

Kinetics of the Liquid-Phase Oxidation of 1,4-Dioxane in the Presence of Inhibitors

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Abstract—The kinetics of 1,4-dioxane oxidation initiated by azodiisobutyronitrile in the temperature range from 323 to 353 K are studied from the rate of oxygen absorption. The oxidation proceeds in the regime of a nonbranched chain reaction with quadratic-law chain termination. The apparent rate constants (fk_7) of 1,4-dioxane oxidation inhibition by 2,6-ditert-butyl-4-methylphenol and quercitin are measured. Quercitin is not inferior to ionol in inhibition efficiency.

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INTRODUCTION

Bioflavonoids prepared by extraction from plants [1–3] have proved to be efficient low-toxicity antioxidants. Therefore, the development of new systems for the investigation of antioxidant properties of plant extracts containing various flavonoids is an urgent task. 1,4-Dioxane can serve as a potential substrate in solving this problem. However, the literature contains no experimental data on its oxidation kinetics, which are necessary when this substrate is used as a model system in the investigation of the antioxidant properties of flavonoids. Semiempirical formulas for calculation of the rate constants of chain propagation and termination are presented only in one work [4]. In this connection, in the present work we studied the kinetics of 1,4-dioxane oxidation with atmospheric oxygen initiated by azodiisobutyronitrile.

EXPERIMENTAL

1,4-Dioxane ($C_4H_8O_2$) was purified according to an earlier described procedure [5]. Azodiisobutyronitrile (AIBN) was twice recrystallized from freshly distilled ethanol and dried in vacuo. Quercitin (3,3',4',5,7-pentahydroxyflavon) (high-purity grade) was not additionally purified. Ionol (2,6-di-*tert*-butyl-4-methylphenol) was recrystallized from ethanol, and the isolated crystals were dried and sublimed in vacuo.

Experiments were carried out in a glass reactor, which was loaded with a solution of the initiator in 1,4-dioxane and maintained at a certain temperature for several minutes. Oxygen absorption in the gas phase was monitored using a universal manometric differential setup, whose design is detailed elsewhere [6]. The

oxidation rate of 1,4-dioxane (w) was calculated from the initial portion of the oxygen absorption curve. The inhibited oxidation of 1,4-dioxane was carried out in the presence of ionol or quercitin.

Initiation rates were calculated using the equation $w_i = k_i[AIBN]$, where k_i is the initiation rate constant (s^{-1}). It was assumed in the calculation of the initiation rate that $k_i = 2ek_d$, where k_d is the AIBN decomposition rate constant and e is the probability of radical escape into the bulk. The AIBN decomposition rate constant was calculated from reference data presented for the decomposition of this initiator in cyclohexanol ($\log k_d = 17.70 - 35/(4.575T \times 10^{-3})$, $e = 0.5$) [7]. The chosen k_d value agrees satisfactorily with the rate constant of AIBN decomposition in 1,4-dioxane measured from the rate of nitrogen evolution [8] and with the rate constant of AIBN decomposition in hydrocarbon media and aromatic solvents [9].

RESULTS AND DISCUSSION

Kinetics of the Liquid-Phase Oxidation of 1,4-Dioxane

The liquid-phase oxidation of 1,4-dioxane was carried out at 323–353 K, and the AIBN concentration was varied in an interval of $(1-30) \times 10^{-3}$ mol/l. The experimental results (Table 1) indicate a linear dependence of w on $w_i^{0.5}$. The oxidation rate is independent of the oxygen concentration ($[O_2] = 2 \times 10^{-3}-10^{-2}$ mol/l). The dependence of the oxidation rate on the substrate concentration was studied in the 1,4-dioxane concentration range of 4.7–11.7 mol/l, and distilled water was used as the solvent (Table 1). A linear relationship was shown

Table 1. Dependences of the initial rate of 1,4-dioxane oxidation on the initiation rate, [RH], and temperature

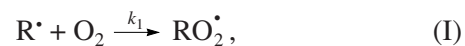
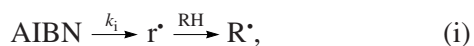
| T, K | $w_i \times 10^7, \text{mol l}^{-1} \text{s}^{-1}$ | $[RH], \text{mol l}^{-1}$ | $w \times 10^6, \text{mol l}^{-1} \text{s}^{-1}$ | $k_2(2k_6)^{-0.5} \times 10^4, \text{l}^{0.5} \text{mol}^{-0.5} \text{s}^{-0.5}$ | $k_2^*, \text{l mol}^{-1} \text{s}^{-1}$ |
|--------|--|---------------------------|--|--|--|
| 323 | 0.3 | 11.7 | 0.5 | 3.2 ± 0.2 | 11.0 |
| | 0.7 | | 1.1 | | |
| | 1.6 | | 1.5 | | |
| 333 | 0.1 | 11.7 | 0.6 | 4.4 ± 0.1 | 15.3 |
| | 0.2 | | 0.7 | | |
| | 0.5 | | 0.9 | | |
| | 1.0 | | 1.5 | | |
| | 1.1 | | 1.5 | | |
| | 1.2 | | 1.54 | | |
| | 1.3 | | 2.0 | | |
| | 6.3 | | 4.1 | | |
| | 0.3 | | 0.9 | | |
| | 1.4 | | 2.3 | | |
| 343 | 3.6 | 11.7 | 4.4 | 6.6 ± 0.3 | 21.1 |
| | 7.1 | | 6.6 | | |
| | 2.0 | | 3.2 | | |
| | 10.6 | | 2.7 | | |
| 347 | 9.4 | 11.7 | 2.4 | 5.7 ± 0.2 | 23.9 |
| | 7.0 | | 1.8 | | |
| | 4.7 | | 1.0 | | |
| | 1.0 | | 2.3 | | |
| | 1.0 | | 2.9 | | |
| 347 | 1.0 | 11.7 | 2.3 | — | — |
| 353 | 1.0 | 11.7 | 2.9 | 7.8 ± 0.2 | 28.7 |
| | 1.0 | | 2.5** | | |
| | 4.8 | | 6.7 | | |
| | 10 | | 8.7 | | |
| | 10 | | 9.4 | | |

* The constant k_2 was calculated using Eq. (2); it was assumed in the calculation that $2k_6$ is virtually temperature-independent and is $10^9 \text{ l mol}^{-1} \text{ s}^{-1}$ [17, 18].

** Oxidation was carried out in an oxygen atmosphere.

to exist between w and $[RH]$ in the concentration range examined.

Thus, under the conditions of our experiment, 1,4-dioxane is oxidized via a radical chain mechanism with quadratic-law chain termination [9–12]:



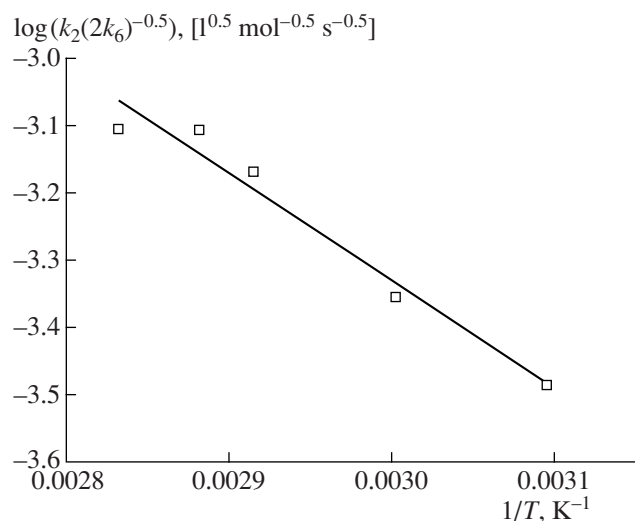


Fig. 1. Arrhenius plot of $k_2(2k_6)^{-0.5}$ ($r = 0.98$).

Here, the reactions are numbered as in the conventional scheme of liquid-phase hydrocarbon oxidation.

The experimental results obtained are satisfactorily

Table 2. Dependences of the initial rate of 1,4-dioxane oxidation on the temperature and the ionol concentration ($w_i = 1 \times 10^{-7} \text{ mol l}^{-1} \text{ s}^{-1}$)

| $T, \text{ K}$ | $[\text{InH}] \times 10^4, \text{ mol/l}$ | $w_0 \times 10^6, \text{ mol l}^{-1} \text{ s}^{-1}$ | $f k_7(2k_6)^{-0.5}, \text{ l}^{0.5} \text{ mol}^{-0.5} \text{ s}^{-0.5}$ |
|----------------|---|--|---|
| 333 | 0 | 1.5 | 0.88 ± 0.06 |
| | 0.6 | 1.4 | |
| | 0.9 | 1.3 | |
| | 1.0 | 1.5 | |
| | 1.5 | 1.2 | |
| | 1.9 | 1.3 | |
| | 2.0 | 1.0 | |
| | 2.2 | 1.0 | |
| | 4.0 | 0.8 | |
| | 4.4 | 0.9 | |
| 347 | 5.6 | 0.8 | 1.2 ± 0.07 |
| | 7.0 | 0.6 | |
| | 8.6 | 0.6 | |
| | 0 | 2.5 | |
| | 0.1 | 2.1 | |
| | 0.4 | 2.0 | |
| | 0.9 | 1.6 | |
| | 1.3 | 1.5 | |
| | 1.8 | 1.4 | |
| | 2.6 | 1.3 | |
| | 3.5 | 1.2 | |
| | 5.5 | 0.9 | |
| | 7.0 | 0.5 | |
| | 8.1 | 0.4 | |

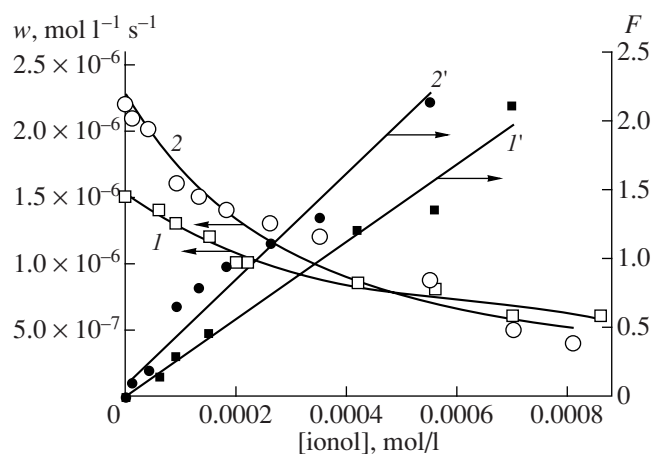


Fig. 2. Plots of (1, 2) w and (1', 2') the parameter F versus the ionol concentration: (1, 1') 333 K ($r = 0.98$) and (2, 2') 347 K ($r = 0.97$); $w_i = 1 \times 10^{-7} \text{ mol l}^{-1} \text{ s}^{-1}$.

described as follows:

$$w = k_2(2k_6)^{-0.5}[\text{RH}]w_i^{0.5}. \quad (1)$$

Hereafter, k_2 and $2k_6$ are the rate constants of chain propagation and termination on the peroxy radicals of 1,4-dioxane, respectively. The $k_2(2k_6)^{-0.5}$ values were determined from our results using Eq. (1) (Table 1). These values characterize the oxidizability of 1,4-dioxane. The temperature dependence of $k_2(2k_6)^{-0.5}$ is plotted in Fig. 1. In the 323–353 K range, this dependence in the coordinates of the Arrhenius equation is linear and is described by the expression

$$\begin{aligned} \log(k_2(2k_6)^{-0.5}) \\ = (1.5 \pm 0.5) - (30.7 \pm 2.8)/\theta, [\text{l}^{0.5} \text{ mol}^{-0.5} \text{ s}^{-0.5}]. \end{aligned} \quad (2)$$

Here $\theta = 2.303 \times 10^{-3}RT$, kJ/mol.

It should be mentioned that the value of $k_2(2k_6)^{-0.5} = 4.9 \times 10^{-4} \text{ l}^{0.5} \text{ mol}^{-0.5} \text{ s}^{-0.5}$ (333 K) is quite consistent with the value of $k_2(2k_6)^{-0.5} = 4.5 \times 10^{-4} \text{ l}^{0.5} \text{ mol}^{-0.5} \text{ s}^{-0.5}$, which was calculated by the semiempirical formulas from the strength of the C–H bonds in 1,4-dioxane [4, 9, 13, 14]. The measured oxidizability parameter also agrees well with the results obtained earlier [15]. The difference between the $k_2(2k_6)^{-0.5}$ value measured at 303 K [16] and our data can be due to the error associated with the extrapolation procedure.

The chain propagation rate constants k_2 are given in Table 1. Since the recombination rate constants of the peroxide radicals of 1,4-dioxane in the medium of the substrate itself was not measured, in the calculations we took $2k_6 = 10^9 \text{ l mol}^{-1} \text{ s}^{-1}$, relying on the $2k_6$ data measured in an aqueous medium [17, 18].

Antioxidant Activity of Inhibitors

A series of experiments on the dependence of the rate of 1,4-dioxane oxidation in the presence of ionol on its concentration was carried out to determine the efficiency of ionol as the inhibitor. The reaction was carried out in 1,4-dioxane in an air atmosphere. The introduction of ionol into the substrate being oxidized decreases the rate of oxygen absorption due to the appearance of an additional channel of peroxy radical consumption via reaction (VII):



As follows from the experimental data (Table 2), the presence of ionol in 1,4-dioxane being oxidized shortens the chain length to $\geq 6-5$ units and, hence, the chain regime is retained. To determine the quantitative characteristics of the antioxidant activity of ionol, we used Eq. (3), which is valid for the reactions with long chains [19]:

$$F = w/(w_0 - w_i) - (w_0 - w_i)/w = fk_7[\text{InH}](2k_6w_i)^{-0.5}, \quad (3)$$

where F is the inhibition effect parameter; w and w_0 are the initial rates of oxygen absorption in the absence and presence of the antioxidant, respectively; $[\text{InH}]$ is the initial antioxidant concentration; $2k_6$ and fk_7 are the rate constants of termination of the oxidation chain via the recombination of the peroxy radicals of 1,4-dioxane and their decay via the reaction with the antioxidant, respectively; and f is the stoichiometric inhibition coefficient.

The experimental results (Table 2) obtained for the oxidation of 1,4-dioxane in the presence of ionol are satisfactorily described by Eq. (3) (Fig. 2). The inhibition rate constant $fk_7 = 2.8 \times 10^4 \text{ l mol}^{-1} \text{ s}^{-1}$ at 333 K, obtained by us under conditions such that $2k_6 = 10^9 \text{ l mol}^{-1} \text{ s}^{-1}$ [17, 18], agrees well with the known rate constant $fk_7 = 2 \times 10^4 \text{ l mol}^{-1} \text{ s}^{-1}$ [20].

An analysis of the kinetics of the initiated chain oxidation of 1,4-dioxane in the presence of ionol suggests that our results are reliable and makes it possible to use this system as a model reaction in the study of the antioxidant efficiency of natural water-soluble compounds.

The antioxidant efficiency of quercetin was studied in the model system of the liquid-phase oxidation of 1,4-dioxane ($T = 333$ and 347 K , $w_i = 1 \times 10^{-7} \text{ mol l}^{-1} \text{ s}^{-1}$). Experimental data, namely, the change in the oxidation rate upon the addition of quercetin (Table 3), were processed using Eq. (3). As a result, we obtained satisfactory linear relationships between the parameter F and the quercetin concentration (Fig. 3), which made it possible to calculate $fk_7(2k_6)^{-0.5}$ (Table 3).

The $fk_7(2k_6)^{-0.5}$ values measured by us in the above-described model system with ionol are compared in Table 4 with the known data obtained for other model systems. The results of studying the inhibition effi-

Table 3. Dependence of the initial rate of 1,4-dioxane oxidation on the quercetin concentration ($w_i = 1 \times 10^{-7} \text{ mol l}^{-1} \text{ s}^{-1}$)

| $T, \text{ K}$ | $[\text{InH}] \times 10^4, \text{ mol/l}$ | $w_0 \times 10^7, \text{ mol l}^{-1} \text{ s}^{-1}$ | $fk_7(2k_6)^{-0.5}, \text{ l}^{0.5} \text{ mol}^{-0.5} \text{ s}^{-0.5}$ |
|----------------|---|--|--|
| 333 | 0.0 | 13.7 | 1.5 ± 0.03 |
| | 1.5 | 10.2 | |
| | 2.3 | 8.7 | |
| | 2.4 | 8.1 | |
| | 3.6 | 6.3 | |
| | 4.6 | 4.7 | |
| | 6.0 | 4.2 | |
| | 8.0 | 3.4 | |
| | 12.0 | 1.8 | |
| 347 | 18.0 | 1.5 | |
| | 0.0 | 21.1 | 2.3 ± 0.11 |
| | 1.2 | 14.3 | |
| | 2.0 | 12.9 | |
| | 3.0 | 8.6 | |
| | 4.0 | 6.9 | |
| | 6.0 | 4.4 | |
| | 7.0 | 3.1 | |

ciency of quercetin obtained in other model systems are also given for comparison in Table 4.

The rate constants of the reaction of the peroxy radical of 1,4-dioxane with quercetin are $fk_7 = 5.1 \times 10^{-4} \text{ l mol}^{-1} \text{ s}^{-1}$ (333 K) and $7.6 \times 10^{-4} \text{ l mol}^{-1} \text{ s}^{-1}$

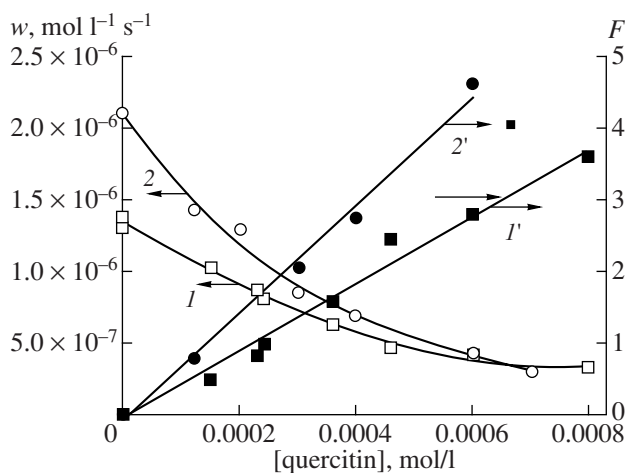


Fig. 3. Plots of ($I, 2$) the initial rate of 1,4-dioxane oxidation and ($I', 2', r = 0.99$) the inhibition efficiency parameter versus the quercetin concentration at (I, I') 333 and ($2, 2'$) 347 K; $w_i = 1 \times 10^{-7} \text{ mol l}^{-1} \text{ s}^{-1}$.

Table 4. Dependence of the antioxidant activity of ionol and quercetin on the substrate nature

| Inhibitor | T, K | Substrate | $fk_7(2k_6)^{-0.5}$, $l^{0.5} \text{ mol}^{-0.5} \text{ s}^{-0.5}$ | $fk_7 \times 10^{-4}$, $l \text{ mol}^{-1} \text{ s}^{-1}$ |
|-----------|------|--|--|--|
| Ionol | 333 | 1,4-Dioxane | 0.88 | 2.8* |
| Ionol | 347 | 1,4-Dioxane | 1.2 | 3.8* |
| Quercitin | 333 | 1,4-Dioxane | 1.6 | 5.1* |
| Quercitin | 347 | 1,4-Dioxane | 2.4 | 7.6* |
| Quercitin | 331 | Ethylbenzene | 6.75 [21] | 2.9** |
| Quercitin | 323 | Methyl linoleate in chlorobenzene solution | – | 43 [23] |
| Quercitin | 323 | Methyl linoleate in tertbutyl alcohol solution | – | 2.1 [23] |
| Ionol | 348 | Isopropyl alcohol | – | 10 [24] |
| Quercitin | 348 | Isopropyl alcohol | – | 25 [24] |

* In the calculation, it was assumed that $2k_6 = 10^9 \text{ l mol}^{-1} \text{ s}^{-1}$ [17, 18].

** In the calculation, it was assumed that $2k_6 = 1.9 \times 10^7 \text{ l mol}^{-1} \text{ s}^{-1}$.

(247 K). As can be seen from the data presented, the inhibition activity of quercetin is approximately two times higher than that of the standard inhibitor ionol.

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