



Alumina-catalyzed Baeyer–Villiger oxidation of cyclohexanone with hydrogen peroxide

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ABSTRACT

Alumina catalyzes the Baeyer–Villiger oxidation of cyclohexanone, using 70 wt.% aqueous or anhydrous hydrogen peroxide as oxidant. The best methodology was to carry out the reaction in ethyl acetate under azeotropic water removal at 90 °C, and a molar ratio cyclohexanone:oxidant of 1:4. Under these conditions, the conversion was 53% with a selectivity of 98% for ϵ -caprolactone. The weak and strong acid sites of alumina were correlated with the substrate conversion and hydrogen peroxide consumption for the Baeyer–Villiger oxidation. It is shown that the weak acid sites, which activate hydrogen peroxide for the catalytic epoxidation of nucleophilic olefins, are also responsible for the Baeyer–Villiger oxidation. Stronger acid sites, however, also participate in the Baeyer–Villiger oxidation, by activation of the carbonyl group. The interaction of the carbonyl group with strong acid sites also reduces the hydrogen peroxide decomposition.

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1. Introduction

Many traditional oxidation processes are associated with the use of stoichiometric high-oxidation-state transition metals, hazardous solvents and the production of large volumes of toxic waste [1]. Therefore, there is an increasing interest in catalytic systems able to perform these reactions in a more environmentally friendly way, using non-toxic reagents, oxidants and solvents.

Baeyer–Villiger reaction is an important oxidation process, providing a direct pathway to oxidize ketones to esters or lactones by organic peracids or alkyl hydroperoxides, usually operating in homogeneous phase [2]. The reaction can be catalyzed by acid, base, enzyme, or transition metal-containing materials [3].

ϵ -Caprolactone is an important chemical used in the synthesis of polyesters. Currently, the main industrial process for the production of ϵ -caprolactone is the oxidation of cyclohexanone with *m*-chloroperbenzoic acid [4]. The disadvantages of this method are problems related with the transport and storage of dangerous reagents, and the regeneration of the organic peroxide at the end of the reaction [3].

Recently, several papers about heterogeneous catalysts used to perform the Baeyer–Villiger oxidation have been published [5–8]. These catalysts can act in three ways: (i) activating H_2O_2 by increasing its nucleophilicity and facilitating the attack by the oxidizing species on the carbonylic carbon, (ii) activating the carbonyl group of the substrate, or even (iii) activating simultaneously the O–O bond and carbonyl moiety [3].

The use of hydrogen peroxide and a heterogeneous catalyst allows a clean oxidation and the catalyst can be easily removed and reused [3]. We have shown that transition metal-free alumina is an efficient catalyst for the epoxidation of olefins with hydrogen peroxide [9]. In a detailed study, we showed that the weak acid sites of the alumina are responsible for the epoxidation, while the strong acid sites decompose the hydrogen peroxide [10].

In this report, we show that Baeyer–Villiger oxidation of cyclohexanone is also possible using hydrogen peroxide and transition metal-free alumina as catalyst. Furthermore, we perform some competitive reactions between cyclooctene epoxidation and cyclohexanone oxidation in order to elucidate the active sites for the Baeyer–Villiger oxidation.

2. Experimental

2.1. Materials

The sol–gel alumina was synthesized as described in our previous paper [11]. Commercial alumina (Fluka, 99%, 507C type,

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100–125 mesh, neutral) was used without treatment. The anhydrous solution of hydrogen peroxide (24 wt.%) in ethyl acetate was prepared by azeotropic distillation. Please note that 30 or 50 wt.% H_2O_2 aqueous solutions can be used as starting material for the preparation of the anhydrous solution of hydrogen peroxide. **WARNING:** the concentration of hydrogen peroxide in ethyl acetate should not be higher than to 25 wt.%. The azeotropic distillation should be carried out in a system in which the oxygen generated by hydrogen peroxide decomposition is allowed to be released to outside. Although no accident has happened in our laboratory over 10 years, it is strongly recommended to carry out this azeotropic distillation behind a protection-shield and in a fume-hood.

The aqueous solution of hydrogen peroxide (70 wt.%) was supplied by Peroxidos do Brasil S.A. and was used without pretreatment. The H_2O_2 content of the obtained solution was determined by iodometric titration in a deaerated solution, as described elsewhere [11].

2.2. Catalytic reactions

The reactions were carried out in a 50 ml two-necked round bottom flask with a Dean–Stark glassware. 10 mmol of cyclohexanone (Merck, 99%) or 10 mmol of cyclohexanone + 10 mmol of cyclooctene (Acros, 95%), 40 mmol of aqueous (70 wt.%) or anhydrous H_2O_2 in ethyl acetate (24 wt.%), 10 ml of ethyl acetate and 5 mmol of di-*n*-butyl-ether (internal standard, Acros, >99%) for 1 h at 90 °C were heated. Immediately before addition of 300 mg of the catalyst, a sample was taken from the reaction mixture for GC analysis (blank). The reactions were monitored by taking aliquots from the reaction mixture at different reaction times. MnO_2 was added to the aliquots to decompose the residual H_2O_2 and $MgSO_4$ to remove water. The aliquots were analyzed using a Hewlett–Packard HP 5890 Series II gas chromatograph equipped with a HP Ultra 2 capillary column (25 m × 0.2 mm × 0.33 μ m) and a flame ionization detector (FID). The products were quantified using calibration curves obtained with standard solutions. Unknown products were identified by GC–MS using an HP 5970 Series mass selective detector. Selectivities are always given with respect to the converted substrate. The recycling tests were carried out with cyclohexanone as substrate. The catalyst was removed from the reaction mixture after 20 h by filtration, washed with ethyl acetate, dried at 90 °C for 3 h and subjected to another catalytic reaction.

3. Results and discussion

3.1. Baeyer–Villiger oxidation

Fig. 1 shows the results obtained using anhydrous hydrogen peroxide and commercial or sol-gel alumina in the Baeyer–Villiger oxidation of cyclohexanone without azeotropic water removal (Dean–Stark distillation). The conversion with sol-gel alumina was 70% after 20 h, showing higher activity in comparison to commercial alumina (conv. 44%). However, the selectivity for ϵ -caprolactone was 33% in both cases. In both reactions, the mass balance did not reach 100%. The analysis of the reaction mixture by electron spray mass spectrometry showed the presence of ϵ -hydroxyhexanoic acid, as result of ϵ -caprolactone hydrolysis. Under the GC conditions ϵ -hydroxyhexanoic acid is not volatile and, therefore, not detectable by GC, corroborating for lacking of the mass balance as well.

To avoid hydrolysis of ϵ -caprolactone, we decided to use a Dean–Stark distillation for azeotropic water removal (Fig. 2). Under this procedure, both aluminas had approximately the same activity (conv. 53%). We, therefore, used commercial alumina in the following reactions. Furthermore, 70 wt.% aqueous H_2O_2 was shown

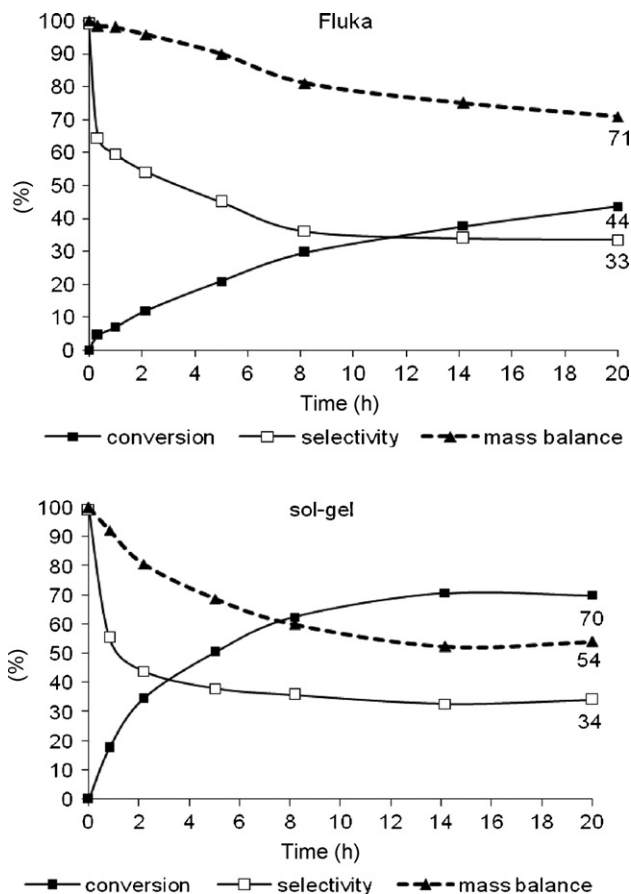


Fig. 1. Conversion of cyclohexanone, selectivity to ϵ -caprolactone and mass balance for the Baeyer–Villiger oxidation. Conditions: 10 mmol of cyclohexanone; 10 ml of ethyl acetate; 40 mmol of 24 wt.% anhydrous hydrogen peroxide; 300 mg of alumina; 90 ± 2 °C.

to be as good as anhydrous H_2O_2 . Therefore, the aqueous oxidant solution was used to facilitate the reaction procedure, since 70 wt.% aqueous H_2O_2 is readily commercially available [12]. As shown in Fig. 2, the selectivity to ϵ -caprolactone was now very good (98%). Furthermore, the mass balance closed to $100 \pm 2\%$.

The temperature of the reaction medium proved to be an important variable in the process. The temperature has to be maintained

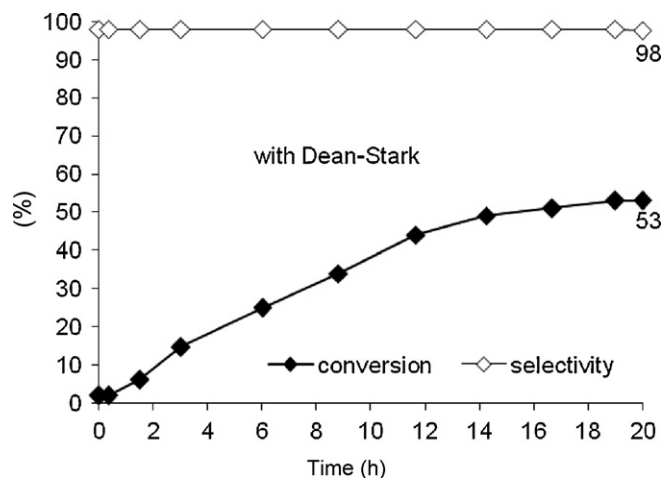


Fig. 2. Conversion and selectivity to ϵ -caprolactone in the Baeyer–Villiger oxidation with simultaneous removal of water. Conditions: 10 mmol of cyclohexanone; 10 ml of ethyl acetate; 40 mmol of 70 wt.% aqueous H_2O_2 ; 300 mg of commercial alumina; 90 ± 2 °C.

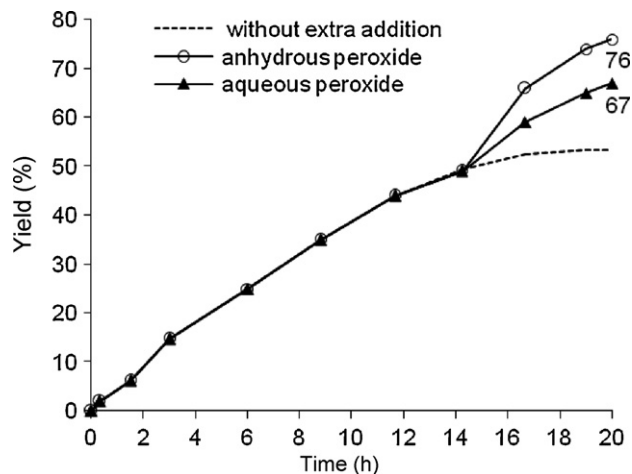


Fig. 3. Conversion of cyclohexanone in the Baeyer–Villiger oxidation with simultaneous removal of water and hydrogen peroxide addition after 14 h. Conditions: 10 mmol of cyclohexanone; 10 ml of ethyl acetate; 40 mmol of 70 wt.% aqueous H_2O_2 ; 300 mg of commercial alumina; $90 \pm 2^\circ\text{C}$; addition of 20 mmol of aqueous H_2O_2 (▲); addition of 20 mmol of anhydrous H_2O_2 (○).

at $90 \pm 2^\circ\text{C}$. At 105°C , the conversion after 20 h falls to 36%. The conversion at 80°C is also lower (32%), due to the incomplete removal of water by azeotropic distillation.

All oxidations were practically finished after 14 h. The iodometric titration of the reaction mixture revealed that the amount of H_2O_2 present at the reaction endpoint was ca. 5 mmol. A catalytic test using just 5 mmol of H_2O_2 , instead of 40 mmol, showed that no reaction proceeds under this condition. Therefore, the reaction endpoint is due to the lack of catalytic activity of alumina under low H_2O_2 concentration.

In another experiment, new amount of the oxidant (40 mmol) was added after 14 h of reaction. The results (Fig. 3) show that the addition of H_2O_2 strongly increased the yield of ϵ -caprolactone, maintaining the selectivity at 98%. Therefore, the catalyst is still active. Please note that the addition of anhydrous H_2O_2 after 14 h is preferred, since the reaction mixture after 14 h already contains high amount of ϵ -caprolactone.

In order to determine the catalyst stability, we filtered the catalyst after reaction at 90°C for 20 h, washed it with ethyl acetate and dried it at 90°C for 3 h. As shown in Fig. 4, the catalyst

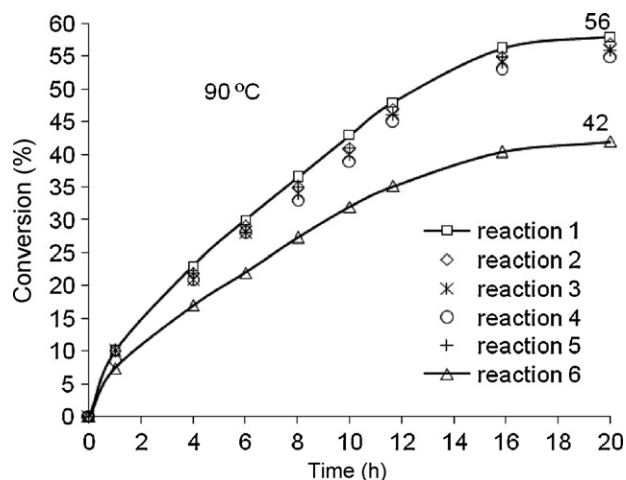


Fig. 4. Recycling of the alumina at 90°C with simultaneous removal of water. Conditions: 10 mmol of cyclohexanone; 10 ml of ethyl acetate; 40 mmol of aqueous H_2O_2 70%; 300 mg of alumina.

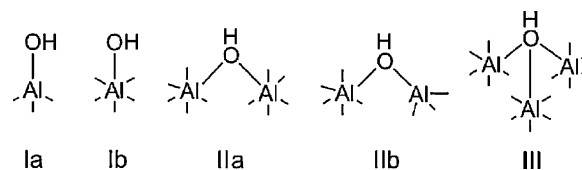


Fig. 5. Idealized hydroxyl configurations on the alumina surface according to the Knözinger–Ratnasamy model [15].

gave the same conversions for 5 consecutive reactions, proving a good stability under the reaction conditions. The selectivity for ϵ -caprolactone under these reactions was always better than 98%. Recycling tests lower different temperatures showed that water is related to catalyst deactivation during the reactions [13,14]. Furthermore, ϵ -hydroxyhexanoic acid, formed by hydrolysis of ϵ -caprolactone, adsorbs on the alumina surface, blocking some Al–OH sites involved in the activation of H_2O_2 [13]. At 90°C , however, the removal of water is quite effective, allowing five consecutive reactions without significant losses in conversion and in selectivity.

3.2. Investigation of the active alumina sites

According to the Knözinger and Ratnasamy model [15], alumina surfaces show five hydroxyl sites (Fig. 5). Recently, Rinaldi et al. assigned the different types of Al–OH sites to their activities in epoxidation and H_2O_2 decomposition [10]. H_2O_2 activation on the alumina surface is proposed to occur by reaction of the weak type Ia Brønsted acid sites with H_2O_2 , giving the superficial hydroperoxides, Al–OOH, that are responsible for the polarization of O–O bond, allowing the oxygen transfer to the nucleophilic olefin [10,17]. Moreover, the weakest and more abundant type Ib Al–OH sites have no role in the activation of H_2O_2 , because these sites are poisoned by preferential chemisorption of acetate on the alumina surface [10,13]. The strong acid sites IIa, IIb and III are related to the H_2O_2 decomposition [10].

In order to investigate which of these sites promote the Baeyer–Villiger oxidation, we performed reactions in the presence of both cyclohexanone and cyclooctene (Fig. 6).

Both kinds of oxidation happen simultaneously and both reactions were slower when both substrates are present, suggesting that the same active sites are responsible for both oxidations. At the very first view, this result is somehow unexpected, as cyclooctene is a nucleophilic substrate while cyclohexanone is an electrophilic substrate. However, it can be considered as a direct consequence

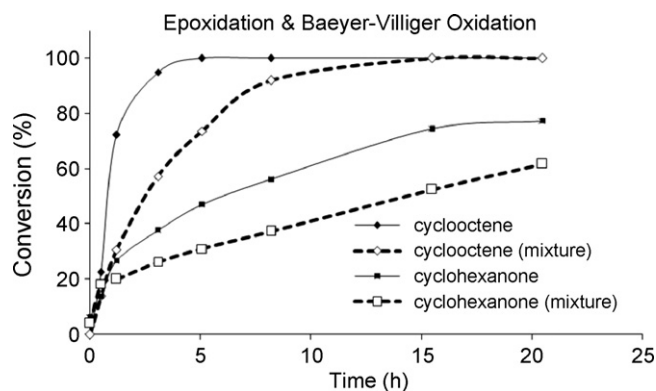


Fig. 6. Conversion of cyclooctene and of cyclohexanone in the simultaneous epoxidation and Baeyer–Villiger oxidation. Conditions: 10 mmol of cyclohexanone and 10 mmol of cyclooctene; 10 ml of ethyl acetate; 80 mmol of 70 wt.% aqueous H_2O_2 ; 300 mg of commercial alumina; $90 \pm 2^\circ\text{C}$.

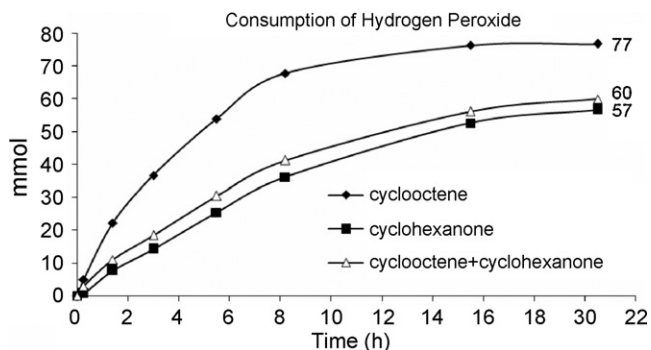


Fig. 7. Consumption of hydrogen peroxide in the parallel epoxidation of cyclooctene and Baeyer–Villiger oxidation of cyclohexanone. Conditions: 10 mmol of cyclohexanone and 10 mmol of cyclooctene; 10 ml of ethyl acetate; 80 mmol of 70 wt.% aqueous H_2O_2 ; 300 mg of commercial alumina; $90 \pm 2^\circ C$.

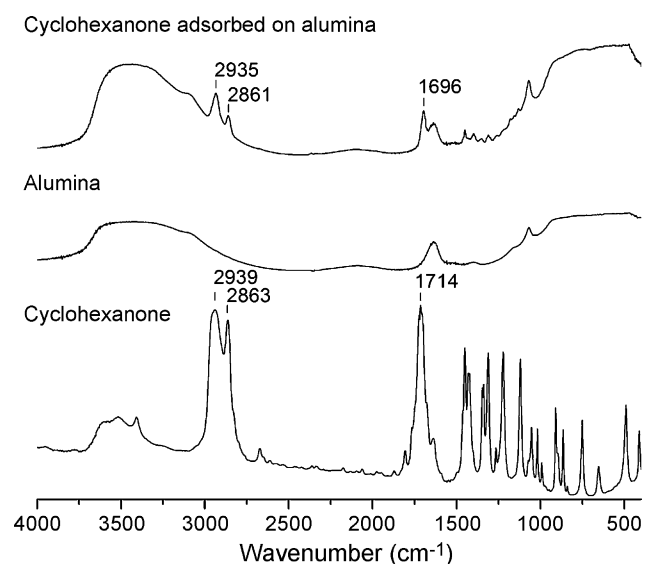


Fig. 8. FT-IR spectrum of neat cyclohexanone (liquid), alumina, and cyclohexanone adsorbed on alumina.

of O–O bond activation by reaction of H_2O_2 with the alumina surface, which creates non-equivalent partial charges on the oxygen atoms [16], allowing the Al–OOH sites to react as an electrophile and as well as a nucleophile, but using different oxygen sites [3,16]. Moreover, the type Ia-like Al–OOH site cannot be regarded as a well-defined species. Since $\gamma-Al_2O_3$ is a poorly crystalline material, a wide distribution of slightly different geometries for type Ia-like Al–OOH site is possible, resulting different reactivity behavior [10].

We also investigated the H_2O_2 consumption during the reactions using the two substrates separately and together. As shown in Fig. 7, the consumption of hydrogen peroxide reduced strongly when cyclohexanone is present, which means that the reaction is more selective with respect to the use of the oxidant.

The FT-IR spectrum of alumina exposed to a saturated atmosphere of cyclohexanone reveals that cyclohexanone is strongly interacting with the alumina surface. A redshift of 18 cm^{-1} in $\nu_{C=O}$ is detected for cyclohexanone adsorbed on alumina (Fig. 8). The interaction between cyclohexanone and alumina surface is supposed to occur on strong acid sites, decreasing the amount of these sites for H_2O_2 decomposition. These results are confirmed when using the two substrates simultaneously, as the H_2O_2 consumption is as low as that observed for cyclohexanone oxidation alone.

To ponderate the real importance of the ketone/alumina interaction, it is important to take into account that the catalytic system H_2O_2 /alumina is unable to epoxidize electron-deficient C=C bonds [17]. Although the polarization of the O–O bond in Al–OOH sites results in O atoms with non-equivalent electron densities, the O–O bond activation seems not to be the only requisite to enable Baeyer–Villiger oxidation.

As it was already mentioned, the strict temperature control is essential to achieve good conversions. At $80^\circ C$, the water removal is not efficient by azeotropic distillation. The residual water competes with the substrate for the strong acid sites, decreasing the performance of alumina for Baeyer–Villiger oxidation. On the other hand, the ketone/alumina interaction is probably not sufficiently effective at $105^\circ C$, resulting also in low lactone productivities. Therefore, the interaction of the carbonyl group with alumina surface is essential for the Baeyer–Villiger oxidation using H_2O_2 /alumina.

4. Conclusions

Alumina is an active catalyst for the Baeyer–Villiger oxidation of cyclohexanone with hydrogen peroxide as oxidant. To obtain good results the water must be removed from the reaction system in order to avoid hydrolysis of the lactone formed. The water removal is also important to allow an effective interaction between cyclohexanone and the strong acid sites. Conversions of more than 50% with 98% of selectivity for ϵ -caprolactone can be obtained under optimized conditions. By simultaneously epoxidation of cyclooctene and Baeyer–Villiger oxidation of cyclohexanone, we found that the Al–OOH-like type Ia sites are responsible for the oxygen transfer to the substrates. The interaction of cyclohexanone with the alumina surface seems to have a pivotal role in the Baeyer–Villiger reaction, since the alumina/ H_2O_2 system is unable to epoxidize electron-deficient C=C bonds. The deactivation of strong acid sites is another important aspect of cyclohexanone/alumina interaction, since it decreases the H_2O_2 decomposition and, therefore, increases the selectivity for the oxidant use.

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