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CHEMICAL THERMODYNAMICS AND THERMOCHEMISTRY

The Thermolysis of α-Pinene and Verbenone Epoxides in Supercritical Solvents

V. I. Anikeev[a], I. V. Il'ina[b], K. P. Volcho[b], A. Ermakova[a], and N. F. Salakhutdinov[b]

[a] *Boreskov Institute of Catalysis, Siberian Division, Russian Academy of Sciences,*
pr. Akademika Lavrent'eva 5, Novosibirsk, 630090 Russia

[b] *Vorozhtsov Institute of Organic Chemistry, Siberian Division, Russian Academy of Sciences, Novosibirsk, Russia*

e-mail: anik@catalysis.nsk.su

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Abstract—Thermal transformations of α-pinene and verbenone epoxides were studied in supercritical solvents with complex compositions, including CO_2, lower alcohols (ethanol and isopropanol), and water, over the temperature and pressure ranges 387–575 K and 135–215 atm. The main product from α-pinene epoxide in a supercritical solvent containing water was campholenic aldehyde and pinocamphone; the total content of these products in the reaction mixture was 80%. Suggestions concerning the mechanism of the thermal isomerization of α-pinene epoxide depending on the acidity of supercritical solvents were made. The direction of verbenone epoxide transformations was independent of the presence of water in the mixture. The main identified products were ketoalcohols with *para*-menthane and camphane frameworks.

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INTRODUCTION

Monoterpenoids are widespread in nature and are valuable renewable raw material for pharmaceutical and cosmetic industries and the production of gustatory additives, pesticides, etc. [1, 2]. Many transformations leading to the production of valuable substances from monoterpenes and their derivatives are related to acid-catalyzed skeletal rearrangements [3]. At the same time, monoterpenoids, as a rule, experience many transformations in acid media and give complex mixtures of products, which decreases the effectiveness of their technological applications on the one hand and imposes severe requirements on selective catalysts on the other. For instance, transformations of α-pinene epoxide in acid media can produce 200 different compounds in addition to the desired product, campholenic aldehyde, which is a key compound in the synthesis of many fragrant substances [4].

Reactions based on terpenoid transformations in supercritical solvents are an alternative to the methods applied currently. Studies of the thermolysis of α- and β-pinene monoterpenes and sulfate turpentine in supercritical lower alcohols showed that, when monoterpenes react in supercritical solvents, the rate of their transformations increases substantially compared with similar reactions in the gas or liquid phases [6–10]. At the same time, the reactivity of such labile compounds as terpenoid epoxides has not been studied in supercritical solvents.

In this work, we for the first time studied the transformations of α-pinene and verbenone epoxides in supercritical two-component solvents containing CO_2 and ethanol or isopropanol and certain amounts of water if necessary. The use of supercritical CO_2 allowed us to decrease the critical temperature of the solvent compared with that of, for instance, water or lower alcohols. The reaction could therefore be performed under supercritical conditions at a lower temperature.

EXPERIMENTAL

We used (-)-α-pinene epoxide (ACROS ORGANICS) containing 95.0% major component. Verbenone epoxide was synthesized by the epoxidation of verbenone with hydrogen peroxide in the presence of NaOH as recommended in [11]; the content of the major component was no less than 98.0%.

Experimental studies of α-pinene and verbenone epoxide transformations were performed on a laboratory unit [6–10, 12] with the use of tubular reactors 3 and 6 m long with an inside diameter of 1.75 mm (reactor volumes were 7.2 and 14.4 cm^3). Reaction mixtures were supplied to the reactors in two flows. The first flow was supercritical CO_2; it was introduced into a mixer by a syringe pump situated at the entrance of the reactor through a heat exchanger, where it was heated to the temperature of the reaction. CO_2 flow rate varied from 2.5 to 4.0 ml/min. The second flow was a mixture of α-pinene or verbenone epoxide with a solvent (alcohol); it was introduced into the same mixer by a piston pump. The molar ratio between α-pinene or verbenone epoxide, alcohol, and water was ~1 : 89.4 : 9.6, respectively.

The mixture was introduced into the reactor at a 1 ml/min rate. As a result, for instance, at a CO_2 flow rate of 2.5 ml/min, the molar ratio between the components of the mixture fed into the reactor was CO_2 : α-pinene (verbenone) epoxide : alcohol : water = 77 : 0.3 : 20.5 : 2.2.

The reaction mixture at the exit of the reactor was cooled and analyzed. The composition of reaction products in the liquid phase was determined by chromato-mass spectrometry on a Hewlett-Packard 5890/II gas chromatograph with an HP MSD 5971 quadrupole mass spectrometer as a detector. Analyses were performed using an HP-5 quartz column (5% diphenyl–95% dimethylsiloxane copolymer) 30 m long with a 0.25 mm inside diameter and a 0.25 μm stationary phase film thickness.

The contact time τ of the reaction mixture was calculated as the ratio between reactor volume V_R (cm^3) and the total mixture flow rate at the entrance of the reactor Q (cm^3/s). The thermolysis of epoxides was performed over the temperature and pressure ranges 160–250°C and 135–215 atm.

The critical parameters of the mixture and the conditions (temperature and pressure) under which the mixture in the reactor was in the single-phase supercritical state were determined by performing thermodynamic calculations. We constructed phase diagrams for the known initial mixture compositions and found the T_{cr} and p_{cr} critical values (Table 1). The summed fraction of CO_2 and alcohol in the initial mixtures was more than 0.95 and almost did not change during the reactions. We therefore assumed that the position of the critical point changed insignificantly during the thermolysis of α-pinene and verbenone.

RESULTS AND DISCUSSION

Water in the critical parameter region is in the strongly dissociated state [12, 13] and can exhibit the properties of an acid or basic catalyst, which is advantageous for certain chemical transformations [14, 15]. With α-pinene or verbenone epoxide rearrangements, the addition of water to a supercritical solvent creates acid properties of the system. We can therefore expect the formation of the products of acid catalyzed transformations of the epoxides.

The Isomerization of α-Pinene Epoxide

At the first stage, we studied the isomerization of α-pinene epoxide in a solvent containing CO_2, ethanol, and water in the supercritical state. Table 2 (experiments nos. 1–5) shows that, as expected, an increase in reaction temperature at constant contact time and pressure increased the degree of α-pinene epoxide transformation. The main identified products were campholenic aldehyde and carveol. Smaller amounts of pinocamphone and isocampholenic aldehyde were also detected. The reaction was accompanied by the formation of other substances such as high-molecular-weight oligomers, the content of which increased as the temperature grew. The formation of all the identified compounds was in close agreement with modern views on the directions of α-pinene epoxide transformations in the presence of acids [3].

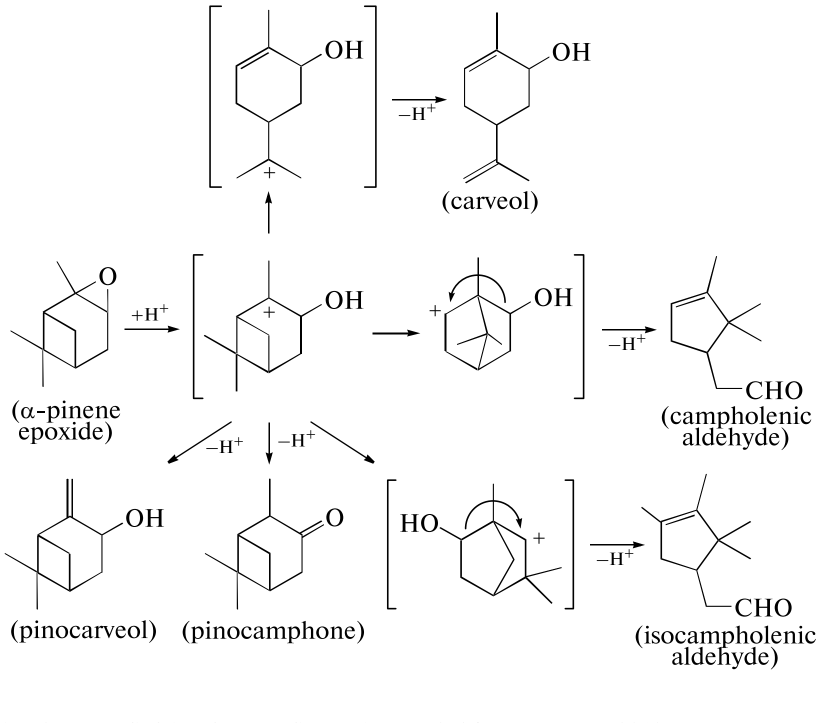


Table 1. Critical parameters of the mixtures under study

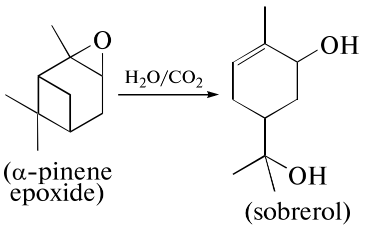
Component	Content, mol %					T_{cr}, K	P_{cr}, atm
	CO_2	C_2H_5OH	C_3H_7OH	H_2O	$C_{10}H_{16}O$		
1	71.3	24.0	0	4.2	0.5	413.4	169.7
2	81.8	15.4	0	2.6	0.2	372.8	152.3
3	77.2	0	20.5	2.2	0.28	399.6	146.9
4	78.55	0	20.95	0	0.5	396.8	145.8

Table 2. Results of the thermolysis of α-pinene epoxide in supercritical solvents

No.	T, K	P, atm	Product composition, mol %						
			α-pinene epoxide	campholenic aldehyde	pinocamphone	isocampholenic aldehyde	carveol	pinocarveol	other products
Ethanol, H_2O									
1	387	140	87.5	3.7	0.8	0.6	2.4	–	5.0
2	420	140	78.5	7.5	0.7	0.8	5.0	–	7.5
3	453	140	68.2	7.1	0.8	0.7	3.1	–	20.1
4	453	140	63.3	8.5	0.6	0.9	3.5	–	23.2
5	453	140	85.1	4.9	0.8	0.7	1.1	–	7.4
Isopropanol, H_2O									
6	486	175	80.8	9.9	1.6	3.1	1.7	–	2.9
7	513	180	80.1	10.6	2.5	3.2	1.7	–	1.9
8	513	215	75.9	13.1	3.2	3.8	2.0	–	2.0
9	438	140	78.6	9.6	2.7	2.3	4.5	–	2.3
10	455	140	67.2	17.6	2.8	3.1	4.1	1.3	3.9
11	485	140	42.9	26.3	5.3	6.2	10.5	2.9	5.9
12	500	140	2.2	47.5	14.0	13.7	2.1	1.6	18.9
Isopropanol									
13	465	135	51.6	28.7	10.3	5.2	–	2.5	1.7
14	520	135	–	54.1	25.5	8.3	4.0	4.6	3.5
15	575	135	–	37.1	20.2	11.9	5.2	1.4	24.2

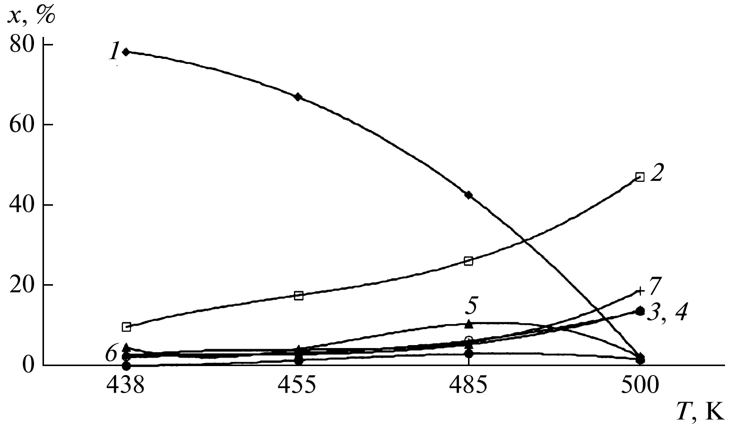
Note: τ = 120 s in experiments nos. 1–8 and 240 s in the other experiments. CO_2 flow rate was 3.5 and 4.5 ml/min in experiment nos. 4 and 5 and 25 ml/min in the other experiments. Mixture flow rate was 1 ml/min.

As with the thermal isomerization of monoterpenoids [7–9] in supercritical lower alcohols, ethanol remained unreacted and stable; that is, the products of the addition of alcohol or water were not observed. Also note that sobrerol was not found in reaction products. Sobrerol is known [16] to form in the reaction of α-pinene epoxide with water saturated with carbon dioxide at normal pressure and temperature (16–25°C),



An increase in the flow rate of supercritical CO_2 from 2.5 to 3.5 ml/min (the other parameters being equal) insignificantly increases the conversion of α-pinene epoxide (Table 2, nos. 3, 4). An increase in CO_2 flow rate to 4.5 ml/min substantially decreases the degree of α-pinene transformations (Table 2, nos. 4, 5) because of a decrease in the contact time of the reaction mixture.

The replacement of ethanol used as a solvent with isopropanol considerably increased the selectivity of the process with respect to campholenic aldehyde (Table 2, nos. 6, 7), but the degree of α-pinene epoxide conversion at the same contact time and even a higher temperature decreased noticeably. Note that, conversely, the conversion of α-pinene in thermal isomerization in various supercritical lower alcohols [6] increases as the length of alcohol hydrocarbon chains grows.



Changes in the content (x) of α-pinene epoxide and reaction products depending on temperature: (*1*) α-pinene epoxide, (*2*) campholenic aldehyde, (*3*) pinocamphone, (*4*) isocampholenic aldehyde, (*5*) carveol, (*6*) pinocarveol, and (*7*) other products. Reaction conditions: isopropanol–CO_2–water mixture, pressure 140 atm, contact time 240 s.

We did not perform special studies of the influence of supercritical solvent pressure on the rate and selectivity of α-pinene epoxide transformations. Nevertheless, a comparison of the data obtained in two experiments (Table 2, nos. 7, 8) performed at the same temperature but different pressures (180 and 215 atm) shows that an increase in pressure slightly increases the degree of transformation of initial α-pinene epoxide.

An increase in the reaction mixture contact time by two times (an increase in the length of the reactor) allowed us to obtain an almost complete conversion of α-pinene epoxide over the same temperature range (Table 2, nos. 9–12) on the one hand and gave grounds to claim the reaction to be substantially irreversible on the other. Moreover, selectivity with respect to the desired product, campholenic aldehyde, then approached 50% (Table 2, no. 12). Pinocamphone and isocampholenic aldehyde were also formed in substantial amounts (~14%). Note that pinocarveol, not observed at shorter contact times, was also identified in the reaction mixture.

According to the temperature dependences of the mole fractions of α-pinene epoxide and reaction products, the degree of α-pinene epoxide transformation sharply increases as the temperature rises from 438 to 500 K. At the same time, temperature variations do not noticeably influence selectivity with respect to the main transformation products, with the exception of a decrease in the relative content of carveol as the reaction temperature increases from 485 to 500 K. A decrease in the fraction of carveol can be caused by secondary reactions of its isomerization, which is substantiated by an increase in the content of other not identified products in the reaction mixture.

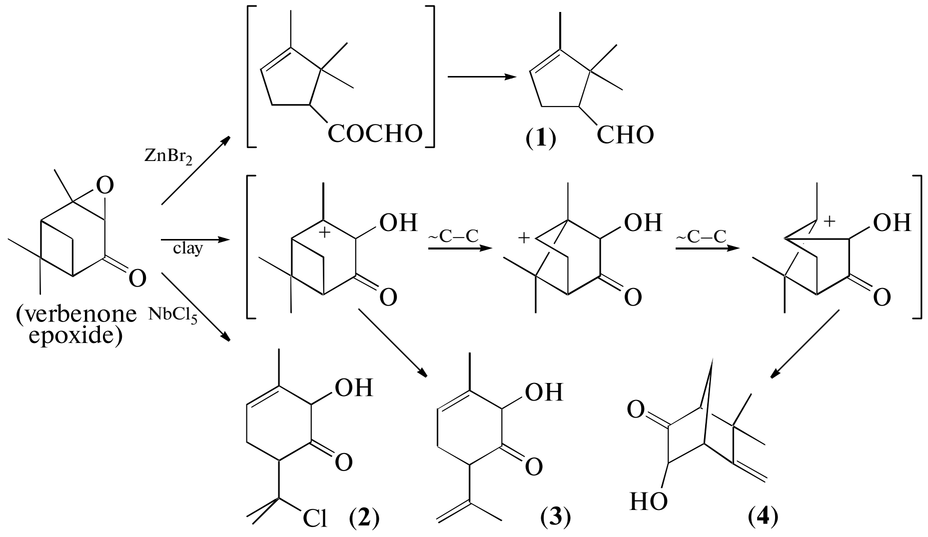
To determine the influence of water on the mechanism of the reaction, we studied α-pinene epoxide transformations in a supercritical solvent only comprising CO_2 and isopropanol. The results were compared with those given above. The same isomerization products were formed in the absence of water, earlier believed to be responsible for the appearance of the acid properties of the supercritical solvent that we used, as in its presence (Table 2, nos. 13, 14). The only substantial difference was a sharp increase in the content in the reaction mixture of compounds with a not opened pinane skeleton, pinocamphone and pinocarveol; their total content was higher than 30%. Note that pinocamphone is a valuable initial compound for the preparation of chiral ligands [17, 18] and has noticeable biological activity [19].

An increase in reaction temperature from 520 to 575 K decreased the fraction of campholenic aldehyde and pinocamphone, probably, because of their transformations into other products (Table 1, no. 15).

In [20], the thermal isomerization of α-pinene epoxide was studied in an autoclave at 533–567 K. Reaction duration was 8–16 h. It was shown that the main low-molecular-weight product was pinocamphone (yield up to 14%); the reaction was accompanied by considerable resinification (up to 33 wt %). The structure of the products of α-pinene epoxide transformations in supercritical solvents and the literature data on the reactivity of α-pinene epoxide under "usual" conditions [3, 20] lead us to suggest that, in the absence of water, two types of processes occur in parallel in the isopropanol– CO_2 system. These are the thermal isomerization of α-pinene epoxide into pinocamphone and acid-catalyzed isomerization into campholenic aldehyde, pinocamphone, and other substances. Just in these series of experiments (see Table 2, nos. 14, 15), the largest content of campholenic aldehyde (up to 54.1%) was observed.

The Isomerization of Verbenone Epoxide

Verbenone epoxide differs from α-pinene epoxide by the presence of the oxo group,



In acid media, the direction of its transformations substantially depends on the nature of the acid catalyst. For instance, in the presence of $ZnBr_2$, verbenone epoxide transforms into aldehyde **1** formed through the detachment of the CO molecule from an intermediate analogue of campholenic aldehyde [21]. With $NbCl_5$, the formation of chlorine-containing compound **2** with a *para*-menthane skeleton was observed [22]. Holding verbenone epoxide with montmorillonite clay resulted in the formation of α-ketoalcohols **3** and **4** [11].

Transformations of verbenone epoxide were studied in a supercritical solvent containing CO_2, isopropanol, and water at a constant pressure and variable temperature. The results are represented by two series of experiments (Table 3). In the first series, the thermolysis of verbenone epoxide was performed with the participation of water. In the second series, water was absent.

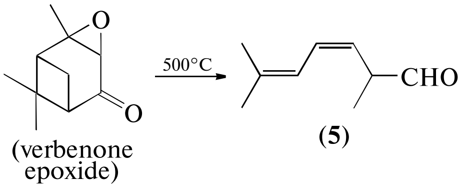
In all the cases, the main identified products were ketoalcohols with the *para*-menthane and camphane frameworks, namely, 2-hydroxy-6-isopropenyl-3-methylcyclohex-3-enone (**3**) and 3-hydroxy-6,6-dimethyl-5-methylenebicyclo[2.2.1]heptane-2-one (**4**). The absence of compound **1** with the cyclopentane framework was unexpected, because the formation of substances with the cyclopentane framework (campholenic and isocampholenic aldehydes) was the main process in α-pinene transformations in supercritical solvents (Table 2).

Table 3. Verbenone epoxide thermolysis products in supercritical solvents at various temperatures according to the chromato-mass spectrometry data, $p = 140$ atm

No.	T, K	Content of mixture components, mol %			
		verbenone epoxide	**3**	**4**	other products
1	462	90.87	1.06	2.83	5.24
2	513	36.56	6.18	14.20	43.06
3	468	82.48	1.32	4.15	12.05
4	513	34.46	7.15	15.95	42.44

Note: The reaction was performed in a solvent containing CO_2 and isopropanol in experiment nos. 1 and 2 and in a solvent containing CO_2, isopropanol, and water in experiment nos. 3 and 4.

Also note that reaction products did not contain 2,6-dimethyl-3,5-heptadienal **5**, which was the main product of the pyrolysis of verbenone epoxide studied in [23] (773 K, contact time 0.5 s, residual pressure 200 torr),



It follows from Table 3 that the presence of water in the supercritical solvent has no substantial influence on the quantitative and qualitative product composition. Only some increase in the yield of products with retention of selectivity is observed. Note that the absence of noticeable water influence on the direction of transformations of such a labile compound under acid conditions as verbenone epoxide is quite unexpected.

Verbenone epoxide transformations were accompanied by the formation of “other products,” namely, unidentified compounds, whose fraction in reaction mixtures exceeded the total amount of compounds **3** and **4**. Although the number of unidentified products reached eight, three of them were the main ones. The molecular weights of all the three substances was 166; that is, they, like compounds **3** and **4**, are verbenone epoxide isomerization products and are not oligomers.

To summarize, we for the first time studied the thermal transformations of α-pinene and verbenone epoxides in supercritical solvents with complex compositions comprising CO_2, lower alcohols, and water over the temperature and pressure ranges 387–575 K and 135–215 atm. We showed that, in the presence of ethanol in the supercritical solvent (CO_2, alcohol, water), the degree of α-pinene epoxide conversion was higher than in the presence of isopropanol, but selectivity with respect to the desired product (campholenic aldehyde) was substantially lower. In both systems containing water, campholenic aldehyde and carveol were the main identified products.

When the thermolysis of α-pinene epoxide was performed in isopropanol in the absence of water, its selective transformation into campholenic aldehyde (the main product) and pinocamphone was observed. The total content of these products in the reaction mixture was up to 80%. The composition of the products led us to suggest that the thermal isomerization of α-pinene epoxide and its acid-catalyzed isomerization then occurred in parallel.

As distinct from α-pinene epoxide, verbenone epoxide transformations in supercritical solvents occur almost identically irrespective of the presence of water to produce compounds with the *para*-menthane and camphane frameworks as identified products. It was shown that α-pinene and verbenone transformations in supercritical solvents with various compositions can be treated as new methods for the preparation of the desired isomerization products in short (up to 4 min) contact times in a continuous mode.

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