

# Co(II)-catalysed oxidation of $\alpha$ -pinene by molecular oxygen Part IV

Marja K. Lajunen\*, Maria Myllykoski, Janne Asikkala

Department of Chemistry, University of Oulu, Linnanmaa, P.O. Box 3000, FIN-90014 Oulu, Finland

Received 13 August 2002; accepted 2 December 2002

## Abstract

This paper reports the results of studies related to air oxidations of (–)- $\alpha$ -pinene, catalysed by plain Co(II) salts without a sacrificial co-oxidant. CoCl<sub>2</sub>, CoBr<sub>2</sub>, Co(OAc)<sub>2</sub> and Co(NO<sub>3</sub>)<sub>2</sub>-catalysed air oxidations were performed at 60, 80 or 100 °C. The favourable effect of a small amount of *tert*-butyl hydroperoxide or glacial acetic acid on these air oxidations is discussed. © 2002 Elsevier Science B.V. All rights reserved.

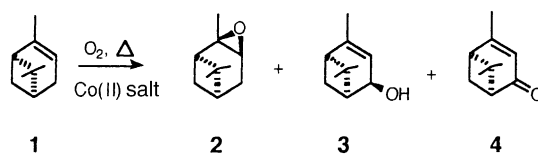
**Keywords:** Air oxidation; Co(II) catalyst;  $\alpha$ -Pinene; *t*-BuOOH

## 1. Introduction

$\alpha$ -Pinene (**1**) is a valuable starting material, e.g. for its important oxidation products pinene oxide (**2**) and verbenone (**4**). We have studied air oxidation of (–)- $\alpha$ -pinene (**1**) in order to improve the preparation of the allylic oxidation product verbenone (**4**). Our interest in this  $\alpha,\beta$ -unsaturated ketone is related to its use as a building block of Taxol™ A-ring [1,2].

Our recent paper on air oxidation of (–)- $\alpha$ -pinene (**1**), catalysed by Co(II) pyridine complexes under solvent-free conditions, reported that air oxidations in which the catalyst was a ready-made complex or was generated from its components, Co(II) salt and a derivative of pyridine in situ, proceeded equally well [3]. A literature survey of air oxidations catalysed by Co(II) salts revealed that Co(II) salts were mainly used for air oxidations of aromatic hydrocarbons to carboxylic acids and often the catalyst was a multi-metal

compound or a Co(II) halide or acetate in the presence of an alkali metal halide [4–12]. The most studied catalyst in these systems was Co(OAc)<sub>2</sub> [5,7,13,14]. This inspired us to study the catalytic activity of plain CoCl<sub>2</sub>, CoBr<sub>2</sub>, Co(OAc)<sub>2</sub> and Co(NO<sub>3</sub>)<sub>2</sub> in (–)- $\alpha$ -pinene air oxidation by looking out the yield of verbenone (**4**), and to compare their catalytic activity to the activity of [Co(4-methylpyridine)<sub>2</sub>Br<sub>2</sub>], hereafter [Co(4-mepy)<sub>2</sub>Br<sub>2</sub>].



During our studies with Co(II) pyridine complexes, we found that a small amount of glacial acetic acid or *tert*-butyl hydroperoxide promoted air oxidation [15,16]. Therefore, we wanted to study the effect of these reagents in connection with Co(II) salts, too. In this report, the results of (–)- $\alpha$ -pinene air oxidations catalysed by cobalt(II) halide, acetate or nitrate,

\* Corresponding author. Tel.: +358-8-5531632;

fax: +358-8-5531629.

E-mail address: [marja.lajunen@oulu.fi](mailto:marja.lajunen@oulu.fi) (M.K. Lajunen).

and the effects of *tert*-butyl hydroperoxide and glacial acetic acid on these air oxidations, are presented.

## 2. Experimental

### 2.1. Reagents

Cobalt(II) salts and (–)- $\alpha$ -pinene (99%) were purchased from Aldrich and Fluka, respectively, and used as such. *tert*-Butyl hydroperoxide (70%, the remainder water, Aldrich) was extracted by  $\text{CH}_2\text{Cl}_2$  and the organic phase was dried by refluxing with a Dean–Stark trap [17]. (**Caution: Please note, peroxides may explode during distillation.**) Anhydrous *t*-BuOOH was stored over molecular sieves (3 Å) in the refrigerator. Solvents were dried and distilled using standard methods. Oxygen flow was controlled by Brooks Mass Flow Meter Model 5850TR. Progress of the reaction was monitored by TLC (on silica gel 60 F<sub>254</sub> plates from Merck) and GC (Perkin-Elmer AutoSystem XL<sup>TM</sup>, column OV-1701, length 25 m, i.d. 0.25 mm, phase layer 0.25  $\mu\text{m}$ ). The TLC chromatograms were visualized by UV light and staining with an ethanolic anisaldehyde/glacial acetic acid/ $\text{H}_2\text{SO}_4$  reagent. Reaction temperatures refer to bath temperatures.

### 2.2. A typical air oxidation experiment

(–)- $\alpha$ -Pinene (3.0 ml, 25.2 mmol) air oxidation was performed in a thermostated glass reactor (bath 60–100 °C) equipped with a gas inlet in the bottom and a reflux condenser. The Co(II) catalyst (0.15 mol %) was added and molecular oxygen was passed through the reactor (5 ml/min) under atmo-

spheric pressure. Glass beads (diameter 2 mm, 5 ml) in each reactor worked as oxygen dispensers.

Air oxidation products were identified by comparison with the authentic samples derived from our earlier studies [3,15]. Products were not isolated or separated at this time. We were interested in a relative percentage of main components determined by GC analysis. Peaks over 0.8% in size were included in calculations.

## 3. Results and discussion

### 3.1. Co(II) salts versus complexes in air oxidation of (–)- $\alpha$ -pinene

$\text{CoCl}_2$ -,  $\text{CoBr}_2$ -,  $\text{Co(OAc)}_2$ - or  $\text{Co(NO}_3)_2$ -catalysed (–)- $\alpha$ -pinene air oxidations were performed at 60, 80 or 100 °C. The amount of the catalyst was 0.15 mol % and the oxygen flow 5 ml/min. For comparison, one reactor contained  $[\text{Co(4-mepy)}_2\text{Br}_2]$  as a catalyst and the other plain (–)- $\alpha$ -pinene without a catalyst. At the lowest temperature, 60 °C, the cobalt(II) salts did not catalyse air oxidation at all after 23 h, while the  $[\text{Co(4-mepy)}_2\text{Br}_2]$ -catalysed reaction produced 17% of pinene oxide (2), 10% of *trans*-verbenol (3) and 27% of verbenone (4). The plain (–)- $\alpha$ -pinene without a catalyst did not react either. The same air oxidations were performed at 80 °C and Co(II) salts were practically inactive. Only  $\text{Co(OAc)}_2$  or  $\text{Co(NO}_3)_2$  showed slight signs of catalytic activity after 23 h. The reaction temperature was raised to 100 °C and the same air oxidations were repeated. At this temperature, all the salts catalysed the reaction,  $\text{Co(NO}_3)_2$  and  $\text{Co(OAc)}_2$  being the most active ones (Fig. 1). Presumably, the detected catalytic activity

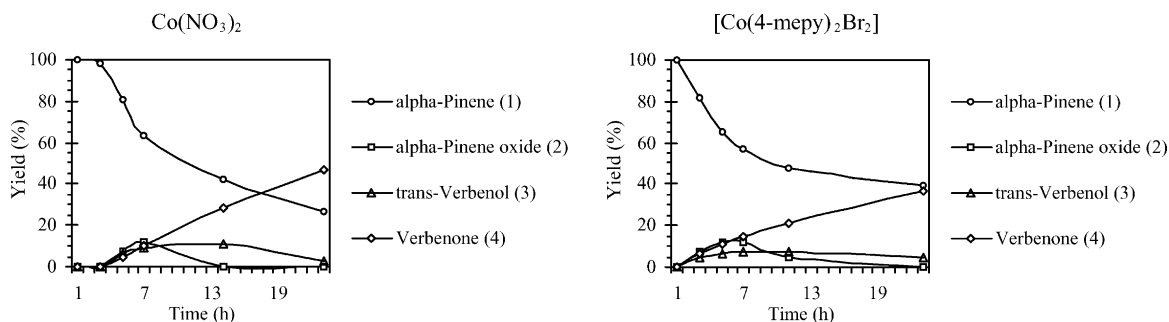


Fig. 1. Air oxidation of (–)- $\alpha$ -pinene catalysed by  $\text{Co(NO}_3)_2$  and Co(II) complex at 100 °C.

consisted partly of autoxidation of  $\alpha$ -pinene at 100 °C because the uncatalysed reaction produced verbenone as well [16]. Salts compared to  $[\text{Co}(4\text{-mepy})_2\text{Br}_2]$  produced proportional or better yields of verbenone, but they initiated air oxidation more slowly than the complex. The product distribution was similar regardless of whether the air oxidations were catalysed by a Co(II) salt or by a complex [3]. The yield of pinene oxide was the highest with  $\text{Co}(\text{OAc})_2$ , but all salts, as well as the above Co(II) complex, resulted in its rearrangement to  $\alpha$ -campholene aldehyde and other minor products during the reaction [3].

### 3.2. *tert*-Butyl hydroperoxide in connection with Co(II) salts

In a recent paper, it was reported that a small amount (11.5 mol %) of *tert*-butyl hydroperoxide (*t*-BuOOH) had a useful influence upon (–)- $\alpha$ -pinene air oxidation at mild temperatures [16]. Therefore, a known amount of *t*-BuOOH was added to the air oxidation mixture, and its effect was compared with a reaction without it. Air oxidations were performed as before at 60, 80 and 100 °C. The same Co(II) salts or com-

plex were used as catalysts. In addition to these, 0.5 ml (11.5 mol %) of *t*-BuOOH was added into each reactor. The addition of hydroperoxide instantly started air oxidation and speeded it up with every catalyst and at each temperature. Results for the air oxidation catalysed by  $\text{Co}(\text{NO}_3)_2$  are presented in Fig. 2. The use of *t*-BuOOH also led to less further rearrangement of pinene oxide. The aid of *t*-BuOOH was the most significant with Co(II) salts at 60 °C, where salts in the absence of *t*-BuOOH had no catalytic activity at all. An increase of the temperature to 80 °C still accelerated the air oxidation, but at 100 °C the reaction rate steadied or slightly decreased, except for  $\text{Co}(\text{NO}_3)_2$ , with which the rate of air oxidation still increased.  $\alpha$ -Pinene air oxidation with *t*-BuOOH (10 mol %) but without a catalyst at 60 °C resulted in a slow oxidation yielding 8% of verbenone (4) in 23 h (Fig. 2). Thus, the hydroperoxide, as such, had a minor effect and the accelerating effect of *t*-BuOOH is a consequence of its reaction with cobalt(II) salt.

Air oxidation of (–)- $\alpha$ -pinene in the presence of *t*-BuOOH seems to follow a similar mechanism whether the catalyst is Co(II) salt or a complex [16]. The role of the Co(II) compound is to accomplish the

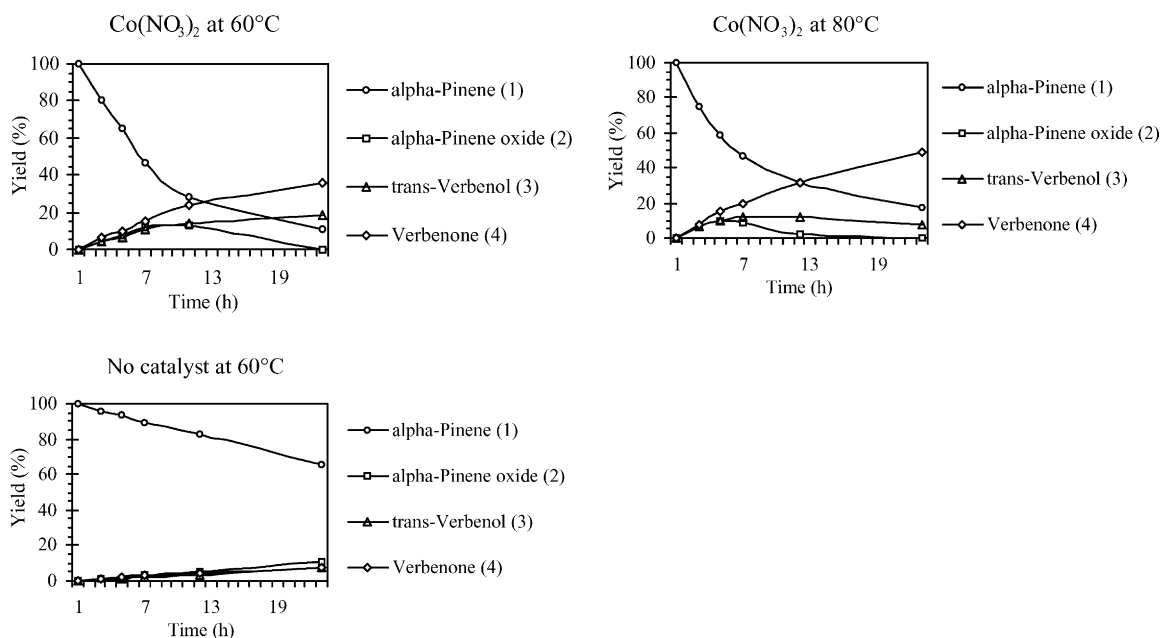
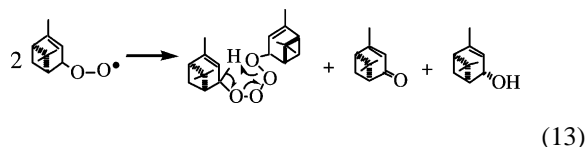
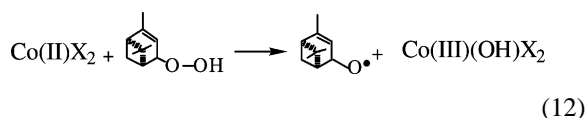
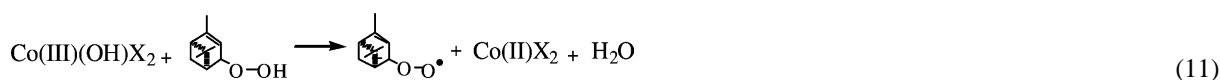
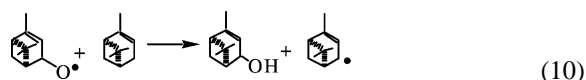
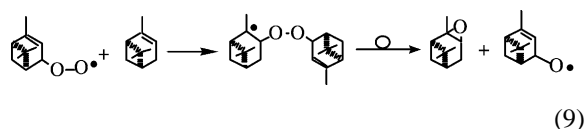
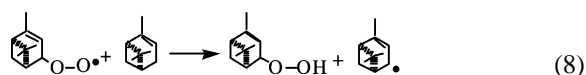
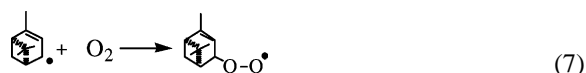
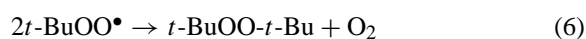
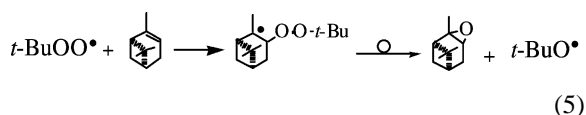
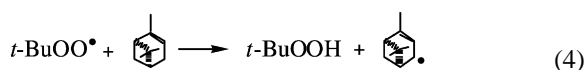
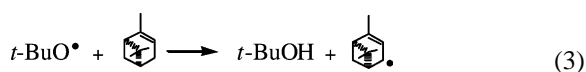
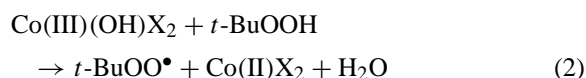
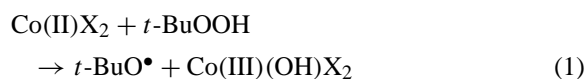


Fig. 2. *tert*-Butyl hydroperoxide (11.5 mol %) aided air oxidation of (–)- $\alpha$ -pinene catalysed by  $\text{Co}(\text{NO}_3)_2$  at 60 or 80 °C and without a catalyst.

rapid decomposition of alkyl hydroperoxide, leading to its concurrent reduction and oxidation and to generation of alkoxy and alkylperoxy radicals. Alkoxy and alkylperoxy radicals are able to react with a hydrocarbon compound, in this case (–)- $\alpha$ -pinene, and produce allyl radicals, which react with molecular oxygen. The Co(III) compound also reacts with *t*-BuOOH or verbenyl hydroperoxide, and thus regenerates Co(II). *t*-BuOOH is quickly used up in the formation of *tert*-butanol, whereupon the radicals derived from (–)- $\alpha$ -pinene affect the chain propagation. The steps of this mechanism are presented in Eqs. (1)–(13) [18–21].



### 3.3. Glacial acetic acid with Co(II) salts

We have recently reported the favourable effect of a small amount of glacial acetic acid on  $\alpha$ -pinene air oxidation catalysed by Co(II) complexes [3]. A series of reactions of  $\alpha$ -pinene catalysed by Co(II) salts was performed in the presence of glacial acetic acid (GAA) (150 or 500  $\mu\text{l}$ ), and with and without *t*-BuOOH. These reactions were compared with the [Co(4-mepy)<sub>2</sub>Br<sub>2</sub>]- and [Co(py)<sub>2</sub>Br<sub>2</sub>]-catalysed reactions at 60 °C. GAA, together with Co(II) salts, had a beneficial influence. CoCl<sub>2</sub>, CoBr<sub>2</sub> and Co(NO<sub>3</sub>)<sub>2</sub> with 500  $\mu\text{l}$  (17 vol.%) of GAA initiated air oxidation directly. GAA dissolved Co(II) salt and thereby helped the salt to dissolve in  $\alpha$ -pinene and catalyse the reaction. The reactions yielded both verbenone and *trans*-verbenyl acetate, as did the reaction catalysed by [Co(4-mepy)<sub>2</sub>Br<sub>2</sub>]. Co(OAc)<sub>2</sub> behaved differently. Air oxidation catalysed by it needed an induction time of 4 h before the reaction started. However, at the end of the reaction, the yield of verbenone was comparable to other Co(II) salts, though the yield of *trans*-verbenyl acetate was the lowest. Typically, the amount of pinene oxide was very low with every catalyst, supposedly as a consequence of the rearrangement being affected by the acidic reaction conditions [3]. The Co(OAc)<sub>2</sub> catalyst, together with 500  $\mu\text{l}$  of GAA, led to the complete disappearance of pinene oxide among the reaction products. Fig. 3 exemplifies the effect of GAA on the Co(NO<sub>3</sub>)<sub>2</sub>-catalysed air oxidation at 60 °C.

When 150  $\mu\text{l}$  (5 mol %) of GAA was used together with the same Co(II) salts as catalysts, besides verbenone, no acetate was detected. The start of air oxidation was a little bit slower compared to the above reactions. The amount of pinene oxide exceeded 10%

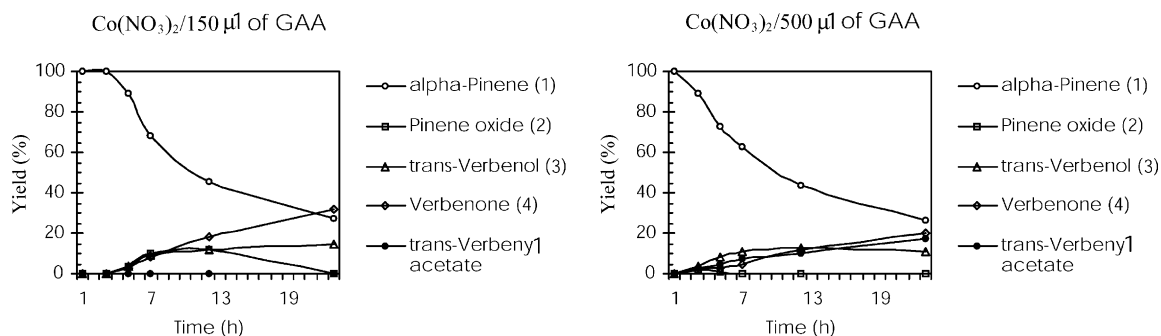


Fig. 3. The effect of glacial acetic acid (150  $\mu\text{l}$  and 500  $\mu\text{l}$ ) on air oxidation of (–)- $\alpha$ -pinene catalysed by  $\text{Co}(\text{NO}_3)_2$  at 60 °C.

before its rearrangement began. The total yield of verbenone was about 30% in 23 h when either a Co(II) salt or complex was used as the catalyst.

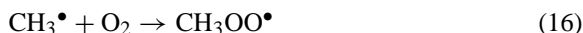
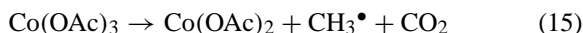
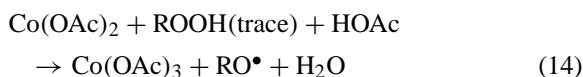
The progress of the reactions was followed by GC. Retention times of verbenone and *trans*-verbenyl acetate in GC chromatogram were very close to each other. The mass spectrometric study of their formation showed that in every air oxidation aided by GAA (5 or 17 mol % of GAA), the formation of verbenone started first and was faster than the formation of *trans*-verbenyl acetate, which immediately followed, especially in connection with 17 mol % of GAA.

The effect of GAA on air oxidation catalysed by  $[\text{Co}(4\text{-mepy})_2\text{Br}_2]$  was shown as an acceleration of the reaction rate and as a minor increase in the yield of verbenone.

As reported earlier [3], the increase in the amount of GAA resulted in the rearrangement of pinene oxide and in the formation of *trans*-verbenyl acetate. The effect of the increasing amount of GAA on  $\text{CoBr}_2$ -catalysed air oxidation was studied at 60 °C. The amount of GAA varied from 100  $\mu\text{l}$  (3.3%) to 1000  $\mu\text{l}$  (33%).  $\text{CoBr}_2$  without GAA did not catalyse air oxidation at that temperature. The increasing amount of GAA resulted in a slightly increasing acceleration of the reaction and from the beginning led to the rearrangement of pinene oxide (Table 1). Finally, no pinene oxide was detected at all when the reaction mixture contained 1000  $\mu\text{l}$  of GAA. The large amount of GAA in the reaction directed the product formation, besides verbenone, to *trans*-verbenyl acetate. Furthermore, the yield of *trans*-verbenol stayed constantly low during the reaction compared to reactions with less GAA. This indicates that acetate forma-

tion is a competitive reaction to oxidation of *trans*-verbenol.

Partenheimer [7] compared the activity of several metal acetates in air oxidation with GAA and noticed that cobalt had the strongest ability to decompose GAA. He studied the reaction between  $\text{Co}(\text{OAc})_2$  and  $\text{O}_2$  in acetic acid, and concluded that, under reflux conditions,  $\text{Co}(\text{OAc})_3$  was the active species. Oxidation of  $\text{Co}(\text{OAc})_2$  in acetic acid affected by a trace amount of peroxide adventitiously present in the reaction mixture resulted in relatively high concentrations of radicals (Eqs. (14) and (15)). Other Co(II) salts with acetic acid perhaps form mixed Co(III) complexes which cleave like  $\text{Co}(\text{OAc})_3$  and correspondingly form methyl radicals capable of initiating autoxidations.



This deduction is supported by a catalytic air oxidation of mesitylene with  $\text{CoBr}_2$  in acetic acid which was reported to take place via trivalent Co [22,23]. In addition,  $\text{CoCl}_2$  was shown to form a complex in binary mixture of acetic acid with benzene and hexane. It was predominantly assumed to be in the form of a  $[\text{CoCl}_2(\text{HAc})_2]$  complex [24].

Thus, the favourable influence of GAA on  $\alpha$ -pinene air oxidation came from a dissolving effect of GAA to cobalt salts and possibly from a radical cleavage of mixed cobalt(III) acetates.

Table 1

The effect of the increasing amount of glacial acetic acid on CoBr<sub>2</sub>-catalysed air oxidation of (–)- $\alpha$ -pinene at 60 °C

GAA ( $\mu$ l)	Time (h)	Reaction mixture (%)				
		$\alpha$ -Pinene (1)	Pinene oxide (2)	<i>trans</i> -Verbenol (3)	Verbenone (4)	<i>trans</i> -Verbenyl acetate
100	2	86	5	4	2	–
	4	67	11	8	6	–
	6	60	11	10	9	–
	12	44	5	12	21	–
	24	30	–	15	39	–
250	2	87	3	4	3	–
	4	71	4	8	8	–
	6	64	–	10	12	–
	12	50	–	13	20	1
	24	34	–	14	34	3
500	2	83	2	6	6	–
	4	66	1	10	10	2
	6	59	–	12	13	2
	12	45	–	13	12	9
	24	26	–	11	33	8
1000	2	83	–	7	6	–
	4	64	–	9	13	5
	6	55	–	10	14	6
	12	37	–	8	16	11
	24	16	–	5	39	20

### 3.4. *tert*-Butyl hydroperoxide and glacial acetic acid with Co(II) salts

*t*-BuOOH (500  $\mu$ l, 11.5 mol%), in combination with glacial acetic acid (500  $\mu$ l, 17 mol%) in the reaction mixture, still accelerated air oxidation of (–)- $\alpha$ -pinene with CoCl<sub>2</sub>, CoBr<sub>2</sub> and Co(OAc)<sub>2</sub> at 60 °C. The amount of verbenyl acetate increased with

these catalysts as exemplified with CoCl<sub>2</sub> in Fig. 4. On the other hand, the yield of verbenone did not increase, rather it slightly decreased. All catalysts showed almost equal catalytic activity. The combined use of *t*-BuOOH and GAA caused the immediate rearrangement of pinene oxide to other products. In addition to reactions presented in Eqs. (1)–(13), more reactions arise from a decomposition of GAA by

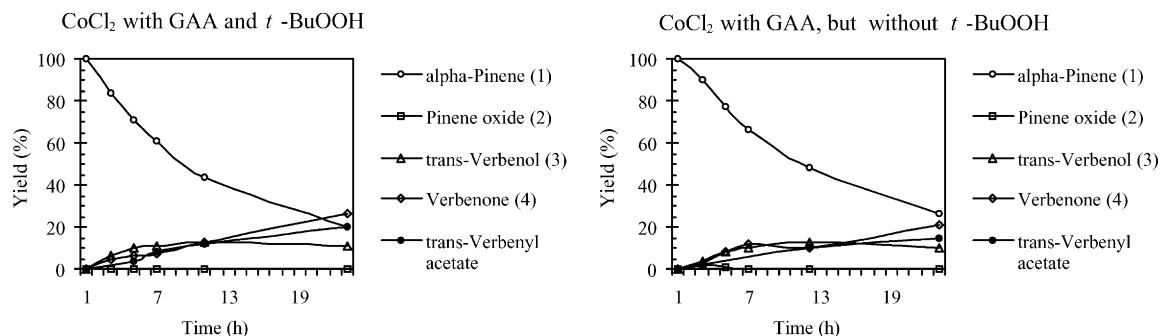


Fig. 4. The effect of glacial acetic acid (500  $\mu$ l) and *tert*-butyl hydroperoxide (500  $\mu$ l) on air oxidation of (–)- $\alpha$ -pinene catalysed by CoCl<sub>2</sub> at 60 °C.

forming radicals, which react further (Eqs. (14)–(16)). The complete lack of pinene oxide in the product mixture is likely to be a result of the reaction of epoxide with acid and its rearrangement.

#### 4. Conclusions

The studied Co(II) salts, CoCl<sub>2</sub>, CoBr<sub>2</sub>, Co(OAc)<sub>2</sub> and Co(NO<sub>3</sub>)<sub>2</sub>, as such did not show catalytic activity in air oxidation at temperatures below 100 °C. A small amount of *tert*-butyl hydroperoxide in the reaction mixture made all the Co(II) salts catalytically active, even at 60 °C. Glacial acetic acid in place of hydroperoxide had a similar activating effect. The favourable influence came from a dissolving effect of glacial acetic to the cobalt salts acid and possibly from a radical cleavage of mixed cobalt(III) acetates formed in the reaction conditions. Glacial acetic acid in the reaction mixture led to the formation of *trans*-verbenyl acetate and reduced the amount of verbenol, which otherwise would oxidise to verbenone. A large excess of glacial acetic acid might even stop the further oxidation of *trans*-verbenol.

#### Acknowledgements

The authors thank TEKES (Technology Development Centre, Finland) for financial support.

#### References

- [1] P.A. Wender, T.P. Mucciario, J. Am. Chem. Soc. 114 (1992) 5878–5879.
- [2] P.A. Wender, L.A. Wessjohann, B. Peschke, D.B. Rawlins, Tetrahedron Lett. 36 (1995) 7181–7184.
- [3] M. Lajunen, T. Maunula, A. Koskinen, Tetrahedron 56 (2000) 8167–8171.
- [4] T.I.A. Gerber, A. Wiechers, A.T. Noah, B. Zeelie, S. Afr. J. Chem. 51 (1998) 178–185.
- [5] M.F.T. Gomes, O.A.C. Antunes, J. Mol. Catal. 121 (1997) 145–155.
- [6] A. Goosen, A. Ramplin, C.I. Townsin, S. Afr. J. Chem. 45 (1992) 90–92.
- [7] W. Partenheimer, J. Mol. Catal. 67 (1991) 35–46.
- [8] P. Li, H. Alper, J. Mol. Catal. 61 (1990) 51–54.
- [9] E.-A.I. Heiba, R.M. Dessau, W.J. Koehl, Prepr. Am. Chem. Soc., Div. Pet. Chem. 14 (1969) A44–A56.
- [10] V.A. Adamyan, Yu.V. Geletii, M. Hronec, I.V. Zakharov, Kinet. Katal. 34 (1993) 645–649.
- [11] Y. Mitsuru, H. Takeuchi, T. Kamei, Patent Jpn. Kokai Tokkyo Koho JP 03271249 A2 911203.
- [12] M. Morita, K. Sakura, H. Takeuchi, Patent Jpn. Kokai Tokkyo Koho JP 01121237 A2 890512.
- [13] W. Partenheimer, in: D.D. Blackburn (Ed.), Catalysis of Organic Reactions, Marcel Dekker, New York, 1990 (Chapter 20).
- [14] A.S. Hay, H.S. Blanchard, Can. J. Chem. 43 (1965) 1306–1317.
- [15] M. Lajunen, A.M.P. Koskinen, Tetrahedron Lett. 35 (1994) 4461–4464.
- [16] M. Lajunen, J. Mol. Catal. A: Chem. 169 (2001) 33–40.
- [17] B.S. Furniss, A.J. Hannaford, P.W.G. Smith, A.R. Tatchell, Vogel's Textbook of Practical Organic Chemistry, fifth ed., Longman, London, 1989, 1135 pp.
- [18] R. Hiatt, T. Mill, F.R. Mayo, J. Org. Chem. 33 (1968) 1416–1420.
- [19] R. Hiatt, K.C. Irwin, C.W. Gould, J. Org. Chem. 33 (1968) 1430–1435.
- [20] R.A. Sheldon, J.K. Kochi, Metal-Catalysed Oxidation of Organic Compounds; Academic Press, New York, 1981 (Chapter 3).
- [21] O.L. Magelli, C.S. Sheppard, in D. Swern (Ed.), Organic Peroxides, vol. I, Wiley/Interscience, New York, 1970 (Chapter 1).
- [22] S.A. Samodumov, K.I. Matkovskii, Dopovidi Akad. Nauk. Ukr. RSR 3 (1966) 373–375.
- [23] S.A. Samodumov, K.I. Matkovskii, Katal. Katal. 2 (1966) 71–79.
- [24] I.A. Vershinina, O.A. Golubchikov, Izv. Vyssh. Uchebn. Zaved. Khim. Khim. Teknol. 37 (1994) 48–51.