Synthesis and Thermal Stabilising Properties of Sulphur-Containing Derivatives of Mono- and Binuclear Cyclohexylphenols

A. F. MARKOV[1,2], A. E. PROCENKO[1,2] and N. V. KANDALINTSEVA[1,2]

[1]*Research Institute of Antioxidant Chemistry, Novosibirsk State Pedagogical University, Ul. Vilyuyskaya 28, Novosibirsk 630126 (Russia)*

E-mail: chemistry@ngs.ru

[2]*Novosibirsk Institute of Antioxidants, Ul. Vilyuyskaya 28, Novosibirsk 630126 (Russia)*

Abstract

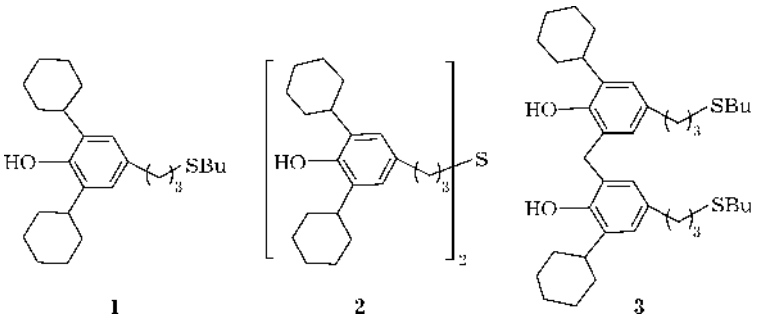
Basing on 4-hydroxypropyl-2,6-di-*tert*-butylphenol, the synthesis of *o*-cyclohexyl-*p*-thiaalkylphenols with various structure was carried out through a series of intermediate stages. For the compounds synthesised, reaction rate constant values for the interaction with free peroxide radicals were determined. It has been shown that *p*-thiaalkyl-*o*-cyclohexylphenols exhibit high values of antioxidative efficiency and thermal stability, and could be applied as thermal stabilisers for mineral oils and other synthetic materials.

INTRODUCTION

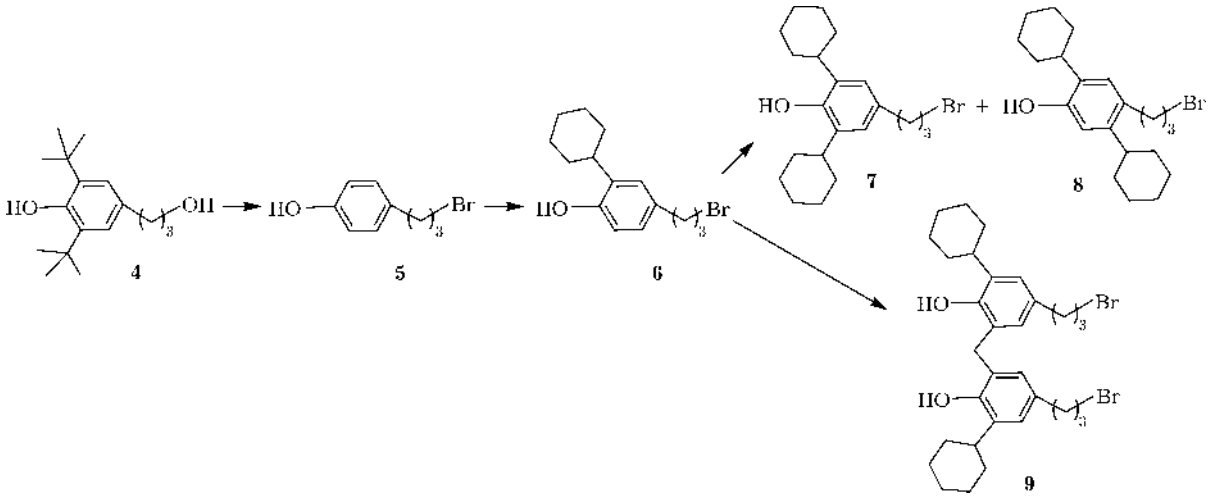
Additives with antioxidative properties those promote the increase in the service life period (or storage stability) as well as in the quality improvement for polymers, rubbers, fuels and technical oils are widely used in modern manufacturing of these products. The urgency for searching novel antioxidants is caused by a permanent extending the assortment and areas of application with respect to synthetic organic materials.

For the last years, one of the basic tendencies in the development of the assortment of antioxidative additives consists in the creation of multifunctional (hybrid) inhibitors. A highly important place among them is occupied by thio derivatives of 2,6-di-*tert*-butylphenol whose high efficiency is caused by a synergetic combination of antiradical activity of the phenolic fragment with an anti-peroxide action exhibited by sulphur-containing groups [1]. In the studies on the laws of variation of anti-oxidative activity (AOA) of such compounds depending on their structure it was established [2] that the highest efficiency can be exhibited by the compounds of sulphide type, the molecules of those contain an equal number of sulphide and phenolic groups. In this connection, as far as AOA is concerned, 4-alkylthiomethyl-2,6-di-*tert*-butylphenols are ranking below their analogues, in whose structure the sulphur atom is separated from the aromatic nucleus by two or more methylene links.

On the other hand, it is known that 2,6-di-*tert*-butylphenols are ranking in antiradical activity below less shielded phenols, including 2,6-dicyclohexyl substituted ones [3]. According to the data from [4–6], cyclohexyl substituted *p*-allkylphenols and methylene-bis-phenols are used as high efficient thermal and light stabilisers and anti-aging agents for rubbers, polyolefines, plastics, and mineral oils. At the same time, the data concerning sulphur-containing *o*-cyclohehylphenols are rather scarce. In the STN International Databases only insignificant number of cyclohehylphenol thio derivatives is mentioned, in whose molecular structure the atom of sulphur being attached directly to the aromatic nucleus [7] or being separated from it with the only methylene link [8–10]. There are no data concerning the compounds containing in the molecule a sulphur atom separated from the cyclohexyl-substituted phenolic nucleus with several methylene links.



Scheme 1.



Scheme 2.

The present work is devoted to the synthesis of sulphur-containing cyclohexylphenols **1–3** as well as to the investigation of thermal stabilising properties of these compounds (Scheme 1).

EXPERIMENTAL

Compounds **1–3** were synthesized from corresponding bromo derivatives obtained as the result of the following transformations (Scheme 2).

As an initial synthon, alcanol **4** was used; for this substance to obtain an efficient method was proposed earlier based on the reaction of 2,6- di-*tert*-butylphenol with allyl alcohol [11, 12].

4-(3-Bromopropyl)phenol (5). A mixture of 120 g (0.45 mol) of alcanol **4** and of 384 mL of 41 % hydrobromic acid (2.67 mol) was boiled (with azeotrope distilled away) during 12 h. Then the reaction mixture obtained was cooled and treated with toluene. An extract was washed out with water, dried with the use of Na_2SO_4, the solvent being distilled off. A residue was distilled in vacuum. The yield of a target bromopropane **5** obtained amounted to 87.9 g (91 %), b.p. being 121–124 °C (at 1 mm Hg), m.p. 38–40 °C (from pentane). ^{1}H NMR spectrum (δ, ppm): 2.08–2.14 m (2H, $CH_2C\underline{H}_2CH_2$), 2.70 t (2H, $ArC\underline{H}_2$), 3.37 t (2H, CH_2Br), 5.00 s (1H, OH), 6.76 d (2H, H_{arom}, J = 8 Hz), 7.14 d (2H, H_{arom}, J = 8 Hz). Found, %: C 50.33, H 5.21, Br 36.97. $C_9H_{11}BrO$; Calculated: C 50.26, H 5.15, Br 37.15.

2-Cyclohexyl-4-(3-bromopropyl)phenol (6). A mixture of 53.8 g (0.25 mol) of compound **5** and 6 mL of 57 % chloric acid (51 mmol) was heated up to 120 °C, then 12.7 mL (125 mmol) of cyclohexene was added dropwise and then the mixture was stirred during 0.25 h. To the reaction mixture were added 200 mL of water, 100 mL of benzene and 50 mL of 10 % NaOH solution, and then it was thoroughly intermixed. After this procedure, the obtained organic extract and alkaline aqueous extract were separated from each other. An organic layer was successively washed out with two 50 mL

portions of 10 % NaOH solution, then it was neutralized with HCl, washed out with water, dried with the use of Na_2SO_4, and then the solvent was distilled off. A residue was distilled in vacuum. The yield of compound 6 amounted to 18.6 g (50 %), b.p. being 203–206 °C (at 1–2 mm Hg). ^{1}H NMR spectrum (δ, ppm): 1.29 m (^{1}H, *cyclo*-C_6H_{11}), 1.78 m (1H, *cyclo*-C_6H_{11}), 1.88 m (4H, *cyclo*-C_6H_{11}), 2.14 m (2H, $ArCH_2C\underline{H}_2$), 2.71 t (2H, $ArC\underline{H}_2$), 2.83 m (1H, *cyclo*-C_6H_{11}), 3.41 t (2H, CH_2Br), 4.97 s (1H, OH), 6.68 d (1H, H_{arom}, J = 8 Hz), 6.89 dd (1H, H_{arom}, J = 8 Hz, 2 Hz), 7.02 d (1H, H_{arom}, J = 2 Гц). Found, %: C 60.70, H 7.23, Br 26.78. $C_{15}H_{21}BrO$. Calculated: C 60.61, H 7.12, Br 26.88.

2,6- and 2,5-Dicyclohexyl-4-(3-bromopropyl) phenols. A mixture of 6.77 g (31.5 mmol) bromopropane **5** and 0.74 mL of 57 % chloric acid (6.3 mmol) was heated up to 120 °C, then 6.5 mL (64.2 mmol) of cyclohexene was added dropwise and then the mixture was stirred during 0.25 h, cooled and treated with toluene. The extract obtained was washed out with water, dried over Na_2SO_4, and then the solvent was distilled off. A residue was distilled in vacuum. A fraction with b.p. of 220–225 °C (at 1–2 mm Hg) was twice recrystallised from hexane (a filtrate was stored). The yield of 2,6-dicyclohexyl-4-(3-bromopropyl)phenol **7** amounted to 7.76 g (65 %), m.p being at 74–75 °C. ^{1}H NMR spectrum (δ, ppm): 1.30–1.36 m (2H, *cyclo*-C_6H_{11}), 1.42–1.47 m (8H, *cyclo*-C_6H_{11}), 1.79–1.83 m (2H, *cyclo*-C_6H_{11}), 1.87–1.91 m (8H, *cyclo*-C_6H_{11}), 2.05 m (2H, $ArCH_2C\underline{H}_2$), 2.71 t (2H, $ArC\underline{H}_2$), 2.76 m (2H, *cyclo*-C_6H_{11}), 3.37 t (2H, CH_2Br), 4.70 s (1H, OH), 6.86 s (2H, H_{arom}). Found, %: C 66.60, H 8.41, Br 20.86. $C_{21}H_{31}BrO$. Calculated: C 66.48, H 8.24, Br 21.06.

From a hexane filtrate the solvent was distilled off, a residue was chromatographed on silica gel (petroleum ether/diethyl ether as an eluent, the ratio being 4 : 1). Thus 2,5-dicyclohexyl-4-(3-bromopropyl)phenol **8** was isolated, with m.p. at 116–119 °C. ^{1}H NMR spectrum (δ, ppm): 1.27 m (2H, *cyclo*-C_6H_{11}), 1.38 m (8H, *cyclo*-C_6H_{11}), 1.75 m (4H, *cyclo*-C_6H_{11}), 1.85 m (6H, *cyclo*-C_6H_{11}), 2.04 m (2H, $ArCH_2C\underline{H}_2$), 2.63 m (1H, *cyclo*-C_6H_{11}), 2.70 m (2H, $ArC\underline{H}_2$; 1H, *cyclo*-C_6H_{11}), 3.38 t (2H, CH_2Br), 4.35 s (1H, OH), 6.51 s (1H, H_{arom}), 6.85 s (1H, H_{arom}). Found, %: C 66.68, H 8.42, Br 20.83. $C_{21}H_{31}BrO$. Calculated: C 66.48, H 8.24, Br 21.06.

S-(3-(3,5-dicyclohexyl-4-hydroxyphenyl)-propyl) isothiuronium bromide (10). A mixture of 21.61 g (57 mmol) of bromopropylphenol **7** and 4.77 g (62.7 mmol) of thiocarbamide was dissolved in 100 mL butanol and then it was boiled during 5 h in an argon atmosphere. Then the solvent was distilled off, a residue was crystallized from toluene and recrystallised from water The yield of isothiuronium bromide **10** amounted to 15.9 g (61 %), m.p. being at 191–193 °C. ^{1}H NMR spectrum (δ, ppm): 1.27–1.54 m (10H, *cyclo*-C_6H_{11}), 1.77–1.88 m (10H, *cyclo*-C_6H_{11}), 2.00 m (2H, $ArCH_2C\underline{H}_2$), 2.69 t (2H, $ArC\underline{H}_2$), 2.96 m (2H, *cyclo*-C_6H_{11}), 3.13 t (2H, CH_2S), 4.84 s (1H, OH), 6.84 s (2H, H_{arom}). Found, %: C 59.19, H 7.96, Br 17.73, N 6.15, S 7.15. $C_{22}H_{35}BrN_2OS$. Calculated: C 59.31, H 7.92, Br 17.94, N 6.29, S 7.20.

4-(3-Butylthiopropyl)-2,6-dicyclohexylphenol (1). A mixture of 5 g (11 mmol) of isothiuronium bromide **10**, 0.94 g (24.2 mmol) of NaOH and 1.22 g (13.2 mmol) of 1-chlorobutane was dissolved in 10 mL of ethanol in an argon atmosphere, then it was heated and boiled during 1 h. Further the reaction mixture was cooled, neutralized with hydrochloric acid; water was added and after this procedure the mixture was treated with benzene. The extract obtained was washed out with water, dried with the use of Na_2SO_4, the solvent was distilled off. The residue obtained was distilled in vacuum. The yield of target sulphide **1** amounted to 2.99 g (70 %), b.p. being 229–232 °C (at 1–2 mm Hg). ^{1}H NMR spectrum (δ, ppm): 1.02 t (3H, $CH_2\underline{Me}$), 1.37 m (2H, *cyclo*-C_6H_{11}), 1.51 m (8H, *cyclo*-C_6H_{11}; 2H, $C\underline{H}_2Me$), 1.65 m (2H, $C\underline{H}_2Et$), 1.86 m (2H, *cyclo*-C_6H_{11}), 1.94 m (8H, *cyclo*-C_6H_{11}; 2H, $ArCH_2C\underline{H}_2$), 2.56 m (4H, CH_2SCH_2), 2.68 t (2H, $ArC\underline{H}_2$), 2.80 m (2H, *cyclo*-C_6H_{11}), 4.79 s (1H, OH), 6.85 s (2H, H_{arom}). Found, %: C 77.13, H 10.33, S 8.33. $C_{25}H_{40}OS$. Calculated: C 77.26, H 10.37, S 8.25.

Bis-(3-(3,5-dicyclohexyl-4-hydroxyphenyl)-propyl)sulphide (2). To a mixture of 0.22 g (3.3 mmol) of KOH, 1.46 g (13.1 mmol) of Na_2S and 6 mL of propanol-2 in an argon atmosphere was added a solution of 8 g (21 mmol) of bromopropylphenol **7** in 6 mL of propanol-2. The reaction mixture was stirred during 3 h at 20 °C, then during 3 h at 50 °C; after this it was acidified with hydrochloric acid and

conditioned during 0.5 h at 50 °C, and then it was cooled and treated with benzene. The extract obtained was washed out with water and dried over Na_2SO_4. The solvent was distilled off; the residue obtained was crystallised from hexane. The yield of sulphide **2** amounted to 3.57 g (54 %), m.p. being 132–134 °C. ^{1}H NMR spectrum (δ, ppm): 1.26–1.31 m (4H, *cyclo*-C_6H_{11}), 1.41–1.47 m (16H, *cyclo*-C_6H_{11}), 1.77–1.82 m (4H, *cyclo*-C_6H_{11}), 1.83–1.90 m (16H, *cyclo*-C_6H_{11}, 4H, $ArCH_2C\underline{H}_2$), 2.49 t (4H, CH_2S), 2.60 t (4H, $ArC\underline{H}_2$), 2.66–2.72 m (4H, *cyclo*-C_6H_{11}), 4.48 s (2H, OH), 6.76 s (4H, H_{arom}). Found, %: C 79.81, H 9.72, S 5.24. $C_{42}H_{62}O_2S$. Calculated: C 79.94, H 9.90, S 5.08.

2,2′-Methylene-bis-(4-(3-bromopropyl)-6-cyclohexylphenol) (9). To 23.6 g (79.5 mmol) of compound **6** in 10 mL of glacial acetic acid was added 1.19 g (39.6 mmol) of paraformaldehyde and 6.5 mL of 37 % hydrochloric acid (77 mmol). The mixture was stirred during 2 h at 80 °C in an argon environment. After cooling, 100 mL of water was added, and then the mixture was treated with benzene. The extract obtained was washed out with water and dried with the help of Na_2SO_4. The solvent was distilled off; the residue obtained was crystallised and then recrystallised from hexane. The yield of target methylenebisphenol **9** amounted to13.7 g (57 %), m.p. being 104–105 °C. ^{1}H NMR spectrum (δ, ppm): 1.25 m (2H, *cyclo*-C_6H_{11}), 1.38 m (8H, *cyclo*-C_6H_{11}), 1.74 m (2H, *cyclo*-C_6H_{11}), 1.82 m (8H, *cyclo*-C_6H_{11}), 2.09 m (4H, $ArCH_2C\underline{H}_2$), 2.66 t (4H, $ArC\underline{H}_2CH_2$), 2.69 m (2H, *cyclo*-C_6H_{11}), 3.37 t (4H, CH_2Br), 3.86 s (2H, $ArC\underline{H}_2Ar$), 6.11 s (2H, OH), 6.84 d (2H, H_{arom}, J = 2 Hz), 6.95 d (2H, H_{arom}, J = 2 Hz). Found, %: C 61.42, H 7.12, Br 26.11. $C_{31}H_{42}Br_2O_2$. Calculated: C 61.39, H 6.98, Br 26.35.

2,2′-Methylene-bis-(4-(3-chloropropyl)-6-*tert*-butylphenol) (11). This compound was obtained in a similar manner as previous one from 2-*tert*-butyl-4-(3-chloropropyl)phenol (synthesised in the reaction of alcanol **4** with concentrated HCl [13]). The yield of methylenebisphenol **11** amounted to 71 %, m.p. being at 102–104 °C. ^{1}H NMR spectrum (δ, ppm): 1.38 s (18H, *t*-Bu), 2.03 m (4H, $ArCH_2C\underline{H}_2$), 2.66 t (4H, $ArC\underline{H}_2CH_2$), 3.47 t (4H, CH_2Cl), 3.88 s (2H, $ArC\underline{H}_2Ar$), 5.96 s (2H, OH), 6.95 d (2H, H_{arom}, J = 2 Hz), 6.96 d (2H, H_{arom}, J = 2 Hz). Found, %: C 69.84, H 8.35, Cl 15.53. $C_{27}H_{38}O_2Cl_2$. Calculated: C 69.66, H 8.23, Cl 15.23.

2,2′-Methylene-bis-(4-(3-butylthiopropyl)-6-cyclohexylphenol) (3). In 5 mL of propanol-2 were dissolved 4.2 mL (40 mmol) of butanethiol-1 and 1.7 g (41.2 mmol) of NaOH. The solution obtained was cooled down to 10 °C and then in an argon atmosphere was added dropwise to a solution of 10 g (16.5 mmol) methylenebisphenol **9** in 5 mL of propanol-2. The mixture was heated, stirred during 2 h at 40 °C, and then it was cooled and treated with benzene. The extract obtained was washed out with water, dried over Na_2SO_4. The solvent was distilled off. The yield of target methylene-bis-phenol **3** amounted to 9.7 g (94 %). ^{1}H NMR spectrum (δ, ppm): 0.90 t (6H, $CH_2\underline{Me}$), 1.25 m (2H, *cyclo*-C_6H_{11}), 1.38 m (8H, *cyclo*-C_6H_{11}), 1.39 m (4H, $C\underline{H}_2Me$), 1.54 m (4H, $C\underline{H}_2Et$), 1.74 m (2H, *cyclo*-C_6H_{11}), 1.82 m (8H, *cyclo*-C_6H_{11}), 1.84 m (4H, $ArCH_2C\underline{H}_2$), 2.49 t (4H, CH_2S), 2.50 t (4H, CH_2S), 2.59 t (4H, $ArC\underline{H}_2CH_2$), 2.69 m (2H, *cyclo*-C_6H_{11}), 3.85 s (2H, $ArC\underline{H}_2Ar$), 6.07 s (2H, OH), 6.83 d (2H, H_{arom}, J = 2 Hz), 6.92 d (2H, H_{arom}, J = 2 Hz). Found, %: C 75.09, H 9.81, S 10.04. $C_{39}H_{60}O_2S_2$. Calculated: C 74.94, H 9.68, S 10.26.

2,2′-Methylene-bis-(4-(3-ethylthiopropyl)-6-*tert*-butylphenol) (12). This compound was obtained in a similar manner as previous one from chloro derivative **11** and bromoethane. The yield amounted to 55 %, m.p. being 65–67 °C. ^{1}H NMR spectrum (δ, ppm): 1.26 t (6H, $SCH_2\underline{Me}$), 1.38 s (18H, *t*-Bu), 1.87 m (4H, $ArCH_2C\underline{H}_2$), 2.53 m (8H, $C\underline{H}_2SC\underline{H}_2$), 2.61 t (4H, $ArC\underline{H}_2CH_2$), 3.89 s (2H, $ArC\underline{H}_2Ar$), 5.82 s (2H, OH), 6.96 d (2H, H_{arom}, J = 2 Hz), 7.25 d (2H, H_{arom}, J = 2 Hz). Found, %: C 71.95, H 9.45, S 12.65. $C_{31}H_{48}O_2S_2$. Calculated: C 72.04, H 9.36, S 12.41.

^{1}H NMR spectra were registered using a Bruker DRX 500 with the operation frequency of 500.13 MHz, for samples of isothiuronium bromide **10** dissolved in CD_3OD ($SiMe_4$ being as a reference), for samples of other compounds dissolved in $CDC1_3$ ($CHC1_3$ being as a reference). Melting point was determined using a PTP device.

Thermal analysis of compound **2** was carried out with the use of a MOM derivatograph (Hungary) within a temperature range amounting to 20–500 °C with the heating rate of 5 °C/min in air, at the Novosibirsk Institute of Organic Chemistry, SB RAS (Russia)). The mass

TABLE 1

Reaction rate constant values (k) for the interaction of phenolic compounds with cumylperoxide radicals, 10^4 L/(mol · s)

Compounds						CO-3	Ionol	ZKF	2246
1	**2**	**3**	**12**	**13**	**14**				
19.5	20.0	16.2	17.9	16.0	2.5	2.4	2.4	30.5	27.2
		2.5	1.6					1.2	1.6

of a sample was 49 g; Al_2O_3 was used as a reference. The record sensitivity for a differential thermal analysis (DTA) curve was 1/5 of a maximum value, that for a thermogravimetry (TG) curve being 100 mg and that for a differential thermogravimetry (DTG) curve being 1/5; platinum crucibles were of cup-shaped type.

The reaction rate constants k for the interaction of the synthesised compounds with free peroxide radicals were determined using a manometric technique in a model reaction of AZBN initiated oxidation of cumene (Acros Organics, the USA) at 60 °C; with the help of the techniques and installations described earlier [14–16]. The main experiments on cumene oxidation were carried out under the following conditions: [AZBN] = 3–6 mmol, oxidation process initiation rate $W_i = (0.38–1.44) \cdot 10^{-7}$ mol/(L · s), the oxidation chain length was not less than 76, the concentration of antioxidants amounted to $(2.5–5.0) \cdot 10^{-5}$ mol/L. The plotting of kinetic curves and mathematical treatment were carried out using Origin 6.0 software. All the measurements were 5–8 times repeated. Average k values with root mean square deviation less than 20 % are presented in Table 1.

The oxidation of paraffin oil (TatChemFarm-Preparaty JSC) and hexadecane (Russia) was carried out using a gasometer similar the set-up described in [14]. The pressure of oxygen was maintained at 1 atm, volume of the sample under oxidation amounted to 5 mL. Basing on the data obtained, kinetic curves were plotted. From such a plot, the induction period value was determined graphically as an intersection point of two tangents to a kinetic curve, those are corresponding to initial and final oxidation process rate values [14]. Every measurement was 3–5 times repeated. Figures 1, 2 demonstrate average τ values, with root mean square deviation less than 5 %.

As reference antioxidants, we used 2,6-di-*tert*-butyl-4-methylphenol (ionol, Acros Organics), as well as structural analogues of compounds **1–3** such as 2,6-dicyclohecsyl-4-methylphenol **13** (obtained via alkylation of *p*-cresol with the use of a method by Kolka [17]), 2,6-di-*tert*-butyl-4-(3-butylthiopropyl) phenol **14**

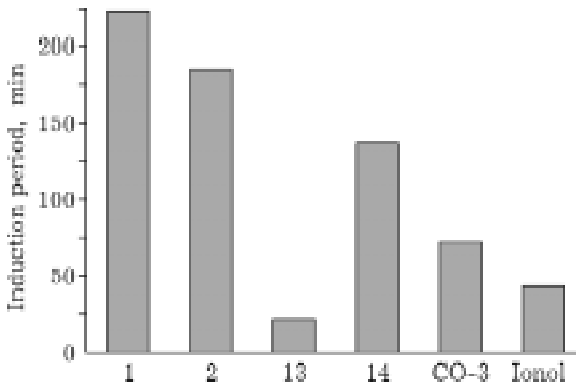


Fig. 1. Diagram of the induction period values for the process of inhibited oxidation of paraffinic oil at 180 °C. Sulphide **2** and CO-3 concentrations being 0.875 μmol/g; the concentrations of other antioxidants amounting to 1.75 μmol/g.

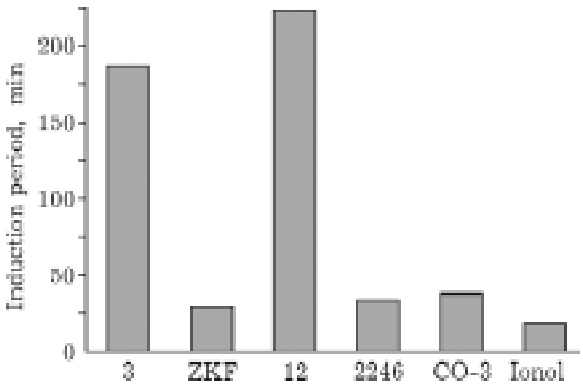


Fig. 2. Diagram of the induction period values for the process of inhibited oxidation of hexadecane at190 °C. Ionol concentration 2.25 μmol/g; the concentrations of other antioxidants amounting to 1.125 μmol/g.

(synthesised according to [18]), bis[3-(3,5-di-*tert*-butyl-4-hydroxyphenyl)propyl]sulphide (CO-3 stabiliser [19]), 2,2′-methylene-bis-(4-methyl-6-cyclohexylphenol) (Vulkanox ZKF, [20]), 2,2′-methylene-bis-(4-methyl-6-*tert*-bulylphenol) (Antioxidant 2246, Sterlitamak Petrochemical Plant JSC) and 2,2′-methylenebis-(4-(3-ethylthiopropyl)-6-*tert*-butylphenol) **12**.

RESULTS AND DISCUSSION

A key stage in the synthesis of semiproducts for compounds **1–3** consists in the introduction of cyclohexyl ortho substituents into the molecule of bromopropylphenol **5**.

Earlier the authors of [17] proposed an efficient method for selective *o*-alkylation of phenols using alkenes in the presence of aluminum phenolates, which has later received a wide recognition. Unfortunately, in the case under consideration the use of the method mentioned is impossible because of the presence of bromine atom in the para-substituent within the molecule of phenol **5**. In this connection, less selective acid catalysts were used in the present work.

The alkylation of bromo derivative such as **5** was carried out using cyclohexene and cyclohexanol in the presence of catalytic additions of various H-acids (H_2SO_4, H_3PO_4, $HClO_4$, HBr) with a variation in molar ratio of reagents, as well as in temperatures and in the synthesis process duration. The best results were obtained with the use of 57 % $HClO_4$ and cyclohexene at 120 °C. In this case the process proceeded with a high reaction rate, and the formation of *o*-alkylated products was not observed.

When the molar ratio between the reagents **5** and C_6H_{10} amounted to 2 : 1, respectively, a monocyclohexyl-substituted phenol **6** was obtained. With the use of a surplus of cyclohexene, the basic products of the reaction were presented by isomers such as **7** and **8** (with a quantitative ratio amounting to 19 : 1, respectively). The composition and the structure of bromo derivatives **7** and **8** were confirmed with elemental analysis and NMR spectral data. So, a distinctive feature of ^1H NMR spectrum of 2,5-dicyclohexyl-substituted phenol **8** consists in the presence of signals from two types of aromatic hydrogen atoms, as well as in the differences in chemical shifts for the hydrogen atoms those are bonded to Ca atoms of *o*- and *m*-cyclohexyl substituents.

It should be noted that with the use of corresponding 4-(3-chloropropyl)phenol instead of bromide **5**, the relative 2,5-isomer content in alkylate increased up to 13 %, and when 4-methylphenol being alkylated the yield of 3,5-dicyclohexyl-4-methylphenol amounts to as much as 30 %.

The syntheses of sulphur-containing derivatives such as **1–3** were carried out using the techniques developed earlier for the obtaining of corresponding derivatives basing on *o*-*tert*-butyl-*p*-(ω-halogenoalkyl)phenols [19, 21]. The asymmetricl sulphide **1** was obtained from bromide **7** through intermediate synthesis of an isothiuronium salt; the symmetric sulphide **2** was obtained through the interaction of bromide **7** with sodium sulphide; the methylene-bis-phenol **3** was obtained via the reaction of corresponding bromo derivative **9** with butanethiol.

For cyclohexylphenols synthesised and for their *tert*-butyl-substituted analogues, reaction rate constants of the interaction with free cumylperoxide radicals were measured. From data presented in Table 1 one may conclude that 2,6-dicyclohexyl-substituted phenols **1**, **2**, **13** surpass their *tert*-butyl-substituted analogues such as **14**, CO-3 and ionol in reactivity with respect to active radicals. The k values for corresponding compounds differ by a factor of 6.7–8.3.

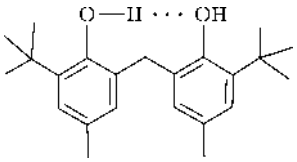
It is known [3], that the reactivity of alkylphenols in the reaction with free peroxide radicals is determined by the two basic factors effecting independently from each other. These factors are: ArO–H bond energy that depends on the distribution of electronic density in the molecule of a phenol, and stereochemical shielding of the phenolic OH group. As this takes place, the constant k increases both with the decrease of OH bond energy and (or) with the reduction of spatial shielding degree for the OH group.

Moreover, it is known, that cyclohexyl-substituted phenols are characterised by a somewhat stronger OH bond as compared to their *tert*-butylated analogues. So, according to the data from [22], for 2,6-dicyclohexylphenol **13** the OH bond amounts to 82.5 kcal/mol, and for ionol it is 81.2 kcal/mol. Thus one may believe that cyclohexyl-substituted phenols **1**, **2**,

13 can react with free peroxide radicals more actively due to smaller spatial shielding of the phenolic OH group.

From the analysis of the kinetic curves obtained during the oxidation of cumene in the presence of methylenebisphenols under investigation one can conclude that the inhibition occurred due to two types of phenolic OH groups with different k values.

According to the data from [15], the non-equivalence of OH groups in the molecule of the antioxidant 2246 could be caused by the formation of an intramolecular hydrogen bond:



In this case for the OH group whose hydrogen atom does not participate in the formation of such a bond, the k value should be higher in comparison with corresponding mononuclear phenols. On the contrary, for the OH group whose hydrogen atom participates in the formation of hydrogen bond, the k value should be lower.

Para-thiaalkyl substituted methylenebisphenols **3** and **12** were 1.5–1.9 times inferior to corresponding *p*-cresols such as ZKF and 2246 in k values. Most likely, a considerable size of *p*-substituents in the compounds **3**, **12** do not allow their molecules to take on the conformation that is an optimum one for the formation of intramolecular hydrogen bond. As a result, the hydrogen bond in the molecules of *p*-thiaalkylphenols **3**, **12** should be less strong, and its activation effect on the reactivity of OH group would be less pronounced.

The thermal stabilizing properties of the compounds synthesized were studied in model auto-oxidation reactions by the examples of paraffinic oil (180 °C) and hexadecane (190 °C). The efficiency of the compounds under investigation was judged form the induction period values for the inhibited oxidation of a substratum.

The data obtained (see Figs. 1, 2) indicate that for both model systems irrespective of the nature of *o*-substituent, *p*-thiopropylphenols surpassed corresponding derivatives of *p*-cresol in antioxidative activity. Most likely, this fact is connected with a combined manifestation of the antioxidative effects of phenolic and sulphide groups.

As far as the oxidation of paraffin oil is concerned, 2,6-dicyclohexyl-4-methylphenol 13 is less efficient with respect to the thermal stabilising properties than ionol, and sulphur-containing 2,6-dicyclohexylphenols **1** and **2** are more efficient than their *tert*-butyl substituted analogues such as sulphide **14** and the CO-3 stabiliser by a factor ranging from 1.6 to 2.6.

By the example of the model reaction of hexadecane auto-oxidation it has been demonstrated that the introduction of a sulphide fragment into the *p*-alkyl substituents of 2,2'-methylenebisphenols results in a considerable increase in the AOA. Regarding the ability to inhibit the auto-oxidation of hexadecane, sulphides **3** and **12** surpass significantly (by a factor of 6.2–6.6) their prototypes such as Vulkanox ZKF and 2246 industrial stabilisers, as well as ionol and its sulphur-containing analogue, CO-3 stabiliser.

Alongside with the anti-oxidative properties, an important property of an antioxidative thermal stabiliser for polymers and mineral oils is characterised by its own thermal stability. It is commonly supposed that the thermal stability threshold is presented by the minimal temperature corresponding to an inhibitor mass loss value amounting to 5 % [23].

By the example of the CO-3 stabiliser and sulphide **2** it was demonstrated that sulphur-containing derivatives of 2,6-dicyclohexylphenol surpass corresponding 2,6-di-*tert*-butylphenols not only in AOA, but also in their own thermal stability. According to the results of thermal analysis, the sample of sulphide **2** when heated in air loses 5 % of initial mass at 270 °C. According to the data from [23], for the CO-3 stabiliser this parameter amounts to 225 °C.

CONCLUSION

As a whole, the data obtained indicate that *p*-thiaalkyl-*o*-cyclohexylphenols are characterised by high antioxidative efficiency and thermal stability in comparison with *o*-*tert*-butyl substituted analogues those have received wide recognition as practical antioxidants, and could find application as thermal stabilizers for mineral oils and other synthetic materials.

REFERENCES

1 E. I. Terakh, A. E. Prosenko, V. V. Nikulina, O. V. Zaytseva, *Zh. Prikl. Khim.*, 76 (2003) 261.
2 E. I. Terakh, Issledovaniye zakonomernostey vzaimosvyazi struktury i ingibiruyushchey aktivnosti v ryadakh serosoderzhashchikh alkilfenolov (Candidate's Dissertation in Chemistry), Novosibirsk, 2004.
3 V. A. Roginskiy, Fenolnye antioksidanty: reaktsionnaya sposobnost' i effektivnost', Nauka, Moscow, 1988.
4 JP Appl. 51059780, 1976.
5 EP Pat. 273864, 1988.
6 WO Pat. 02/24805, 2002.
7 F. M. Egidis, I. V. Kokhanova, Vsesoyuz. nauch.-tekhn. konf. "Sintez i issledovaniye effektivnosti khimikatyov-dobavok dlya polimernykh materilov" (Proceedings), Tambov, 1969, p. 381.
8 SU Inventor's certificate 825516, 1981.
9 JP Appl. 05323600, 1993.
10 RU Pat. 2255946, 2003.
11 SU Inventor's certificate 858306, 1979.
12 JP Appl. 2001-64220, 2001.
13 RU Pat. 1162781, 1993.
14 V. F. Tsepalov, in: Issledovaniye sinteticheskikh i prirodnykh antioksidantov *in vivo* i *in vitro*, Nauka, Moscow, 1992, p. 16.14
15 V. F. Tsepalov, A. A. Kharitonova, G. P. Gladyshev, N. M. Emmanuel, *Kinetika i Kataliz*, 18 (1977) 1267.
16 V. F. Tsepalov, A. A. Kharitonova, G. P. Gladyshev, N. M. Emmanuel, *Ibid.*, 18 (1977) 1403.
17 A. J. Kolka, J. P. Napolitano, G. G. Ecke, *J. Org. Chem.*, 21 (1956) 712.
18 P. I. Pinko, E. I. Terakh, E. A. Gorokh *et al.*, *Zh. Prikl. Khim.*, 75 (2002) 1694.
19 RU Pat. 1370952, 1993.
20 SU Inventor's certificate 1062282, 1979.
21 P. I. Pinko, Sintez, svoystva i antiokislitelnaya aktivnost' ω-(4-gidroksiaril)-alkantiolov i proizvodnykh na ikh osnove (Candidate's Dissertation in Chemistry), Novosibirsk, 2003.
22 M. A. Boyko, Vzaimosvyaz' elektrokhimicheskoy aktivnosti alkil- i tio(amino)alkilzameshchennykh fenolov s ikh stroyeniem, kislotnymi i protivookislitelnymi svoystvami (Author's abstract of Candidate's Dissertation in Chemistry), Novosibirsk, 2006.
23 A. P. Krysin, O. N. Nikulicheva, V. P. Fadeeva, E. V. Chibiryaeva, Termicheskiy analiz fenolnykh stabilizatorov polimernykh materialov (Preprint NIOCh, SB RAS), Novosibirsk, 1992.
24 JP Appl. 51059780, 1976. [C. A. 85:109822].
25 EP Pat. 273864, 1988. [C. A. 110:38718].
26 JP Appl. 05323600, 1993. [C. A. 120:311599].