Oxidation of α-pinene to verbenone using silica–titania co-gel catalyst

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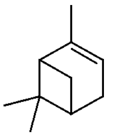
α-pinene can be oxidised to verbenone with ca. 60% selectivity using a commercial silica–titania co-gel catalyst with *tert*-butyl hydroperoxide as oxidant. Using cyclohexene as a model reagent, it is suggested that the formation of verbenone is probably via the formation of a hydroperoxy intermediate.

Keywords: α-pinene oxidation, verbenone, silica–titania co-gel

1. Introduction

Silica–titania co-gels have been extensively used as oxidation catalysts for alkenes and allylic alcohols [1–7]. The reason for this considerable interest is that the pore sizes of silica–titania co-gels permit the reaction of relatively large substrates of interest to the fine chemical industry. In contrast, the microporous titanium silicalite, TS-1, has pores that permit only relatively small molecules [8] and, hence, is limited in its application to the oxidation of large molecules, such as terpenes. Most studies use organic hydroperoxides as oxidant but, recently, there has been interest in modifying the surface of titania–silica co-gels with organic molecules [9–12] to modify the hydrophilic nature and thereby permit the use of hydrogen peroxide as oxidant.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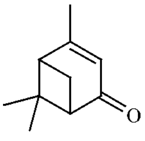

II

Recently, there has been interest in the oxidation of α-pinene **I** to verbenone **II**. Verbenone is one of the many products that can be isolated from the auto-oxidation of α-pinene with air, but the amount of allylic oxidation products in this process is very low [13]. The reason for interest in verbenone as a desirable product is that it can provide a possible starting point for the synthesis of the A-ring of taxol [14,15]. The synthesis of verbenone for the oxidation of α-pinene with oxygen using a homogeneous cobalt catalyst has been described by Lajunen and Koskinen [16], and selectivities of over 70% have been observed. Palladium chloride [17] combined with copper chloride has been used for the oxidation of α-pinene in acetic acid using oxygen as oxidant resulting in a complex mixture of products. In addition, Mn(III) salen complexes with iodosylbenzene as oxidant [18] lead to the oxidation of α-pinene to α-pinene oxide with 55% selectivity.

A number of studies have investigated the oxidation of α-pinene using heterogeneous catalysts and microporous molecular sieves. For example, Trong et al. [19] have utilised modified Ti-MCM-41 for the oxidation of α-pinene to α-pinene oxide with 100% selectivity. Hansen et al. [20] have studied the alkoxylation of α-pinene using zeolite β. Recently, Wilson et al. [21] have reported a supported zinc triflate catalyst for the isomerisation of α-pinene oxide and Villa et al. [22] have shown the use of a reusable tungsten catalyst for terpene oxidation based on Venturello anion $\{PO_4[WO(O_2)_2]_4\}^{3-}$. However, to date, there have been no reports concerning the synthesis of verbenone using heterogeneous catalysts. In this paper, we report our observations that a commercial silica–titania co-gel catalyst can give high selectivities (ca. 60%) to verbenone for the allylic oxidation of α-pinene.

2. Experimental

2.1. Catalytic materials

Two samples of commercial silica–titania co-gels designated EP350 and EP50 od were supplied by Unilever Research and Engineering and these have been fully described by McDaniel [23]. EP50 od is a mesoporous silica–titania co-gel with an average pore size of 5 nm (pore volume 2.35 $ml\,g^{-1}$, 550 $m^2\,g^{-1}$, 2.5 wt% Ti). EP350 is identical to EP50 od with the addition of 0.98 wt% Cr added by impregnation. When uncalcined, the Cr is present as Cr^{3+} and, when calcined, as Cr^{6+}.

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Table 1
Oxidation of cyclohexene with uncalcined EP350 at 80 °C.[a]

Reaction time (h)	Conversion (%)	Product selectivity (%)				
		Cyclohexene oxide	Cyclohexen-2-ol	Cyclohexen-2-one	Methoxycyclohexen-2-ol	Cyclohexen-1-ol
0.5	1.0	50	0	50	0	0
1.0	3.3	18	48	34	0	0
2.0	19.0	5	45	31	7	12
4.0	53.9	1	40	24	13	22
8.0	58.1	tr	37	22	18	23

[a] Reaction conditions: cyclohexene 3 g, catalyst 0.2 g, methanol 20 ml, hydrogen peroxide 4.2 g (30% w/v).

Table 2
Oxidation of cyclohexene with calcined EP350 at 80 °C.[a]

Reaction time (h)	Conversion (%)	Product selectivity (%)				
		Cyclohexene oxide	Cyclohexen-2-ol	Cyclohexen-2-one	Methoxycyclohexen-2-ol	Cyclohexen-1-ol
0.5	3.7	0	41	59	0	0
1.0	9.4	0	41	59	0	0
2.0	21.7	2	24	36	19	19
4.0	45.8	1	31	29	18	21
8.0	57.6	tr	32	32	25	11

[a] Reaction conditions: cyclohexene 3 g, catalyst 0.2 g, methanol 20 ml, hydrogen peroxide 4.2 g (30% w/v).

Table 3
Oxidation of cyclohexene with calcined EP50 od at 80 °C.[a]

Reaction time (h)	Conversion (%)	Product selectivity (%)				
		Cyclohexene oxide	Cyclohexen-2-ol	Cyclohexen-2-one	Methoxycyclohexen-2-ol	Cyclohexen-1-ol
0.5	2.4	29	21	50	0	0
1.0	5.0	16	20	50	14	0
2.0	9.8	6	18	48	18	0
4.0	15.0	5	21	44	30	0
8.0	29.0	1	18	50	31	0

[a] Reaction conditions: cyclohexene 2 g, catalyst 0.2 g, methanol 20 ml, hydrogen peroxide 2.8 g (30% w/v).

2.2. Catalytic oxidation reactions

For cyclohexene oxidation, the following conditions were typically used. Cyclohexene (3 g) and catalyst (0.2 g) were stirred together at the required reaction temperature in methanol (20 ml) as solvent. Hydrogen peroxide (4.2 g, 30% w/v) was then added and samples were taken for GC analysis at regular intervals and product identification was confirmed using GC/MS. For α-pinene oxidation, *tert*-butyl hydroperoxide extracted into chlorobenzene was used as oxidant.

3. Results and discussion

Cyclohexene oxidation was investigated initially as a model substrate for α-pinene. Cyclohexene oxidation was studied using the EP350 co-gel catalyst at 80 °C and the results are shown in table 1. At low conversion, very high selectivities to cyclohexene oxide are observed. However, at conversion levels of significance, methoxycyclohexen-2-ol, cyclohexen-2-ol, cyclohexen-1-ol and cyclohexen-2-one became the major products and the selectivity to cyclohexene oxide decreases. The reaction with calcined EP350 (table 2) indicates that, at low conversion with this material, cyclohexene oxide is not the preferred product, rather cyclohexen-2-ol and cyclohexen-2-one are formed. Cyclohexene oxidation using the silica–titania co-gel EP50 od, which did not contain chromium, at low conversion gave appreciable selectivities to cyclohexene oxide, in addition to cyclohexen-2-ol and cyclohexen-2-one (table 3). At higher conversion levels, the selectivity to cyclohexene oxide decreased and methoxy cyclohexen-2-ol was formed. However, the selectivity to cyclohexen-2-one and cyclohexen-2-ol remained fairly constant and no cyclohexen-1-ol was observed. To determine if cyclohexene oxide undergoes hydrolysis/solvolysis, an experiment was carried out using EP350 as catalyst (0.2 g) with cyclohexene oxide (2 g) in methanol (20 ml) and hydrogen peroxide (2.8 g, 30% w/v). After only 5 min the conversion of cyclohexene oxide was 100% and two products were observed, methoxycyclohexen-2-ol (91%) and cyclohexen-1,2-diol (9%).

The formation of cyclohexen-2-ol and the corresponding ketone for silica–titania co-gel catalysts is well known and results from the competing oxidation of the allylic C–H bond rather than the carbon–carbon double bond. When chromium was absent from the catalyst, the highest yields of cyclohexene oxide and its solvolysis prod-

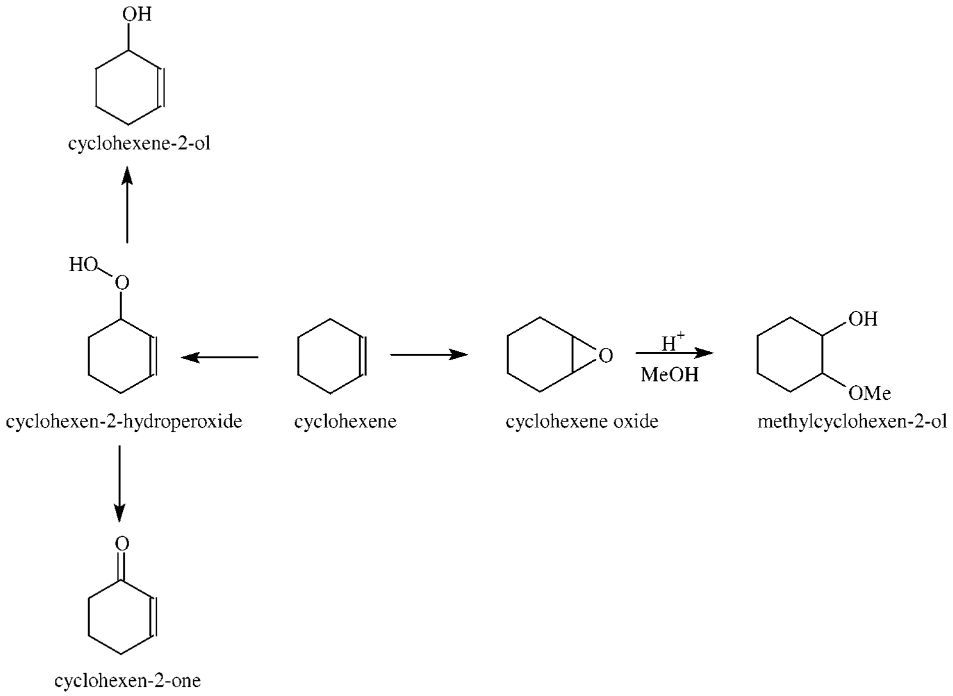

Figure 1. Oxidation of cyclohexene.

Table 4
Oxidation of α-pinene with calcined EP350[a] at 80 °C.

Reaction time (h)	α-pinene conversion (%)	Verbenone selectivity[b] (%)
0.5	4.0	50
1.0	7.0	57
2.0	21.0	57
4.0	28.0	57
8.0	32.0	63

[a] α-pinene 1 g, catalyst 0.1 g, *tert*-butanol 10 ml, *tert*-butyl hydroperoxide 0.83 g, 80% in di-*tert*-butyl ether.

[b] Broad range of by-products with selectivities to individual components $<2\%$.

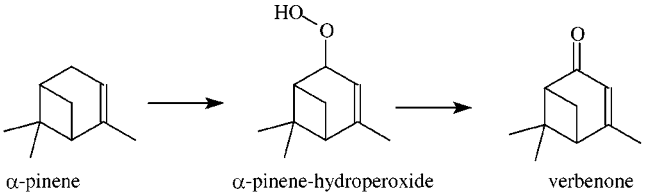

Figure 2. Oxidation of α-pinene.

ucts methoxycyclohexen-2-ol are formed by two competing pathways (figure 1). Cyclohexen-2-ol and cyclohexen-2-one are formed *via* the decomposition of the hydroperoxy radical and Ti^{4+} centres can catalyse this process. The addition of Cr^{3+} (uncalcined EP350) or Cr^{6+} (calcined EP350) enhances this radical decomposition and this is most marked with Cr^{6+}. With Cr^{6+} present, the dominant product is cyclohexen-2-one, whereas with Cr^{3+} cyclohexen-2-ol is preferred.

From these experiments with the model reagent cyclohexene, it was expected that the oxidation of α-pinene using the silica–titania co-gel calcined EP350 could lead to the formation of verbenone (**III**). Experiments with hydrogen peroxide as oxygen donor showed that it was not possible to obtain a two-phase system (i.e., a solid catalyst phase and a single liquid phase containing reactants and solvent) as had been possible with cyclohexene. For this reason, *tert*-butyl hydroperoxide was selected as oxygen donor. Blank experiments in the absence of catalysts for reaction at 80 °C showed that verbenone could be produced at a yield of only ca. 4% and that a complex range of numerous products were observed, including α-pinene epoxide, *trans*-verbenol, pinocarveol, *cis*- and *trans*-3-pinene-2-ol, 1,2-pinenediol. However, all these products were produced only in trace amounts. With the silica–titania co-gel catalyst EP50 od, similar results to the blank reaction were observed. However, with calcined EP350 as catalyst, significantly enhanced yields of verbenone were observed (table 4) and selectivities of ca. 60% are observed. Again, a complex range of by-products were observed but no other product was formed with selectivities in excess of 2%. It is suggested that verbenone is formed by decomposition of a hydroperoxy species (figure 2) by analogy with the formation of cyclohexen-2-one from cyclohexene. No attempt has been made to optimise this result but it is apparent that the silica–titania co-gel catalysts, appropriately modified, could provide a novel synthetic pathway to verbenone.

Acknowledgement

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