UDC 541.127:547.689

Antioxidant Properties of Nitrogen-containing Derivatives of Polysubstituted Fullerene C_{60}

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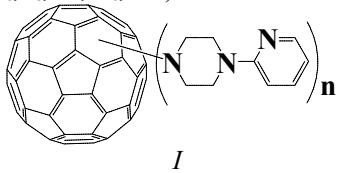
The phenomenon of catalytic termination oxidation chains by exomodified fullerenes with nitrogen-containing heterocyclic substituents in the model reaction of initiated oxidation of benzyl alcohol was revealed. The rate constants and stoichiometric factors of chain termination in the oxidation of benzyl alcohol have been determined.

Fullerenes and their derivatives are interesting for both fundamental and applied science because of their versatility. The study of these compounds in recent 20 years has demonstrated the huge potential of their application in various fields of science, medicine and technology [1, 2].

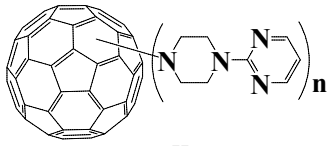
One of the most valuable area of scientific investigation is the search for compounds with high antioxidant activity. Previously, we have studied the antioxidant and anti tear properties of the free fullerene C_{60} and its polyhalogenated derivatives [3].

In this paper, the group of novel modified fullerenes based on C_{60} and 1-(2-pyridyl)piperazine or 2-(1-piperazinyl)pyrimidine obtained from addition of different quantities of nitrogen-containing heterocyclic substituents has been studied. Exohedral fullerenes are differ on their structure and the amount of nitrogen-containing groups added to it (I_6, I_8, I_{14}, II_6, II_{12}):



, n = 6, 8, 14

I



, n = 6, 12.

II

The aim of this work is a study of free radical oxidation of benzyl alcohol in the presence of exohedral nitrogen-containing fullerenes in order to determine relations between their structure and antioxidant activity.

Experimental

Volumetric determination of antioxidant activity of nitrogen-containing derivatives of fullerene C_{60} was performed on the model reaction of radical chain initiated oxidation of benzyl alcohol (BA) under experimental conditions (50 ± 0,2 °C and the rate of initiation W_i = 2,98 10^{-8} mol/l·s) in the kinetic mode of oxidation [4] on the gasometrical device. It allows to measure the rate of oxygen absorption W from 10^{-8} to 10^{-4} mol/(l·s) and conversion of substrate oxidation of 0,1–1,0 % under the kinetic mode of oxidation. Standard deviation of measurements is 3–5 % [5].

Benzyl alcohol "pure" quality was dried over calcinated K_2CO_3 (during 24 h). It was distilled with Ferum (III) acetylacetonate in an argon atmosphere for removing peroxides. Fraction which boils at 73–74 °C/0,6 kPa was used.

The distillate was passed through the chromatography column (column height 70 cm, diameter 2,0–2,5 cm) with activated charcoal and aluminum oxide with subsequent vacuum distillation in an argon atmosphere. The experimental achievement of a permanent, close to the described in the literature value of the oxidation parameter $k_2/k_6^{1/2}$ (k_2 and k_6 – the rate constant of propagation and quadratic termination of oxidation chains of BA) was accepted as the purity criterion of BA [6, 7].

2,2'-Azo-*bis*-isobutyronitrile (AIBN) "pure" quality (Merck, Germany) was selected as the initiator of the oxidative processes. AIBN was purified by crystallization from ethanol (saturated solution temperature is 35°C). Melting point is 105–106 °C (decomposes), which corresponds to the literature data.

Chlorobenzene (Merck, Germany) was used as inert solvent for oxidation. Dehydration and purification of chlorobenzene were fulfilled as described [8].

The constant of initiation rate (k_i, s^{-1}) was calculated according to equation [9]:

$\lg k_i = 16{,}9 - 33\,500/4{,}57T$.

The commercial samples of fullerene C_{60} received from Hoechst (Germany) with a purity > 99,4 % (wt%) were used.

Samples of nitrogen-containing fullerenes I_6, I_8, I_{14}, II_6, II_{12} were synthesized at the Institute of Problems of Chemical Physics of Russian Academy of Sciences, and they were described in the paper [10].

Results and Discussion

It is known that two types of free radicals: alkyl $C_6H_5C^{\bullet}HOH$ ($R^{\bullet}$) and peroxyl $C_6H_5CH(OO^{\bullet})OH$ ($ROO^{\bullet}$) are formed and taken part in elementary stages in the oxidation of benzyl alcohol. The chain mechanism of oxidation reactions was studied in detail [6, 7].

$\text{Initiator} \rightarrow 2R^{\bullet}$	chain initiation	(*i*)
$RH + O_2 \rightarrow R^{\bullet} + HOO^{\bullet}$		
$2RH + O_2 \rightarrow 2R^{\bullet} + H_2O_2$		
$RH + 2O_2 \rightarrow 2HOO^{\bullet} + >C=C<$		
$R^{\bullet} + O_2 \rightarrow ROO^{\bullet}$	chain propagation	(1)
$ROO^{\bullet} + RH \rightarrow ROOH + R^{\bullet}$		(2)
$ROOH \rightarrow RO^{\bullet} + HO^{\bullet}$	degenerate chain branching	(3)
$ROOH + R'H \rightarrow RO^{\bullet} + R'^{\bullet} + H_2O$		
$2\,ROOH \rightarrow ROO^{\bullet} + H_2O + RO^{\bullet}$		
$ROOH + >C=C< \leftrightarrow RO^{\bullet} + >C(OH)-C<$		
$ROOH + >C=O \rightarrow$ Free radicals		
$R^{\bullet} + R^{\bullet} \rightarrow R-R$	chain termination	(4)
$R^{\bullet} + ROO^{\bullet} \rightarrow ROOR$		(5)
$RO_2^{\bullet} + RO_2^{\bullet} \rightarrow ROH + R'COR'' + O_2$		(6)
$ROO^{\bullet} + InH \rightarrow ROOH + In^{\bullet}$	chain termination by inhibitor with peroxyl radical	(7)
$R^{\bullet} + InH \rightarrow RH + In^{\bullet}$	chain termination by inhibitor with alkyl radical	(8)

Investigated nitrogen-containing fullerenes inhibit auto- and initiated (Fig. 1, *a*) oxidation of the BA at partial pressures of oxygen P_{O_2} = 0,02–0,10 MPa.

Earlier we have defined stoichiometric factor of inhibition (*f*) in the oxidation of BA by fullerene C_{60}. It shows how many radicals react with an inhibitor molecule and products of its transformation until the oxidation process reaches the uninhibited state [11]. Stoichiometric factor of chain termination in the oxidation of benzyl alcohol for fullerene C_{60} is close to two. It agrees with the process of radical polyaddition to fullerene, i.e. the process stops on the formation of dialkyl- and diperoxylfullerens. Halogenated derivatives of fullerene C_{60} (fluorinated, chlorinated, brominated) also stoichiometrically inhibit auto- and initiated oxidation of organic substrates (benzyl alcohol, hexamethylphosphoramide, methyl oleate, oils, biodiesel) [12, 13].

Stoichiometric factor of chain termination in the oxidation of BA in the presence of exohedral nitrogen-containing fullerenes (Full) is described below:

$$f = \tau W_i / [\text{Full}]_0 >> 16,$$

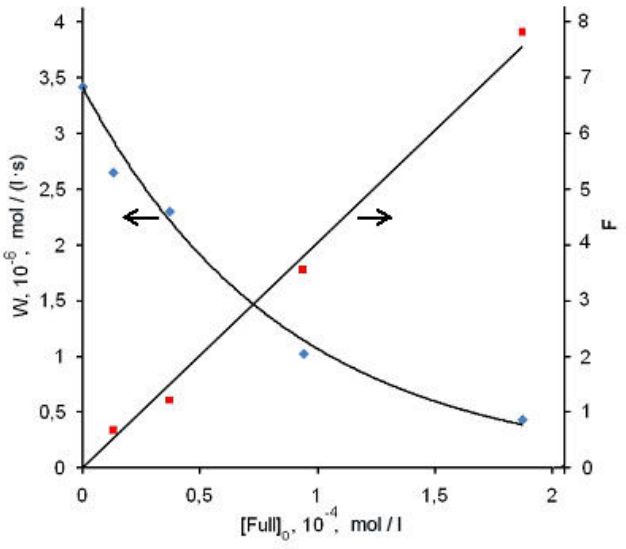
wherein τ – the induction period; W_i – free radicals generation rate by thermal decomposition of 2,2'-azo-*bis*-isobutyronitrile.

Studied fullerenes reveal the new and unique (for fullerenes) ability – catalytic (multiple) inhibition oxidation chains of BA.

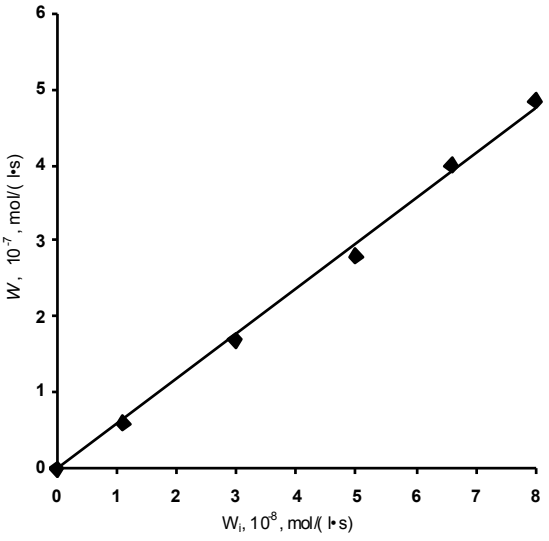
It was found that the initial rate in the inhibited oxidation of BA is inversely proportional to the concentration of fullerenes (Fig. 1, *a*, fullerene I_{14}) and it is in direct ratio to the rate of oxidation chains initiation (Fig. 1, *b*). Although, the rate dependence in the inhibited oxidation of BA (W) on the partial pressure of oxygen (P_{O_2}) is associated with the chemical structure of exomodified nitrogen-containing fullerenes.

The oxidation rate W does not depend on the partial pressure of oxygen in the range of 0,02–0,10 MPa with adding fullerenes I_8 or I_{14} into oxidizable BA. The obtained kinetic regularities showed that fullerenes I_8 and I_{14} take part in the catalytic chain termination in the oxidation with peroxyl ($ROO^{\bullet}$), instead of alkyl ($R^{\bullet}$) radicals.

The antioxidant activity of inhibitors is characterized by their effective rate constant of interaction with peroxyl radi-



a



b

Fig. 1. *a* – Dependence of benzyl alcohol oxidation rate W (1) and parameter F (2) on the initial concentrations of fullerene I_{14}; *b* – the dependence of benzyl alcohol oxidation rate W on the initiation rate of free radicals W_i at $[I_{14}]_0 = 2{,}8 \cdot 10^{-4}$ mol/l

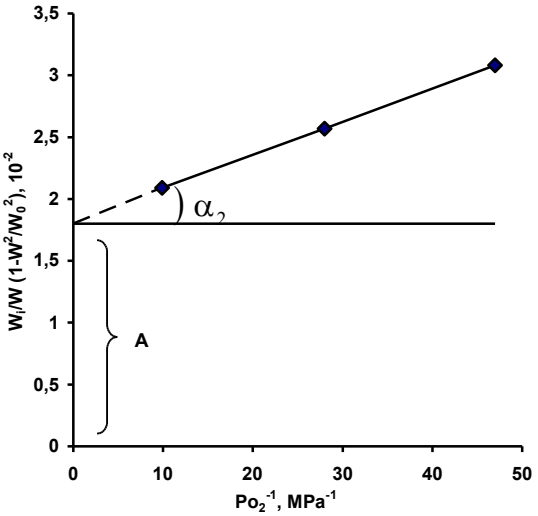


Fig. 2. Dependence of parameter $W_i / W\,(1-W^2/W_0^2)$ on $P_{O_2}^{-1}$ (oxidation of benzyl alcohol inhibited by fullerene $[I_6] = 1{,}18\cdot10^{-4}$ mol/l)

cals k_7 [5, 9]. It should consider the detail calculation of the rate constant for chains termination of BA inhibited oxidation k_7 with fullerene I_{14} as an example. The BA oxidation rate reaches its limiting value $W_\infty = 0{,}17\cdot10^{-4}$ mol/(l·s) with increasing of initial concentrations $[I_{14}]$ to $2{,}8\cdot10^{-4}$ mol/l. The chain length of the stabilized oxidation is $\nu = W_\infty/W_i = 5{,}7$ under these conditions.

k_7 values were calculated according to equation [9]:

$$k_7 = (W_0\cdot W^{-1} - W\cdot W_0^{-1})\cdot (W_i\, k_6)^{1/2}/f\,[I_{14}].$$

Experimentally, the value of k_7 can be obtained from the dependence of the parameter F (the degree of the braking effect of the inhibitor $W_0\cdot W^{-1} - W\cdot W_0^{-1}$) on the initial concentration of fullerene $[I_{14}]$ (Fig. 1, *a*) [5, 9]:

$$W_0\cdot W^{-1} - W\cdot W_0^{-1} = \frac{fk_7[I_{14}]_0}{\sqrt{W_i k_6}}$$

The rate of BA oxidation (W_0) is equal to $3{,}42\cdot10^{-6}$ mol/(l·s) in the absence of inhibitor.

According to the plot (Fig. 1, *a*), it was defined the slope ratio of straight line 2 for coordinates $[I_{14}]$–F

$$\mathrm{tg}\alpha_1 = \frac{F}{[I_{14}]_0}.$$

The value $k_7 = 2{,}78\cdot10^3$ l/(mol·s) could be determined under the rate of initiation $W_i = 2{,}98\cdot10^{-8}$ mol/(l·s), the constant value $k_6 = 2{,}8\cdot10^7$ l/(mol·s) [6, 7], $\mathrm{tg}\,\alpha_1 = 4\cdot10^4$ l/mol and stoichiometric factor $f = 16$.

The rate of BA oxidation (W) inhibited by fullerenes I_6, I_{16}, II_{12} decreases symbatically with decreasing of oxygen partial pressure in the range from 0,10 to 0,02 MPa. The rate of uninhibited BA oxidation (W_0) is not depend on P_{O_2} for the same experimental conditions. Such patterns are unique kinetic test, which indicates the participation of fullerene in chain termination in the BA oxidation simultaneously with alkyl $R^\bullet$ and peroxyl $ROO^\bullet$ radicals [4, 9], and they are described by the equation (for example, choose a fullerene I_6) [12]:

$$W_i/W\left(1 - W^2/W_0^2\right) = A + BPo_2^{-1},$$

wherein $A = \dfrac{fk_7[I_6]_0}{k_2[BA]}$, $B = \dfrac{fk_8[I_6]_0}{k_1\gamma}$,

Henry coefficient $\gamma = [O_2]/Po_2$.

The dependences of the parameter $W_i/W(1-W^2/W_0^2)$ on $P_{O_2}^{-1}$ were plotted (Fig. 2) based on experimental data. Taking into account values $A = 1{,}8\cdot10^{-2}$, $[I_6]_0 = 1{,}18\cdot10^{-4}$ mol/l, $[BA]_0 = 9{,}64$ mol/l, $k_2 = 6{,}6$ l/(mol·s) and $f = 16$ the rate constant of fullerene I_6 interaction with peroxyl radicals was determined as $k_7 = 0{,}61\cdot10^3$ l/(mol·s).

Taking into account values of $B = \mathrm{tg}\,\alpha_2 = 2{,}7\cdot10^{-3}$ (Fig. 2), $[I_6]_0$, Henry coefficient $\gamma = (10{,}86 \pm 0{,}8)\cdot10^{-2}$ mol/(l·MPa) [14] and $f = 16$ the parameter $k_8/k_1 = 0{,}114$ could be determined.

Taking into account estimated on the known methodology [14] $k_1 = (7{,}9 \pm 0{,}6)\cdot10^8$ l/(mol·s), the rate constant of the interaction of fullerene I_6 with alkyl radicals has been calculated as $k_8 = 0{,}11\cdot10^7$ l/(mol·s).

The percentage ratio of oxidation chain termination on inhibitor with peroxyl radicals (β) was determined by equation [15]:

$$\beta = \frac{k_7[ROO^\bullet]}{k_7[ROO^\bullet] + k_8[R^\bullet]} = \frac{A}{A + BPo_2^{-1}}.$$

For fullerene I_6 it were β = 87 % (at 0,1 MPa) and 58,3 % (at 0,02 MPa).

The rate constants of chain termination in the BA oxidation by exomodified nitrogen-containing fullerenes for comparison with the best known scavengers of free alkyl and peroxyl radicals are presented in the table.

Among the investigated nitrogen-containing fullerenes series sample II_{12} has revealed the highest antioxidant efficiency at the interaction with the alkyl radicals, achieving

The rate constants of chains termination of benzyl alcohol oxidation by exomodified nitrogen-containing fullerenes and percentage (β)

Fullerene	$k_{ROO^\bullet}\cdot10^2$, l/(mol·s)	$k_{R^\bullet}\cdot10^7$, l/(mol·s)	β, %	
			0,1 MPa O_2	0,02 MPa O_2
C_{60}	1,4*	1,3*	23,4	6
I_6	6,1	0,11	87	58,3
I_8	10	–	–	–
I_{14}	27,8	–	–	–
II_6	6,18	0,064	91,7	71,8
II_{12}	4,25	0,6	47,1	15,7
1-(2-pyridyl)piperazine	4,74	0,15	–	–
2-(1-piperazinyl)pyrimidine	24,8	–	–	–
2,6-di-*tret*-butyl-4-methylphenol (Ionol)	130	–	–	–
Stable nitroxides 2,2',6,6'-tetra-methylpiperidine series	–	0,8–2	–	–

* – $[C_6H_5CH_2OH]_0 = 4{,}82$ mol/l in chlorobenzene

the best antioxidants – stable nitroxyl radicals of 2,2',6,6'-tetramethylpiperidine series [15].

It was found that exohedral nitrogen-containing fullerenes interact less actively with peroxyl radicals (k_7), than well-known industrial scavenger of peroxyl radicals 2,6-di-*tert*-butyl-4-methylphenol (Ionol), but unlike Ionol they actively interact with alkyl radicals (k_8).

For all examined fullerenes the observed time of termination effect is many times greater than the induction period, calculated on the basis of assumption that the test substances are once consumed in the BA oxidation.

This can lead to prolonged inhibition in the oxidation processes of organic compounds that is important for the application of these compounds as components and compounds to prevent early oxidation or aging of fuels, lubricants and industrial organic products.

Possible peculiarities of chain termination catalysis in oxidation probably could be clarified by the detailed mechanisms of chemical reactions involving nitrogen-containing exohedral derivatives of fullerene C_{60}, which yet have to be explored.

Thus, according to the research results it can be suggested that there is a new field of application of nitrogen-containing fullerenes as catalytic inhibitors of the chain termination in oxidation of organic substrates.

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Was received to the editorial office 03.12.2013.

Антиокиснювальні властивості полізаміщених азотвмісних похідних фулерену C_{60}

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Виявлено явище каталітичного обриву ланцюгів окиснення екзомодифікованими фулеренами з азотвмісними гетероциклічними замісниками в модельній реакції ініційованого окиснення бензилового спирту. Визначено константи швидкості та стехіометричні коефіцієнти обриву ланцюгів окиснення бензилового спирту.

Антиокислительные свойства полизамещенных азотсодержащих производных фуллерена C_{60}

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Обнаружено явление каталитического обрыва цепей окисления экзомодифицированными фуллеренами с азотсодержащими гетероциклическими заместителями в модельной реакции инициированного окисления бензилового спирта. Определены константы скорости и стехиометрические коэффициенты обрыва цепей окисления бензилового спирта.