., 620016, Ekaterinburg, Russia

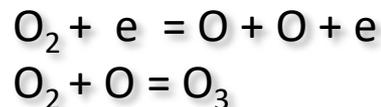
fil@iep.uran.ru

* The work was supported by the Russian Foundation for Basic Research, grants #20-48-660062 and #20-08-00882.

Abstract

- Air purification from vapors of volatile organic compounds by non-equilibrium plasma generated by discharges is always accompanied by the formation of ozone. Ozone is a highly toxic gas, so it is very important to know what part of it goes to destroy impurities, and what is in excess. Organic compounds have a wide variety of reactivity, so ozone reacts with them at different rates.
- Using the method of competing reactions by means of groups of model mixtures, the relative reactivity of compounds of different classes in relation to ozone was estimated. As an example, studies of the effect of a pulsed corona discharge lasting 20-45 ns on air with admixtures of carbonyl, aromatic and unsaturated compounds are presented. It is shown that unsaturated compounds have the highest activity in relation to ozone. This research will be useful for the development of combined plasma-catalytic methods of air purification.

One of the methods of air purification from VOC vapors is methods using non-equilibrium plasma of pulsed discharges [1-3]. The use of non-equilibrium plasma makes it possible to initiate plasma-chemical processes in flows without significant thermal heating. Обработка воздушных потоков неравновесной плазмой всегда сопровождается образованием озона:



Ozone is obtained from atomic oxygen as a result of its deactivation by molecular oxygen in excess. Ozone is a highly toxic gas, so catalysts are used to remove it. The catalysts also allow the products of incomplete VOC conversion to be further oxidized using a catalyst. Therefore, the use of a catalyst in plasma chemical methods has no alternative. This explains the promise of combined plasma-catalytic methods [3-5]. However, the study of non-catalytic methods is also necessary to clarify the main mechanisms of VOC destruction in plasma.

Reactionability of VOCs in relation to ozone

Ozone has a high oxidative capacity and reacts with many compounds, but the rate of interaction is usually not sufficient for the oxidation of products "in real time", in gas flows. Table I shows the rate constants of reactions of ozone with the substance (k_{O_3}), and for comparison, the reaction rate constants with atomic oxygen (k_O) for some characteristic VOCs are also presented. These constants are taken from [6]. In all cases, conditions close to room temperature (298–300 K) were chosen, which is typical for applications of non-equilibrium atmospheric-pressure plasma. Table data show that unsaturated compounds have the highest reactivity, but they also react with a relatively low speed. Thus, in the 3rd column, the half-transformation time is represented for reactions of a substance with equal concentrations of substance $[X_i]$ and ozone $[O_3]$: $[X_i] = [O_3] = 100$ ppm (parts per million), calculated using the formula typical for second-order reactions with equal reagents concentrations: $t_{O_3} = [X_i]^{-1}k_{O_3}^{-1}$. It can be seen that the transformation proceeds at a low speed and this should be taken into account when developing cleaning devices. With atomic oxygen, substances react at a relatively high rate, as can be seen from the values of k_O , but taking into account that the reaction of deactivation of atomic oxygen $O + O_2 + M \rightarrow O_3$ proceeds with the constant $k = 5.51 \cdot 10^{-34} \text{ cm}^6 \cdot \text{s}^{-1}$ [7], taking into account also that $[M] = [O_2] + [N_2] \sim 2.7 \cdot 10^{19} \text{ cm}^{-3}$, $[O_2] \sim 0.5 \cdot 10^{19} \text{ cm}^{-3}$; for the bimolecular process: $k \sim 1.5 \cdot 10^{-14} \text{ cm}^3 \cdot \text{s}^{-1}$. Simple estimates show that for typical $[X_i] \sim 250$ ppm or less, the process of atomic oxygen disposal with the formation of ozone significantly prevails over its reaction with compound X_i .

Table I. Rate constants of VOCs for reaction with ozone [6].

VOC	Reaction parameters for O_3		
	K_{O_3} (298 – 300 K)	K_O	t, s (100 ppm)
Styrene $C_6H_5CH=CH_2$	$1.4 \cdot 10^{-17}$	$2.9 \cdot 10^{-14}$	29
a-methylstyrene $C_6H_5C(CH_3)=CH_2$	$1.5 \cdot 10^{-17}$		27
Acrylonitrile $CH_2=CHCN$	$1.38 \cdot 10^{-19}$	$4.9 \cdot 10^{-13}$	2952
Methylmethacrylate $CH_2=C(CH_3)COOCH_3$	$6.7 \cdot 10^{-18}$		61
Acrolein $CH_2=CHCOH$	$3.63 \cdot 10^{-19}$		1122
Crotonaldehyde $CH_3-CH=CHCOH$	$1.74 \cdot 10^{-18}$	$8.49 \cdot 10^{-13}$	234
Dichloroethylene $CCl_2=CH_2$	$9.01 \cdot 10^{-21}$	$2.9 \cdot 10^{-13}$	$4.5 \cdot 10^4$
Trichloroethylene $CHCl=CCl_2$	$5.0 \cdot 10^{-20}$	$1.4 \cdot 10^{-13}$	8150
Tetrachloroethylene $CCl_2=CCl_2$	$1.0 \cdot 10^{-21}$	$1.94 \cdot 10^{-13}$	$4 \cdot 10^5$
Acetone CH_3COCH_3		$9.83 \cdot 10^{-16}$	
Ethyl acetate $CH_3COOC_2H_5$		$5.78 \cdot 10^{-15}$	
Hexane C_6H_{14}		$1.7 \cdot 10^{-10}$	
Benzene C_6H_6	$1.72 \cdot 10^{-22}$	$3.16 \cdot 10^{-14}$	$2.4 \cdot 10^6$
Toluene $C_6H_5CH_3$	$3.90 \cdot 10^{-22}$	$7.63 \cdot 10^{-14}$	$1 \cdot 10^6$
Orthoxylene $C_6H_4(CH_3)_2$	$5.0 \cdot 10^{-21}$		$8.1 \cdot 10^4$
Chloroform $CHCl_3$	$3.01 \cdot 10^{-20}$		
Dichloroethane CH_2ClCH_2Cl		$2.00 \cdot 10^{-15}$	

Experimental setup for study VOC conversion in pulsed corona discharge plasma



Fig. 1. Appearance of the experimental installation

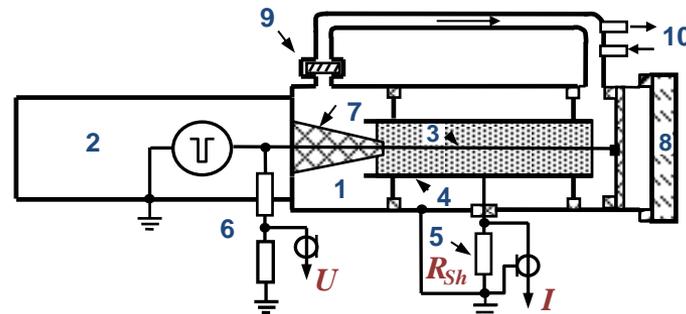


Fig. 2. Functional diagram of the experimental installation.

- 1 – plasma chemical reactor (PCR) chamber; 2 – HV generator;
 3 – potential electrode (cathode); 4 – external electrode (anode);
 5 – shunt; 6 – voltage divider; 7 – insulator; 8 – viewing window;
 9 – fan; 10 – sampling on the metering loop of the chromatograph

Table II. Experimental setup parameters

Parameter	Experimental setup	
	Installation I	Installation II
High voltage generator	SM-4	SM-2
Pulse duration (on 1/2 of pulse height)	20 ns	45 ns
Voltage (amplitude)	105 kV	62 kV
Current (amplitude)	540 A	65 A
Pulse energy	0.5–0.7 J	0.08–0.150 J
Pulse repetition rate	10 Hz	48 Hz

- The experimental setup is described in detail in [8]. The high-voltage pulse generator is built using switches on SOS diodes. The principle of operation of such a generator is well described in [9]. The gas system of the plasma chemical reactor has a volume of 26 dm³. The discharge part consists of a cylinder with a diameter of 85 mm and a length of 56 cm, along the axis of which a potential electrode from a guitar string with a diameter of 0.24 mm is stretched.
- Analysis of the VOC content was performed by gas-chromatographic method. The content of O₃ was estimated by absorption at a wavelength of 255 nm on UV-spectrometer "Specord-200" in a gas quartz cell of 1 cm thick using absorption tables [10].

Participation of ozone in the processes of VOC conversion in air flows under the influence of non equilibrium plasma of electric discharges

The amount of ozone produced per unit of energy consumed when treating clean dry air with a pulse discharge can be a measure of the efficiency of converting electrical energy into chemical energy. When various substances (VOC_s) are added to the air, they affect the ozone concentration in different ways:

- Intercept atomic oxygen, competing with molecular oxygen.
- Directly react with ozone to themselves or their products of transformation.
- Catalyze the decomposition of ozone through their decomposition products.

Research methodology

The experimental method is based on the one described earlier [8,11-13]. In the course of experiments, the concentration dependences of impurities X_i on the energy (specific energy) introduced into the unit volume of gas e were studied. The specific energy E was calculated for a series of pulses using the formula:

$$E = E_p f t / V,$$

where V is the volume of the gas system, $V = 26 \text{ dm}^3$; f - pulse repetition frequency; t - time of the pulse series. The pulse energy was calculated from the waveforms $U(t)$ and $I(t)$ for each pulse series using the formula:
 $E_p = \int U(t) I(t) dt.$

First, an experiment is performed to process a mixture that simulates the composition of air and determine the dependence of component concentration $[X_i]$ on the specific energy E , i.e., energy input per 1 dm^3 of the air mixture. As a rule, at $[\text{O}_3]$ up to 2000 ppm, the dependency is straight and it is convenient to approximate a straight line, from the slope of which it is possible to obtain the plasma chemical yield of ozone G_{O_3} [molecule/100 eV], taking into account the conversion of dimensions: $1 \text{ ppm} \cdot \text{dm}^3 \cdot \text{J}^{-1} = 0.433 \text{ molecule}/100 \text{ eV}$. The G_R value was determined from the slope of concentration dependencies obtained experimentally in the initial region as:

$$G_R \approx \sum_{i=1}^N \Delta[X_i] / \Delta E \text{ at } E = 0.1 E_{\text{max}}.$$

Formal description

The process of removing impurities can be described in a simplified way using the formal kinetics method by a system of equations with an energy trend [13]:

$$\begin{cases} \frac{d[X_i]}{dE} = -k_i[X_i][R] \\ \frac{d[R]}{dE} = G_R - \sum_{i=1}^N k_i[X_i][R] \end{cases}, \quad (1)$$

where $[R]$ is the concentration of the formal reagent, k_i is the required constants, i - the component number, N is the number of components, G_R is the plasma chemical yield of the reagent R .

Since R is the sum of all active reagents involved in removing impurities: $R = \Sigma(R_j)$, where j is the number of selected processes. Suppose that some of these processes occur with the participation of ozone, then, separating them separately, we get: $R = \Sigma(R_{j-1}) + R_{O_3}$. By denoting $R_A = \Sigma(R_{j-1})$ for simplicity, we can estimate the proportion of processes $d_{O_3} = R_{O_3} / (R_{O_3} + R_A)$. The right parts of the system (1) can be rewritten with this assumption, while assuming that $G_R = G_A + G_{O_3}$, where G_{O_3} is the operating time of ozone, and G_A – production of all other active particles. The convenience of this separation is that G_{O_3} can be determined experimentally directly.

Method of competing reactions

The method of competing reactions allows us to obtain relative characteristics with high accuracy and identify the main operating factors of processes. Mixtures of components were used and ozone concentrations were measured:

A. Unsaturated compounds

- 1. Methylmethacrylate+ styrene*
- 2. Styrene+ α -methylstyrene+acrylonitrile*
- 3. Methylmethacrylate+ crotonaldehyde*
- 4. Styrene+ trichloroethylene*

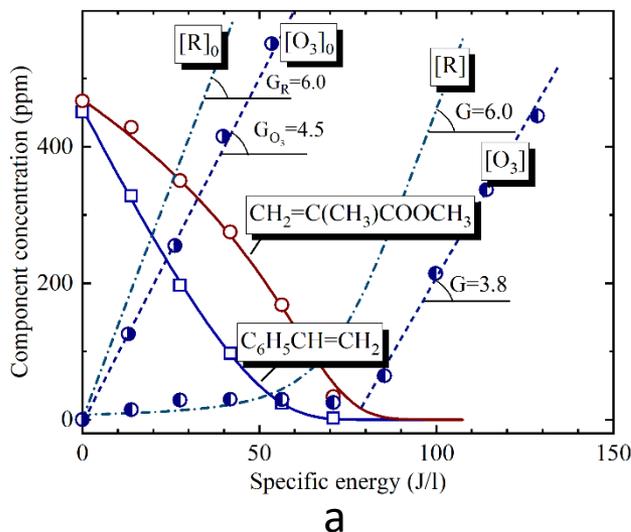
B. Substances with moderate functionality

C. Aromatic compounds

The results of the above combinations of model mixtures are described below.

A. Unsaturated compounds

1. Methylmethacrylate (MMA)+ styrene



2. Styrene + α -methylstyrene+acrylonitrile

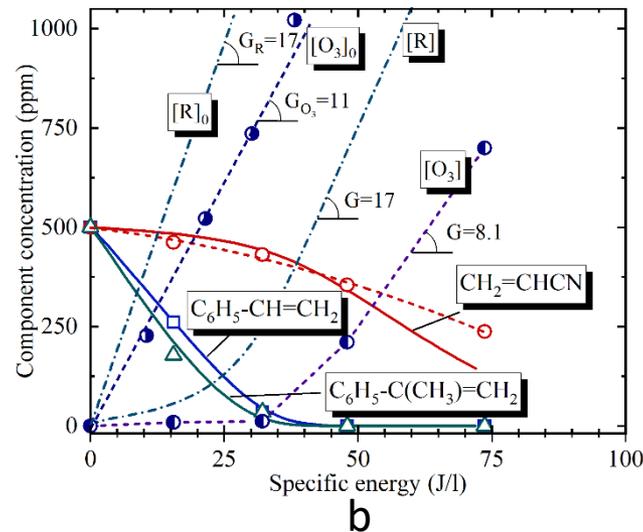


Fig. 3. Impurities concentration $[X_i]$, formal reagent concentration $[R]$ and ozone concentration $[O_3]$ vs specific energy E in air: (a) X_1 = styrene ($C_6H_5CH=CH_2$) and X_2 = methylmethacrylate ($CH_2=C(CH_3)COOCH_3$) with initial concentrations of 450 and 470 ppm, respectively; (b) X_1 = styrene ($C_6H_5CH=CH_2$), X_2 = α -methylstyrene ($C_6H_5C(CH_3)=CH_2$), and X_3 = acrylonitrile ($CH_2=CHCN$). The initial concentrations of all components are 500 ppm. $[R]_0$ and $[O_3]_0$ – concentrations of the formal reagent R and ozone O_3 in pure air, respectively. Markers represent experimental data, solid and dash-dotted lines represent calculated data, and dashed lines represent approximations of experimental data. The slopes of the asymptotes show a plasma chemical yield G , (molecule/100 eV).

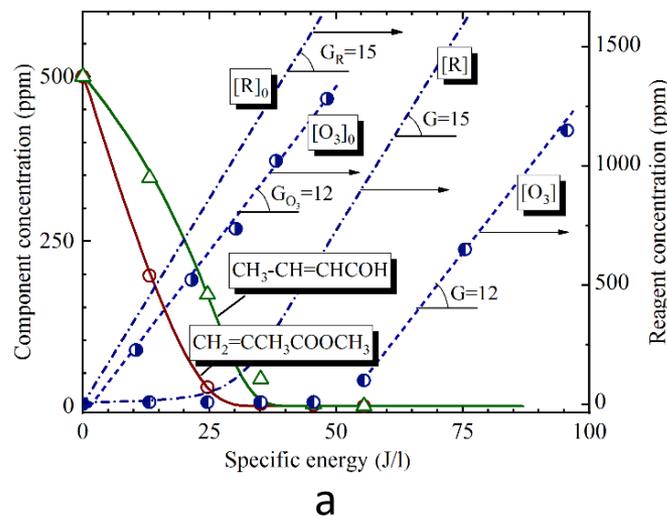
1. *Methylmethacrylate + styrene*

The study of this vapor mixture is described in detail in [13]. The experiment was performed on “Installation 1” (see Table II). In this experiment, a similar pulse generator was used, but the charging voltage in the primary circuit was lower, which led to an increase in the energy efficiency of the process while maintaining the basic laws. The results are shown in Fig. 3a. The yield of the formal reagent $G_R = 6$ molecule/100 eV (hereafter G units will be omitted for simplicity), while $G_{O_3} = 4.5$. Ozone production begins after the unsaturated compounds are removed. Value $G_A = G_R - G_{O_3} = 1.5 > 0$, which means that ozone (or atomic oxygen, as a precursor of ozone), is the main, but not the only, participant in the process of removing impurities. The solution of the inverse kinetic problem for system (1) gives the ratio of constants $k_2/k_1 = 0.40$ for styrene (k_1) and methyl methacrylate (MMA), (k_2), whereas the ratio of constants, according to $k_2/k_1 = 0.47$ (see Table I), which suggests that the processes without the involvement of ozone affect the MMA to a greater extent than styrene.

2. Styrene + α -methylstyrene + acrylonitrile

The results of the study of the mixture of vapors of three compounds on “Installation 2” (see Table II) are shown in Fig. 3b. In this experiment, the discharge voltage is reduced, resulting in a significantly reduced discharge current. This led to a significant increase in the efficiency of using the discharge energy, which can be seen from the high values of the plasma chemical yield $G_{O_3} = 11$ and $G_R = 17$. Value $G_A = G_R - G_{O_3} = 6.0 > 0$, which indicates that ozone is the main, but not the single participant in the process of removing impurities. The solution of the inverse kinetic problem for the system (1) gives the ratio of constants as 1 : 1.3 : 0.05 for styrene, α -methylstyrene, and acrylonitrile, respectively. The ratio of constants, according to Table I: 1 : 1.1 : 0.01. Obviously, in this case, α -methylstyrene, like styrene, quantitatively binds ozone, but α -methylstyrene is removed better than styrene through other channels. For acrylonitrile, interaction with ozone (or its precursor, atomic oxygen) is not the main removal process. In addition, as shown in Fig. 1b by the dashed line, the experimental dependence for acrylonitrile is poorly described by the simplified system of equations (1). Acrylonitrile is removed worse than the system solution predicts, this indicates that one acrylonitrile molecule is removed by more than one conditional molecule of the formal reagent, i.e. the order of the reaction for acrylonitrile in (1) is less than one.

3. Methyl methacrylate+ crotonaldehyde



4. Styrene+ trichloroethylene

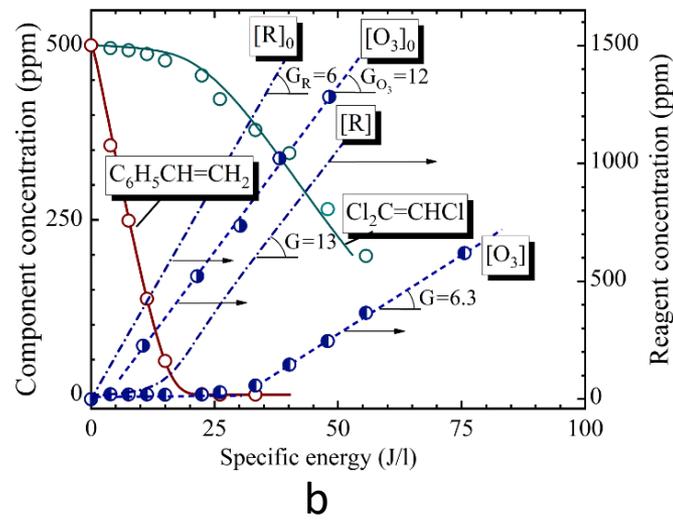


Fig. 4. Impurities concentration $[X_i]$, formal reagent concentration $[R]$ and ozone concentration $[O_3]$ vs specific energy E in air: (a) X_1 = crotonaldehyde ($CH_3H=CHCOH$), X_2 = methyl methacrylate ($CH_2=CCH_3COOCH_3$), and X_3 = acrylonitrile ($CH_2=CHCN$); (b) X_1 = trichloroethylene ($CCl_2=CHCl$) and X_2 = styrene ($C_6H_5CH=CH_2$). The initial concentrations of all impurities components are 500 ppm. $[R]_0$ and $[O_3]_0$ – concentrations of the formal reagent R and ozone O_3 in pure air, respectively. Markers represent experimental data, solid and dash-dotted lines represent calculated data, and dashed lines represent approximations of experimental data. The slopes of the asymptotes show a plasma chemical yield G , (molecule/100 eV).

3. Methylmethacrylate + crotonaldehyde

The experiment was performed on “Installation 2” (see Table II). Figure 4a shows the results of the experiment. Values $G_{O_3} = 12$ and $G_R = 15$. The general patterns are similar to the previous experiment. As in the previous case, $G_A = G_R - G_{O_3} = 3.0 > 0$, which also indicates that ozone is the main, but not the only, participant in the process of removing impurities. The solution of the inverse kinetic problem for the system (1) gives the ratio $k_2/k_1 = 0.38$ for MMA and crotonaldehyde, whereas the ratio of constants $k_2/k_1 = 0.33$ (see Table II), which indicates that processes without ozone affect the crotonaldehyde to a greater extent than the MMA.

4. Styrene + trichloroethylene

The experiment was performed on “Installation 2” (see Table II). Figure 4b shows the results of the experiment. In this case $G_{O_3} = 12$ and $G_R = 16$. Value $G_A = G_R - G_{O_3} = 4.0 > 0$, which also means that ozone is the main, but not the only participant in the process of removing the amount of impurities. The solution of the inverse kinetic problem for the system (1) gives as 1 : 0.01 for styrene and trichloroethylene (TCE), respectively. The ratio of reaction constants with ozone, according to Table I: 1 : 0.0035. For TCE the interaction with ozone (or its precursor, atomic oxygen) is not the main removal process. It should be noted that the plasma chemical yield of ozone ($G = 6.3$ as shown by the dashed line) after removal of styrene is significantly different from G_{O_3} , which may indicate that the decomposition products of TCE catalyze the decomposition of ozone.

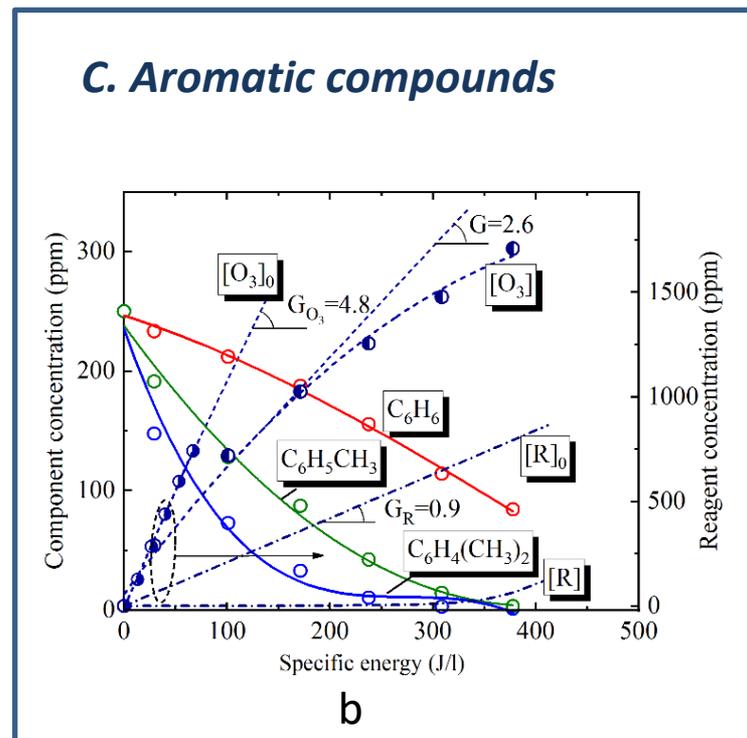
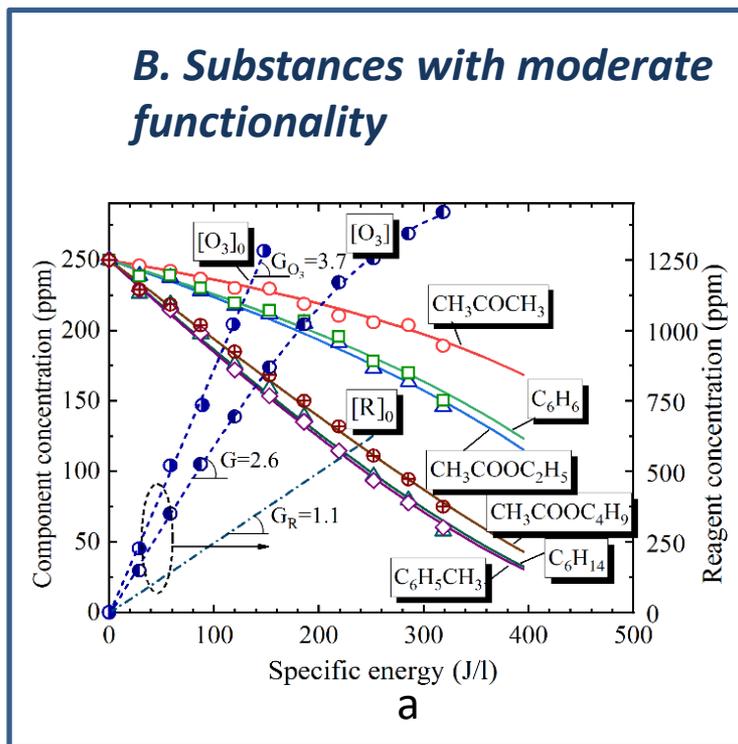


Fig. 5. Impurities concentration $[X_i]$, formal reagent concentration $[R]$ and ozone concentration $[O_3]$ vs specific energy E in air: (a) X_1 = acetone (CH_3COCH_3), X_2 = benzene (C_6H_6), X_3 = ethylacetate ($CH_3COOC_2H_5$), X_4 = butylacetate $CH_3COOC_4H_9$), X_5 = hexane (C_6H_{14}), and X_6 = toluene ($C_6H_5CH_3$); (b) X_1 = benzene (C_6H_6), X_2 = toluene ($C_6H_5CH_3$), X_3 = *o*-xylene ($C_6H_4(CH_3)_2$). The initial concentrations of all impurities components are 250 ppm. $[R]_0$ and $[O_3]_0$ – concentrations of the formal reagent R and ozone O_3 in pure air, respectively. Markers represent experimental data, solid and dash-dotted lines represent calculated data, and dashed lines represent approximations of experimental data. The slopes of the asymptotes show a plasma chemical yield G , (molecule/100 eV).

B. Substances with moderate functionality

These VOCs are widely used as solvents. The standard mixture described in [6, 8] was used for the study using “Installation 1” (see Table II). Figure 6a shows the results of the experiment. It should be noted that the removal of the components of these mixture requires significant energy consumption compared to unsaturated compounds, as can be seen from the small value $G_R = 1.1$, with $G_{O_3} = 3.7$. This may indicate that processes involving ozone and its precursors (such as atomic oxygen) are not the main processes leading to the removal of impurities. According to the Table I, the rate constants of ozone with this compounds ions are extremely insignificant. However, it should be noted that the plasma chemical yield of ozone during the experiment is significantly reduced: from the values of $G_{O_3} = 3.7$ to $G_{O_3} = 1.2$ or less. This is probably due to the participation of products of conversion of components in reactions with ozone. The solution of the inverse kinetic problem gives the ratio of reactivity relative to toluene: 0.17 : 0.32 : 0.37 : 0.80 : 0.95 : 1.0 for acetone, benzene, ethylacetate, butylacetate, hexane and toluene, respectively, are in good agreement with the solution of the inverse kinetic problem using equations (1), as evidenced by the lines.

C. Aromatic compounds

Aromatic compounds are products of coking plants, valuable chemical raw materials and are highly toxic. In this experiment, a mixture of three aromatic compounds was studied: benzene, toluene, and *o*-xylene. The experiment was performed on “Installation 1” (see Table II). Figure 5b shows the results of the experiment. In this experiment, two components were deliberately used from the previous mixture-toluene and benzene, and *o*-xylene was added to them. It should be noted that the solution of the inverse kinetic problem did not give acceptable results, so the lines in Fig. 3b denotes one of the most suitable extrapolations by a polynomial. In this case, also $G_{O_3} = 4.8$ and $G_R = 0.9$; $G_A = G_R - G_{O_3} = -3.9$, which indicates that processes involving ozone and its precursors (as atomic oxygen) are not the main processes leading to the removal of impurities and during processing, ozone is produced. As in the previous case, a significant part of the ozone appears to be spent on the oxidation of incomplete conversion products. The ratio of relative reactivity of toluene relative to: 0.30 : 1.0 : 1.86 for benzene, toluene and xylene, respectively. It is very important to note that the relative reactivity of benzene here is very close to the value obtained by a mixture of moderate functionality compounds (0.32), which confirms the effectiveness of using the method of competing reactions to increase the information content of experiments.

CONCLUSIONS

- The method of competing reactions with the use of model mixtures allows us to effectively identify the role of ozone as one of the main actors in air purification processes using non-equilibrium plasma of pulsed discharges. A method for estimating the degree of ozone participation is proposed, based on a comparison of plasma chemical outputs of ozone and a formal reagent.
- It is shown that in the removal of such unsaturated compounds as styrene, MMA, crotonaldehyde and α -methylstyrene, ozone is the main participant in the removal processes. In the removal of acrylonitrile, ozone and its precursor (atomic oxygen) play a minor role, which explains the relatively high energy consumption for removal. In the removal of trichloroethylene, ozone does not play an important role; its removal is mainly due to the reaction with other components of the discharge plasma. In this case, the products of incomplete conversion of trichloroethylene participate in the decomposition of ozone.
- In the removal of many compounds with moderate reactivity, such as ketones, esters and aromatics, ozone precursors and ozone play a minor role. This explains the high energy intensity of their removal. In this case, incomplete conversion products interact with ozone and / or its precursors, resulting in a significant portion of the resulting ozone being neutralized by the decomposition products of the compounds.
- The proposed method of model mixtures, based on the method of competing reactions, allows us to effectively assess the ozone yield in the process of plasma chemical air purification, which is very important for optimizing the catalytic stage of plasma-catalytic air purification methods.

References

- [1] J. Schnelle, R. Dunn, M. Ternes, R. F. Dunn, and M. E. Ternes, *Air Pollution Control Technology Handbook*, Second Edition. CRC Press, 2015.
- [2] A. M. Vandembroucke, R. Morent, N. De Geyter, and C. Leys, “Non-thermal plasmas for non-catalytic and catalytic VOC abatement,” *J. Hazard. Mater.*, vol. 195, pp. 30–54, Nov. 2011.
- [3] G. Xiao et al., “Non-Thermal Plasmas for VOCs Abatement,” *Plasma Chem. Plasma Process.*, vol. 34, no. 5, pp. 1033–1065, Sep. 2014.
- [4] W. C. Chung, D. H. Mei, X. Tu, and M. B. Chang, “Removal of VOCs from gas streams via plasma and catalysis,” *Catalysis Reviews - Science and Engineering*, vol. 61, no. 2. Taylor and Francis Inc., pp. 270–331, 03-Apr-2019.
- [5] S. Ojala et al., “*Catalysis in VOC abatement*,” *Top. Catal.*, vol. 54, no. 16–18, pp. 1224–1256, 2011.
- [6] <https://kinetics.nist.gov/kinetics/>
- [7] Hippler, H., Rahn, R. & Troe, J. Temperature and pressure dependence of ozone formation rates in the range 1-1000 bar and 90-370 K. *J. Chem. Phys.* 93, 6560–6569 (1990).
- [8] I. E. Filatov, V. V. Uvarin, and D. L. Kuznetsov, “Estimation of Qualitative and Quantitative Parameters of Air Cleaning by a Pulsed Corona Discharge Using Multicomponent Standard Mixtures,” *Tech. Phys.*, vol. 63, no. 5, pp. 680–688, 2018.
- [9] S. N. Rukin, “Pulsed power technology based on semiconductor opening switches: A review,” *Review of Scientific Instruments*, vol. 91, no. 1. American Institute of Physics Inc., p. 011501, 01-Jan-2020.
- [10] L. T. Molina and M. J. Molina, “Absolute absorption cross sections of ozone in the 185- to 350-nm wavelength range,” *J. Geophys. Res.*, vol. 91, no. D13, p. 14501, Dec. 1986.
- [11] I. E. Filatov, V. V. Uvarin, and D. L. Kuznetsov, “Application of standard mixtures for the estimation of characteristics of non-equilibrium plasma of atmospheric pressure pulsed discharges,” *J. Phys. Conf. Ser.*, vol. 1147, no. 1, p. 012122, Jan. 2019.
- [12] I. E. Filatov, V. V. Uvarin, and D. L. Kuznetsov, “Cleaning air from multicomponent impurities of volatile organic compounds by pulsed corona discharge,” *Tech. Phys. Lett.*, vol. 42, no. 9, pp. 927–931, Sep. 2016.
- [13] I. E. Filatov, V. V. Uvarin, and D. L. Kuznetsov, “The Use of Competitive Reactions for Studying the Process of Unsaturated Organic Compound Vapor Removal from Air by Pulsed Discharge Plasma,” *Tech. Phys. Lett.*, vol. 46, no. 1, pp. 94–97, Jan. 2020. vol. 91, no. 1. American Institute of Physics Inc., p. 011501, 01-Jan-2020.