FORECASTING OF CATALYTIC ACTIVITY OF PHTHALIMIDE COMPOUNDS IN THE PROCESS OF LIQUID-PHASE AEROBIC OXIDATION OF ALKYLAROMATIC HYDROCARBONS

V. S. Kabanova[1], E. A. Kurganova[1], A. S. Frolov[1], V. V. Plakhtinsky[1], V. A. Shakun[2]

Victoria S. Kabanova, Postgraduate Student; **Ekaterina A. Kurganova**, Doctor of Chemical Sciences, Professor; **Alexander S. Frolov**, Candidate of Chemical Sciences, Associate Professor; **Vladimir V. Plakhtinsky**, Doctor of Chemical Sciences, Professor; **Vladimir A. Shakun**, Candidate of Chemical Sciences, Associate Professor.

[1]Yaroslavl State Technical University, Yaroslavl, Russia, *kabanovavs@ystu.ru*
[2]Samara State Technical University, Samara, Russia, *shakyh@mail.ru*

Abstract. *The authors calculated the single occupied molecular orbital energies of the substrate radical and the phthalimide catalyst radical by the Hartree-Fock quantum chemical method (PM7). According to the research, low numerical values of ΔE_{SOMO} characterise N-hydroxyphthalimide derivatives containing electron-donating substituents in their structure and possess high catalytic activity. Application of such compounds allows ones to intensify essentially the process of alkylaromatic hydrocarbons aerobic liquid-phase oxidation with preservation of feedstock conversion high parameters and selectivity of its hydroperoxide formation. The calculated data are in good agreement with the experimentally obtained data. Hence, the proposed method can be used to evaluate the catalytic activity of phthalimide compounds with respect to a wide range of aromatic hydrocarbons.*

Introduction

Aerobic liquid-phase oxidation of alkylaromatic hydrocarbons is a key stage of "Cumene" technology for the production of phenol and its alkyl derivatives with various ketones [1, 2]: "Halcon-process" for the joint synthesis of propylene oxide and styrene [3, 4], oxidative transformations of cyclohexane into valuable products [5, 6], and a number of other processes for the production of multi-purpose oxygen-containing organic compounds.
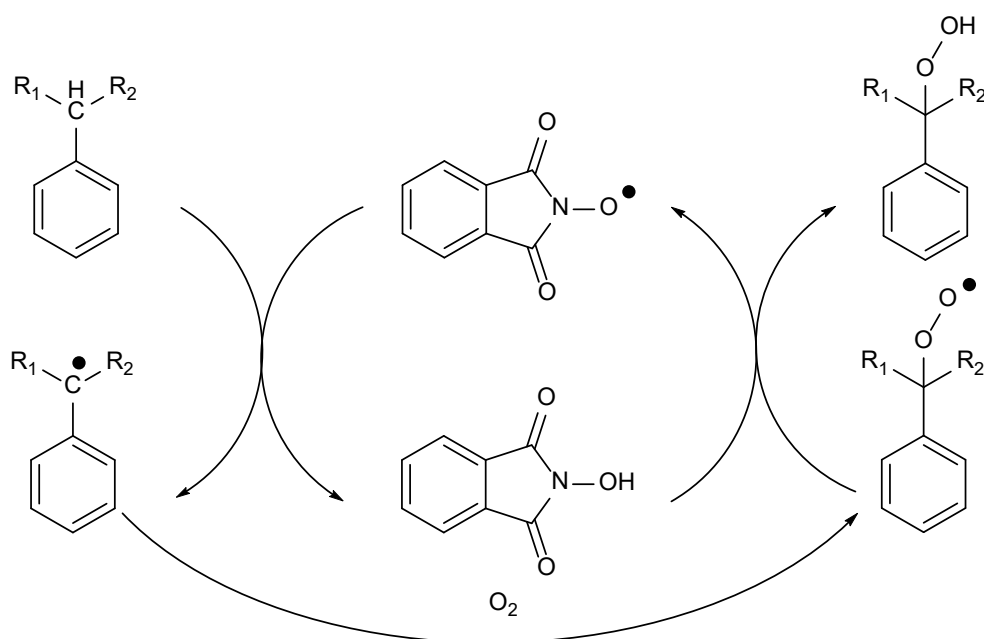
The oxidation of aromatic hydrocarbons to the corresponding hydroperoxides or acids in industry is conducted under the presence of metal salts of variable valence such as cobalt, manganese, copper, nickel, etc. [7]. The main disadvantage of these catalytic systems using is their low efficiency. It associated primarily with a slight increase in the process rate compared

to oxidation, when the initiators of the reaction are hydroperoxides or other additives, such as azobisisobutyronitrile (AIBN). Moreover, the use of metal salts in large amounts tends to cause premature decomposition of the target reaction products. It reduces the selectivity of the process [8].

To eliminate these disadvantages, scientists [9-11] proposed the use of the currently promising technology of organic catalysis. In recent years, *N*-hydroxyphthalimide (NHPI) has attracted much attention because of its nontoxicity, ease of preparation by phthalic anhydride and hydroxylamine, and high activity towards various types of organic substrates [12, 13]. Therefore, the use of this compound as a catalyst allows ones to increase the conversion of oxidised hydrocarbon by 2-3 times with selectivity of its hydroperoxide formation over 90% [2, 14].

Intensification of the process becomes possible due to the involvement of *N*-hydroxyphthalimide in the chain of free-radical transformations of the initial hydrocarbon. As a result of H atom detachment, the O-H bond in the NHPI molecule is cleaved to form *N*-oxyphthalimide radical (PINO). It exhibits electrophilic character and can again transform into the NHPI molecule, forming a hydrocarbon radical. When interacting with molecular oxygen, generates a hydroperoxide radical that initiates a chain reaction and completes the process of hydrocarbons catalytic oxidation (Fig. 1).

Fig. 1. Scheme of aromatic hydrocarbons catalytic oxidation in the presence of *N*-hydroxyphthalimide

However, the obstacle restraining its application in these processes is the limited solubility of NHPI in hydrocarbons, despite the high efficiency of *N*-hydroxyphthalimide in the oxidation reaction of alkylaromatic hydrocarbons. Therefore, scientists have been synthesising derivatives of *N*-hydroxyphthalimide with greater solubility.

The present paper considers the prospects of using *N*-hydroxyphthalimide and its derivatives in aerobic liquid-phase oxidation of alkylaromatic hydrocarbons to their hydroperoxides. According to available information in the scientific and technical literature [2, 15], these compounds have a certain efficiency with respect to oxidative transformations of

hydrocarbons. Determination of their catalytic activity and feasibility of their use in the studied processes was conducted using quantum-chemical calculations.

Main body

The starting substances used in this work were: isopropylbenzene (cumene) by Alfa Aesar; 4-isopropyl-*o*-xylene, purity not less than 99% according to gas-liquid chromatography, obtained according to the method [15]; *p-tret*-butylcumene, purity not less than 99%, obtained according to the method [16]; *sec*-butylbenzene, content of the main substance 99.3% [17], and *N*-hydroxyphthalimide [18] and its derivatives synthesised at the Yaroslavl State Technical University, Yaroslavl, Russia.

According to the method [19], we conducted the aerobic liquid-phase oxidation of hydrocarbons in a flow-closed-type unit in a glass reactor with a volume of 10 cm^3 at atmospheric pressure (Fig. 2). We put the calculated amount of hydrocarbon and catalyst into the reactor at a given temperature, supplied oxygen and conducted the process under continuous stirring. The advantages of such an installation are the use of small amounts of initial hydrocarbon, the implementation of the process in kinetic mode, the ability to measure the amount of oxygen absorbed during the reaction. We analysed the oxidate at the end of the reaction by iodometric titration [20] for its tertiary hydroperoxide content of the corresponding hydrocarbon.
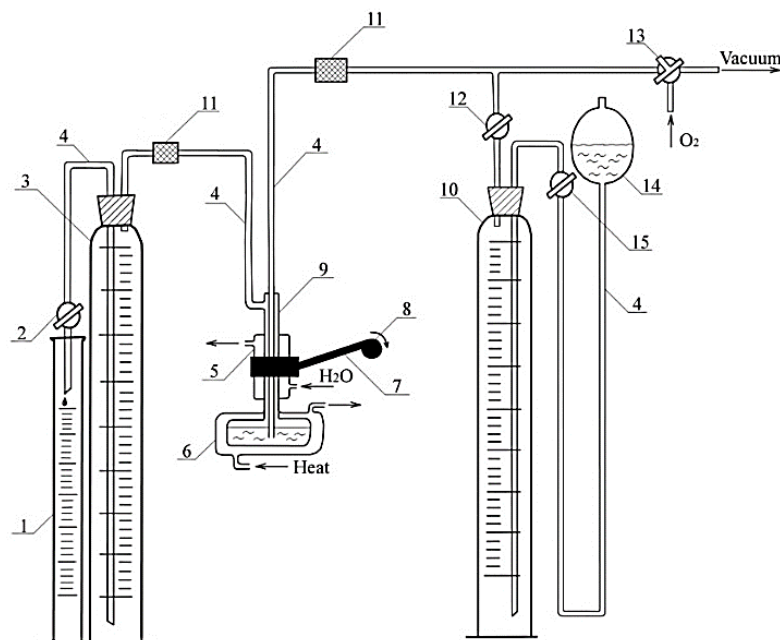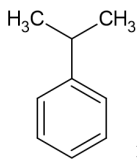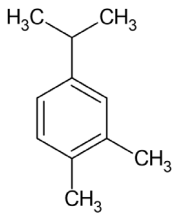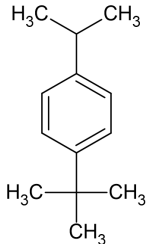

Fig. 2. Schematic diagram of the unit for liquid-phase aerobic oxidation of alkylaromatic hydrocarbons:
1 - measuring cylinder; 2, 12, 15 - taps; 3, 10 - gas burettes; 4 - connecting hose; 5 - reactor holder; 6 - reactor;
7 - electric motor pulley; 8 - connecting rod; 9 – reflux condenser; 11 - chlorocalcium tube; 13 - three-way tap;
14 - pressure vial

However, to determine the catalytic efficiency of *N*-hydroxyphthalimide and some of its derivatives (*N,N*-dihydroxypyromellitimide, *N*-hydroxyphthalonimide, etc.) in hydrocarbon oxidation processes, researchers have proposed the calculation of Gibbs free energy, enthalpy of reactants, transition states and reaction products [21, 22], as well as the strength of the NO-H bond in the NHPI molecule [23]. Moreover, the activity of the catalyst decreases with increasing NO-H bond strength. As an alternative, the present study proposes a method for evaluating the catalytic activity of phthalimide compounds by calculating the energy of singly occupied molecular orbitals (SOMO). We conducted quantum-chemical calculations using the MOPAC 2016 software package [24]. We optimised the geometry of molecules and their radicals using the quantum chemical method PM7 (semi-empirical unconstrained Hartree-Fock method).

Initially, the proposed method of quantum-chemical calculation of the catalytic activity of *N*-hydroxyphthalimide and its derivatives was applied to study the oxidative capacity of cumene, 4-isopropyl-*o*-xylene, and *p-tret*-butylcumene. The following experimental data were obtained as a result of studying some technological parameters on the mentioned hydrocarbons oxidation process (Table 1).
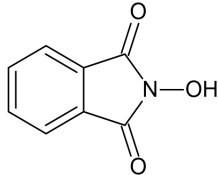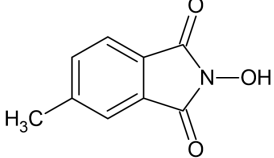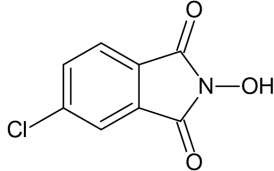
Table 1. Study results of isopropylbenzene, 4-isopropyl-*o*-xylene, and *p-tret*-butylcumene regularities of the oxidation process in the presence of *N*-hydroxyphthalimide and its derivatives. Temperature is 120 °C. Catalyst content is 2% wt. of hydrocarbon charge

Hydrocarbon and its structure	Catalyst	Time, min	The HP content in the reaction products, % wt.
Isopropylbenzene	NHPI	150	47.9
	4-methyl-NHPI	120	48.6
	4-chloro-NHPI	120	20.4
4-Isopropyl-*o*-xylene	NHPI		14.9
	4-methyl-NHPI	90	21.7
	4-chloro-NHPI		11.0
p-tret-Butylcumene	NHPI	75	31.9
	4-methyl-NHPI	30	35.1
	4-chloro-NHPI	40	14.0

By Table 1, *N*-hydroxyphthalimide and 4-methyl-*N*-hydroxyphthalimide are the most effective catalysts for aerobic oxidation of the studied hydrocarbons; it allows us to intensify this process significantly. In order to substantiate the obtained results for each of the studied hydrocarbons and phthalimide catalysts, by the quantum-chemical method PM7 we calculated the value of ΔE_{SOMO}, corresponding to the difference between the energies of the once occupied molecular orbital of the substrate radical (E_{SOMO} (R•)) and the catalyst radical (E_{SOMO} (r•)).

Table 2. Values of ΔE_{SOMO} depending on the structure of phthalimide catalyst and hydrocarbon

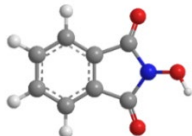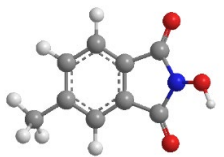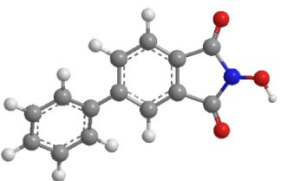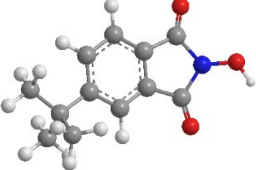| Catalyst and its structure	ΔE_{SOMO}, eV		
	Isopropylbenzene	4-Isopropyl-*o*-xylene	*p-tret*-Butylcumene
NHPI	1.45	1.90	2.30
4-methyl-NHPI	1.37	1.83	2.00
4-chloro-NHPI	1.61	2.08	2.60

The studied phthalimide compounds were found to be catalytically active in the aerobic liquid-phase oxidation of isopropylbenzene, 4-isopropyl-*o*-xylene, and *p-tret*-butylcumene, since the calculated values of ΔE_{SOMO} are in the range from 0 to 4 eV [25, 26]. Moreover, the smaller the numerical value of ΔE_{SOMO}, the easier is the capture of the hydrocarbon radical, and, consequently, the more efficient is the chain initiation in the course of hydrocarbon oxidative transformations [17].

According to Tables 1 and 2, *N*-hydroxyphthalimide and its derivatives containing electron-donor substituents in the benzene ring (e.g., 4-methyl-*N*-hydroxyphthalimide) have higher catalytic activity compared to compounds containing electron-acceptor substituents in their structure (4-chloro-*N*-hydroxyphthalimide).

Therefore, the use of *N*-hydroxyphthalimide derivatives containing electron-donating groups in the aromatic ring due to their high efficiency in the oxidation reaction was proposed to intensify the process of *sec*-butylbenzene aerobic liquid-phase oxidation [17] – a key stage in the co-production of phenol and methyl ethyl ketone. Thus, 4-methyl-*N*-hydroxyphthalimide, 4-phenyl-*N*-hydroxyphthalimide and 4-*tret*-butyl-*N*-hydroxyphthalimide were synthesised and used as such compounds (Table 3).

Table 3. Hydroperoxide content of reaction products and ΔE_{SOMO} as a function of phthalimide compound structure for the reaction of *sec*-butylbenzene aerobic liquid-phase oxidation. Temperature is 140 °C, catalyst content is 2% wt of hydrocarbon charge, reaction time is 40 min

Catalyst		The HP content in the reaction products, % wt.	E_{SOMO} (r•), eV	E_{SOMO} (R•), eV	ΔE_{SOMO}, eV
NHPI		32.4	-9.68		1.68
4-methyl-NHPI		39.4	-9.61		1.61
4-phenyl-NHPI		35.9	-9.63	-8.00	1.63
4-*tert*-butyl-NHPI		40.1	-9.56		1.56

where r• = [phthalimide structure] N—O•, R• = [structure] C• with CH₃, CH₂—CH₃ groups
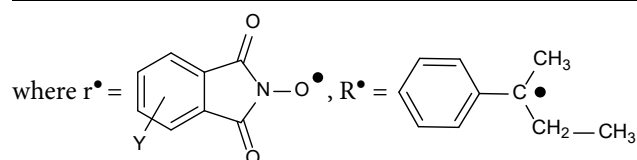
Hence, methyl and *tert*-butyl derivatives of *N*-hydroxyphthalimide, characterised by low values of the SOMO energy difference, have high catalytic activity in comparison with *N*-hydroxyphthalimide. This agrees well with the experimentally obtained data (Fig. 3).
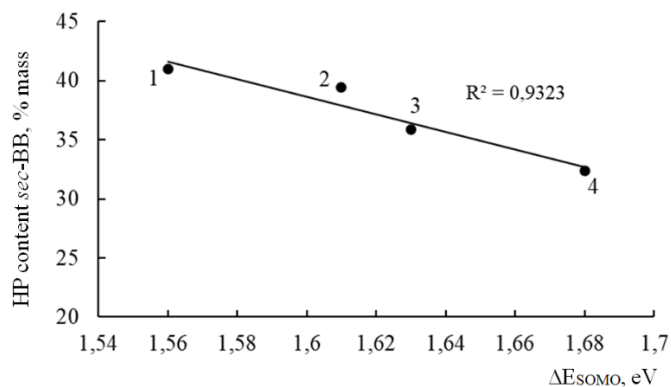
Fig. 3. Correlation dependence between ΔE_{SOMO} and hydroperoxide content in products of *sec*-butylbenzene liquid-phase aerobic oxidation in the presence of *N*-hydroxyphthalimide and its electron-donor derivatives as follows: 1 - 4-*tret*-butyl-*N*-hydroxyphthalimide, 2 - 4-methyl-*N*-hydroxyphthalimide, 3 – 4-phenyl-*N*-hydroxyphthalimide, 4 - *N*-hydroxyphthalimide. Temperature is 140 °C, catalyst content is 2% wt

The different reactivity of *N*-hydroxyphthalimide and its derivatives is explained on the basis of pre-reaction complexes formation between hydrocarbon molecule and *N*-oxyphthalimide radical (A), as well as between hydrocarbon peroxyradical and catalyst molecule (B):

A   B
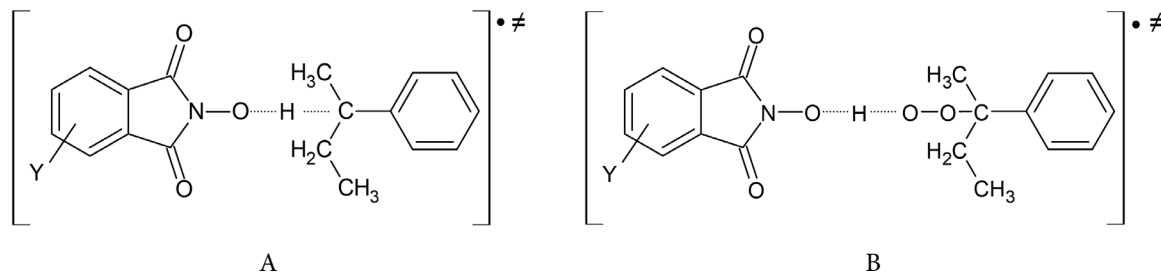
The electron-donating substituent contained in the aromatic core of the *N*-oxyphthalimide radical increases the spin density on the oxygen atom. As a result, the reactivity of this radical and the stability of its complex increase. At the same time, electron acceptor substituents in the aromatic ring reduce the spin density on the oxygen atom and the complex stability.

However, despite the high catalytic activity of *N*-hydroxyphthalimide derivatives containing electron-donor substituents, the oxidation of alkylaromatic hydrocarbons to their hydroperoxides in the presence of *N*-hydroxyphthalimide is preferable due to the availability of feedstock, low cost, and relatively simple technology of its preparation.

Conclusions

The use of *N*-hydroxyphthalimide and its derivatives makes it possible to intensify significantly the process of aromatic hydrocarbons aerobic oxidation. Moreover, phthalimide catalysts containing electron-donor substituents in their structure have higher catalytic activity compared to electron-acceptor groups. The study contains conclusions about the influence of the structure of *N*-hydroxyphthalimide derivatives on the oxidation process. It is in good agreement with the experimental data obtained. The quantum-chemical calculations of single occupied molecular orbitals energies of the hydrocarbon radical and catalyst radical can be applied to determine the catalytic activity of phthalimide compounds in the liquid-phase aerobic oxidation of alkylaromatic hydrocarbons.

References

1. **Kharlampovich, G.D. & Churkin, Y.V.** (1974) *Phenols*, M.: Khimiya (in Russian).
2. **Kurganova, E.A., Kabanova, V.S., Frolov, A.S., Koshel, G.N., Smurova, A.A. & Bajov, E.I.** (2023) Hydroperoxide method of phenol and its alkyl derivatives synthesis in combination with ketones of aliphatic and alicyclic series, *Neftegaz.RU,* 137(5), pp. 34-40 (in Russian).
3. **Kurganova, E.A., Bayov, E.I., Frolov, A.S., Kabanova, V.S., Koshel, G.N. & Petukhov, A.A.** (2023) Principles of aerobic oxidation of ethylbenzene to hydroperoxide under the presence of phthalimide catalysts, *From Chemistry Towards Technology Step-By-Step,* 4(2), pp. 8-16 [online]. Available at: https://doi.org/10.52957/2782-1900-2024-4-2-8-16 (accessed 10.02.2024) (in Russian).

4. **Serebryakov, B.R., Masagutov, R.M. & Pravdin, V.G.** (1989) *New processes of organic synthesis*, M.: Khimiya (in Russian).

5. **Frolov, A.S., Kurganova, E.A., Yarkina, E.M., Lebedeva, N.V., Koshel, G.N. & Kalenova, A.S.** (2018) Intensification of the cyclohexane liquid phase oxidation process, *Tonkie khimicheskie tekhnologii,* 13(4), pp. 50-57 [online]. Available at: https://doi.org/10.32362/2410-6593-2018-13-4-50-57 (accessed 12.02.2024) (in Russian).

6. **Yun, Hong, Dalei, Sun & Yanxiong, Fang.** (2018) The highly selective oxidation of cyclohexane to cyclohexanone and cyclohexanol over VAlPO$_4$ berlinite by oxygen under atmospheric pressure, *Chemistry Central Journal,* 36(12) [online]. Available at: https://doi.org/10.1186/s13065-018-0405-6 (accessed 20.02.2024).

7. **Emanuel, N.M., Denisov, E.T. & Mayzus, Z.K.** (1965) *Chain reactions of hydrocarbon oxidation in liquid phase*, M.: Nauka (in Russian).

8. **Nazimok, V.F., Ovchinnikov, V.I. & Potekhin, V.M.** (1987) *Liquid-phase oxidation of alkylaromatic hydrocarbons.* M.: Khimiya (in Russian).

9. **Aoki, Y., Sakaguchi, S. & Ishii, Y.** (2005) One-pot synthesis of phenol and cyclohexanone from cyclohexylbenzene catalyzed by *N*-hydroxyphthalimide (NHPI), *Tetrahedron*, 61(22), pp. 5219-5222 [online]. Available at: https://doi.org/10.1016/j.tet.2005.03.079 (accessed 10.02.2024).

10. **Orlinska, B. & Zawadiak, J.** (2013) Aerobic oxidation of isopropylaromatic hydrocarbons to hydroperoxides catalyzed by *N*-hydroxyphthalimide, *Reaction Kinetics, Mechanisms and Catalysis,* 110(1), pp. 15-30 [online]. Available at: https://doi.org/10.1007/s11144-013-0581-2 (accessed 08.02.2024).

11. **Sawatari, N., Yokota, T., Sakaguchi, S. & Ishii, Y.** (2001) Alkane oxidation with air catalyzed by lipophilic *N*-hydroxyphthalimides without any solvent, *J. Org. Chem.,* 66(23), pp. 7889-7891 [online]. Available at: https://doi.org/10.1021/jo0158276 (accessed 12.02.2024).

12. **Recupero, F. & Punta, C.** (2007) Free Radical Functionalization of Organic Compounds Catalyzed by *N*-Hydroxyphthalimide, *Chemical Reviews*, (107), pp. 3800-3842 [online]. Available at: https://doi.org/10.1021/cr040170k (accessed 23.01.2024).

13. **Galli, C., Gentili, P. & Lanzalunga, O.** (2008) Hydrogen Abstraction and Electron Transfer with Aminoxyl Radicals: Synthetic and Mechanistic Issues, *Angewandte Chemie International Edition,* 47(26), pp. 4790-4796 [online]. Available at: https://doi.org/10.1002/anie.200704292 (accessed 12.02.2024).

14. **Koshel, G.N., Smirnova, E.V., Kurganova, E.A., Ekimova, I.D., Lebedeva, N.V., Koshel, S.G. & Plakhtinsky, V.V.** (2010) Intensifying the oxidation of isopropylbenzene, *Kataliz v promy`shlennost,* (3), pp. 26-29 (in Russian).

15. **Frolov, A.S.** (2016) Hydroperoxide method of xylenols preparation using acetone: Ph.D. Yaroslavl (in Russian).

16. **Yarkina, E.M., Kurganova, E.A., Frolov, A.S., Koshel, G.N., Nesterova, T.N., Shakun, V.A. & Spiridonov, S.A.** (2020) *Para-tret*-butylcumene synthesis, *Tonkie khimicheskie texnologii,* 16(1), pp. 26-35 [online]. Available at: https://doi.org/10.32362/2410-6593-2021-16-1-26-35 (accessed 10.02.2024) (in Russian).

17. **Kabanova, V.S., Frolov, A.S., Kurganova, E.A., Sapunov, V.N., Koshel, G.N. & Baev, E.I.** (2024) Study of the kinetic regularities of the process of liquid phase oxidation of *sec*-butylbenzene in the presence of *N*-hydroxyphthalimide, *Kataliz v promyshlennosti,* 24(3), pp. 39-49 [online]. Available at: https://doi.org/10.18412/1816-0387-2024-3-39-49 (accessed 14.02.2024) (In Russian).

18. **Fieser, L.F. & Fieser, M.** (1967) *Reagents for Organic Synthtsis.* Wiley: New York.

19. **Frolov, A.S., Kurganova, E.A., Koshel', G.N. & Nesterova, T.N.** (2015) Liquid-phase oxidation of isopropyl-meta-xylene to tertiary hydroperoxide, *European Journal of Analytical and Applied Chemistry,* (1), pp. 16-22 [online]. Available at: https://doi.org/10.1134/s1070427214070088 (accessed 22.02.2024).

20. **Antonovsky, V.L. & Buzlanova, M.M.** (1978) *Analytical chemistry of organic peroxide compounds.* M.: Khimiya (in Russian).

21. **Koshel, G.N., Soloviev, M.E., Kurganova, E.A., Rumyantseva, Y.B. & Frolov, A.S.** (2013) Quantum chemical analysis of the reaction thermodynamics of hydrocarbon oxidation in the presence of *N*-hydroxyphthalimide, *Vestnik Kazanskogo texnologicheskogo universiteta,* 16(2), pp. 302-304 (in Russian).

22. **Yufei, Yang, Jieyi, Ma, Junyan, Wu, Weixia, Zhu & Yadong, Zhang.** (2022) Experimental and theoretical study on *N*-hydroxyphthalimide and its derivatives catalyzed aerobic oxidation of cyclohexylbenzene, *Chinese Journal of Chemical Engineering*, 44(1), pp. 124-130 [online]. Available at: https://doi.org/10.1016/j.cjche.2021.06.017 (accessed 12.02.2024).

23. **Novikova, K.V., Kompanets, M.O., Kushch, O.V. & Kobzev, S.P.** (2011) Substituted *N*-hydroxyphthalimides as oxidation catalysts, *Reaction Kinetics and Catalysis Letters,* 103(1), pp. 31-40 [online]. Available at: https://doi.org/10.1007/s11144-011-0289-0 (accessed 08.02.2024).

24. *MOPAC 2016* [online]. Available at: http://openmopac.net/MOPAC2016.html (accessed 10.02.2024).

25. **Matsui S., Kuroda H., Hirokane N., Makio H., Takai T., Kato K., Fujita T. & Kamimura Makoto.** Method for preparation of hydroperoxides. 2186767 RU. Published 2002 (in Russian).

26. **Matsui S. & Fujita T.** (2001) New cumene-oxidation systems: O2 activator effects and radical stabilizer effects, *Catalysis Today,* (71), pp. 145-152.