ALMA MATER STUDIORUM – Università di Bologna

FACOLTÀ DI CHIMICA INDUSTRIALE

Dipartimento di Chimica Industriale e dei Materiali

NEW CATALYTIC PROCESSES FOR THE SYNTHESIS OF ADIPIC ACID

Tesi di dottorato di ricerca in

CHIMICA INDUSTRIALE (Settore CHIM/04)

Presentata da
Ing. **Katerina Raabova**

Relatore
Prof. Dr. **Fabrizio Cavani**

Coordinatore
Prof. Dr. **Fabrizio Cavani**

Correlatore
Dr. **Stefano Alini**

ciclo XXIII

Anno 2010

Oxidation of cyclohexanone with molecular oxygen catalyzed by Keggin-type polyoxometalates

Oxidation of cyclohexanone with hydrogen peroxide: Baeyer-Villiger oxidation

Two step synthesis of adipic acid, starting from cyclohexene via 1,2-cyclohexanediol

-Abstract-

The aim of my Ph.D. research was to study the new synthetic ways for the production of adipic acid.

Three different pathways were studied: i) oxidation of cyclohexanone with molecular oxygen using Keggin – heteropolycompounds as the catalyst, this research was done together with Radici Chimica, Spa. ii) Baeyer – Villiger oxidation of cyclohexanone with hydrogen peroxide in the presence of two different heterogeneous catalysts, titanium silicalite and silica grafted decatungstate, iii) two step synthesis of adipic acid starting from cyclohexene via 1,2-cyclohexanediol. Again, this research was done in collaboration with Radici Chimica, Spa. The first step was catalyzed by H_2WO_4 in the presence of the phase transfer catalyst, the oxidant was hydrogen peroxide. The second step, oxidation of 1,2 – cyclohexanediol was performed in the presence of molecular oxygen and the heterogeneous catalyst – ruthenium on alumina.

The results of my research showed that:

i) Oxidation of cyclohexanone with molecular oxygen using Keggin heteropolycompounds is possible, anyway the conversion of ketone is too low and the selectivity to adipic acid is lowered by the consecutive reaction to form lower diacids: glutaric and succinic acid. Moreover it was found out, that there are two mechanisms involved: redox type and radicalic chain-reaction autoxidation. The presence of the different mechanism is influenced by the reaction condition.

ii) It is possible to perform thermally activated oxidation of cyclohexanone and obtain non negligible amount of the products (caprolactone and adipic acid). Performing the catalyzed reaction it was demonstrated that the choice of the reaction condition and of the catalyst plays a crucial role in the product selectivity, explaining the discrepancies between the literature and our research.

iii) Interesting results can be obtained performing the two step oxidation of cyclohexene via 1,2-cyclohexanediol. In the presence of phase transfer catalyst it is possible to obtain high selectivity to alcohol with stoichiometric amount of oxidant (hydrogen peroxide). In the second step of the synthesis, oxidation of 1,2 cyclohexanediol, the conversion of alcohol is rather low with modest selectivity to adipic acid.

1. Introduction

The growing attention to the human living environment caused that many researcher focused their studies on finding greener, environmentally friendlier processes as the alternative to currently used one. Green processes can be described as the processes which use raw materials efficiently, avoid the use of toxic and hazardous reagents and solvents and where the formation of waste or undesirable by-products is minimized. To better understand of the concept of green chemistry P.T Anastas and J.C. Warner defined twelve principles which describe it [1].

Table 1: Twelve principles of green chemistry

Prevention	It is better to prevent waste than to treat or clean up waste after it has been created
Atom Economy	Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product
Less Hazardous Chemical Syntheses	Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment
Designing Safer Chemicals	Chemical products should be designed to effect their desired function while minimizing their toxicity
Safer Solvents and Auxiliaries	The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used
Design for Energy Efficiency	Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure
Use of Renewable Feedstocks	A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable
Reduce Derivatives	Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste
Catalysis	Catalytic reagents (as selective as possible) are superior to stoichiometric reagents
Design for Degradation	Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment
Real-time analysis for Pollution Prevention	Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances
Inherently Safer Chemistry for Accident Prevention	Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires

Applying these twelve principles on the case of the synthesis of adipic acid, it is evident (for the reason which will be discussed further) that this process is far from being called green.

This is the reason why during my PhD course my research was focused on finding greener alternatives to the currently used process of the synthesis of adipic acid.

To fulfill the requirements of the green process, the choice of the oxidant is one of the key aspects. The choice of the oxidizing agent is very important not only from the environmental but also from economic point of view. The preferred oxidant is the one which has high amount of active oxygen and with harmless by-products. Considering these facts molecular oxygen and hydrogen peroxide are the oxidants of the choice. Molecular oxygen has 100% content of active oxygen, hydrogen peroxide 47% [2]. In the case of oxidizing with molecular oxygen no by-product is formed, hydrogen peroxide, on the other hand, gives rise to harmless water as the by-product. Although hydrogen peroxide is not a cheap oxidant and its synthesis does not belong to the most efficient one (performed by sequential oxidation and reduction of anthraquinone), compared to other possible oxidizing agents, it can be considered as the very good one.

For this research different catalytic systems were employed, both homogeneous and heterogeneous, because both of them are advantageous from specific points of view. Heterogeneous catalyst can be very easily separated from the reaction mixture and can be reused in the reaction. On the other hand homogeneous catalysts can achieve high selectivities; they are represented by higher activity per unit mass of metal, there are no diffusion problems (mass transfer limitation) and are active at mild conditions.

My study was divided in three parts on the basis of the starting material and oxidizing agent:

1) Oxidation of cyclohexanone with molecular oxygen with homogeneous and heterogeneous catalysts was studied with the purpose to see if it is possible to substitute strong corrosive nitric acid, which is used as the oxidizing agent for this reaction.
2) Baeyer-Villiger oxidation of cyclohexanone with hydrogen peroxide in the heterogeneous catalytic system as the possible alternative to the currently used processes which employ organic acids as the oxidizing agents.
3) Two step oxidation of cyclohexene, using stoichiometric amount of hydrogen peroxide for the first step of the synthesis with subsequent oxidation of the

intermediate - 1,2-cyclohexanediol with molecular oxygen in heterogeneous catalytic system.

References

[1] P.T Anastas, J.C. Warner, Green Chemistry: Theory and Practice, Oxford University Press (1998) New York

[2] G. Centi, F. Cavani et al., Selective oxidation by heterogeneous catalysis, Kluwer Academic/Plenum Publishers (2000) New York

2. Adipic acid

Adipic acid (AA) is one of the most important aliphatic acids with the following chemical formula: COOH $(CH_2)_4$ COOH. Little of adipic acid occurs naturally, but it is produced on large scale all around the world [1].

2.1 Physical chemical properties

Under the normal conditions (room temperature and atmospheric pressure) adipic acid is an odorless, sour tasting solid present as a white powder. The melting point of the acid is 152 °C. It is soluble in polar solvents; the solubility of adipic acid in water grows with increasing temperature [1].

2.2 Application of adipic acid

Adipic acid is an important chemical intermediate; the main use of AA is a manufacture of Nylon 6,6. This polymer was first synthesized by Wallace Hume Carothers in 1935 in the laboratories of DuPont and after three years DuPont patented the process. Figure 2.1 shows the reaction for production of Nylon 6,6 [1].

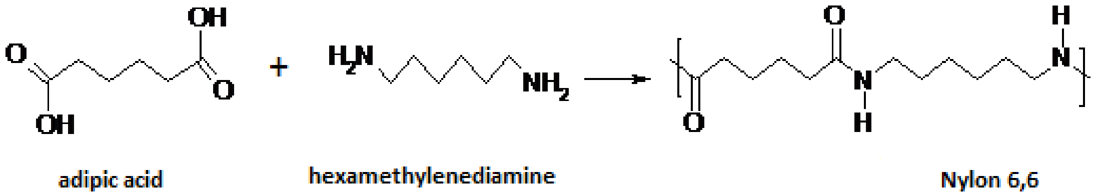


Figure 2.1: The production of Nylon 6,6

Nylon 6,6 is mainly used for production of fibers (fishing lines, tires, carpets, home furnishing, and in tough fabrics for backpacks, parachutes, luggage and business cases) and of resins. Nylon resins are used in electrical connectors, auto parts, and items such as self-lubricating bearings, gears and cams [2].

Although the main use of adipic acid is the above written, there are more ways of using adipic acid as can be seen from the figure 2.2.

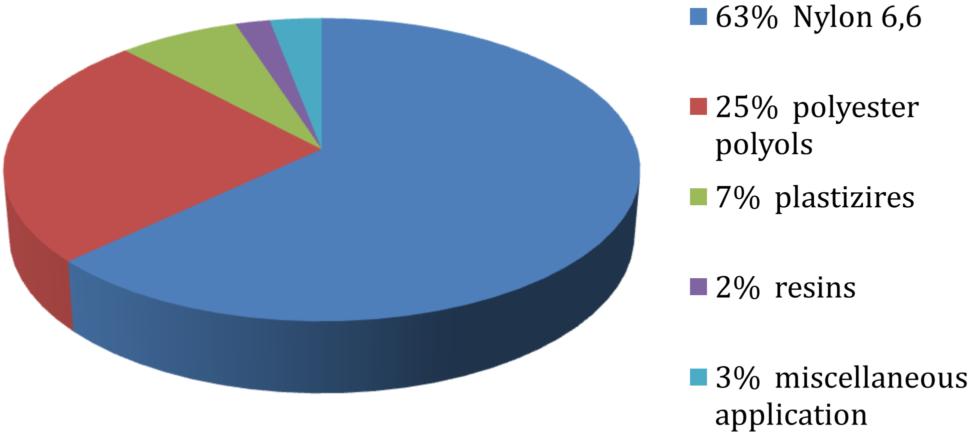


Figure 2.2: Application of AA [2]

2.3 Production of AA

In 2006 the global AA capacity was around 2.8 million metric tons per year. The overall growth for AA is about 3% per year, but the demand is growing faster, in the year 2010 it was expected to be about 5 - 6%. The most rapidly growing sector is the nylon one, where during the past decade it was between 8 - 10% per year. The table 2.1 gives the producers of AA and their capacity [3].

Table 2.1: Main producers of adipic acid

Producer	Capacity (Million tons/year)
Inolex Chem (USA)	0,02
Solutia (USA)	0,40
BASF (Germany)	0,26
Asahi Kasei Corporation (Japan)	0,17
Azot Severodonetsk (Ukraine)	0,03
Lanxess AG (Germany)	0,07
Invista (Koch Ind) (USA, Canada, Singapore, UK)	1,09
Rhodia (France, Brazil, Korea)	0,54
Radici Chimica (Italy, Germany)	0,15
Rivneazot	0,03
China Shenma Group (China)	0,11
PetroChina Liaoyang Petrochemical (China)	0,14
Xinjiang Dushanzi Tianli (China)	0,08
Taiyuan Chemical Industry (China)	0,05
Shandong Bohui Chemical Industry Group (China)	0,08
Shandong Hongye Chemical Industry Group (China)	0,10

2.4 Current industrial processes

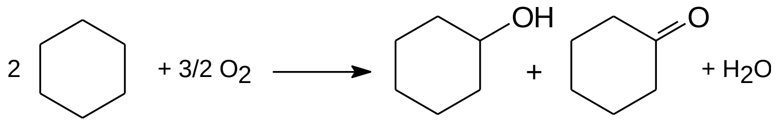
Adipic acid is produced by a two step oxidation process. The first one is (prevalently) oxidation of cyclohexane with air; the second one is an oxidation of

a) a mixture of cyclohexanone/cyclohexanol (called KA oil) or

b) only of cyclohexanol with nitric acid [4].

2.4.1 First step: Oxidation of cyclohexane with air

Cyclohexane is obtained either by the hydrogenation of benzene, of from naphtha fraction in small amounts [2]. Oxidation of cyclohexane was first performed in the year 1940 by DuPont. The process is performed at temperatures between 150 – 180 °C, under the pressure of 10 - 20 atm, in the presence of Co or Mn organic salts. It is a two step process: oxidation and deperoxidation step. Meanwhile the former one can be done without the catalyst, the latter one is always done in the presence of catalyst. The rate limiting step of the process is the synthesis of hydroperoxide; its concentration is optimized by carrying out the oxidation in passivated reactors and in the absence of transition metal complexes in order to avoid the decomposition of hydroperoxide. The deperoxidation step in done in the second reactor, where the catalyst amount and reaction condition are optimized, allowing the OL/ONE ratio to be controlled. For the fact that both of the products are more reactive than the starting material, conversion of cyclohexane is kept low - only about 5-7% in order to avoid consecutive reactions. The selectivity to KA oil is about 75-80%, the by-products are carboxylic acids and cyclohexyl hydroperoxide. The unconverted cyclohexane is recycled [4, 5].



cyclohexane + ½ O_2 → cyclohexanol ΔH$_R$ - 47.4 Kcal/mol;
cyclohexane + O_2 → cyclohexanone ΔH$_R$ - 98 Kcal/mol

The chemistry of the reaction is a homolytic autooxidation. Alcohol is formed from RO• radical (R = C_6H_{11}).

RH (cylohexane) + Co(III) (or In•) → R• (cyclohexyl radical) + Co(II) + H^+ (or InH)

$$R\bullet + O_2 \rightarrow ROO\bullet$$
$$ROO\bullet + RH \rightarrow ROOH \text{ (cyclohexylhydroperoxide)} + R\bullet$$

The role of Co is to accelerate the reaction by decomposition of the intermediate hydroperoxide, ROOH, leading to the formation of alkoxyl or peroxyl radicals (Haber-Weiss mechanism) [6, 7].

$$ROOH + Co(II) \rightarrow RO\bullet + Co(III) + OH^- \text{ (in non-polar solvents)}$$
$$ROOH + Co(III) \rightarrow ROO\bullet + Co(II) + H^+ \text{ (in polar solvents)}$$

Which corresponds to:

$$2\ ROOH \rightarrow RO\bullet + ROO\bullet + H_2O$$

At high concentration of Co(II) it competes with cyclohexane for the alkylperoxy radical:

$$ROO\bullet + Co\ (II) \rightarrow ROOCo(III)$$

And therefore termination step would occur instead of propagation step. In that case catalyst would act as an inhibitor of the reaction.

Russel mechanism of decomposition of secondary cyclohexylperoxy radicals is a prevailing reaction for the formation of alcohol and ketone. It consist in coupling of alkylperoxy radical, which then reacts by a non-radical, six-center 1,5H atom shift, which also is a terminating step of the radical chain reaction.

$$2ROO\bullet \leftrightarrow ROOOOR$$
$$ROOOOR \rightarrow C_6H_{11}OH + C_6H_{11}O + O_2$$

Simplified flow sheet of the synthesis of KA oil is shown in figure 2.3. The reaction is carried out in three in-series reactors, first one being fed by cyclohexane, and all three by air, which should allow better safety and control of the reaction. During the process the products are washed with water and subsequently with caustic solution, (having the concentration between 7 and 20% wt), in order to reduce acid impurities. Caustic solution can be during the process recycled.

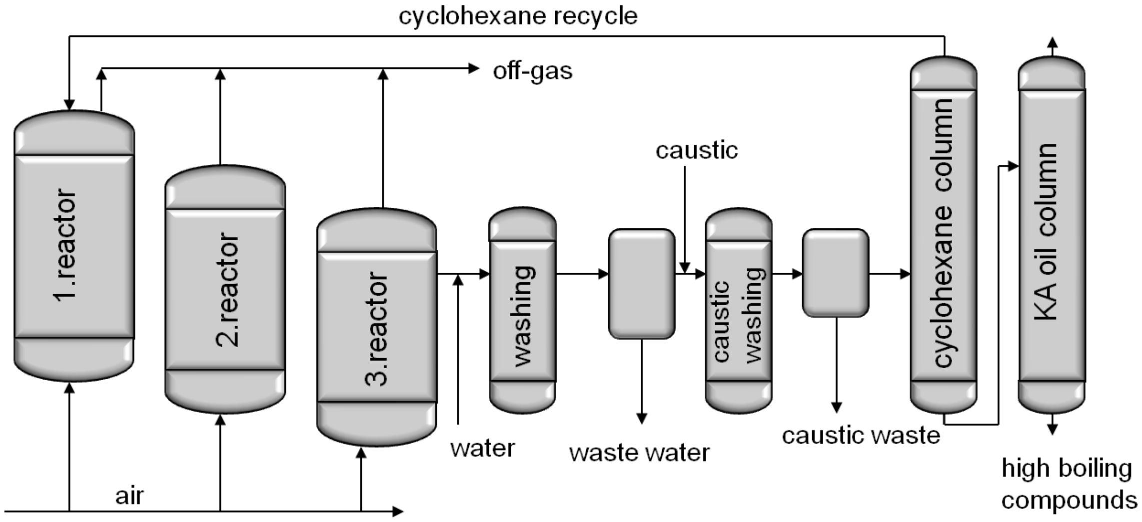


Figure 2.3: Scheme of oxidation of cyclohexane to KA oil
a – reactor of oxidation by air, b – washing, c – decantation of water, d – reactor of decomposition of decantation, e – caustic decantation, f – column of recuperation of cyclohexane, g – column of recuperation of KA oil

Scientific Design Company has developed a variation of this step, it consist in the addition of substantial quantities of anhydrous meta-boric acid as slurry in cyclohexane to the first of a staged series of oxidation reactors. No other catalyst is necessary. Boric acid reacts with cyclohexanol to give a borate ester that stabilizes the product and reduces its tendency to be oxidized further to form either cyclohexanone or degradation products. Conversion is as high as 10% (or even 15%), and selectivity of 90%, with molar ratio Ol/One around 10. The borate ester formed is easily hydrolysed by hot water to boric acid and cyclohexanol. After distillation a 99.5% Ol/One mixture is obtained [2].

2.4.2 Alternative ways of production of KA oil

Although the described synthesis of KA oil is the most used one, there are two alternatives:

a) hydrogenation of phenol to KA oil

b) hydration of cyclohexene to cyclohexanol. Cycloolefin is obtained by selective hydrogenation of benzene. Alcohol is then oxidized by the same procedure used for KA oil [5].

Hydrogenation of phenol has some advantages such as the less complex equipments needed for KA oil manufacture, the selectivity of the process, the high purity of the product and the possibility to directly obtain a mixture of alcohol and ketone with desired ratio. Moreover with increasing ketone/alcohol ratio, it is possible to save hydrogen and nitric acid in the oxidation step.

The hydration of cyclohexene to cyclohexanol is an interesting method because of its precedent step: partial hydrogenation of benzene. This reaction is not thermodynamically favored. In order to obtain non saturated cyclocarbon, it is necessary to perform the hydrogenation in the presence of Pt or Ru powder, coated with a layer of an aqueous solution of zinc sulfate. The reaction is performed in bulk benzene, catalyst is surrounded by the aqueous phase, for this reason the molecules which are soluble in aqueous phase are hydrogenated. The product – cyclohexene is less soluble then benzene and therefore migrates to organic phase thus avoiding to be further hydrogenated. The conversion of benzene is 70 – 75%. The selectivity to cyclohexene is 80% [5]. Product is then hydrated on ZSM-5 catalyst. The advantage of this process is its lower consumption of hydrogen and formation of fewer by-products with respect to above mentioned methods.

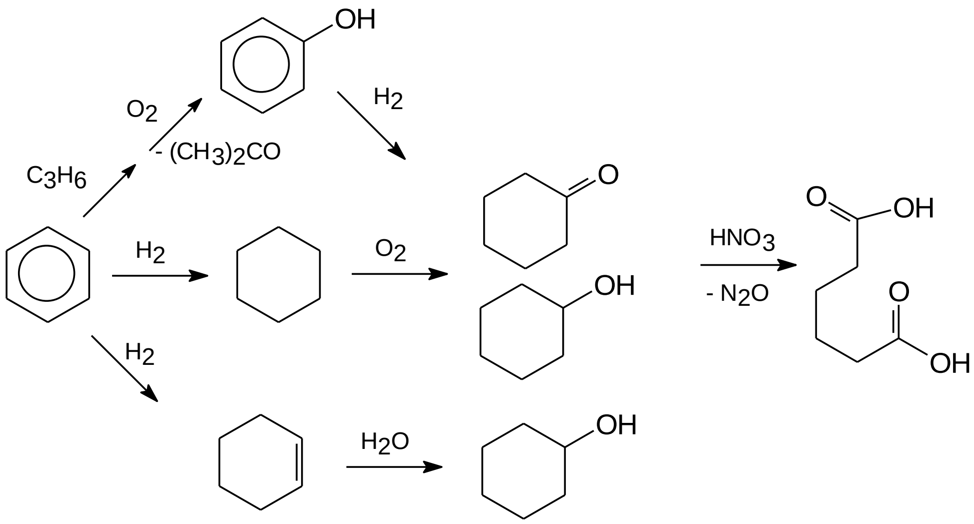
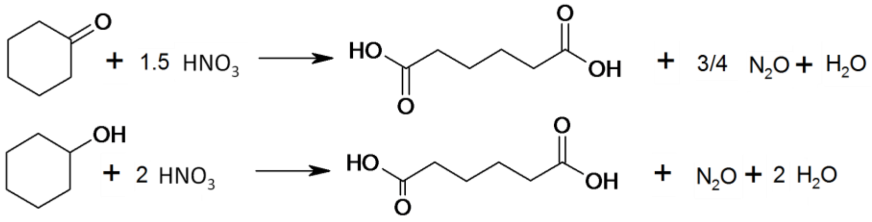


Figure 2.4: Processes used for production of AA

2.4.3 Second step: Oxidation of KA oil with nitric acid

The second step of the synthesis of adipic acid is oxidation of KA oil with a large excess of nitric acid 65% (molar ratio of HNO_3/KA oil is at least 7/1), in the presence of Cu (II) ammonium metavanadate catalyst [4, 9].



Cyclohexanone → AA ΔH_R - 172 Kcal/mol;
Cyclohexanol → AA ΔH_R - 215 Kcal/mol

The reaction is carried out in two in-series reactors, first one operating at 60-80 °C, the second one at 90-100 °C and a pressure of 1 - 4 atm. The molar yield for total KA oil conversion is 95%, the by – products are glutaric acid (selectivity 3%) and succinic acid (selectivity 2%). The simplified flow sheet of the oxidation of KA oil is shown in the figure 2.5.

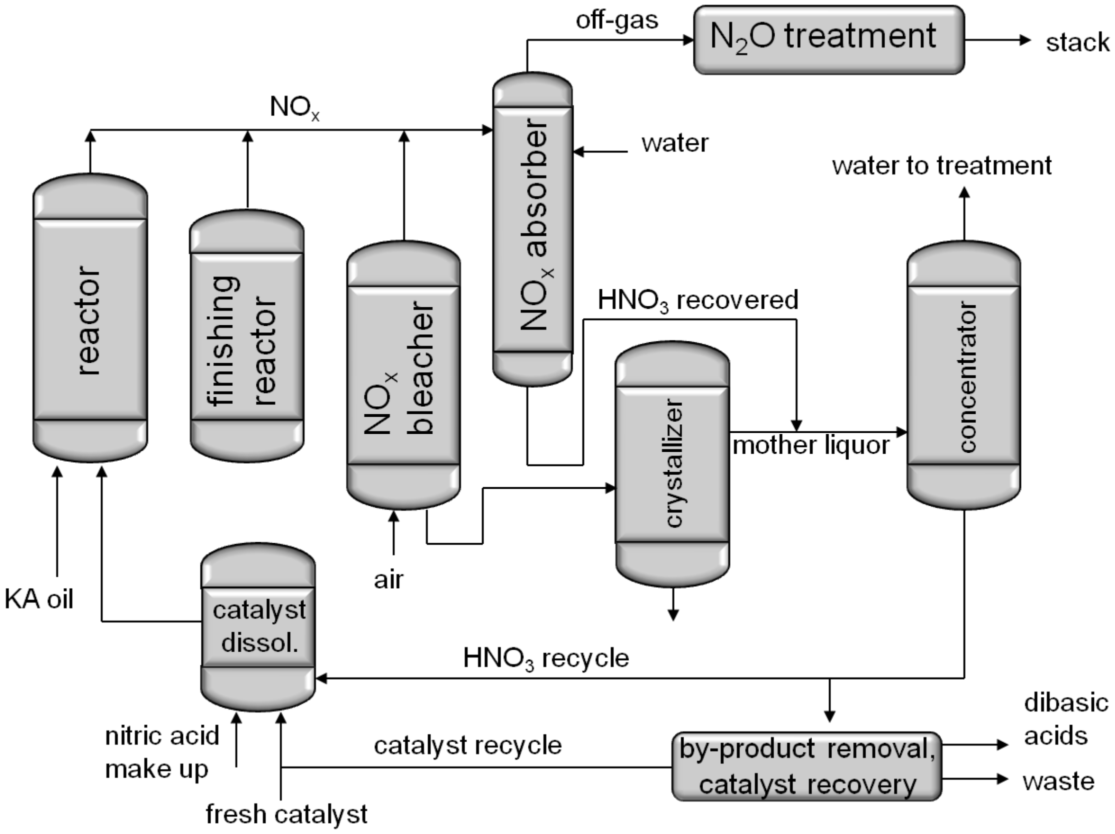


Figure 2.5: Simplified flow sheet of the oxidation of KA oil.

The reaction mechanism of the oxidation of KA oil was studied already in 1963 [10, 11] and recently has been revised. As can be seen from the figure 2.6 the first step is the oxidation of cyclohexanol to cyclohexanone, which is nitrosated by nitrous acid to produce 2-nitrosocyclohexanone. This intermediate can undergo various reactions. In the presence of HNO_2, the nitrosoketone can be hydrolyzed to the α-diketone and hydroxylamine (Claisen-Manasse reaction). Another possibility is that oxime is oxidized by stronger oxidant to yield α-diketone and NOx. α-diketone is further oxidized to AA Anyway the main path is the formation 2-nitro-2-nitrosocyclohexanone which is hydrolyzed to 6-nitro-6-hydroximinohexanoic acid. Acid further undergoes oxidative hydrolysis to AA via intermediate adipomonohydroxamic acid. In this case the consumption of nitric acid is completed and 2 mol of nitric acid are consumed per mole of cyclohexanone [2].

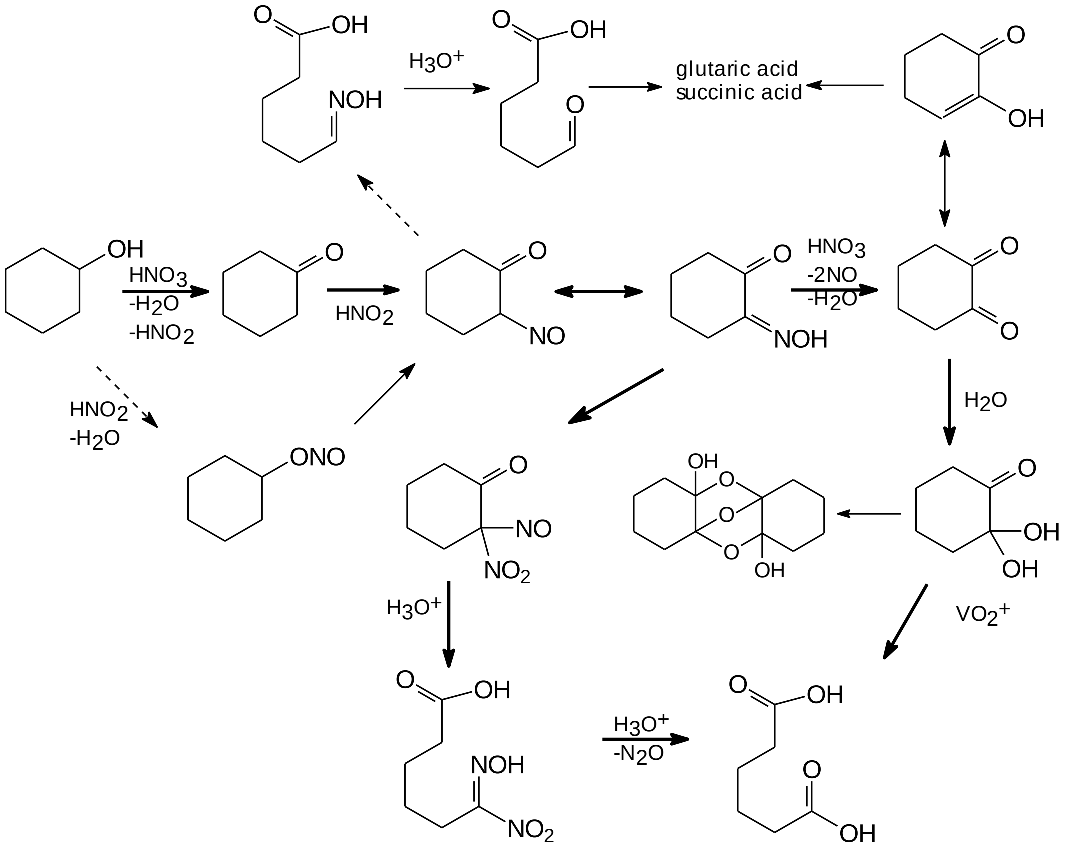


Figure 2.6: The main reactions involved in the oxidation of KA oil, taken from [2]

2.5 Environmental impact of the second step

The intermediate of the nitric oxidation is HNO_2, which eventually decomposes to NO and NO_2. These two gases can be simply recovered in water by absorption in a multistage column, yielding nitric acid solution, which can be reused in the oxidation process [2].

$$2NO + O_2 \rightarrow 2NO_2$$

$$3NO_2 + H_2O \rightarrow 2HNO_3 + NO$$

Because of the poor solubility of NO_x in water, the key factors for this process are the temperature and the pressure. It is possible to have a complete recovery of NO_x.

Meanwhile the co-products of the nitric oxidation of KA oil, NO and NO_2 are easily recoverable, as shown above, co-production of N_2O represents a big drawback of the second step of the synthesis of AA.

Nitrous oxide belongs to so called longed lived greenhouse gases LLGHGS (other being CH_4, CO_2 and radioactively active constituents such as ozone and different types of aerosol), which contributes to the climatic changes [18]. The estimated atmospheric lifetime of N_2O is 150 years and the estimated impact of N_2O is a 6% increase in the ozone depletion layer. Although the absolute concentration of N_2O is relatively low, 300 ppbv, it influences climatic changes as a result of one of its stratospheric removal reaction:

$$N_2O + O(1D) \rightarrow NO + NO\ (61.7\%)$$

$$\rightarrow N_2 + O_2\ \ (38.3\%)$$

The equation shows that the major part of N_2O is converted to NO, which is unambiguously implicated in catalytic ozone destruction [22].

The emission factor of adipic acid is estimated to be about 300 kg of N_2O per ton of adipic acid, depending on the amount of catalyst used and KA oil composition. In 1990, adipic acid production was the largest source of industrial N_2O emissions. By 1999 all major adipic acid producers have implemented N_2O abatement technologies and, as a result, this source has been decreased substantially [21]. Consequently, currently the production of nitric acid is the largest industrial source of N_2O.

2.6 Methods for N_2O abatement

As already mentioned above, because of the law restriction, industries producing adipic acid had to implement N_2O abatement technology in order to decrease the emission of N_2O. The possible methods of the abatements are:

1) Catalytic dissociation of N_2O to N_2 and O_2
2) N_2O decomposition in boilers – thermal destruction
3) Conversion of N_2O into recoverable NO [2]

2.6.1 Catalytic abatement

The catalytic decomposition is a highly exothermic reaction (-19.6 Kcal/mol), and for the fact that it does not require any other chemical compound it can be considered as the simplest method for the removal of N_2O.

1. $N_2O + * \leftrightarrows N_2O*$
2. $N_2O* \rightarrow N_2 + O*$
3. $2\, O* \leftrightarrows O_2 + 2\, *$
4. $N_2O + O* \rightarrow N_2 + O_2 + *$

Where * is the active site of the catalyst.

There are few classes of catalyst suitable for this reaction such as: noble metals (Pt, Au), pure or mixed metal oxides (spinel, perovskite – types, oxides from hydrotalcites), supported systems (metal or metal oxides on alumina, silica, zirconia) and zeolites [14, 15]. Unfortunately there are some problems connected to the strong exothermity of the reaction like:

a) sintering of the catalyst or their supports,

b) high investment costs for the careful selection of special heat resistant materials for reactors bodies,

c) difficulty in respecting the environmental regulation: with increasing temperature of the catalytic bed increases the risk of formation NOx, whose concentration is limited by the law.

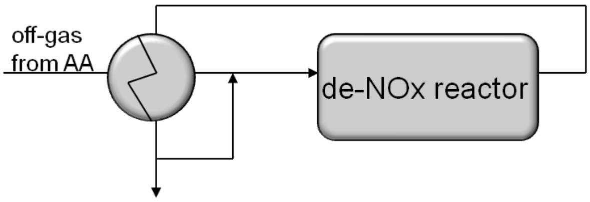


Figure 2.7: Schematic diagram of the catalytic abatement of N_2O

During the process part of the treated and cooled gas is recycled back to dilute the N_2O stream stemming from AA production, thus avoiding high local temperature rises and leveling out the heat production over the entire bed, see figure 2.7. Typically the inlet reactor temperatures are about 450-500 °C, and 700-800 °C at the outlet, considering the inlet concentration of N_2O about 12 %.

Radici in order improve the process of the abatement developed process in which the gaseous flow containing N_2O is subdivided into three flows that are fed separately to the three catalytic layers (figure 2.8) [16,17]. The flow exiting the final catalytic bed exhibits residual nitrous oxide content below 500 ppm and is subdivided into two flows, one being vented to the atmosphere and one being mixed with the feed to the first catalytic bed and re-circulated into the nitrous oxide decomposition process.

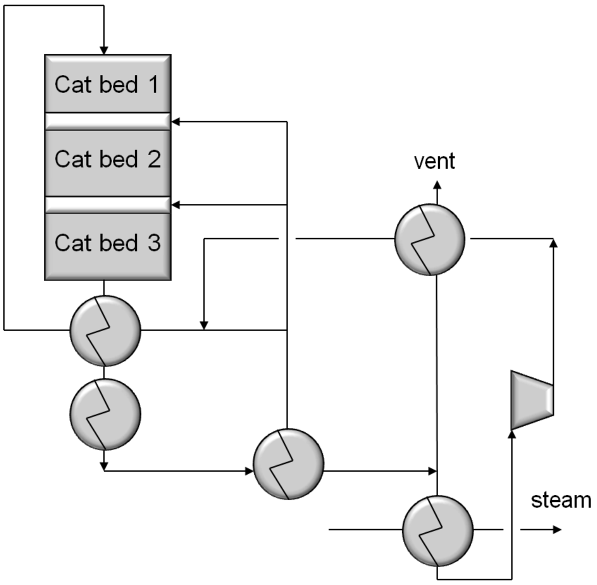


Figure 2.8: Simplified flow sheet of N_2O abatement designed by Radici

2.6.2 Thermal decomposition

Two methods can be distinguished in this case, depending whether the decomposition takes place at oxidizing condition or as a result of burning in a reducing flame. The former one results in a formation of NO, NO_2 which are further absorbed in water. Nitric acid solution is obtained and further used. The second one is based on using sub-stoichiometric combustion condition, to minimize the formation of NOx. Reducing atmosphere is generated by adding an excess of methane and to the gas mixture fed to the burner (containing O_2 and N_2O). Excess of methane produces an unburnt share (CO and H_2) which is a driving force for reduction of nitrogen oxides to nitrogen. Equations bellow shows the thermal abatement of N_2O – reducing method.

$4\ N_2O + CH_4 \rightarrow CO_2 + 2\ H_2O + 4N_2$

$4\ NO + CH_4 \rightarrow CO_2 + 2H_2 + 2\ N_2$

$2\ O_2 + CH_4 \rightarrow CO_2 + H_2O$

$H_2O + CO_2 + 2\ CH_4 \rightarrow 3CO + 5\ H_2$

$N_2O \rightarrow \frac{1}{2}\ O_2 + N_2$

2.6.3 Using N_2O as a reactant

It is possible to recover N_2O from the off gas in pure form and again use it as an oxidizing agent. An innovative solution has been proposed by Solutia and Boreskov Institut of Catalysis, the proposed process was hydroxylation of benzene to phenol in the presence of ZSM-5 catalyst exchanged with Fe^{3+}. Phenol could be further hydrogenated to cyclohexanol and used for the synthesis of adipic acid [19]. The scheme is given in figure 2.9.

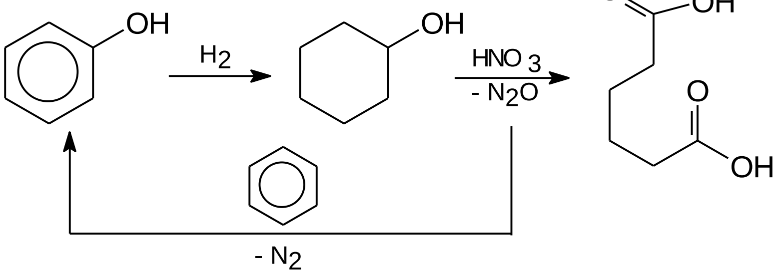


Figure 2.9: Proposed integrated process

Although good results have been obtained in this process (selectivity to phenol more than 95 %) and pilot unit has already been constructed, the process has not been put into commercial operation due to rapid catalyst deactivation caused by tar deposition, low efficiency with respect to N_2O and to the poor economics of such small sized phenol plants, suited to balance the adipic acid process units.

Another proposition was to use N_2O as an oxidizing agent in the synthesis of cyclododecanone, a raw material for Nylon – 12 [20]. This has been proposed by BASF and from October the 2009 it has been in commercial use. As can be seen from figure 2.11 BASF process uses N_2O as an oxidizing agent for oxidation of cyclododecatriene to produce cyclododecanone, this process is more environmentally friendly compared to the conventional methods of the synthesis of cyclododecanone (figure 2.10).

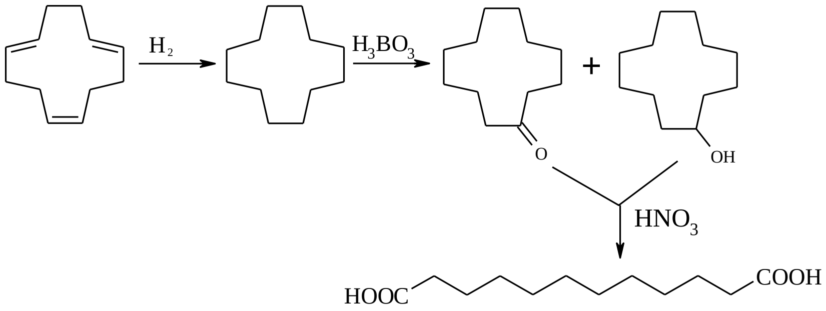


Figure 2.10: Conventional method of synthesis of 1,12 dodecanedioic acid

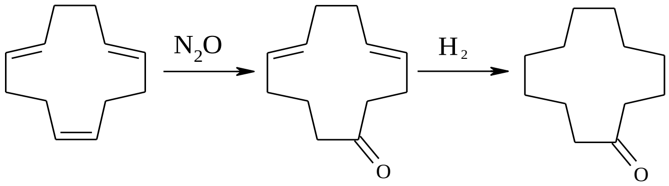


Figure 2.11: New process proposed by BASF

References

[1] ULLMANN'S Encyclopedia of Industrial Chemistry, Wiley-VCH, 2nd edition (2002)

[2] Cavani et al., Sustainable Industrial Processes, Wiley-VCH, 1st edition (2009)

[3] http://www.chemplan.com/chemplan_demo/sample_reports/Adipic_acid.pdf

[4] A. Castellan, J.C.J. Bart et al., Catal. Today 9 (1991) 237

[5] U. Schuchardt, D. Cardoso et al., Appl. Catalysis A 211 (2000) 1

[6] R.A. Sheldon, J.K.Kochi, Adv. Catalysis 25 (1976) 272

[7] US patent 6,700,022

[8] Trettenhahn, M. Nagl et al., Angew. Chemie, Int. Ed. 45(2006) 2794

[9] A. Castellan, J.C.J. Bart et al., Catal. Today 9 (199) 255

[10] W. J van Asselt, D. W. van Krevelen, Rec. Trav. Chim. des Pays-Bas, 82 (1963) 429

[11] W. J van Asselt, D. W. van Krevelen, Chem. Eng. Science 18 (1963) 471

[12] R. F. Weiss, J. of Geophysical Research 86 (1981) 7185

[13] M. A. K. Khalil, R. A. Rasmussen, Telluis 35B (1983) 161

[14] F. Kapteijn, J. Rodriguez-Mirasol et al., Appl. Catalysis B 9 (1996) 25

[15] A. Shimizu, K. Tanaka et al., Chemosphere – Global Change Science 2 (2000) 425

[16] S. Alini, E. Frigo et al., Eur Patent 2002, 1,413,349 (Assigned to Radici Chimica SpA)

[17] S. Alini, E. Frigo et al., Eur Patent 2003, 1,488,845 (Assigned to Radici Chimica SpA)

[18] IPCC Fourth Assessment Report: Climate Change 2007, 7th chapter

[19] W.D. McGhee, US Patent 1998, 5,808,167 (assigned to Solutia)

[20] J. Teles, B. Röβler et al., WO Patent Appl 2005/030689 (assigned to BASF)

[21] IPPC, Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories

[22] M.H. Thiemens, W. C. Trogler, Science 251 (1991) 93

3. Alternative ways for synthesis of adipic acid

For the reasons mentioned in the precedent chapter (using the corrosive acid as an oxidizing agent, the need of abatement of N_2O), there is a great interest to find other methods of synthesis of AA. In this chapter some examples of studied systems which have been proposed for the synthesis of AA will be described. The systems will be divided on the bases of starting material, different oxidizing agents will be discussed (O_2, hydrogen peroxide - HP, tert-Butyl hydroperoxide - TBHP) and examples of some alternative processes will be given.

3.1 First step of the synthesis: oxidation of cyclohexane

Many researchers have been studying the possibility of oxidation of cyclohexane by different kinds of oxidizing agent in homogeneous or heterogeneous phase with the goal to find a system which would permit higher conversion of cyclohexane maintaining the high selectivity to KA oil.

3.1.1 Homogeneous catalysis

Some examples of the homogeneous systems other then salts of Co studied for the first step of synthesis of KA oil are:

1. Keggin type polyoxometalates, like Fe_2Ni-substitued P/W POMs which oxidize cyclohexane in the presence of air at atmospheric pressure [1, 2, 3], another system using air as an oxidizing agent is Fe substituted POMs [4] giving high selectivity to KA oil but low conversion. Co(Fe)-substituted P/W POMs catalyzed the reaction using TBHP [5]. A mixture of heterogeneous homogeneous systems based on a Pt/C –P/W POM catalyzed cyclohexane in the presence of the mixture of H_2-O_2 [6].
2. With different oxidizing agents (HP, TBHP, oxygen, peracetic acid) Cu-based systems have been widely studied. The drawback of these systems is the fact that still they provide low yields and low selectivities; require expensive and environmentally unfriendly components. With polynuclear Cu triethanolamine complexes [7,8] in the oxidation of cyclohexane with aqueous HP in acidic medium at room temperature in acetonitrile and atmospheric pressure 39% yield to KA oil was obtained. The highest

yield to Ol/One reported (69%) was obtained with bis-(2-pyridylmethyl) amine Cu(II) complex and HP as the oxidant [9], in acetonitrile solvent at mild conditions. On the other hand, using O_2 as an oxidizing agent, the yields are usually very low (less than 5%) [10,11].

3. Vanadium-based complexes and salts have been studied for the oxidation of cyclohexane, the oxidizing agent used were oxygen in the presence of coreductants [12], peroxyacetic acid in acetonitrile [13], hydrogen peroxide and O_2 combined oxidants [14,15,16].

These were some examples of the studied systems, for further examples see the literature [17].

3.1.2 Heterogeneous catalysis

3.1.2.1 O_2/air

Great attention was devoted to Au nanosize particles supported on mesoporous materials (MCM-41, ZSM-5, SBA - 15, Al_2O_3) [18,19,129]. Although good results were achieved, Au-SBA-15 gave after 6 hours of the reaction at 150 °C, under the pressure of 0.1 MPa, 18% conversion of cyclohexane with 93% selectivity to KA oil, Au-MCM-41 16% conversion of cyclohexane with 76% S to KA oil [18,19], problems with leaching were detected and loss of catalytic activity during the time. Moreover its real importance is speculative since Au is a noble metal and thus the use of these catalysts is limited from the economical point of view.

To avoid using expensive metal, Wang et al. performed the oxidation of cyclohexane with bismuth incorporated in SBA-15. They succeed in preparation of very active and truly heterogeneous catalysis. After 4 hours of the reaction, at 413 K, under 1 MPa of O_2, they obtained in a solvent free system 17% conversion of cyclohexane and 93% selectivity to KA oil [20].

Aluminophospathes have been studied in details many time with different metals (Ce, Fe, Mn Co, Cr, Zn, Mg) [21, 22, 23, 24,27] resulting in high selectivities to KA oil, for example 92% in the case of CeAlPO-5 [21] or 93,4% in the case of FeAlPO [22]. In some cases the effect of TBHP was studied, and the effect of the acceleration and lowering the introduction period has been confirmed [26]. Moreover, they observed that the diameters pore of molecular sieves greatly influence the products selectivity. With increasing diameter increased the selectivity to AA [24]. Unfortunately almost all the studied catalysts suffered from leaching, the only one which behaved as a heterogeneous catalyst was CeAlPO-5 [21]. Very similar behavior to CeAlPO-5 performed gadolinium containing AlPO-5. Under the same condition as in the case of cerium doped aluminophospahte (416 K, 0.5 MPa, 4 hours, solvent free system) in both cases 13% conversion of cyclohexane was obtained with 92% selectivity to AA. Also in the case of gadolinium the heterogeneous nature of the catalyst was confirmed [28].

Chrome doped mesoporous materials (MCM-41, MCM-48) also performed good activity, but also in this case the leaching showed to be a problem [29]. On the other hand incorporating Bi in mesoporous MCM-41, Quian et al. observed that it is possible to prepare really heterogeneous system, which is able to catalyze oxidation of cyclohexane in solvent free system giving 17% conversion of cyclohexane with 91 % selectivity to KA oil [30].

Other class of molecular sieves which was studied in detail is ZSM-5. This zeolite was doped with different metals such as Co, Fe, Cu, Cr, Ni, Mn [31]. The activities of the catalyst varied in the function of the containing metal, best performance gave Co-ZSM-5, under the pressure 1 MPa, at 393 K in solvent free system gave 97% selectivity to KA oil with 10% of conversion of cyclohexane. But also as in many other cases, leaching of metal occurred.

From other studied systems worth mentioning: i) $Ti_{70}Zr_{10}Co_{20}$ containing icosahedral quasicrystalline phase. This system was studied in a solvent free condition, without any addition of free radical initiator. Results were quite promising, after 6 hour of reaction under the pressure of 1 MPa at 413 K 7% of cyclohexane was converted with 90% selectivity to KA oil. Moreover in contrast to many other catalyst discussed above, any leaching of metals was observed [32] ii) zirconium phosphate, giving 32% conversion of cyclohexane with 90% selectivity to KA oil, using TBHP as the initiator [33].

3.1.2.2 Tert-butyl hydroperoxide

Tert-butyl hydroperoxide gave very good results as an oxidant in the presence of transition metal-substituted polyoxometalates, with “sandwich” like structures, e.g. dinuclear ruthenium polyoxometalate $[(WZnRu^{III}_2)(ZnW_9O_{34})_2]^{11-}$, and dinuclear palladium polyoxometalate, $[(WZnPd^{II}_2)(ZnW_9O_{34})_2]^{12-}$. After 24 hours of the reaction at 75 °C using 1,2 dichlorethan as a solvent, $[(WZnRu^{III}_2)(ZnW_9O_{34})_2]^{11-}$ gave a conversion of cyclohexane 6,5% and turnovers 720 [34].

Different organic complexes incorporated in zeolites were studied for the synthesis of KA oil: iron-phthalocyanines occluded in zeolite Y (FePc-Y) [35] performed the oxidation at room temperature using acetone as a solvent. Conversion of cyclohexane in the presence of FePc-Y was high (up to 25%) with selectivities for cyclohexanone of 95% (giving the byproducts diketones and diols). The observed activities were higher than those obtained with homogeneous FePc complexes. Although FePc-Y showed no leaching, a rapid deactivation was observed under prolonged reaction times. In order to avoid this problem, FePc-Y was embedded in a polydimethylsiloxane membrane [36], but unfortunately in this case the deactiovation of the catalyst was observed (due to sorption of hydrophilic compound formed). Balkus et al. [37] synthesized ruthenium perfluorophthalocyanine encapsulated in NaX and found out, that this catalyst was active at the room temperature and no leaching was observed. The catalyst showed no sign of deactivation, and gave high conversion of cyclohexane with high selectivity to cyclohexanone, 70% conversion with 98,4% selectivitiy to cycloxenanone. Encapsulating chloro- and nitro-substituted phthalocyanines of copper, cobalt and iron in zeolites X and Y also gave very interesting results. Raja et al. studied the oxidation of cyclohexane at ambient temperature using molecular oxygen and alkylhydroperoxides. They found out that using O_2 together with TBHP it is possible to oxidize cyclohexane very efficiently, reached TOF was as high as 400 h^{-1}, main products being cyclohexanone, cyclohexanol, adipic acid and valeraldehyde [38]. They also performed the oxidation with H_2O_2, but the results were not as good as in the case of TBHP.

Also in the oxidation with TBHP mesoporous materials doped with transitional metals (Cr, Ce) were studied. Amorphous silica containing cerium did not performed good activity; the conversion was lower than 3% with very low TOF [39].Very similar result was obtained using chromium containing silicalite. In this case leaching of the metal was observed [40]. Better results were obtained with Cr – MCM-41 using acetonitrile as a solvent. This system behaved heterogeneously, gave very high selectivity to ketone (95%), with very high conversion 92%, but low TOF 3 h^{-1} [41].

3.1.2.3 Hydrogen peroxide

Using the same catalyst as in the case discussed above – Cr-MCM-41, in the same condition but with H_2O_2 as an oxidant, the selectivity was very similar, but the activity drastically dropped, the conversion was only 37% [41]. On the other hand another group of researchers studied the same catalyst in the presence of acetic acid as a solvent, using MEK as an initiator at 373K and found out that after 12 hours 90% of cyclohexane converted giving the selectivity to cyclohexanol of 93%. Performing the same reaction with TBHP no cyclohexanol was detected, resulting in high selectivity to cyclohexanone and the conversion of cyclohexane 61% [42]. Changing chromium to vanadium and performing the oxidation with H_2O_2, acetic acid and MEK as the initiator, did not bring any substantial differences [43]. Also in this case, cyclohexanone was not almost detected. In both cases, chromium and vanadium showed leaching, but only non framework ions. Further test showed that the catalysts were heterogeneous.

As in the case of the TBHP, also with hydrogen peroxide a lot of catalysts based on incorporating organic complexes to molecular sieves have been studied. Armengol et al. [44] used Cu^{2+}- phthalocyanine and Co^{2+}- perfluorophthalocyanine incorporated in faujasite or mesoporous MCM-41 and the only detected products were cyclohexanone and cyclohexanol. Despite the higher activity shown by supported catalysts in comparison to free complexes and its stability towards leaching, conversions and H_2O_2 efficiency were low. Carvalho et al. attempted organofunctionalise MCM-41 with 3-aminopropyltrimethoxysilan and further to activate the catalyst with Cu or Fe. The best results were obtained at 373 K in the presence of $Fe\text{-}(CH_3O)_3Si(CH_2)_3NH_2$-MCM-41 as the catalyst [45]. Using acetone as solvent, a conversion of cyclohexane of 19.5% with a turnover of 88 was obtained after 12h. On the other hand, the H_2O_2 efficiency was only 34% and leaching of the metal occurred progressively. However these results were better in comparison with TS-1 [46], TS – 1 was studied in the same condition as in the previous case, and after 16 hours of the reaction the TON was 59 with 16% of H_2O_2 efficiency.

3.2 Second step of the synthesis: ketone or/and alcohol oxidation

3.2.1 Oxygen

As already said many times before, there is a great challenge to replace HNO_3 with another, greener oxidizing agent. In fact it is possible to replace it with oxygen to perform the oxidation with the catalytic amount of Co and Mn acetate, at the temperature 70-80 °C, using acetic acid as a solvent. In this reaction it is necessary to achieve 100% conversion of KA oil, because its recycling would complicate the whole process [17]. The problematic part of this process is the fact that the reported yields of AA are still too low compared to conventional process and the presence of acetic acid. This solvent causes corrosion problems and also worse the quality of the product.

AA is probably generated via the intermediate formation of 2-hydroxycyclohexanone and 6-oxohexanoic acid. The mechanism may eventually include the formation of the enol tautomer of cyclohexanone, favored by the presence of an acid. The formed cyclohexen-1-ol is then oxidized to 2-hydroperoxycyclohexanone. The hydroperoxide generates 2-hydroxocyclohexanone, which is then cleaved to 6-oxohexanoic acid. The latter is then converted to AA via monoperoxyadipic acid; this step is eventually catalyzed by cobalt [17].

Industry Asahi has been studying this process in detail employing a combination of $Mn(OAC)_2$ and $Co(OAc)_2$ catalyst, using pure oxygen at atmospheric pressure or, in order to avoid explosion hazards, nitrogen diluted air at 12 atm. They succeed in obtaining complete conversion of cyclohexanone and 77% of selectivity to AA [47]. Another very well studied system is oxidation with air or oxygen of cyclohexanone by Keggin polyoxometalates. Although good result have been reached (99% conversion of ketone with 50% selectivity to AA) [48] also in this case the acetic acid as a solvent was involved, moreover in other cases mixture of acetonitrile and methanol was used, resulting in ester of AA (selectivity 54% with 98% conversion) [49] which would be have to transform back to AA and thus the cost of the whole process would be higher.

Among the other studied systems are: supported carbon with platina [50,51] used for the oxidation of ketone or alcohol, nickel promoted tungsten supported on carbide (giving very small selectivity and conversion of cyclohexanone), monomeric V species (acetylacetonate, oxoalkoxide) giving high conversion of cyclohexanone, but low selectivity to AA (only about 30%), $Co(NO_3)_2$ in the presence of acetic acid and water solvent giving 95% conversion of ketone with 72% yield of AA [52].

3.2.2 Hydrogen peroxide

Although for the economic reason it is preferable to use air or oxygen as an oxidizing agent, many studies have been employing aqueous hydrogen peroxide in homogeneous or heterogeneous catalysis. For example Zhu and co-workes has studied the oxidation of cyclohexanone and cyclohexanol (and also cyclohexene) with surfactant-type peroxotungstates and peroxomolybdates, which could also act as a phase transfer agent. After 20 hours of the reaction at 90 °C, they obtained 60% yield of AA in the case of oxidizing cyclohexanone with the tungsten catalyst and 50% oxidizing cyclohexanol. Worth noticing, catalyst based on Mo gave very low yield (between 20 and 30% in the case of cyclohexanol, 40 and 0 % oxidizing the ketone). Better results have been reached oxidizing cyclohexene or 1,2-cyclohexanediol [53].

Good results have been obtained with the H_2WO_4 in solvent free condition, using 3.3 equivalents of H_2O_2 to cyclohexanone. After 20 hours of the reaction at 90 °C 91% yield of AA was detected. Authors suggested that process occurs through multiple steps involving 4 types of oxidative reactions (two alcohol oxidations, Baeyer–Villiger oxidation, and aldehyde oxidation) and hydrolysis, and Bayer Villiger oxidation being the rate limiting step [54].

3.3 One step oxidation of cyclohexane

Performing the synthesis of AA in only one step with air is a very tempting idea not only because of lowering the investment cost but also because avoiding using corrosive oxidizing agent.

Because the first step of the synthesis of AA is done with Co, Mn catalyst, it would be also possible perform the synthesis with the same catalyst in one step, obviously changing the reaction condition.

In fact Asahi almost 70 years ago developed this process, using Co acetate and acetic acid as a solvent, under the pressure of 30 atm of O_2 and temperature 90 – 100 °C.

They succeed in achieving conversion of cyclohexane 50-75% and 75% selectivity to AA (the main by product was glutaric acid) [55,56,57,58].

Since that time a lot of companies tried to optimize the reaction condition and catalyst composition, in order to obtain higher selectivity to AA. For example in the Gulf process the reaction is carried out with the same temperature as the original Asahi process, using the same solvent but with higher concentration of catalyst, the obtained selectivity to AA is 70-75% selectivity with 80-85% conversion of cyclohexane [59,60]. Another patented process – Amoco patent reported 98% conversion of cyclohexane with 88% yield of AA. They performed the reaction at 95 °C, under 70 atm of air pressure; this patent claims that addition of control amount of water is a key parameter [61].

Very good results have been obtained in the oxidation of cyclohexane with N-nhydroxyphthalimide (NHPI) acting as a catalyst [62]. NHPI is a precursor of phthalimido –N-oxyl (PINO) radical, which acts as an initiator in radical reaction, see figure 3.1.

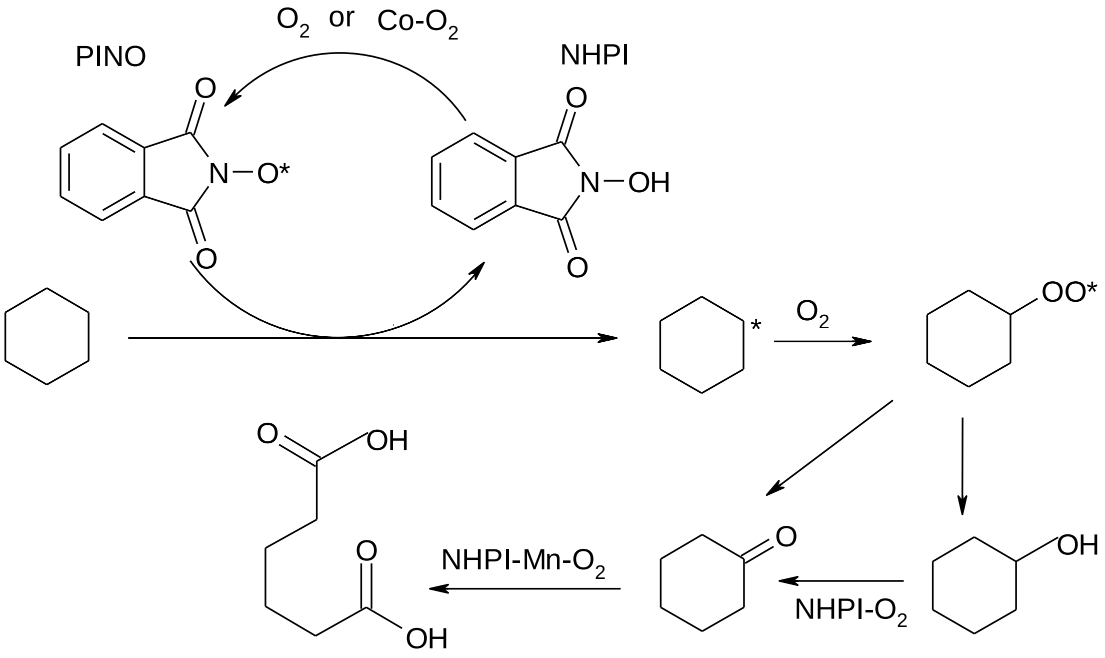


Figure 3.1: Oxidation of cyclohexane with NHPI catalyst, take from [17]

Daicel Chemical Industry has already constructed a 30 ton/year pilot plant. Reported yields are higher than 80%, with 90% conversion after 6 hours of reaction at 100°C and 10 atm [63]. Because of the limited solubility of NHPI in nonpolar solvent acetic acid or acetonitrile has to be added, moreover the reaction need a co-catalyst like organic salts of Mn and Co, which together give synergic effect. The drawback of this reaction is the decomposition of NHPI to phthalimide, which cannot be easily recycled to NHPI.

From heterogeneous catalysts worth noticing:

- Fe-framework substituted AlPO (FeAlPO-31): this catalyst was studied with two different oxidants: air and acetylperoxyborate. In the first case 7% conversion with 65% selectivity to AA was obtained (100 °C, 15 atm and 24 hours) [64,65], oxidizing with acerylperoxyborate at 110°C after 16 hours of the reaction high selectivity to AA was reached (81%) and 88% conversion of cyclohexane [66,67].
- CeO_2 supported on alumina: the oxidation of cyclohexane was performed under 15 atm pressure of O_2 in the presence of cyclohexanone as a co-oxidant at 110 °C. The conversion of cyclohexane was 36% with the yield of AA 42%. The by-products of the reaction were lower bicarboxylic acid (glutaric, succinic), COx and caprolactone [68].
- Ti zeolite beta catalyst: using hydrogen peroxide as oxidant and 2-butanone as a solvent, 47% conversion of cyclohexane with 54% selectivity to AA was obtained after 1 hour of reaction at 96 °C [69].

3.4 Alternative starting materials

3.4.1 Cyclohexene as a starting material

As already mentioned before, cyclohexene can be obtained by partial hydrogenation of benzene (process done by Asahi), although this process achieves good selectivities towards cyclohexene, the problem is deactivation of the catalyst. Another possibility would be partial dehydrogenation of cyclohexane or dehydrohalogenation of cyclohexyl halides. This method would have a potential advantage of recycling hazardous halogenate compounds. Hydrogen treatment of cyclohexyl chloride using silica supported nickel catalyst gave the selectivity to cyclohexene 97% at the temperatures between 200 and 300 °C [70].

On the base of used oxidizing agent, systems can be divided in two classes: using oxygen and using hydrogen peroxide or tert-butyl hydroperoxide.

3.4.1.1 Cyclohexene oxidation by oxygen

In the case the oxidation is done in the absence of a reduction reagent the primary product is 2-cyclohexen-1-one [71,72,73], this ketone is further hydrogenated to cyclohexanone, the reaction proceeds by autooxidation mechanism forming cyclohexene hydroperoxide. If the reaction is carried out in the presence of reduction reagent (isobutyraldehyde), high selectivity to epoxide is obtained (88-94% with complete conversion of substrate) [74]. Oxidation of cyclohexene using isopolyoxomolybdates has been proposed by Asahi. The primary products were cyclohexene oxide, 1,2-cyclohexanediol and 2-cyclohexene-1-ol (see figure 3.2). After 24 hours 37% conversion of cyclohexene was obtained, giving 90% of selectivity to three primary products [75]. But it is evident that this route is disadvantageous for its complexity compared to conventional oxidation of cyclohexane to cyclohexanone.

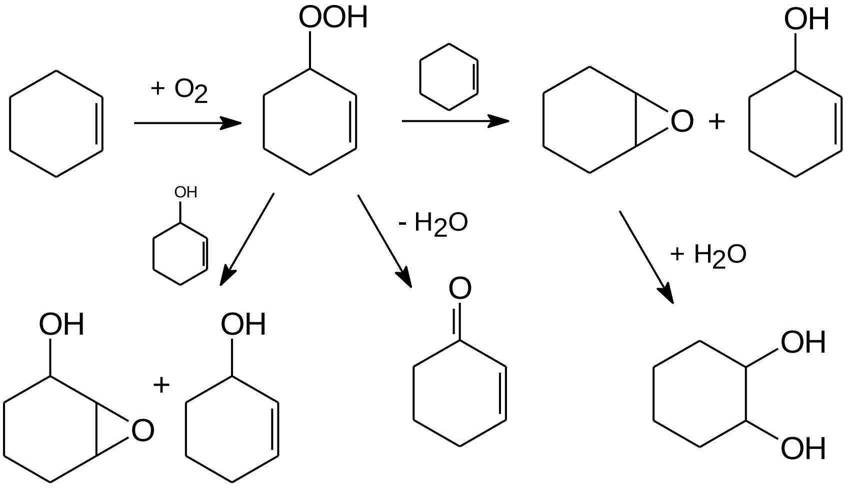


Figure 3.2: Oxidation of cyclohexene with O_2, taken from [17]

Performing the reaction with mechanism other than autoxidation it is possible to follow Wacker type oxidation of cycloeolefin. In this case the primary product is cyclohexanone. Some of the catalysts studied for this reaction were polyoxometalates type: $Pd(OAc)_2$/hydroquinone/$Na_nPMo_xV_{12-x}O_{40}$ gave after 20 hours 58% conversion of cyclohexanone with very low TOF - only 0,6 h^{-1} [76], conversion of 85% was obtained with $PdSO_4/H_3PMo_6W_6O_{40}$ after 24 hours of reaction but still with low TOF $6h^{-1}$ [77]. Best result was obtained by Korean researches using $Pd(NO_3)_2/CuSO_4/H_3PMo_{12}O_{40}$. They reached 97% selectivity of cyclohexanone with 49% conversion of cyclohexene and high

TOF 173 h^{-1} after 1 hour of the reaction at 80 °C and 10 atm [78]. Melgo et al. studied the same system, using hydrogen peroxide as an oxidizing agent and 8 times higher pressure then in the precedent case, they reached 80% conversion of cyclohexene with 97% selectivity to ketone with the TOF 260 h^{-1} [79].

3.4.1.2 Cyclohexene oxidation by HP, TBHP

Compared to oxygen, hydrogen peroxide or tert-butyl hydroperoxide gave much better result and in some cases one step oxidation of cyclohexene to AA was performed. First, one-step oxidation will be discussed.

3.4.1.2.1 One-step oxidation

30% hydrogen peroxide was used to oxidize cyclohexene in the presence of small amounts of Na_2WO_4 and phase transfer catalyst (PTC) (in this case $CH_3(n\text{-}C_8H_{17})NHSO_4$) in the absence of solvent. Cyclohexene was almost quantitatively converted to AA. The aqueous phase of the reaction mixture could be reused. The system is composed of two phases: aqueous solution containing HP and the tungstate and organic cyclohexene phase where the phase transfer catalyst is dissolved. The tungstate reacts in aqueous phase with HP, generating anionic peroxo species which are extracted by PTC to organic phase. The reaction occurs in the organic phase between the peroxo species and cyclohexene, restoring the reduced from of the catalyst [80,81].

By replacing PTC with organic acids the better results have been achieved. In the presence of oxalic acid almost complete conversion of cyclohexene was obtained with 97% selectivity to AA in 24 hours with HP/cyclohexene molar ratio 4,4/1 (the theoretical molar ratio is 4) [82].

From heterogeneous system worth mentioning tetrahedral tungstate unit incorporated in SBA-15, oxidation with HP at 85 °C without any organic solvent gave selectivity of 46% with the total conversion of cyclohexene [83]. Also in the case of titanium framework substituted aluminophosphate TAPO-5 without any organic solvent total conversion of cyclohexene was obtained with 30% selectivity to AA. This system was studied in detail in order to reveal the mechanism of the reaction explaining the presence of cis and trans 1,2 cyclohexanediols and their consecutive reaction (see figure 3.3) [84].

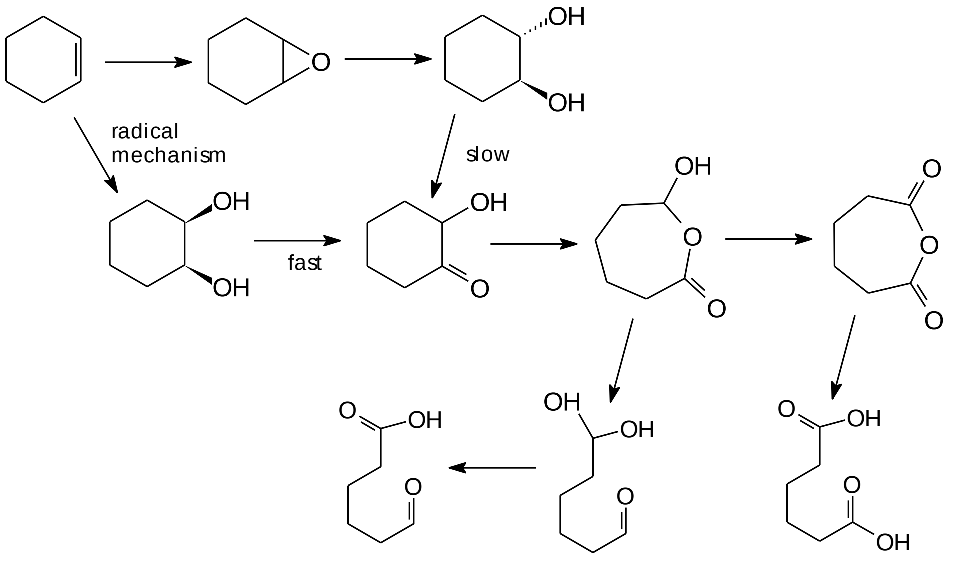


Figure 3.3: Oxidation of cyclohexene with hydrogen peroxide in the presence TAPO-5, taken from [17]

A polymeric microporous membrane (PDVF) separating the organic phase containing cyclohexene and the aqueous phase, with the oxidant (30% HP) and the catalyst has been studied for the direct synthesis of AA. In the aqueous phase succinic acid was added in order to favor contact at the membrane-aqueous interface between the catalytic active species, formed in the aqueous compartment, and the cyclohexene substrate, transported across the membrane. As the catalyst ammonium molybdate ($(NH_4)_6Mo_7O_{24}$) was used. This system gave high yields and selectivity (90%) to AA [85].

Using TBHP as an oxidant and catalyst based on SBA-15 with incorporated alumina and grafted Ti, 80% yield of AA was achieved after 24 hours of reaction. The main by-products were trans-1,2-cyclohexanediol, 2-hydroxycyclohexanone and lower bicarboxylic acid (glutaric and succinic) [86,87].

3.4.1.2.2 Two-Step oxidation

In the two-step oxidation of cyclohexene, the process is done via trans-1,2-cyclohexanediol. This can be done in the presence of metal oxide, ($KMnO_4$, OsO_4) and with TBHP or HP as terminal oxidants. In the case of osmium catalyzed dihydroxylation, Os(VI)/Os(VIII) substrate-selective redox system is involved [88-92] as the reoxidizing agent for Os (VI) to Os (VIII) N-methylmorpholine N-oxide (NMMO) can be used.

Other systems used for the first step of the reaction can be transtition metal complexes H_2WO_4, heteropolyacids or CH_3ReO, zeolites, hydrotalcites, but the main problem is low selectivity caused by the formation of by-products involving C-C bond cleavage [93-98]. Also in the case of performing the catalysis in the presence of other heterogeneous catalysts (zeolites Ti-β, Ti-MCM, Nb-MCM-41, hydrotalcites – $(NH_4)W_{12}O_{41}$) the selectivity was still too low [99-103].

The second step of the synthesis of AA is the cleavage of 1,2-cyclohexanediol. This reaction can be done either with hydroperoxide type of oxidants or with only O_2. Vast literature exits on oxidizing with the first type of oxidants. Oxidation of vic-diols with aqueous hydrogen peroxide was studied using tungstate ions as catalysts [104,105].

Oxidizing trans-1,2-cyclohexanediol with titanium containing Y zeolite with HP, 50% conversion with 80% selectivity to AA was reached [106]. Moreover test of leaching did not reveal any loss of metal. The main intermediate was 2-hydroxycyclohexanone, which was further oxidized to adipic acid. AA subsequently reacts with more hydrogen peroxide to form glutaric and sucinnic acid.

Oxygen as an oxidizing agent could be efficiently used in the case of heteropoly acids [48,52,107-108]. The oxidative cleavage of 1,2-cyclohexanediol in ethanol and atmosphere of oxygen adipic acid ethylester is obtained with 90% selectivity at 62% conversion [107].

Using pyrochlore as the catalyst ($[A_{2+x}Ru_{2-x}O_{7-y}]$ (A=Pb, Bi; $0<x<1$; $0<y<0.5$), at the temperature not higher than 100 °C, under the pressure of 100 psi gave high conversion of the substrate with the selectivity as high as 86% [109,110].

3.4.1.2.3 Three step oxidation of cyclohexene

Cyclohexene can be oxidized to cyclohexene oxide with either homogeneous or heterogeneous catalyst using HP or alkylperoxides. There are two class of catalysts which are active and selective for this kind of reaction: microporous and mesoporous materials containing transitional metals ions isolated in the framework of inorganic matrices or grafted to the surface, among them Ti being one of the best (Ti-HMS, Ti-MCM-41, Ti-MCM-48),titanium silicalite [111-115], and the other one, transtition metal-substituted polyoxometalets [116-118].

From polyoxometalates catalysts worth noticing TBA3{$PO_4[WO(O_2)_2]_4$}, the example of the Venturello complex, which converts cyclohexene almost completely at 70 °C in 5 h reaction time with aqueous HP in acetonitrile solvent, giving 81% yield to the epoxide, 10% to the cyclohexanediol and less than 5% to cyclohexenol and cyclohexenone [116]. Resulting epoxide is further hydrolyzed to trans-1,2-cyclohexanediol.

3.4.2 Butadiene as a starting material

Very innovative process was proposed by BASF, methoxycarbonylation of butadiene in the presence of the Co-based catalyst [119] (figure 3.4). Although the good results have been obtained using this system – yield of AA 72% (based on butadiene), BASF announced that would not proceed with the implementation [120]. Possible explanation would be that extreme reaction condition had to be used (first step is being done under the pressure of 300 atm, the second one under the pressure of 150 – 200 atm).

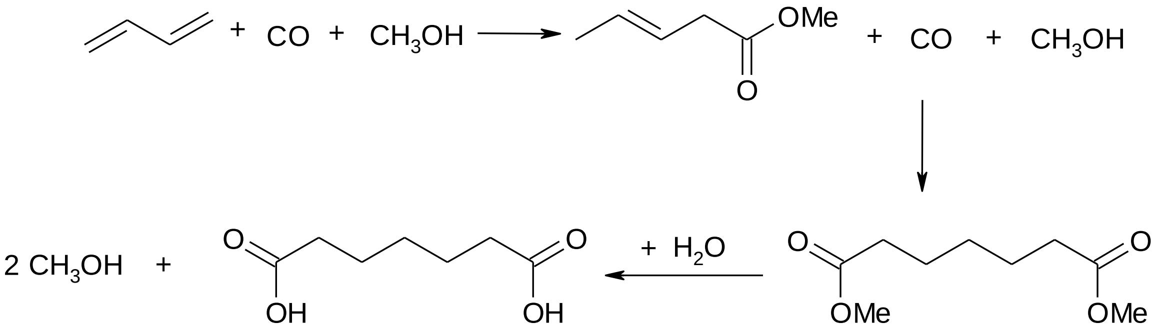


Figure 3.4: Synthesis of AA by methoxycarbonylation of butadiene

Butadiene can be also transformed to AA via hydroxycarbonylation with carbon monoxide and water as was proposed by DuPont and DSM [121] (figure 3.5). Neither this process was commercialized; the main problem is that adding the second equivalent of O and water to form AA, because it rather prefers to undergo acid-catalyzed cyclization to γ – valerolactone. But it seems this problem has been already solved by performing the hydrocarboxlation in the γ – valerolactone solvent, which helps to shift the equilibrium towards pentenoic acid thus avoiding cyclization.

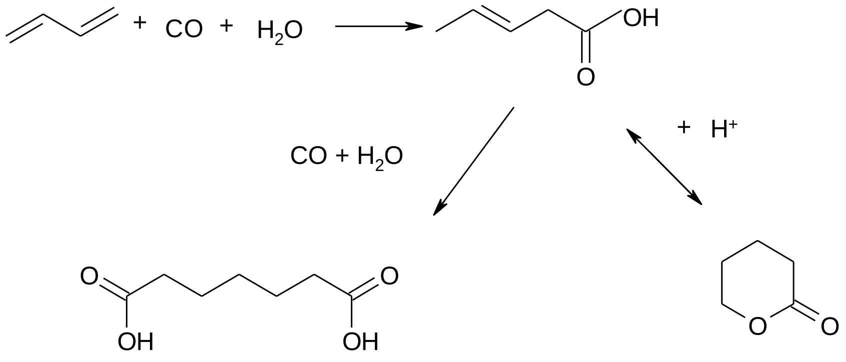


Figure 3.5: Hydoxycarbonylation of butadiene

3.4.3 N-hexane as a starting material

It is very well known that alkanes are difficult to oxidize, and to perform their oxyfunctionalization on terminal positions is almost impossible. This reaction is catalyzed by enzymes with non-heme iron active center. Anyway to try to replicate their ability did not bring expected results [122].

Few years ago Raja et al. announced that they succeed in synthesis of adipic acid by oxidation of n-hexane in air using Co framework substituted aluminophosphate catalyst (Co-AlPO-18, Co-AlPO-5). After the 24 hours of the reaction at 373 K under the pressure of 1.5 MPa, 9.5% of n-hexane was converted with 33.6% selectivity to AA. Among the other detected products were 2 – hexanone and 2 – hexanol [123]. However another attempt to repeat these results with the very similar catalyst failed. Modem et al. [124] tried to perform the oxidation of n-hexane with Mn-AlPO-18, MnAPO-5 finding out that only very small fraction of adipic acid was formed, they suggested that the kinetically-relevant step involves decomposition of hexyl hydroperoxides on Mn redox sites and that n-hexane and cyclohexane proceed via the same oxidation mechanism, involving formation and decomposition of alkyl hydroperoxide intermediates via bound radical-like intermediates [124].

Another attempt to oxidize n-hexane was done with Mn cations stoichiometrically exchanged onto 8-, 10- and 12-membered ring H-zeolites ZSM-58, ZSM-5, ZSM-57, and MOR. But also in this case small selectivity to diacids was obtained. Moreover terminal selectivities decreased with increasing alkane conversion, because unselective noncatalytic autoxidation pathways prevail as ROOH concentrations concurrently increase [125].

3.4.4 D-glucose as a starting material

Another very green synthesis of AA has been proposed by Frost et al. [126-128]. It consist in microbial transformation of D-glucose to cis,cis-muconic via 3-dehydroshikimic acid, protocatechuic acid and catechol. The key parameter of these steps is the presence of three enzymes not typically found in ESTERICHIA Coli. The last step of the reaction is hydrogenation of the cis,cis-muconic, using supported Ru, Pt catalyst. Under the pressure of 3400 kPa of H_2 97% of cis,cis-muconic acid into AA can be converted after 2,5 hours of the reaction at the ambient temperature, see figure 3.6. Anyway still the problems concerning scaling-up and process implementation have to been solved and these problems could make this process economically unsustainable.

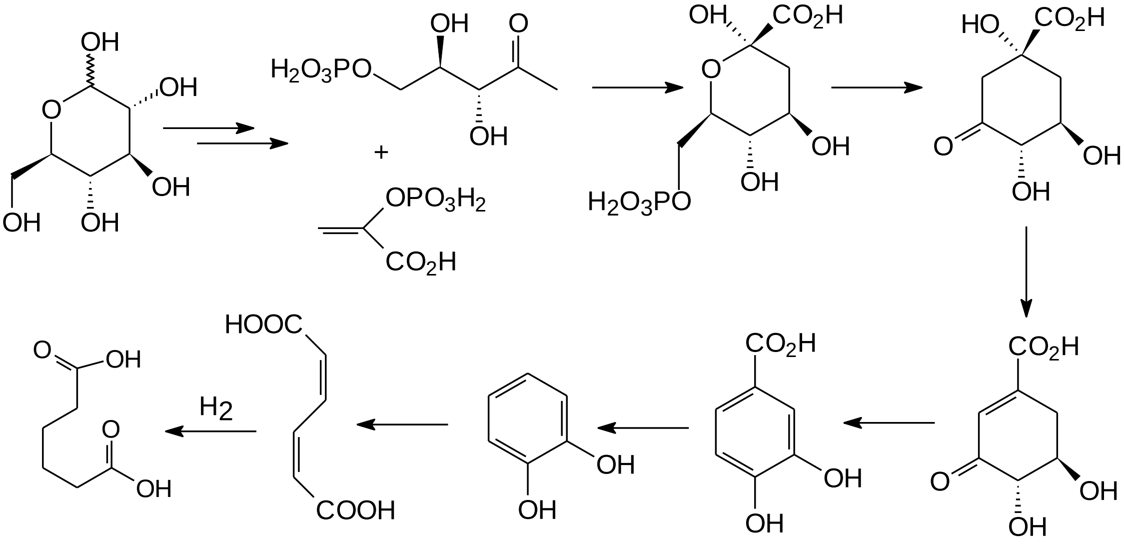


Figure 3.6: Enzymatic transformation of glucose to cis,cis mucconic acid and further hydrogenation to AA, taken from [17]

References

[1] N. Mizuno, N. Nozaki, et al., J. Mol. Catalysis A 117 (1997) 159

[2] T. Hayashi, A. Kishida et al., Chem. Communications 5 (2000) 381

[3] C. Nozaki, M. Misono et al., Chem. Letters 12 (1998) 1263

[4] M. Bonchio, M. Carraro et al., Adv. Synthesis & Catalysis 347 (2005) 1909

[5] M.R. Cramarossa, L. Forti et al., J. Mol. Catalysis A 127 (1997) 85

[6] N. I. Kuznetsova, L. I. Kuznetsova et al., Kinetics and Catalysis 46 (2005) 204

[7] A.M. Kirillov, M.N. Kopylovich et al., Adv. Synthesis & Catalysis 348 (2006) 159

[8] A.M. Kirillov, M.N. Kopylovich et al, Angew. Chemie, Int. Ed. 44 (2005) 4345

[9] A.C. Silvia, T. Loper Ferndandez et al., Appl. Catalysis A 317 (2007) 154

[10] S.I. Murahashi, N. Komyia et al., Pure and Appl. Chemistry 73 (2001) 311

[11] N. Komyia, T. Naota, Y. Oda et al., J. Mol. Catalysis A 117 (1997) 21

[12] G.B. Shul’pin, E.R. Lachter, J. Mol. Catalysis A 197 (2003)

[13] L.G. Cuervo, Y.N. Kozlov et al., J. Mol. Catalysis A 218 (2004) 171

[14] Y.N. Kozlov, G.V. Nizova et al., J. Mol. Catalysis A 227 (2005) 247

[15] Y.N. Kozlov, V.B. Romakh et al., J. Phys. Chem. A 111 (2007) 7736

[16] R.Z. Khaliullin, A.T. Bell et al., J. Phys. Chem. B 109 (2005) 17984

[17] F. Cavani et al., Sustainable Industrial Processes, Wiley-VCH; 1st edition (2009)

[18] R. Zhao, D. Ji, G. Lv et al., Chem. Communications, 7 (2004) 904

[19] G. Lu, R.Zhao, G. Qian, Cat. Letters, 97 (2004) 115

[20] H.-L. Wang, R. Li, Y. – F. Zheng, et al., Helvet. Chim. Acta 90 (2007) 1837

[21] R. Zhao, Y. Wang et al., Green Chemistry, 5 (2006) 459

[22] Ch. Subrahmanyam, B. Viswanathan et al., J. Mol. Catalysis A 223 (2004) 149

[23] G. Sankar, R. Raja et al., Cat. Letters 55 (1998) 15

[24] M. Dugal, G. Sankar et al., Angew. Chemie, Int.Ed. 39 (2000) 2310

[25] J.M. Thomas, R. Raja et al., Stud. Surf. Science Catal. 130 (2000) 887

[26] J.M. Thomas, R. Raja et al., Nature 398 (1999) 227

[27] R. Raja, G. Sankar et al., J. Am. Chem. Soc. 121 (1999) 11926

[28] J. Li, X. Li et al., Cat. Letters, 137 (2010) 180

[29] S.C. Laha, R. Glaser, Micr. and Mes. Mat. 99 (2007) 159

[30] G. Qian, D. Ji et al., J. Catalysis 232 (2005) 378

[31] H.-X. Yuan, Q.-H. Xia, H.-J. Zhan, Appl. Catalysis A 304 (2006) 178

[32] J. Hao, B. Liu et al., Chem. Communications (2009) 3460

[33] L. Liu, Y. Li, et al., Angew. Chemie, Int.Ed., 48 (2009) 2206

[34] R. Neumann, A.M. Khenkin, Inorg. Chem. 34 (1995) 5753

[35] R.F. Parton, G.J. Peere et al., J. Mol. Catalysis A 113 (1996) 445

[36] I.F.J. Vankelecom, R.F. Parton et al., J. Catalysis 163 (1996) 457

[37] K.J. Balkus, M. Eissa et al., Stud. Surf. Sci. Catal. 94 (1995) 713

[38] R. Raja, P. Ratnasamy, Cat. Letters 48 (1997) 1

[39] E. L. Pires, U. Arnold et al., J. Mol. Catalysis A 169 (2001) 157

[40] R. S. da Cruz, J. M. de Souza e Silva et al., J. Mol. Catalysis A 171 (2001) 251

[41] S. Samanta , N.K. Mal et al., J. Mol. Catalysis A 236 (2005) 7

[42] A. Sakthivel, P. Selvam, J. Catalysis 211 (2002) 134

[43] S. K. Mohapatra, P. Selvam, Cat. Letters 93 (2004) 47

[44] E. Armengol, A. Corma et al., Appl. Catalysis A 181 (1999) 305

[45] W. A. Carvalho, M. Wallau et al., J. Mol. Catalysis A 144 (1999) 91

[46] E.V.Spinace, H.O. Pastore et al., J. Catalysis 157 (1995) 631

[47] A. Shimizu, K. Tanaka et al., Bull. Chem. Soc. Jpn. 76 (1993) 2001

[48] A. Atlamsani, J.M. Bregeault et al., J. Org. Chem. 58 (1993) 5663

[49] J.M. Bregeault, B. El Ali et al., Patents FR 88–11075; EP0355075 B1; US 4 983 767; CA 1 322 762; JP 1 8932–55, 1988

[50] M. Besson, F. Gauthard et al, J. Phys. Chem. B 109 (2005) 2461

[51] E. Crezee, A. Barendregt et al., Catal. Today 69 (2001) 283

[52] J.-M. Bregeault, F. Launay et al., C.R. Acad. Sci. Paris Serie 2c, Chimie 4 (2001) 11

[53] W. Zhu, H. Li et al., Catal. Communications 9 (2008) 551

[54] Y. Usui, K. Sato, Green Chemistry 5 (2003) 373

[55] K. Tanaka, Shokubai 17 (1975) 197

[56] K. Tanaka, CHEMTECH (1974) 555

[57] K. Tanaka, Hydrocarbon Process 53 (1974) 114

[58] K. Tanaka, A. Shimizu, JP 20011253845 (assigned to Asahi Chem Co)

[59] A. Onopchenko, J.G.D. Schulz, US Patent 1977, 4,032,569, (assigned to Gulf R&D)

[60] J.G.D. Schulz, A. Onopchenko, US Patent 1981, US 4,263,453 (assigned to Gulf R&D)

[61] C.M. Park, N. Goroff, US Patent 1993, 5,221,800 (assigned to Amoco Corp)

[62] Y. Ishii, J. Mol. Catalysis A 117 (1997) 123

[63] Japan Chemical Week, 30 Aug 2007, 48 (2430) 1

[64] M. Dugal, G. Sankar et al., Angew. Chem. Int. Ed. 39 (2000) 2310

[65] J.M. Thomas, R. Raja, Chem. Commun. (2001) 675

[66] R. Raja, J.M. Thomas al, Chem. Commun. (2006) 448

[67] J.M. Thomas, R. Raja, Catal. Today 117 (2006) 22

[68] C.S. Yao, H.S. Weng, Ind. Eng. Chem. Res. 37 (1998) 2647

[69] US patent 5,739,076

[70] G. Tavoularis, M.A. Keane, J. Mol. Catalysis A 142 (1999) 187

[71] N. Mizuno, D. K. Lyon et al., J. Catalysis 128 (1991) 84

[72] R. Neumann, M. Dahan, J. Chem. Soc., Chem. Commun. (1995) 171

[73] U. R. Pillai, E. Sahle-Demessie et al., Green Chem. 4 (2002) 495

[74] N. Mizuno, H. Weiner et al., J. Mol. Catalysis 114 (1996) 15

[75] Y. Liu, K. Murata et al., Chem. Lett. 33 (2004) 200

[76] T. Yokota, S. Fujibayashi et al., J. Mol. Catalysis A 114 (1996) 113

[77] H. Ogawa, H. Fujinami et al., Bull. Chem. Soc. Jpn. 57 (1984) 1908

[78] Y. Kim, H. Kim et al., J. Appl. Catalysis A: 155 (1997) 15

[79] M. S. Melgo,A. Linder et al., Appl.Catalysis A 273 (2004) 217

[80] K. Sato, M. Aokil et al., Science 281 (1998) 1646

[81] R. Noyori, M. Aoki et al., Chem. Commun. (2003) 1977

[82] Y. Deng, Z. Ma et al., Green Chemistry (1999) 275

[83] C.Y. Cheng, K.J. Link et al., Catal. Comm. 8 (2007) 1060

[84] S. O. Lee, R. Raja et al., Angew. Chem. Int. Ed, 42 (2003) 1520

[85] M. G. Buonomenna, G. Golemme et al., Org. Process Res. & Devel. 14 (2010) 252

[86] G. Lapisardi, F. Chiker et al., Catal. Communications 5 (2004) 277

[87] G. Lapisardi, F. Chiker et al, Micr. Mes. Materials 78 (2005) 289

[88] M. Schröder, Chem. Rev. 80 (1980) 187

[89] K.B. Sharpless, K. Akashi, J. Am. Chem. Soc. 98 (1976) 1986

[90] V. VanRheenen, R.C. Kelly et al., Tetrah. Lett. (1976) 1973

[91] H.C. Kolb, M.S. VanNieuwenhze et al., Chem. Rev. 94 (1994) 2483

[92] K. Akashi, R.E. Palermo et al., J. Org. Chem. 43 (1978) 2063

[93] W.A. Hermann, R.W. Fischer et al., Angew. Chem. Int. Ed. 30 (1991) 1638

[94] M. Schwegler, M. Floor et al., Tetrahedron Lett. 29 (1988) 823

[95] V.Singh, P. T. Deota, Synth. Commun. 18 (1988) 617

[96] T.Oguchi, T. Ura et al., Chem. Lett. (1989) 857

[97] C. Venturello, M. Gambaro, Synthesis (1989) 295

[98] W. A. Herrmann, R. W. Fischer et al., Angew. Chem. Int. Ed. Engl. 300 (1991) 1638

[99] T. Tatsumi, K. Yamamoto et al., Chem. Letters (1992) 815

[100] A. Corma, M.A. Camblor et al., J. Catalysis 145 (1994) 151

[101] A. Corma, M.T. Navarro et al., J. Chem. Soc. Chem. Commun. (1994) 147

[102] T. Tatsumi, K.A. Noyano et al., Chem. Commun. (1998) 325

[103] J. Xin, J. Suo et al., New J. Chem. 24 (2000) 569

[104] M. Shimizu, H. Orita et al., J. Mol. Catal. A 114 (1996) 217

[105] T. Iwahama, S. Sakaguchi et al, Tetrahedron Lett. 36 (1995) 1523

[106] G.P. Schindler, P. Bartl et al., Appl. Catalysis. A 166 (1998) 267

[107] J.M. Brégeault, B. El Ali et al., C.R. Acad. Sci. Paris, serie II, 309 (1989) 459

[108] J.-M. Brégeault, B. El Ali et al., Eur Patent (1990) 0,355,075

[109] U.S patent 4, 959, 494, (assigned to Monsato co.)

[110] T. R. Felthouse, J. Am. Chem. Soc., 109 (1987) 7566

[111] B. Notari, Stud. Surf. Sci. Catal. 37 (1988) 413

[112] M.G. Clerici, Appl. Catalysis 68 (1991) 249

[113] G. Bellussi, A. Carati et al., J. Catalysis 133 (1992) 220

[114] M.G. Clerici, P. Ingallina, J. Catalysis 140 (1993) 71

[115] O.A. Kholdeeva, N.N. Trukhan, Russ. Chem. Rev. 75 (2006) 411

[116] O.A: Kholdeeva, R.I. Maksimovskaya, J. Mol. Catalysis A 262 (2007) 7

[117] R. Neumann, Prog. Inorg. Chem. 47 (1998) 317

[118] C.L. Hill, C.M. Prosser-McCartha, Coord. Chem. Rev. 143 (1995) 407

[119] M. Roper, Stud. Surf. Sci. Catal. 64 (1991) 381

[120] http://www.chemweek.com/sections/business_finance/europe_mideast/6951.html

[121] H. S. Bruner, Jr., S. L. Lane et al., US Patent 1998, 5,710,325 (assigned to Du Pont de Nemours, DSM N.V.)

[122] B.R. Cook, T.J. Reinert et al., J. Am. Chem. Soc. 108 (1986) 7281

[123] R. Raja, G. Sankar et al., Angew. Chem. Int. Ed. 39 (2000) 2313

[124] B. Modén, B.-Z. Zhan et al., J. Phys. Chem. C 111 (2007) 1402

[125] B.-Z. Zhan, B. Moden et al., J. of Catalysis 245 (2007) 316

[126] M. Draths, J.W. Frost, J. Am. Chem. Soc. 116 (1994) 399

[127]J. W. Frost in Green Chemistry, P.T. Anastas and T.C. Williamson (Eds), Oxford, (1998)

[128] U.S patent 5,487,987 (assigned to Purdue research foundation)

[129] L.X. Xu, C.H. He et al., Cat. Letters 114 (2007) 202

- FIRST PART –

Oxidation of cyclohexanone with molecular oxygen catalyzed by Keggin-type polyoxometalates

4. Polyoxometalates (POMs)

First part of my research of the new alternative ways of synthesis of adipic acid was oxidation of cyclohexanone with molecular oxygen in the presence of heteropolyacids and their salts.

POMs belong to large class of nanosized metal-oxygen cluster anions [1]. These are formed a by self assembling process, typically in acidic aqueous solution, can be isolated as a solids with an appropriate counteraction. Equation 4.1 shows the process of the formation of POM.

$$8H^+ + 7WO_4^{2-} \rightarrow W_7O_{24}^{6-}$$

$$23H^+ + HPO_4^2- + 12MoO_4^{2-} \rightarrow PMo_{12}O_{40} + 12\ H_2O$$

Equation 4.1

According to their composition, POM can be divided in two classes:

- Isopolyanions $[M_mO_y]^{p-}$
- Heteropolyanions: $[X_xM_mO_y]^{q-}$ ($x \leq m$)

where M is addenda atom and X is the heteroatom (the central atom when located in the center of polyanion). The known addenda and heteroatoms for POM are shown in the figure 4.1.

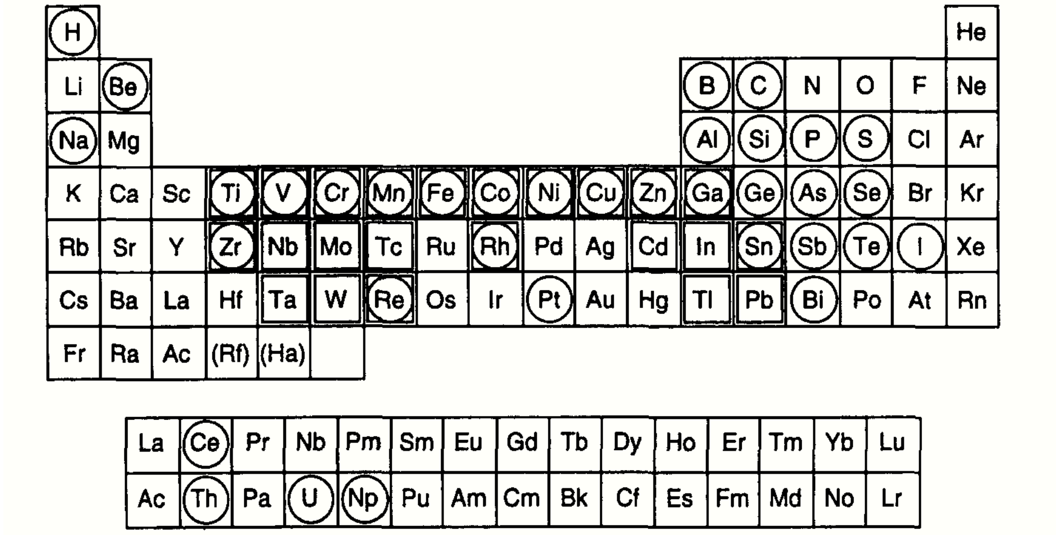


Figure 4.1: Known addenda (□) and hetero (○)-atoms incorporated in heteropolycompounds, taken from [6]

The first POM has been discovered by Berzelius in 1823, it was ammonium molybdophosphate [2]. Since this discovery a lot of POM have been discover, however for almost 100 hundred years nobody knew the exact structure of these compounds. In 1933 Keggin succeed in describing the structure of 12:1 type heteropolyanions by XRD study of $H_3PW_{12}O_{40}$ x5 H_2O [3]. This structure, named after his discover, become one of the most important POM.

4.1 Structure

Generally, solid HPAs form ionic crystals composed of heteropolyanions, countercations (H^+, H_3O^+, $H_5O_2^+$, etc.) and hydration water. The crystal structure of HPAs depends on the amount of hydration water.

The most known POM is the HPA with Keggin structure (figure 4.2). The general formula for the Keggin HPA is $XM_{12}O_{40x-8}$ where X is the central atom (Si^{4+},P^{5+},etc.), X is its oxidation state, and M is the metal ion (Mo^{6+}or W^{6+}). The M^{6+} ions can be substituted by many other metal ions, e.g., V^{5+},Co^{2+},Zn^{2+}, etc.

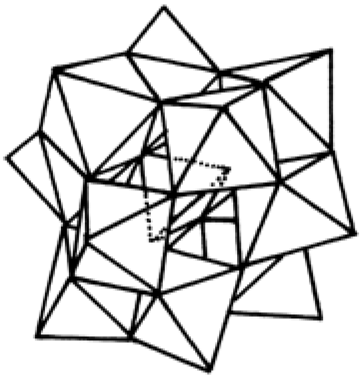


Figure 4.2: The structure of the Keggin HPA

The Keggin anion has a diameter of 1.2 nm, is composed of a central tetrahedron XO_4 surrounded by 12 edge- and corner-sharing metal-oxygen octahedra MO_6. The octahedra are arranged in four M_3O_{13} groups. Each group is formed by three octahedra sharing edges and having a common oxygen atom which is also shared with the central tetrahedron XO_4 [4]. Four type of oxygen can be distinguished in the Keggin structure (see figure 4.3):

- terminal oxygen O_t, which is bonded to the M atom
- O_e oxygen bridging the edge sharing octahedral
- O_c oxygen bridging the corner sharing octahedral
- O_i oxygen bridging the central heteroatom with octahedral triads.

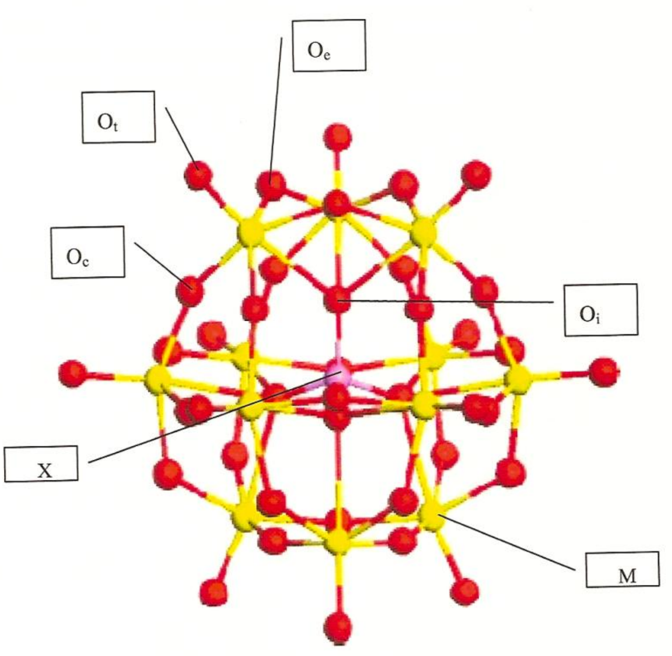


Figure 4.3: The Keggin structure of the $XM_{12}O_{40}$ anion

HPA can be described by three dimensional structure (figure 4.4):

1. <u>Primary structure – the structure of heteropolyatom</u>

The primary structure of Keggin can be characterized by:

- Structural and positional isomery
- Primary structures and vacant

There exist structural isomers of the Keggin α structure, where one or more edge sharing groups of octahedral have been rotated by π/3. These structures are less stable than α isomer due to the increased electrostatic repulsion between neighbouring M^{n+} atoms in adjacent MO_6 octahedra.

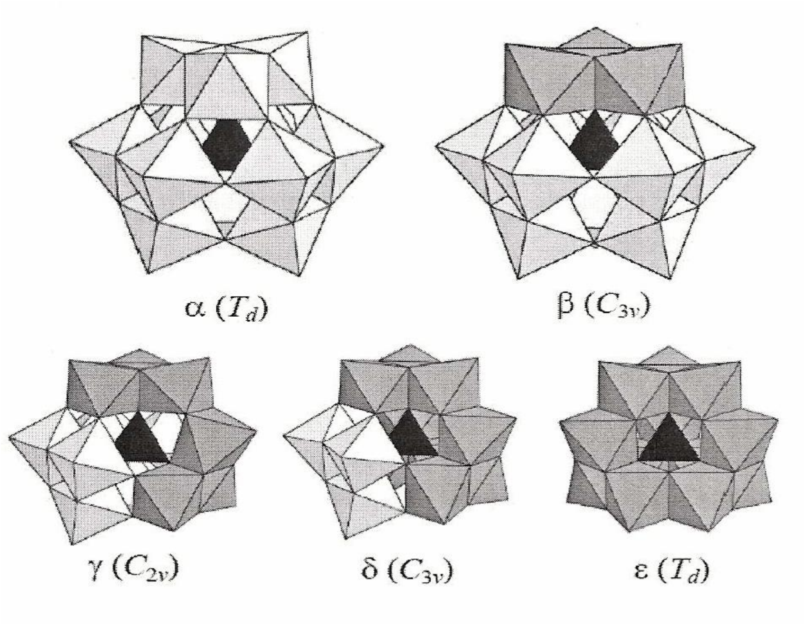


Figure 4.4: Possible isomers of the Keggin POM

Another type of isomery is the positional one. It is created when two different types of addenda atoms are present in the structure, thus having the formula $XM_nM'_{12-n}$.

By removing of one MO_6 octahedron, lacunary Keggin compound is formed having the structure $XM_{11}O_{39}^{n-}$. This transformation can be obtained by the raising pH of the solution. The pH at which the compound is being hydrolyzed is the function of the composition of POM (for example POM containing W is more stable towards hydrolysis than corresponding compound with Mo) and also of the heteroatom (in POM containing 12 atoms of molybdenum it decreases in order: Si > Ti > Ge > P > As) [5].

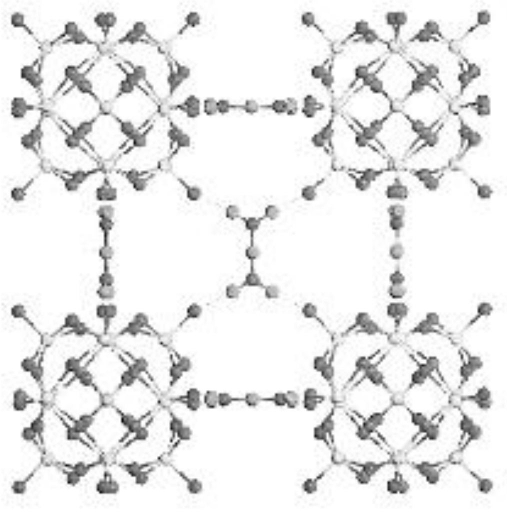


Figure 4.5: Interaction of $H_5O_2^+$ species in the cell unit – in the very stable form O_t oxygen are bonded to one $H_5O_2^+$ specie.

2. Secondary structure - describing crystal structure and packing
3. Tertiary structure - describing the size of the particles, their structure, the porosity, the position of the proton. This structure greatly affect the catalytic function of solid POM

Thus POM in the solid bulk have hierarchic structures as can be seen from the figure 4.6.

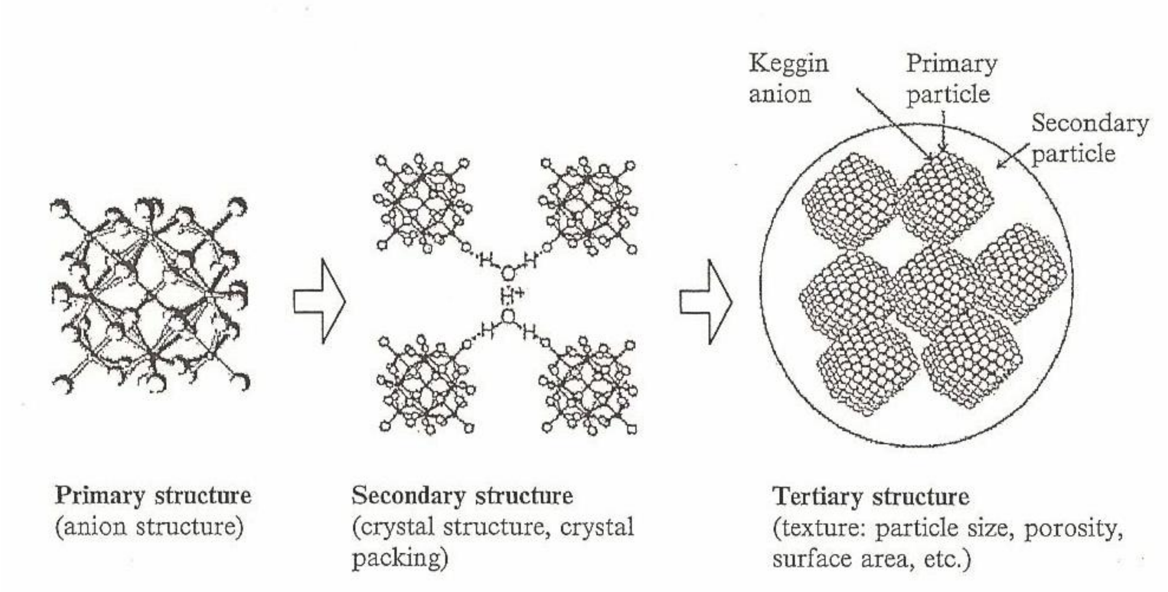


Figure 4.6: Hierarchic structure of POM

Although the Keggin heteropolycompound is the most stable and well known POM, in literature are described other compositions:

- Wells-Dawnson (figure 4.7), having formula $[X_2M_{18}O_{40}]^{2n-16}$, where X is P^{5+}, As^{5+}, S^{6+} and M can be Mo^{6+} ,W^{6+}. These compounds are formed via dimerization of two α PMo_9O_{34} moieties, thus under conditions of pH at which the parrent Keggin compound forms the corresponding trilacunary compound by the loss of MO groups:

$2\ XMo_9O_{31}(H_2O)_3^{3-} \rightarrow X_2Mo_{18}O_{62} + 6H_2O$

Solution of these species are stable to pH up to 6, in the more basic condition they give rise to lacunary species.

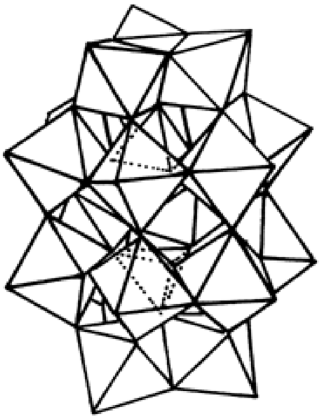


Figure 4.7: Dawson structure

- Anderson-Evans (figure 4.8), having formula $[XM_6O_{24}]^n$, (X = Mn^{4+}, Te^{6+}, Pt^{4+}, Ni^{4+}, M = Mo^{6+}, W^{6+}), Anderson are usually obtained from aqueous solution at pH 4-5. It consists of 6 coplanar octahedra, each octahedra having two terminal oxygens.

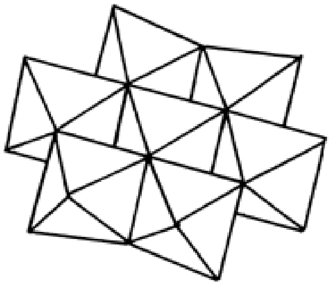


Figure 4.8: Anderson-Ewans structure

- Dexter-Silverton – it is a less common type of 12-heteropolyanions $[XM_{12}O_{42}]^{x-12}$, where M = Mo^{6+} and X = Ce^{4+}, U^{4+}, Th^{4+}. In this anion the central atom is surrounded by twelve oxygen atoms that form an icosahedron as a central polyhedron. The MO_6 octahedra are arranged in face sharing pairs.

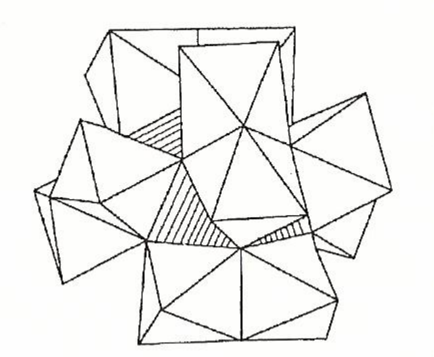


Figure 4.9: Dexter-Silverton structure of HPA

4.2 Salts of HPA

POM can be synthesized in acid and also in salts form. Salts of the heteropolycompounds can be divided in two groups; the first one includes the salts of small metals such as Na^+, which behave like the acid. They are soluble in the water, are thermally unstable, and have a low surface area ($10m^2/g$). The second group contains salts with larger cations (NH_4, K, Cs), these salts are characteristic by high surface area ($200m^2/g$), are insoluble in the water and thermally stable. For the reason that the large cations take up places between the anions leaving little room for the water molecules, this class of salts is usually less hydrated than the former one. Moreover in some cases the large cations are not able to fit enough cations in the lattice and the charge balance is reached with the hydrogen ions. This could explain why in some cases residual proton acidity is left even when the precipitation of neutral salts is expected [5].

4.3 Physical chemical properties

4.3.1 Acid properties

In solutions, the acid properties of POM can be described by the terms of dissociation constants and Hammett acidity function. Heteropolyacids are very strong acids, much stronger than mineral acids and are completely dissociated in aqueous solution; in organic solvent they are partially dissociated.

The acidity can be generated by protons which act as counterions in heteropolyacid and in mixed acidic salts, or by protons which can be developed by other phenomena such as: the dissociation of water coordinated to metal cations, or protons formed by the reduction of the metal ions or of the metal in the primary structure [5].

In the case of the HPC with the Keggin structure, the acid strength does not depend a lot on the composition, HPC containing W being the stronger than the corresponding Mo-HPC. Table 4.1 shows some dissociating constant for HPC and mineral acids in acetone.

Table 4.1: Dissociation constants for HPA and mineral acids

acid	pK1	pK2	pK3
$H_3PW_{12}O_{40}$	1.6	3.0	4.0
$H_4PW_{11}VO_{40}$	1.8	3.2	4.4
$H_4SiW_{12}O_{40}$	2.0	3.6	5.3
$H_3PMo_{12}O_{40}$	2.0	3.6	5.3
$H_3SiMo_{12}O_{40}$	2.1	3.9	5.9
H_2SO_4	6.6		
HCl	4.3		
HNO_3	9.4		

4.3.2 Thermal stability

Generally, POM have a good thermal stability, Keggin POM being among the most stable ones. The Keggin-type PW, SiW, PMo, and SiMo decompose at 465, 445, 375, and 350 °C, respectively [7]. The decomposition causes the loss of their acidity. Substitution of one atom of vanadium (V) for molybdenum (VI) in $H_3PMo_{12}O_{40}$ increases the thermal stability, however the stability decrease upon further substitution. Upon heat treatment of solid $H_4PMo_{11}VO_{40}$, vanadyl and molybdenyl species leave the Keggin unit. Substitution of Cs^+ for proton in $H_4PMo_{11}VO_{40}$ stabilizes the structure, while the presence of water vapor enhances its disintegration [4].

4.3.3 Redox properties

HPA are multielectron oxidants, the mechanism of reduction of HPA involves the transfer of as many as 6 electrons without the collapse of the structure [5]. The redox properties are the function of addenda atoms and of heteropolyatom and counterions. The replacement of one or more Mo atom in the primary structure of Keggin by vanadium leads to the enhacement of oxidation potential due to the vanadium reducibility.

Generally, reactions catalyzed by HPA-n proceed via a stepwise redox mechanism represented by following equations: [7]

$$\mathbf{HPA\text{-}n + Red + mH^+ \rightarrow H_m(HPA\text{-}n) + Ox}$$

$$\mathbf{H_m(HPA\text{-}n) + (m/4)O_2 \rightarrow HPA\text{-}n + (m/2)H2O}$$

This mechanism includes stoichiometric m-electron oxidation of the substrate, Red, by HPA-n to form the product, Ox, followed by reoxidation of the reduced form of the oxidant with dioxygen, where $H_m(HPA\text{-}n))$ is $H_m(PMo_{12-n}{}^{6+}V_{n-m}{}^{5+}V_m{}^{4+})^{(3+n)-}$. It is the $V^{5+} \leftrightarrow V^{4+}$ transformation that is responsible for the redox properties of HPA-n. The reduction of HPA-n in solution is accompanied by protonation to maintain the charge of the polyanion. This clearly shows that the presence of atom of vanadium is essential for the catalytic activity.

4.4 Use of POM

Their versatility permits to use them as homogeneous and heterogeneous, redox and acid catalysts in wide range of reaction.

4.4.1 Homogeneous catalysis

4.4.1.1 Acid catalysis

Acid catalysis by polyoxometalates, and mainly by polyoxometalates with Keggin structure is their oldest field of application in catalysis. Among the typical acid catalyzed reaction belong [8]

- Hydration – dehydration
- Etherification, hydrolysis, etherification
- Hydroxymethylation and dimerizatation – bisphenol A
- Beckmann oxime –amide rearrangement – caprolactam
- Rearrangement of peroxides – phenol

There are some advantages and disadvantages regarding the use of HPA instead of mineral acids (H_2SO_4, HCl) in the acid catalysis in the liquid phase, shown in the table 4.2, respectively 4.3.

Table 4.2

Advantages of HPA
• there are fewer side reaction such as sulfonation and chlorination due to the non reactivity and low basicity of poly ox counter anion
• the higher bronsted acidityof HPA compared to mineral acids leads to rates per proton, that are usually significantly higher for HPA
• HPA are non corrosive and tend to prevent corrosion

Table 4.3

Disadvantages of HPA
• cost and availability
• recovery and/or recycle
• the low Lewis acid type activity precludes the use of HPA in many types of reaction such as Friedel Crafts acylations
• although HPA are strong Bronsted acid, they are not generally considered as superacids

4.4.1.2 Redox catalysis

There are two oxidants with have been predominantly used for the liquid phase oxidation in the presence of POM: molecular oxygen and H_2O_2.The table 4.4 gives small overview of the studied systems.

Well known example for the liquid phase oxidation with molecular oxygen is the Wacker type oxidation of ethylene to acetaldehyde, which is also applicable to other olefins. Instead of conventional $PdCl_2/CuCl_2$, the catalyst for this reaction is $Pd^{2+}/PMo_{10}V_2O_{40}^{5-}$. The main advantage of this system is the possibility to operate in the absence of chlorides and thus less corrosive reaction medium is obtained. In this reaction vanadium acts as a reoxidizing species for the reduced Pd [5].

$$\text{Pd (II)} + \text{Red} + H_2O \rightarrow \text{Ox} + \text{Pd (0)} + 2H^+$$

$$\text{Pd (0)} + \text{HPA-n} + 2H^+ \rightarrow \text{Pd (II)} + H_2\text{HPA-n}$$

$$H_2\text{HPA-n} + 1/2\ O_2 \rightarrow \text{HPA-n} + H_2O$$

The oxidation with the H_2O_2 is usually performed with HPA containing tungsten. In these system HPC are considered to be a precursor of the true active species: In the presence of H_2O_2, $W_{12}O_{40}^{3-}$ is degradated to $PO_4\{WO(O_2)_2\}_4^{3-}$, which had been discovered by Venturello and use for the epoxidation of alkenes (figure 4.10) [9]. High seletivities can be achieved, except with epoxide of lower alkenes, which are soluble in the aqueous phase and therefore undergo consecutive ring opening reaction.

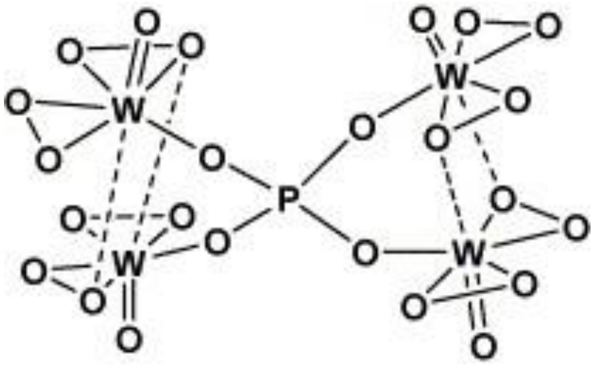


Figure 4.10: Molecular structure of $[PO_4\{WO(O_2)_2\}_4]^{3-}$

Table 4.4

Studied redox reaction for homogeneous catalysis	Oxidant
Oxidation of alcohols to ketones	O_2
Oxidative dehydrogenation of diens to aromatics	O_2
Oxidation of amines	O_2
Epoxidation of olefins	O_2/H_2O_2
Bayer Villiger oxidation of cyclic ketones	O_2
Oxidation of aldehydes to acids	O_2
Oxidation of alkylbenzenes to the corresponding aldehydes	O_2
Oxidative borminations of arenes	O_2
Oxidative couplings of arenes	O_2
Acetoxylations of arenes	O_2
Oxidation of benzene to phenol	O_2/H_2O_2
Oxidation of phenol to quinines	O_2/H_2O_2
Oxidation of isobutene to tert butyl alcohol	O_2
Oxidation of propane to isopropyl alcohol and acetone	O_2
Oxidation of allyalcohol to glycerol	H_2O_2
Oxidation of cyclopentene to glutaraldehyde	H_2O_2
Oxidative cleavage of cycloolefins	H_2O_2
Oxidation of allyphatic and aromatic amines	H_2O_2
Hydroxaltion of arenes and phenols	H_2O_2
Oxidation of cyclohexane to cyclohexanone/cyclohexanole	H_2O_2

4.4.2 Heterogeneous catalysis

In the case of solid catalyst for gas phase there are three different classes of catalysis which have to been distinguished (see figure 4.11) [10]:

(a) ordinary surface-type, where the reactions take place on the two-dimensional surface (outer surface and pore wall) of solid catalysts. The reaction rate is proportional to the surface area in principle

(b) “pseudoliquid” (bulk-I) type, in this case the substrate is absorbed in the interpolyanion space of the ionic crystal and react there, and then the products desorb from the solid. The reaction rate is proportional to the volume of catalyst in the ideal case. This type of catalysis has been observed not only for gas-solid but also for liquid-solid system [11].

(c) bulk-II type, in this type of catalytic oxidation, although the principal reaction may proceed on the surface, the whole solid bulk takes part in redox catalysis owing to the rapid migration of redox carriers such as protons and electrons. The rate is proportional to the volume of catalyst.

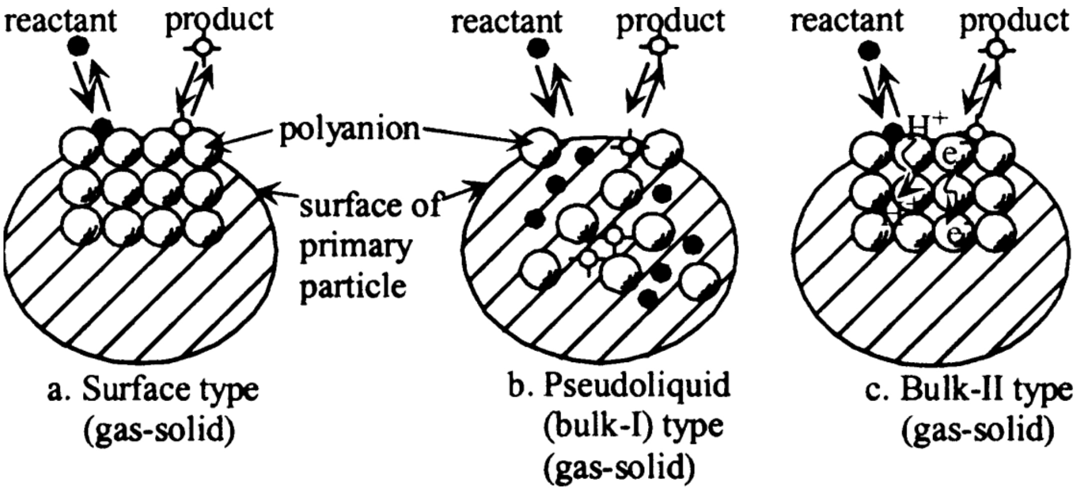


Figure 4.11: Classes of catalysis in the heterogeneous phase, taken from [6]

To perform the heterogeneous catalysis in the liquid phase there are few possibilities how to obtain heterogeneous systems containing HPA: i) preparing unsoluble salt of HPA in studied reaction media, ii) intercalate the HPC to zeolite/hydrotalcites or iii) prepared supported HPA. Great attention has to be devoted to the right choose of the supports, because it influences the properties of HPA (acid strength, catalytic activity, tend to decompose) [8].

4.4.2.1 Acid catalysis

Solid heteropolyacids being the stronger acid, are usually more efficient than conventional acid catalyst such as mineral acid, $SiO_2 – Al_2O_3$, zeolites etc. In particular in organic media, the molar catalytic activity of HPA is often 100 - 1000 higher than of H_2SO_4. This permits to carry out the reaction with lower concentration of catalyst and lower temperature [8]. Table 4.5 shows the catalyzed reaction by solid HPA.

Table 4.5

Reaction catalysed by solid HPA in the order of decreasing acid strenght
Isomerization of alkanes
MeOH to olefins MTO
Alkylation of paraffins
Oligomerizations of alkenes
Friedel Crafts and related reactions
Beckmann rearrangement
Esterification and transesterification
Hydration of alkenes
Hydrolysis
Addition: isobutene + MeOH → MTBE,Alkene + AcOH → alkyl acetate
Isomerization of alkanes
Diels Alder reaction

The remaining problem to be solved is their rapid deactivation during organic reactions due to the formation of carbonaceous deposit on the catalyst surface. Because of their insufficiently high thermal stability, conventional regeneration by burning coke at 500 °C cannot be used.

4.4.2.2 Redox catalysis

The important key in the redox catalysis is the ability of HPA to activate the substrate and/or oxidant. From this point of view, Keggin POM belongs to the most efficient catalysts.

Table 4.6

Heterogeneous gas phase oxidations over HPC
Methacrolein/isobutyric acid/isobutane to methacrylic acid
Ethylene to acetic acid
Isobutene to methacrolein
t-butene/n-butane to maleic anhydride
Methane to formaldehyde/methanol (with N_2O)
Etehen to acetylene/acetaldehyde (with O_2/N_2O)
Propane to acrylic acid
Methanol to formaldhehyd/dimethylether
Ethanol to acetaldehyde/diethylether

The main problem is their limited structural thermal stability of most of the studied HPA, and the fact that the most active compounds (for both kinds of catalysis, acid and redox) are the least stable ones [5].

4.4.3 Commercialized process

Table 4.7 reports the industrial processes, which use HPA as the catalyst.

Table 4.7

Industrial processes using HPA as a catalyst
liquid phase hydration of propylene to 2-propanol
vapour phase oxidation of methacrolein to methacrylic acid
liquid phase hydration of isobutene
biphasic polymerization of tetrahdrofuran to polymeric diol
Ketone amination to imine
hydration of n-butene to n-butanol
direct oxidation of ethylene to acetic acid
Synthesis of ethyl acetate

The first commercialized process was the liquid phase hydration of propylene to 2-propanol in 1972. This process - so called Tokyuama process, is a greener alternative to the older process – hydration of propylene in two steps in the presence of H_2SO_4. The catalyst used is based on water soluble silicotungstate acid/salt.

Ten years later, vapour phase oxidation of methacrolein to methacrylic acid (150 000 tons/year) was commercialized, followed by the liquid phase hydration of isobutene for its separation of butane – butene fraction (in 1984), and in 1989 hydration of n-butene to n-butanol. In 1997 direct oxidation of ethylene to acetic acid started to operate in Japan. This process developed by Showa Denko KK is an alternative to Monsato process, based on carbonylation of methanol [12]. Recently, in 2001, a new process of manufacturing ethyl acetate by the direct reaction of ethylene with acetic acid in the gas phase using 12-tungstosilisic acid supported on silica was developed. This process will operate on a scale 220 000 tons/year [8].

On a smaller scale heteropoly acids are used in Japan as acid catalysts for the polymerisation of tetrahydrofuran in a liquid/liquid biphasic system to a polymeric diol (since 1985) and for the synthesis of glycosides in a homogeneous system. In the USA, ketone amination to imine over a supported HPA in the synthesis of isophorone nitrileimine was commercialised by DuPont in 1996 [13].

4.4.4 Other application of POM

Catalysis is by far the most important use of POM, presently over 80% of the patent applications concerning polyoxometalates is related to catalysis [13]. Other uses include many fields; the most important are shown in the table 4.8.

Table 4.8

The application of POM
Catalysis
Analytical chemistry
Corrosion resistant coatings
Separations, processing radioactive waste, and sorbents of gases
Membranes
Sensors
Cation exchangers
Dyes and pigments
Electrooptics
Electrochemistry, electrodes, fuel cells, and capacitors
Dopants in sol-gel and polymer matrices
Flammability control
Medicine

References

[1] M.T. Pope, Hetero and Isopoly Oxometalates, Springer (1983) Berlin

[2] J.J. Berzelius, Poggendorffs, Ann. Phys. Chem., 6 (1826) 369

[3] J.F. Keggin, Proc. Roy. Soc, (1934) A 144 75 London

[4] I. Kozhevnikov, Catalysis by polyoxometales, Willey and Sons (2002) England

[5] F. Cavani, Catal. Today 41 (1998) 73

[6] T. Okuhara, N. Mizuno et al. M. Adv. Catalysis 41 (1996) 113

[7] I.V. Kozhevnikov, Chem. Rev. 98 (1998) 171

[8] J. J. Borrás-Almenar, POM molecular science 98 (2003) Kluwer academics publisher, Netherlands

[9] C. Venturello, E. Alneri et al., J.Org. Chem 48 (1983) 3831

[10] N. Mizuno, M. Misono, Chem. Rev. 98 (1998) 199

[11] T. Nishimura, T. Okuhara et al., Chem. Letters (1991) 1695

[12] K. Sano, H. Uchida et al., Catalysis Surveys from Japan 3 (1999) 55

[13] http://www.iptonline.com/articles/public/IPTTWELVE96NoPrint.pdf

[14] D.E. Katsoulis, Chem. Review 98 (1998) 359

5. Experimental part

5.1 Catalytic measurement

Catalytic test were carried out in a semicontinuous stirred tank autoclave reactor (50 ml) made out of glass. Oxygen has been continuously fed to the reactor with a standard flow rate of 300 Nml/min. The reactor was equipped with a vapor condenser; the temperature of the cooling liquid was -9 °C.

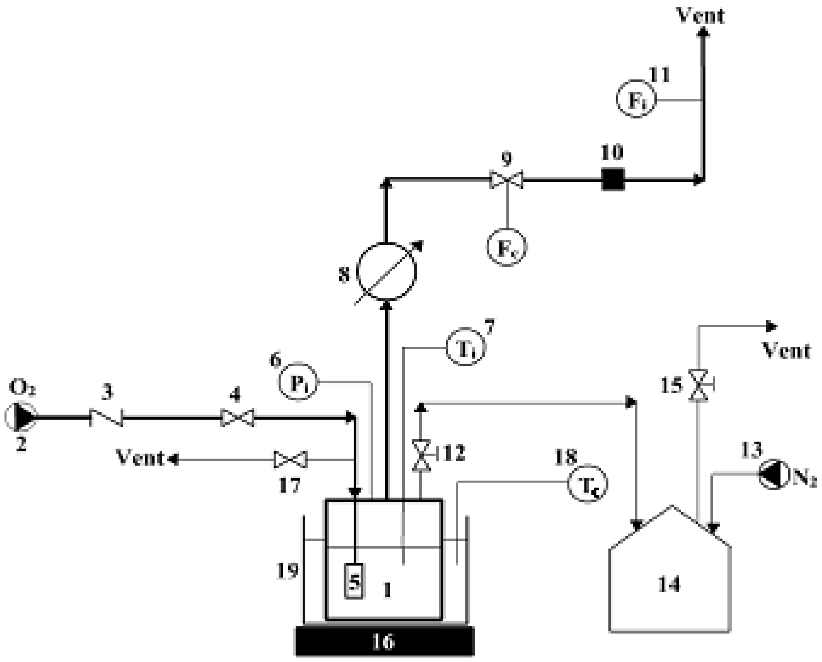


Figure 5.1: The scheme of the reaction plant
1) autoclave; 2) feed of O_2; 3) one way valve; 4) two ways valve; 5) bubbler with porous membrane; 6) pressure indicator; 7) internal thermocouple; 8) vapour condenser; 9) micrometric valve; 10) place of the getting the sample of outgoing gases; 11) flow rate meter 12) rupture disc 13) feeding of N_2; 14)security tank; 15) rupture disc; 16) heating plate; 17) depressurize valve; 18) external thermocouple; 19) bath with silicon oil

Typically the reaction measurements was carried out as follows: the substrate (cyclohexanone) and solvent (H_2O, acetic acid) were loaded in the reactor, overall volume being 50 ml, the catalyst was added. To ensure the good contact between two substrate and solvent, magnetic stirrer was loaded in the reactor. The reactor was heated to the temperature of the reaction (ranging from 70 to 110 °C). When the temperature was reached the valve of oxygen was opened, and the reaction started. The reaction was stopped by closing the valve of the oxygen.

5.2 Treatment of the reaction mixture

The obtained reaction mixture was not suitable for the direct analysis and therefore following chemical treatment of the mixture was necessary to be done: evaporation of the solvent, esterification of the product mixture and the extraction.

5.2.1 Evaporation of the solvent

After the reaction, the volume of the mixture was measured; and subsequently 5 ml of the solution was evaporated at the temperature of 70 °C using the rotating evaporator, letting to evaporate the unconverted cyclohexanone and the solvent.

5.2.2 Esterification of the reaction mixture

After the evaporation, the residual solid was mixed with a commercial mixture of methanol and trifluoroboride (14 % mixture) and heated to 70 °C for one hour in a sealed vessel in order to transform the produced diacids to corresponding dimethylesters.

5.2.3 Extraction of the product

After the esterification it was necessary to separate BF_3 and the rest of the catalyst from the diesters. Therefore the mixture was 5 times extracted with 10 ml of n-hexane. After the extraction, 25 ml of the extract was taken, 10 microliter of decane was added (internal standard) and the mixture was ready for the analysis.

5.3 Analysis of the product

5.3.1 Analysis of the diacids

As written before, the diacids were analyzed in the form of dimethylesters. For the quantitative and qualitative analysis GCMS was used. GCMS Agilent 6890N was equipped with the capillary column HP 5 (5 phenyl methyl siloxane). The temperature program of the analysis was as follows: 2 minutes isothermally at 50 °C, then the temperature increased to 250 °C by 10 °C/min.

5.3.2 Analysis of the gases

Incondensable gases were analyzed by two methods:

a) by sampling from time to time during the reaction 0,5 mL of gases in the effluent stream, and injecting it into a GC VARIAN equipped with a TCD and carbosieve S2 column (length 2 m), with following oven temperature program: 7 minutes at 40 °C, heating rate 10 °C/min to 220 °C with isotherm for 10 minutes.

b) by bubbling the effluent stream in a sodium hydroxide aqueous solution and determining the final amount of excess NaOH by titration—providing an integral amount of CO_2 produced over the entire experiment time and thus more accurate result. The procedure was performed as follows: 1 liter of 1M NaOH was prepared and during the reaction was being bubbled by effluent stream from the reactor. After the reaction 10 ml of the solution was taken, $BaCl_2$ was added to the sample solution (to precipate CO_3^{2-}) and the solution was titrated with HCl with fenolftalein as an indicator. The titration was stopped when the violet/pink solution became transparent.

5.4 Synthesis of the catalysts

5.4.1 Heteropolyacids

The catalysts, Keggin-type polyoxometalates with the composition $H_4PMo_{11}VO_{40}$ (HPA1) and $H_5PMo_{10}V_2O_{40}$ (HPA2) were prepared following the literature [1]. An aqueous solution was prepared by dissolving MoO_3 and H_3PO_4 (85%) in an abundant amount of water, at the temperature not higher than 100 °C (thus avoiding boiling of the solution); the solution was stirred till complete dissolution was obtained. Meanwhile second solution was prepared: 30% H_2O_2 was added to the beaker with distilled water in order to obtain 4 - 6% solution of H_2O_2. Vanadium oxide was added to the solution of H_2O_2 and stirred for 1 hour at 4 °C. The mixture was left in the ice bath for overnight. The former solution was heated to 90 °C, and the second solution was added drop by drop; then the mixed solution was left at 90 °C for 8 h, in order to let most of the solvent evaporate, and was finally left at 80 °C overnight in order to complete the evaporation of the solvent. The obtained wet orange solid was dried at 110 °C for 4 h. The dried solid was characterized by means of FT-IR spectroscopy in order to confirm the formation of the desired Keggin compound.

The overall equation of the preparation of the catalyst is:

$$H_3PO_4 + (12\text{-}n)MoO_3 + (0{,}1n)H_6V_{10}O_{28} + (0{,}2n)H_2O \rightarrow H_{3+n}PMo_{12-n}V_nO_{40},$$

where n is 1 or 2.

5.4.2 Cs salts of heteropolyacids

Corresponding Cs salt of acids were prepared by simple mixing heteropolyacid in water and adding stoichiometric amount of Cs_2CO_3. During the reaction CO_2 was evolved. The stoichiometric for the ion change is

HPA1/Cs_2CO_3 = ½ for $Cs_4PMo_{11}VO_{40}$,(CsHPA1)

HPA2/Cs_2CO_3 = 1/2.5 for $Cs_5PMo_{10}V2O_{40}$,(CsHPA2)respectively .

The obtained catalyst is green. Cs salts of HPA were characterized by means of FT-IR.

5.5 Characterization of the catalysts

5.5.1 Characterization by FT-IR in ATR

To register the IR spectrum, spectrophotometer FT-IR PerKin – Elmer equipped with ATR sampling in order to register the spectrum in attenuated total reflectance was used. The spectra were registered by 16 scans in the spectroscopic range from 4000 to 6000 cm^{-1}.

References

[1] V.F. Odyakov, E.G. Zhizhina et al., Kinet. Catal. 36 (1995) 733

6. Results and discussion

In this chapter the results obtained by studying the oxidation of cyclohexanone with Keggin POM will be described and discussed. For the reaction following catalysts were studied:

- $H_4PMo_{11}VO_{40}$ (called HPA1)
- $H_5PMo_{12}V_2O_{40}$ (called HPA2)
- $Cs_nH_{4-n}PMo_{11}VO_{40}$ ($n \geq 4$)
- $Cs_nH_{5-n}PMo_{10}V_2O_{40}$ ($n \geq 5$)

6.1 Characterization

FT-IR in ATR was the principal method used for the characterization of the prepared catalyst. By this method not only the Keggin structure could be confirmed, but FT-IR spectra should distinguish the sample with the different amount of the atom of vanadium.

6.1.1 FT-IR in ATR – HPA and their salts

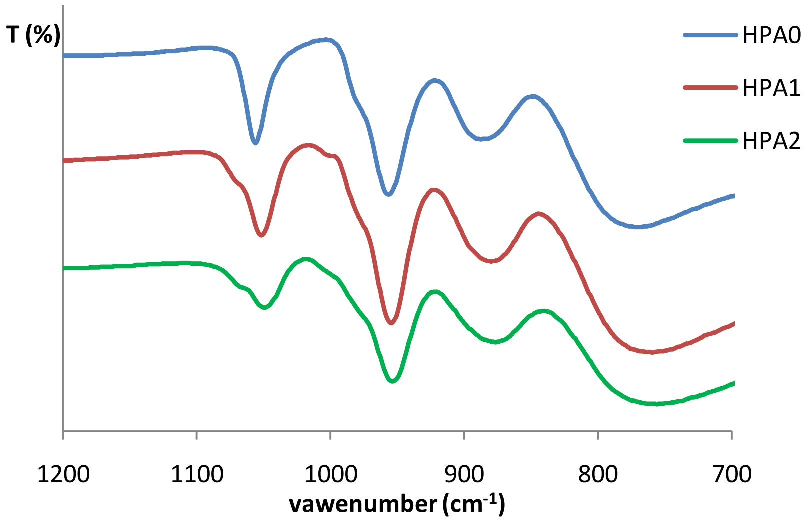


Figure 6.1: IR spectra of HPA: $H_4PMO_{11}VO_{40}$, $H_5PMo_{12}V_2O_{40}$ and $H_3PMo_{12}O_{40}$

Figure 6.1 shows IR spectra obtained for three different samples: HPA1, HPA2 and HPA 0 ($H_3PMo_{12}O_{40}$). An IR spectrum for the latter was measured in order to compare the differences between the catalysts in the function of number of atoms of vanadium in the Keggin unit. The characteristic infrared bands can be found in the range of 700-1200 cm^{-1}.

According to the literature IR spectrum of HPA with the Keggin structure is characterized by four vibration bands [1]:

- Asymmetric stretching of the bond P - O at 1066 cm^{-1}
- Asymmetric stretching of the bond Mo = O_t at 960 cm^{-1}
- Asymmetric stretching of the bond Mo – O_c – Mo and Mo – O_b – Mo at 860 cm^{-1} and 760 cm^{-1} respectively

As can be seen from the figure, the spectra of all three samples confirm the Keggin structure; however there are small differences between HPA 0, HPA1 and HPA2, namely the variation of the position, shape and intensities of the bands. In the case of HPA1 and HPA2 small shift to lower frequencies is observed for the band belonging to Mo-O-Mo vibration and P-O vibration. This shift is proportional to the number of vanadium incorporated in the Keggin unit. Comparing the spectra of the sample of HPA0 with HPA1 and HPA2, we see that the presence of the vanadium gives rises to the shoulder about 1085 cm^{-1}. This observation is in a good agreement with the literature, which explain it by the reduced structure symmetry anion [2].

Moreover comparing the IR spectra of HPA1 and HPA2 it can be seen, that the intensity of the shoulder at 1085 cm^{-1} slightly increases with passing from one atom of vanadium to two atoms of vanadium in the Keggin unit.

As was already said above, for the direct oxidation of cyclohexanone to adipic acid the Cs salts with the different grade of salification were also studied. All the prepared samples with different grade of salification were characterized by FT-IR in ATR spectroscopy. The spectra are shown in the figure 6.2 for $Cs_nH_{4-n}PMo_{11}VO_{40}$ ($n \geq 4$) and figure 6.3 for $Cs_nH_{5-n}PMo_{10}V_2O_{40}$ ($n \geq 5$) respectively.

Spectra of the samples vary quite linearly with the grade of salification, it is very well notable that the bands belonging to the stretching of P-O and M=O bonds are becoming larger and also there is a small shift to higher wavenumber with increasing salification of the samples. Moreover both figures show that with the increasing grade of salification increases the intensity of the shoulder at 1030 cm-1. This peak is attributable to the band of ν(V=O) in free V_2O_5, indicating that a small fraction of V species has segregated from the structure of the V-containing heteropolycompounds [3].

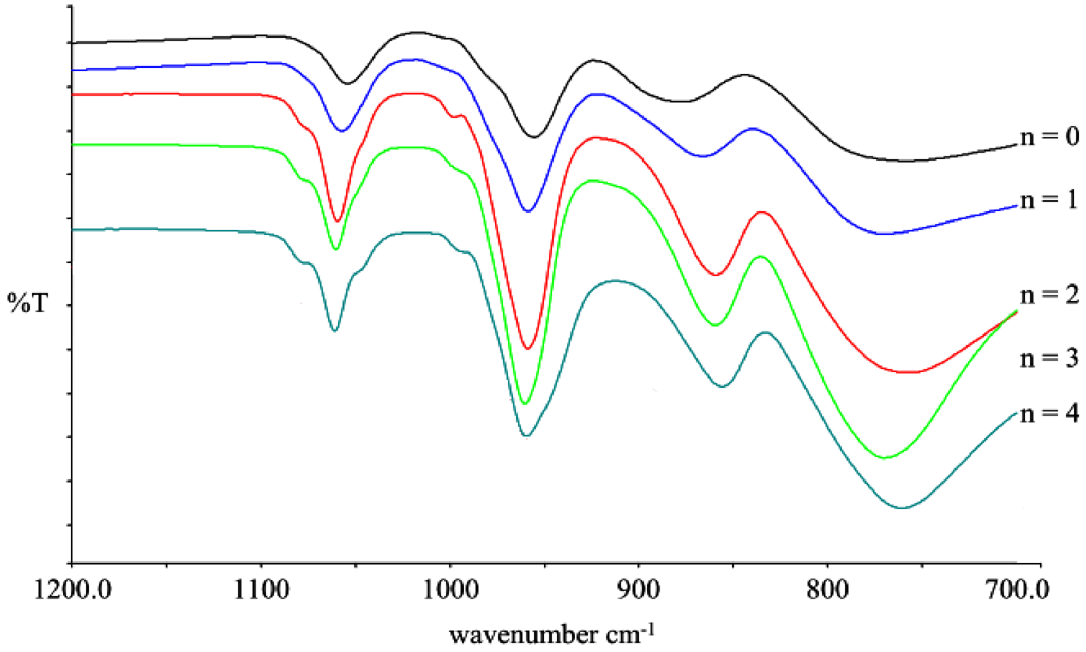


Figure 6.2: IR spectra of the $Cs_nH_{4-n}PMo_{11}VO_{40}$ (n ≥4) with different grade of salification

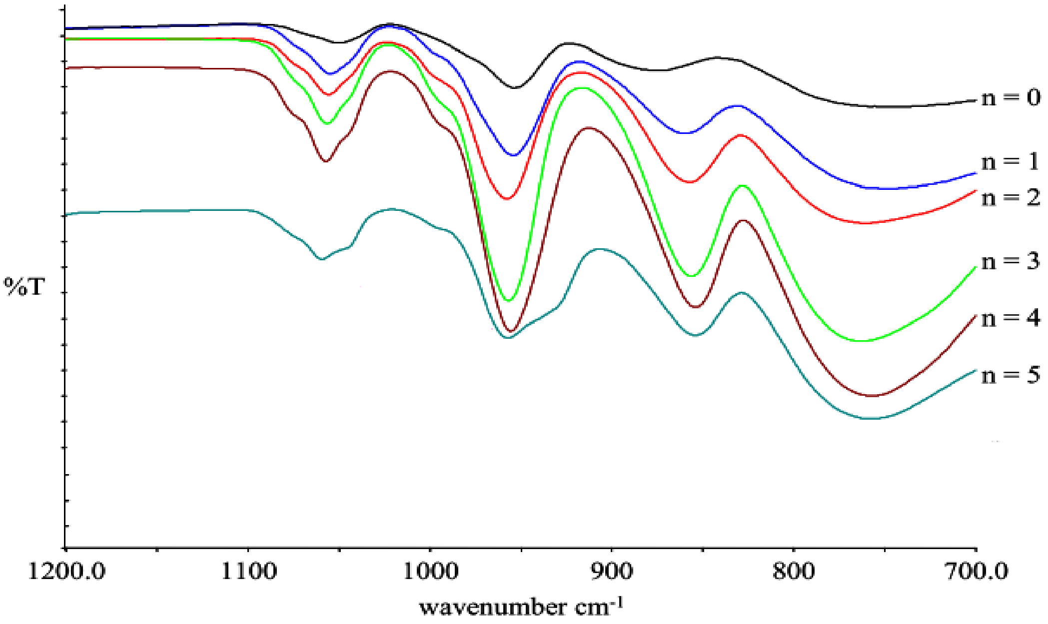


Figure 6.3: IR spectra of $Cs_nH5_{-n}PMo_{10}V_2O_{40}$ (n ≥5) with different grade of salification

6.1.2 FT-IR in ATR – Cs salts of HPA after the reaction

In order to see if the reaction would bring any changes to the structure of the catalyst, the catalyst was separated after the reaction from the reaction mixture by the filtration and consequently IR in ATR was measured used for the reaction. Figure 6.6 and 6.7 show the spectra of the catalyst $Cs_4PMo_{11}VO_{40}$ and $Cs_5PMo_{10}V_2O_{40}$ respectively after the reaction. Confronting the spectra of the catalyst before (figures 6.4 and 6.5) and after the reaction (6.6 and 6.7) it can be said that $Cs_4PMo_{11}VO_{40}$ does not undergo any significant changes in the structure during the reaction.

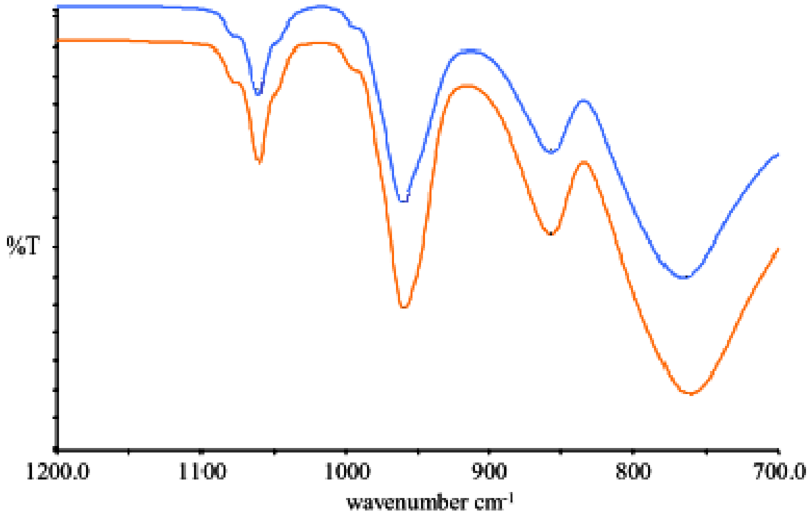


Figure 6.4: IR spectra of $Cs_4PMo_{11}VO_{40}$ used for the reaction

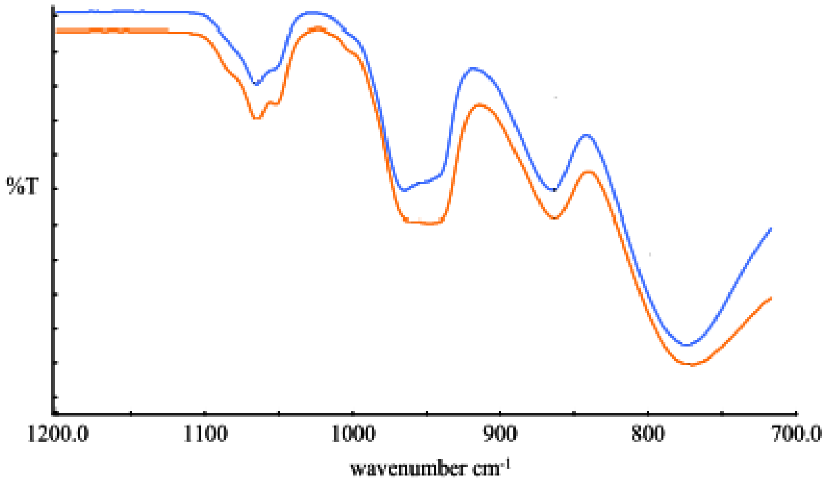


Figure 6.5: IR spectra of Cs_5 $PMo_{10}V_2O_{40}$ used for the reaction

On the other hand, IR spectrum for $Cs_5PMo_{10}V_2O_{40}$ is quite different before and after the reaction. One possible explanation would be that during the reaction partial changes of the Cs^+ ions with H^+ occurred. This would also explain why it was not possible to recover all the catalyst, which was loaded to reactor, because by changing the cation Cs^+ to H^+ the catalyst becomes more soluble in the reaction media. This hypothesis will be discussed further.

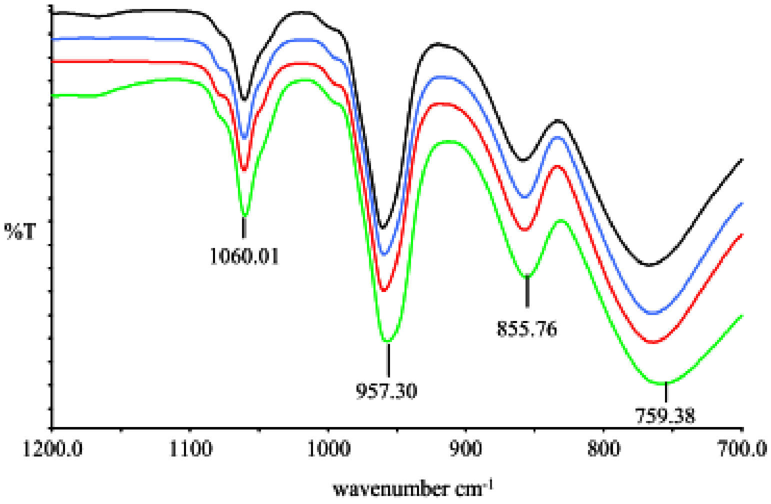


Figure 6.6: IR spectra of Cs_4 $PMo_{11}VO_{40}$ after the reaction

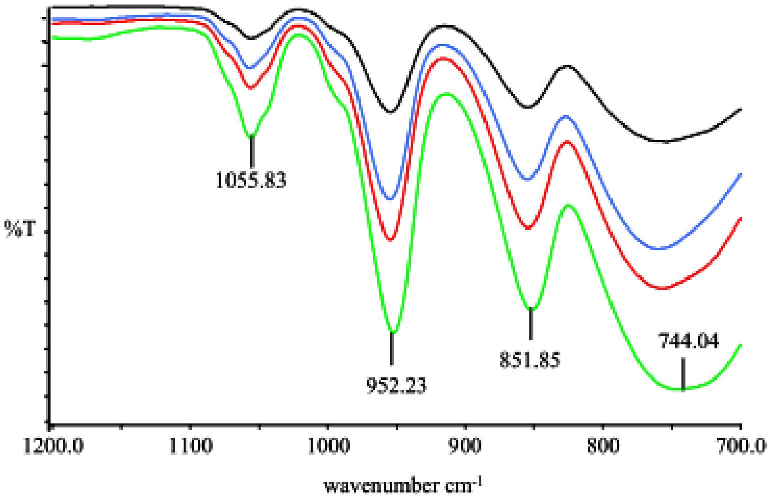


Figure 6.7: IR spectra of Cs_5 $PMo_{10}V_2O_{40}$ after the reaction

6.2 Oxidation of cyclohexanone with molecular oxygen – homogeneous catalysis

This part of the thesis will describe the results which were obtained by the oxidation of cyclohexanone by molecular oxygen in the liquid phase by HPA1 and HPA2 and their Cs salts.

The reactions were performed in the semicontinuous stirred tank reactor, under the pressure of oxygen of 4 bar, the time of reaction varied from 1 to 6 hours, the temperature was in the range of 70-110 °C, the amount of the cyclohexanone was 25 ml, the volume of the solvent was 25 ml and the amount of the catalyst varied from 0.001 to 1.6 g. The product of the reaction was adipic acid (AA). The by-products were: glutaric acid (GA), succinic acid (SA), carbon oxide and carbon dioxide.

6.2.1 Effect of the solvent

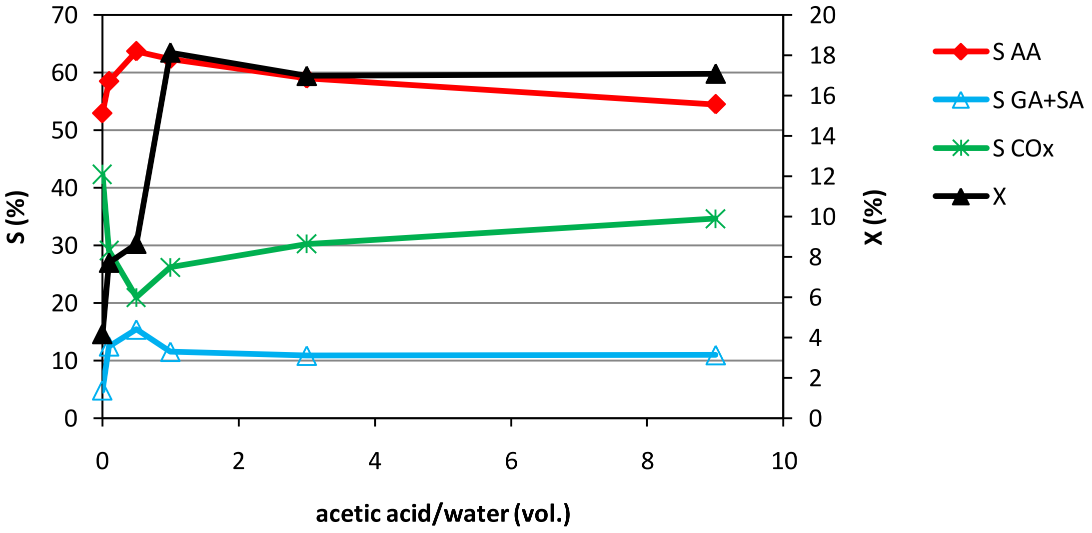


Figure 6.8: Selectivity and conversion in the function of the used solvent. Reaction conditions: HPA1, p = 4 bar, T = 90 °C, Vs = 50 ml, V cone = 25 ml, mol cat/cone = $8.98*10^{-4}$

Figure 6.8 shows the effect of the solvent used on the catalytic activity. These results are taken from the precedent thesis [4]. To explain why it was decided to further study the effect of the solvent on the reaction activity, figure 6.8 taken from [4] is reported. Figure shows that using acetic acid as a co-solvent greatly enhances the activity of the catalyst. Possible explanation for this acceleration would be acceleration of the tautomerism between cyclohexanone and the corresponding enolic form (figure 6.9). Enolic form should be more easily activated by radicalic H abstraction than cyclohexanone itself.

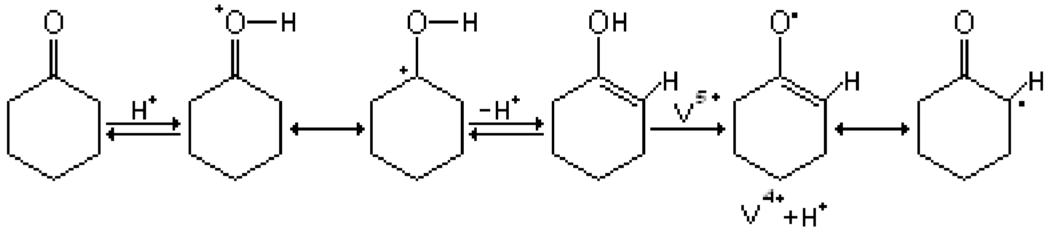


Figure 6.9: The activation of cyclohexanone via protonation and tautomerisation.

But not only is the reaction rate being accelerated by adding some amount of acetic acid, also the presence of acetic acid influenced the distribution of the products. Surprisingly, with the increasing conversion, the selectivity to adipic acid was increasing (and also to GA+SA) with decreasing selectivity to COx. After the maximum of the conversion was reached (using the equivolumetric mixture of acetic acid and water), the selectivity to adipic acid did not change significantly. These results suggested that acetic acid did not only accelerate the reaction but also changed the reaction mechanism.

Considering these results and the possibility of changing the reaction mechanism in the function of the solvent, further catalytic test were aimed to study the reaction activity using equivolumetric mixture of acetic acid and water.

6.2.2 Effect of the reaction time

First, the effect of the reaction time on the catalytic activity of HPA1 and HPA2 was studied. The results for HPA1 are given in the figure 6.10. The figure shows, that the conversion of cyclohexanone linearly increases with the time, after 6 hours conversion being 14%. After 30 minutes of the reaction, the selectivity to AA is high (69%), suggesting, that hypothetically extrapolating the conversion to zero, 100% selectivity to AA would be obtained. But with the time, AA undergoes the consecutive degradation reaction to form GA, SA and COx. Figure 6.11 shows the results obtained in the same condition but with the catalyst having two atoms of V in the Keggin unit HPA2.

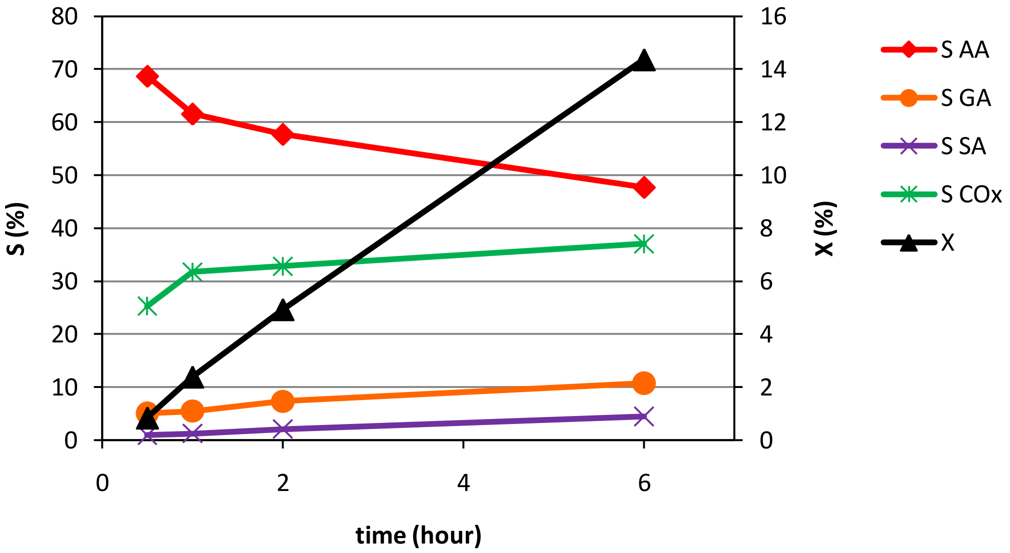


Figure 6.10: Selectivity and conversion in the function of the reaction time. Reaction conditions: HPA1, p = 4 bar, T = 90 °C, H_2O/HAc = 1, Vs = 50 ml, V cone = 25 ml, catalyst/cyclohexanone (molar) = $4.65*10^{-4}$

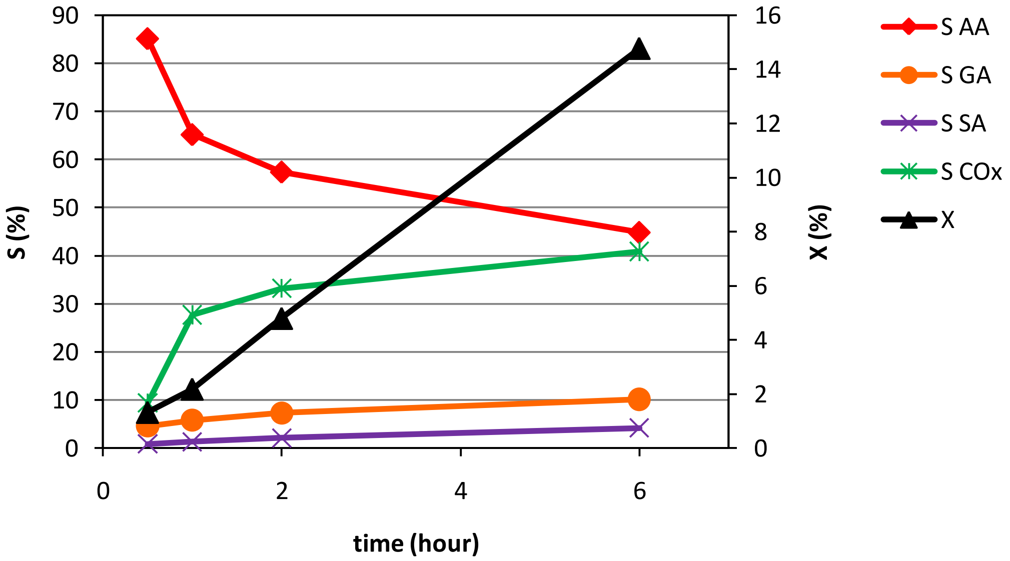


Figure 6.11: Selectivity and conversion as the function of the reaction time. Reaction conditions: HPA2, p = 4 bar, T = 90 °C, H_2O/HAc = 1, Vs = 50 ml, V cone = 25 ml, catalyst/cyclohexanone (molar) = $4.65*10^{-4}$

Observing the figure 6.11, we can see that the catalytic performance of HPA2 is slightly better than of HPA1. There is not such a big difference between the conversions but, selectivity to AA is clearly higher (85% or HPA2 vs. 67 % for HPA1). But also in this case, HPA2 undergoes the consecutive degradation to form glutaric acid and succinic acid.

After the 6 hours of the reaction the selectivity to AA is still relatively high with the highest conversion and so it was decided to carry out further tests with the reaction time of 6 hours.

6.2.3 Effect of the reaction temperature

Another factor which was studied is the temperature of the reaction and the amount of the catalyst. First, the reaction temperature will be discussed.

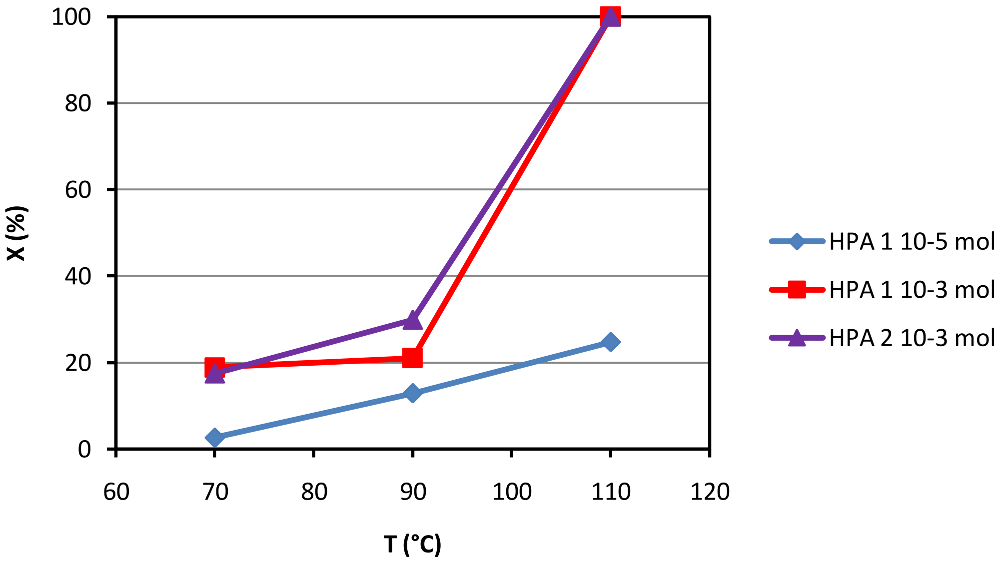


Figure 6.12: Effect of the temperature of the reaction on the conversion, reaction conditions: HPA1, HPA2, p = 4 bar, $H_2O/HAc = 1$, Vs = 50 ml, V cone = 25 ml, catalyst/cyclohexanone (molar) = $4.65*10^{-4}$, $3.7 *10^{-3}$ respectively

Studying the effect of the reaction temperature, two cases were distinguished: oxidation with traces amount of the catalyst (10^{-5} mol) and hundred times higher amount of the catalyst (10^{-3} mol). Observing the figure 6.12, we see that the activity is increasing with the temperature of the reaction. In the case of higher molar ratio of catalyst/cyclohexanone, for both of the samples, at 110 °C the reaction solution became an almost solid substance, very difficult to handle, insoluble in the water. Possible explanation would be that the polymerization of the product of the reaction occurred. It was not possible to quantify the yield of AA, GA and SA. Yield of COx was 10 %, and with regard to the occurred solid material almost complete conversion of cyclohexanone was supposed.

The same effect was studied with corresponding salts of HPA: $Cs_4PMo_{11}VO_{40}$ (CsHPA1) and $Cs_5PMo_{10}V_2O_{40}$ (CsHPA2). The results are reported in the figure 6.13. As in the case above, also here the most active catalyst is that one having 2 atoms of Vanadium in the Keggin unit. On the other hand, at the temperature of 110 °C, the reaction proceeded smoothly and there was not any black solid substance obtained.

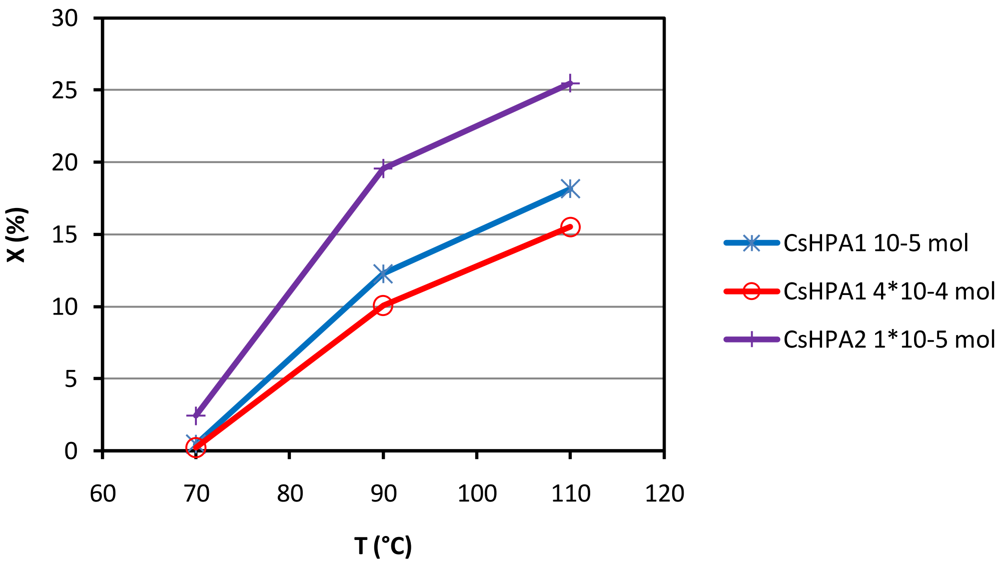


Figure 6.13: Effect of the temperature of the reaction on the conversion. Reaction conditions: CsHPA1, CsHPA2, p = 4 bar, H_2O/HAc = 1, Vs = 50 ml, V cone = 25 ml, catalyst/cyclohexanone (molar) = $4.65*10^{-4}$, $3.7 *10^{-3}$ respectively

Although in the case of Cs salts of heteropolyacids the highest conversion was obtained at 110 °C, in order to have results which could be compared among themselves, it was decided to further continue to study the direct oxidation of cyclohexanone at 90 °C.

6.2.4 Effect of the pressure

To study the effect of the concentration of the oxygen, the reaction in the anaerobic condition were carried out. In this study, both of the catalyst, HPA1 and HPA2 were used as the stoichiometric oxidants to see if the catalysts are able to oxidize cyclohexanone to give adipic acid. Theoretically, HPA1 and HPA2 should undergo stoichiometric reduction by obtaining two electrons from cyclohexanone, thus these reactions should take place:

$$3\ H_4PMo_{11}VO_{40} + C_6H_{10}O \rightarrow 3\ H_4PMo_{11}VO_{39} + C_6H_{10}O_4$$

$$3\ H_5PMo_{10}V_2O_{40} + C_6H_{10}O \rightarrow 3\ H_5PMo_{10}V_2O_{39} + C_6H_{10}O_4$$

In this experiment the amount of the catalyst and cyclohexanone loaded in the reactor were calculated with the purpose to have the yield of adipic acid 0.13 %, supposing the selectivity would be 100 %. Practically, the yields of adipic acid were lower than the theoretical ones, for HPA1 it was 0.005 % and for HPA2 it was 0.024 %. This test showed that HPA2 is clearly more efficient catalyst than HPA1.

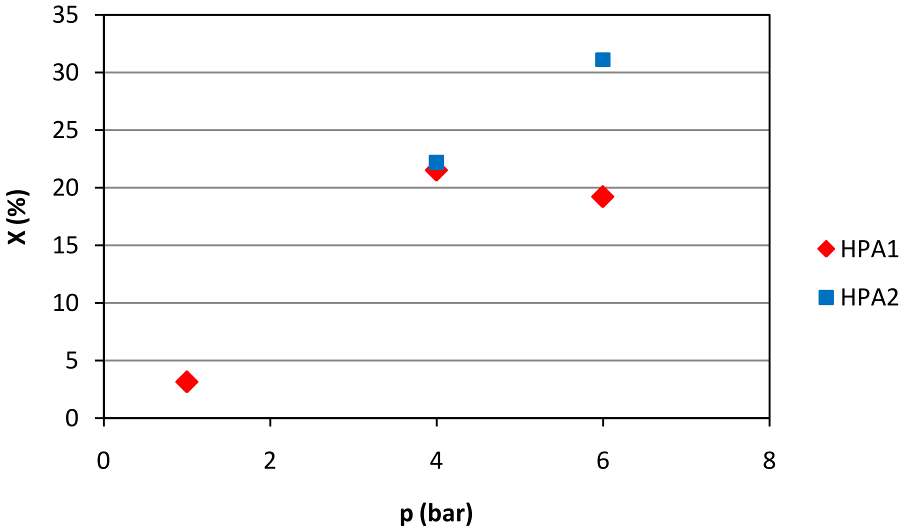


Figure 6.14: Effect of the pressure. Reaction conditions, catalyst/cyclohexanone (molar) = $4.65*10^{-4}$, T = 90 °C, H_2O/HAc = 1, Vs = 50 ml, V cone = 25 ml

Moreover also the effect of the oxygen pressure was studied for both of the catalyst HPA1 and HPA2; the results are shown in the figure 6.14. Quite surprisingly increasing the pressure to 6 bar, HPA1 gave lower conversion of cyclohexanone. One possible explanation for this result would be the hypothesis that in the case of HPA1 the rate limitating step of the reaction does not involve the reaction with oxygen. The behavior of HPA2 is quite different, the conversion is greatly enhances with increasing pressure. These results suggest that the type of prevailing mechanism may be a function of the POM composition, and it may be expected that in the co-presence of both redox and autoxidation mechanisms, the former may become more important when HPA2 is used.

6.2.5 Effect of the amount of the catalyst

Figure 6.15 shows the effect of the amount of the loaded catalyst (expressed as molar ratio of catalyst and cyclohexanone) on the conversion of cyclohexanone. The behavior of the two samples is very similar in the area of the low amount of the catalyst, but moving to higher amount of the catalyst, there is a well notable difference between their activities. Meanwhile the conversion of cyclohexanone remains almost steady in the case of HPA1, higher amounts of HPA2 catalyst caused further increase in the conversion. That confirms that it is possible to accelerate the reaction rate by using a catalyst with enhanced redox properties, even under conditions in which the HPA1 does not provide any further improvement of the cyclohexanone conversion. With HPA2, the higher redox potential leads to a more pronounced effect of the catalyst amount on substrate conversion Anyway neither of these two samples gave proportional dependence of the conversion on the amount of the catalyst.

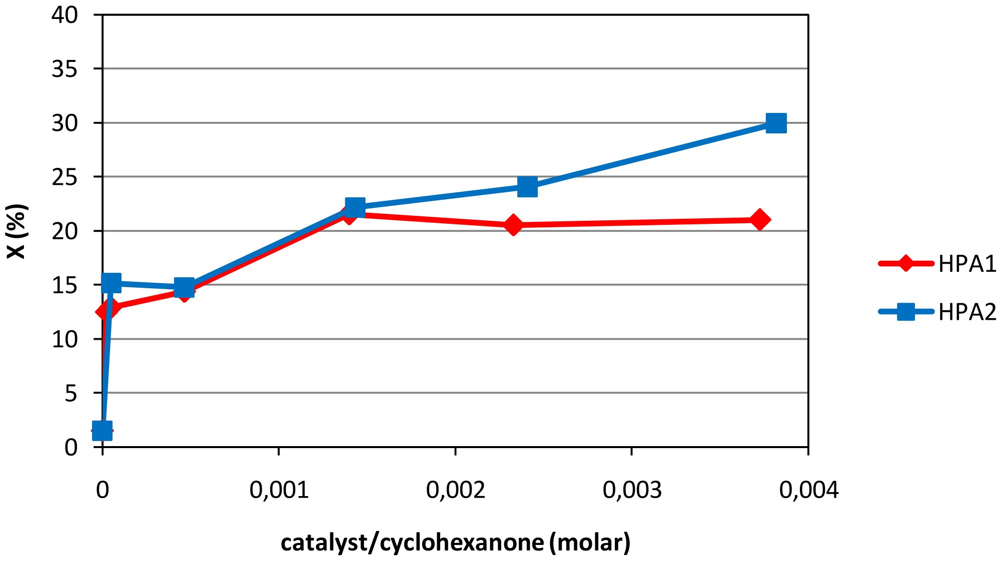


Figure 6.15: Effect of the composition of the catalyst in the function of the catalyst loaded. Reaction conditions: HPA1, HPA2, p = 4 bar, T = 90°C, $H_2O/HAc = 1$, Vs = 50 ml, V cone = 25 ml

Figure 6.15 shows another interesting result regarding the activity in the absence of any catalyst. Performing the blank reaction (loading the reactor as usually but without the catalyst), cca 1.5% conversion of cyclohexanone was detected. The rapid increase from 1.5% to 13% of the conversion in a very small range of the amount of the catalyst (from 0 to 0.0001 mol) could be explained by one of the following hypothesis:

- Working with the very small concentration of the catalyst, it is possible there is autooxidation mechanism involved. In that case, the role of the catalyst would be to act as an initiator of the radical chain reaction. This would be explained by the fact, that an already very small amount of the catalyst causes the rapid increase of the activity. Other increase of the concentration of the catalyst does not bring any significant changes, because of the so called ”chain-termination effect”, which has been already described in the literature for the relatively high amounts of the catalyst-initiator [5]

- It is possible that under conditions of high POM-to-cyclohexanone molar ratio, a redox-type mechanism may prevail over autoxidation. It means that in that case, the factor which would influence the behavior of the catalyst would be the reoxidation of the reduced catalyst - and thus higher amount of the catalyst results in higher amount of the reduced catalyst and in this case the rate determining step become the reoxidation. This would also explain the differences between the two catalysts HPA1 and HPA2, HPA2 having 2 atoms of vanadium is more easily reoxidized by O_2 than HPA1.

Figures 6.16 and 6.17 show the distribution of the products as the function of the catalyst loaded. There are not any big differences in the selectivities, neither the differences between the two studied catalysts HPA1 nor HPA2.

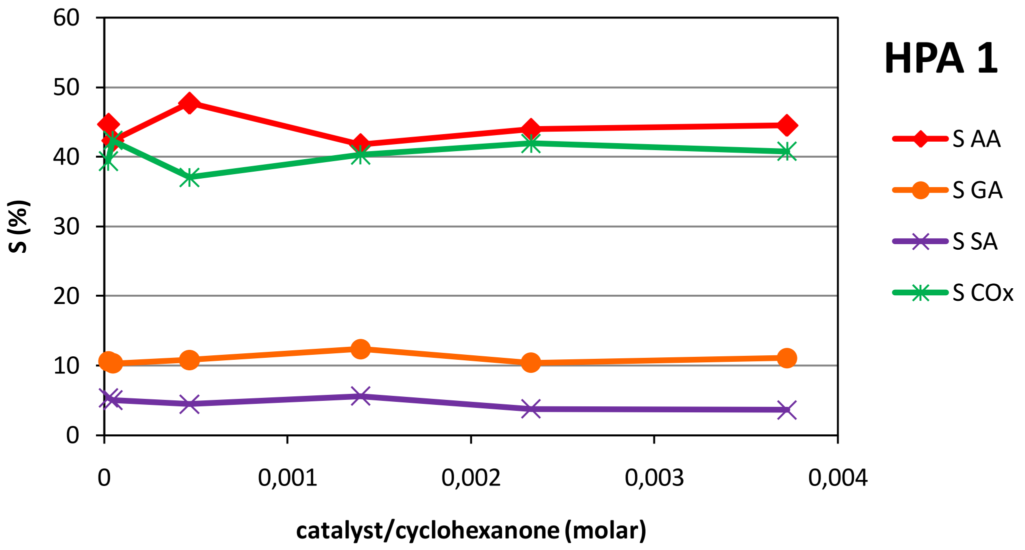


Figure 6.16: Effect of the amount of the catalyst loaded on the selectivities. Reaction conditions: HPA1, p = 4 bar, T = 90 °C, H2O/HAc = 1, Vs = 50 ml, V cone = 25 ml

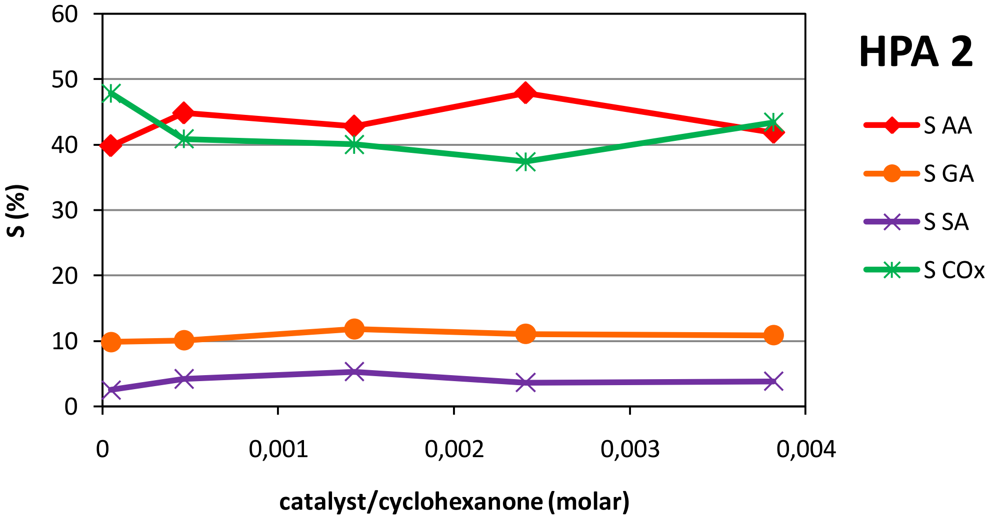


Figure 6.17: Effect of the amount of the catalyst loaded on the selectivities. Reaction conditions: HPA2, p = 4 bar, T = 90 °C, $H_2O/HAc = 1$, Vs = 50 ml, V cone = 25 ml

6.2.6 Effect of the composition of the catalysts – acid vs. Cs salts

Figure 6.18 shows the confrontation of the conversion of cyclohexanone obtained by HPA1 and the corresponding Cs salts.

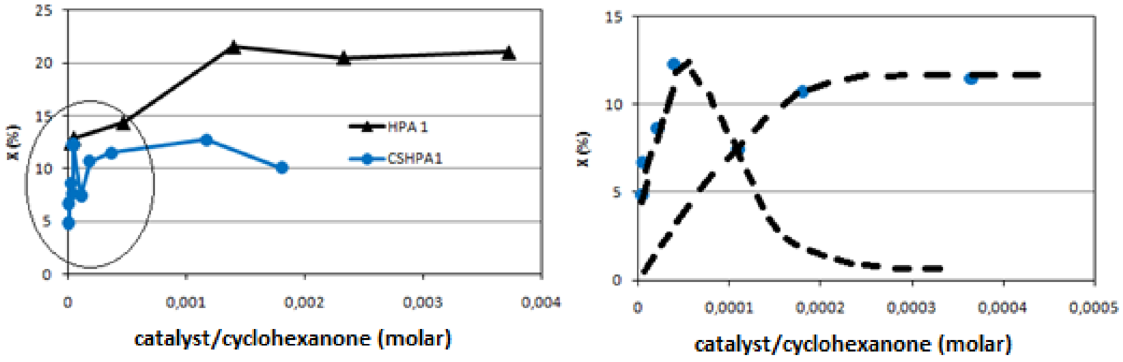


Figure 6.18: Effect of the amount of the catalyst loaded on conversion – comparison between CsHPA and HPA1. Reaction conditions: p = 4 bar, T = 90 °C, $H_2O/HAc = 1$, Vs = 50 ml, V cone = 25 ml

The effect of the amount of the catalyst loaded was again studied as the function of the molar ratio of catalyst and cyclohexanone. In the case of the CsHPA1 a lot of reaction loading traces of catalysts were carried out in order to understand its behavior in these conditions and moreover to be able to hypothesize the possible mechanism of the reaction. The advantage of the use of CsHPA1 was the fact, that in our condition this material should behave as a heterogeneous catalyst. But it was found out that this material does not act as a truly heterogeneous catalyst because during the filtration only part of the material could be the recovered, indicating that our material when loaded in very small amounts could be dissolved in the reaction media. From the figure 6.18 it can be seen, that the behavior of the HPA1 and CsHPA1 is very similar in the area of the traces of the catalyst, but differs a lot moving to the higher amount of the catalyst. This suggests that the fraction of dissolved CsHPA1 probably acts as a real catalyst (initiator) on the contrary to the heterogeneous part of CsHPA1. Moreover there is a strong effect of the inhibition (see the figure 6.18, right part) which could derive either from a chain-termination effect under autoxidation conditions, or even by slower mass transfer caused by the presence of solid insoluble part of the catalyst.

Figure 6.18 also shows that in the beginning there is a very fast increase of the conversion and after the reached maximum, there is a diminution of the conversion, again very rapid, then a slower increase of conversion, until a steady value of conversion is finally reached. This behavior suggests that there is an overlap of the curves and thus overlapping of two different mechanisms:

1. Mechanism of radical propagation, where already very small amount of the catalyst is sufficient to start the reaction, in this case the catalyst acts as an initiator of the reaction till the moment in which also starts to react as an inhibitor and causes the termination of the radical chains.
2. At high ratios of catalyst to cyclohexanone the contribution of radical reaction is insignificant and the redox mechanism is the prevailing one. In these conditions HPC is the stoichiometric catalyst and its role is to transfer the oxygen ion to the substrate.

Very interesting behavior performed CsHPA1 regarding the distribution of the products in the function of the molar ratio of catalyst and cyclohexanone (see figure 6.19). Initially there is a high selectivity to AA, but it further decreases and stabilizes about the 45%. The same behavior is shown by GA and SA. This behavior would be in agreement with the conversion of cyclohexanone, but it seems that the explanation is more complex than just kinetic effect (different contribution of parallel and consecutive reaction). Thus there is a possibility that is caused by the change of the mechanism of the reaction.

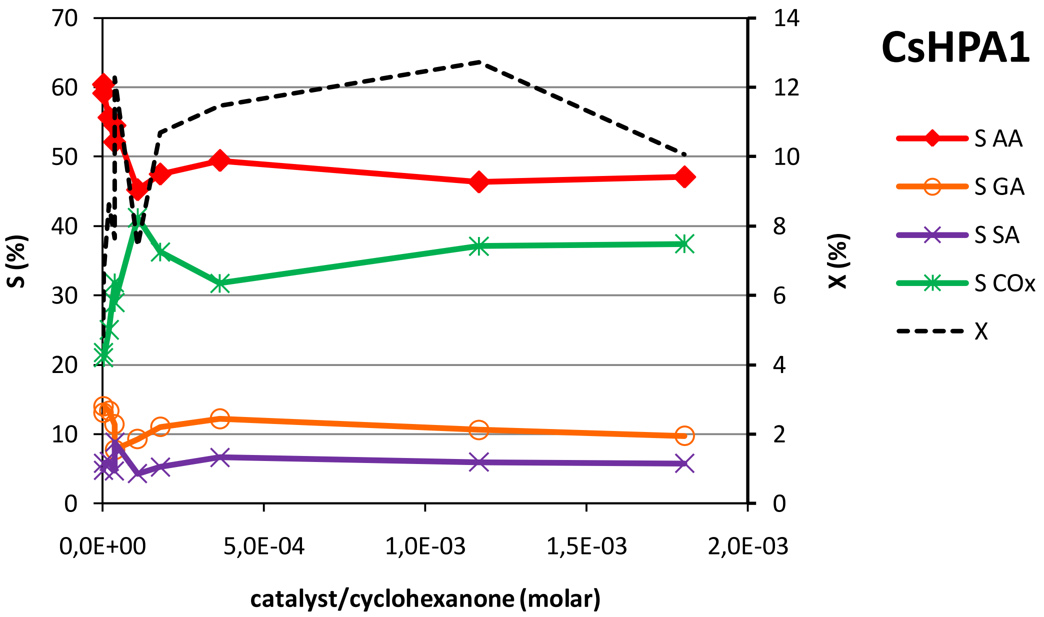


Figure 6.19: Effect of the amount of the catalyst loaded on conversion. Reaction conditions: Cs HPA1, p = 4 bar, T = 90°C, $H_2O/HAc = 1$, Vs = 50 ml, V cone = 25 ml, mol

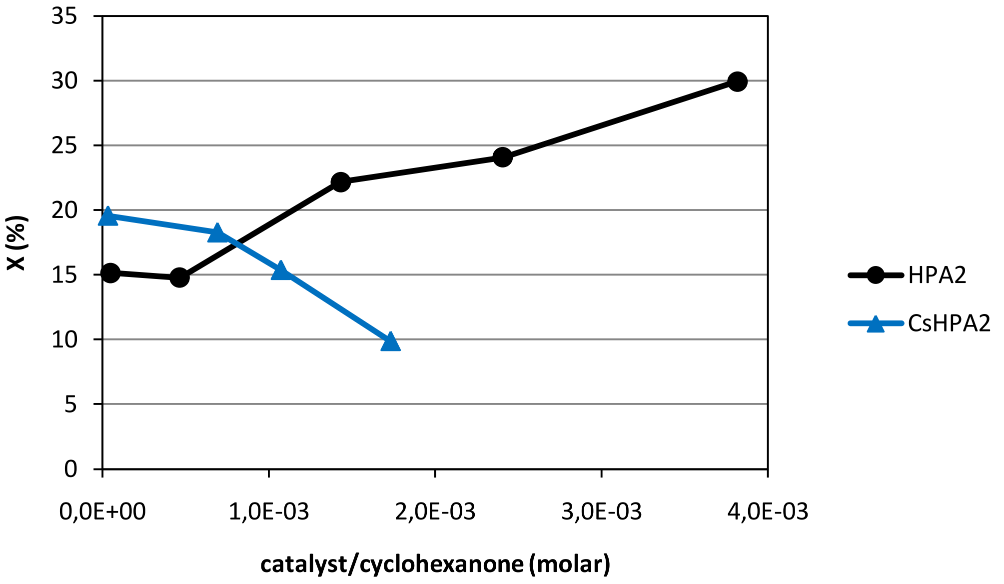


Figure 6.20: Effect of the amount of the catalyst loaded on conversion - comparison between HPA2 and CsHPA2. Reaction conditions: p = 4 bar, T = 90 °C, $H_2O/HAc = 1$, Vs = 50 ml, V cone = 25 ml, mol

The same comparison was done for the catalysts with 2 atoms of vanadium in the Keggin unit. Figure 6.20 shows the comparison of reaction activity of HPA2 and CsHPA2. Also in this case there are not any big differences in their activity in the area of traces of the catalyst, but moving to the higher amount of the catalyst, their activity is quite different, and the inhibition effect for CsHPA2 is well notated. Selectivities to AA, lighter acids and COx, shown in the figure 6.21 and 6.22, are for both catalysts very similar and there is not any particular data which should be described in detail.

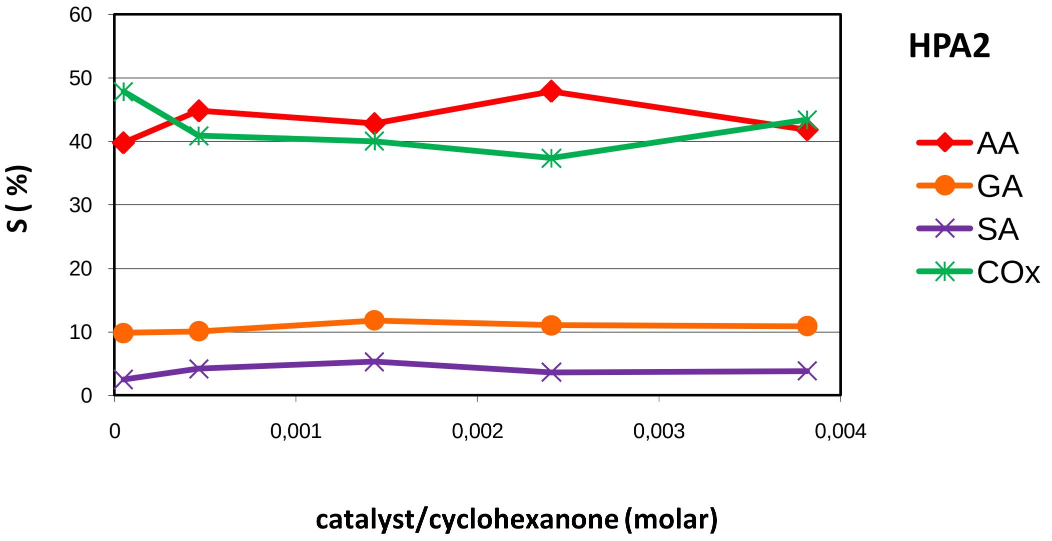


Figure 6.21: Effect of the amount of the catalyst loaded on selectivities. Reaction conditions: HPA2, p = 4 bar, T = 90 °C $H_2O/HAc = 1$, Vs = 50 ml, V cone = 25 ml

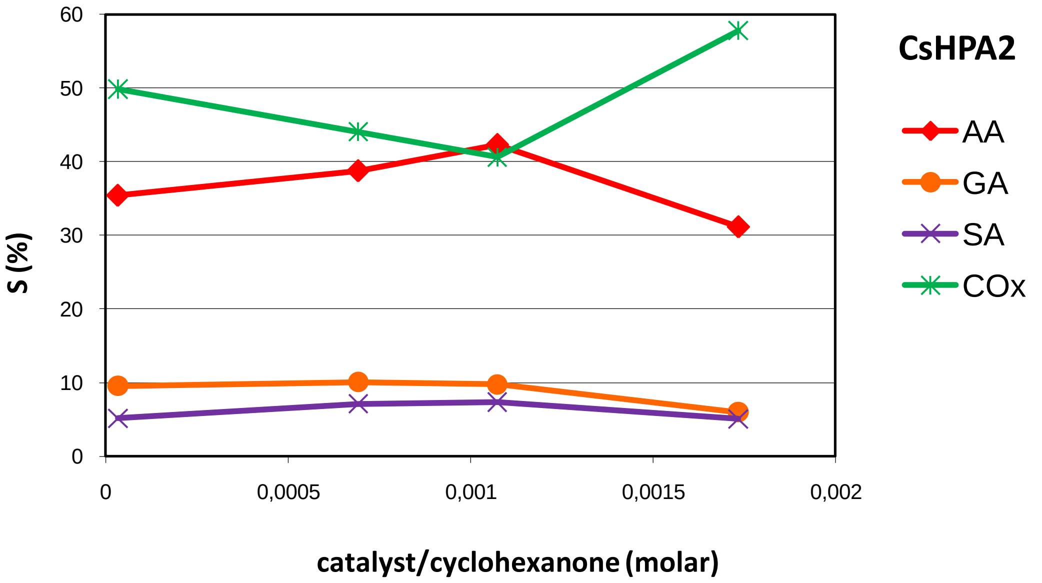


Figure 6.22: Effect of the amount of the catalyst loaded on selectivities. Reaction conditions: CsHPA2, p = 4 bar, T = 90 °C, $H_2O/HAc = 1$, Vs = 50 ml, V cone = 25 ml

6.2.7 Effect of the radical scavenger

Because during the studies of the activity of the HPC in the oxidation of cyclohexanone some questions about the possible mechanism arose, it was decided, to carry out the reaction in the presence of the radical scavenger. For this study it was decided to use 2,6-di-ter-butyl-1-hydroxy-4- methylbenzene (BHT), this compound is known to be one of the most efficient radical scavengers.

So far the results suggested that there were two mechanisms involved (redox and radical mechanism) and that their presence depends on the amount of the catalyst used, for this reason it was decided to carry out the reaction with BHT discriminating two cases: performing the oxidation with traces of the catalyst and with large amount of catalyst. The results of these experiments are summarized in figure 6.23, which shows the conversion of cyclohexanone as a function of both the BHT-to-cyclohexanone ratio and the BHT-to-POM ratio.

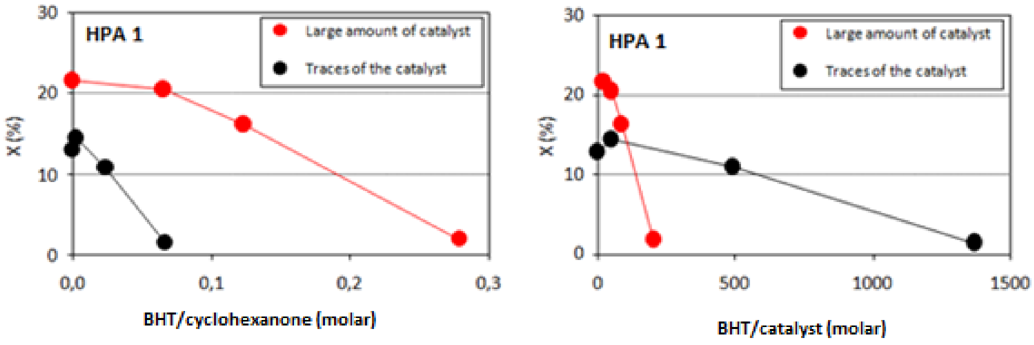


Figure 6.23: Effect of the presence of radical scavenger, effect of the BHT on the conversion in the function of the molar ratio of BHT and cyclohexanone (left), effect of the BHT on the conversion in the function of the molar ratio of BHT and catalyst (right).

It is shown that BHT has a different impact on the reaction activity in the function of the amount of the catalyst. In the tests which were carried out with traces of catalysts, BHT caused the rapid fall of the conversion of cyclohexanone in correspondence of very low BHT to cyclohexanone ratio. On the other hand, for tests carried out with high POM-to-cyclohexanone feed ratio, there was almost no effect on cyclohexanone conversion up to a BHT-to-cyclohexanone ratio of cca 0.1. These results clearly show that the presence of BHT has an effect on the reaction rate under the condition in which the radicalic chain autoxidation has been proposed. It should be also noted, that BHT caused the decrease of the conversion also under conditions in which the redox mechanism contributed to cyclohexanone conversion (at high POM-to-cyclohexanone feed ratio). This suggests that in the case of the redox mechanism, the activation and oxidation of cyclohexanone also occurs with the involvement of radicalic intermediates. In this case, however, the mechanism does not occur via a chain-reaction with free radicals reacting with O_2; rather, it would likely involve the electron transfer from the substrate to the POM and the development of a complex by coordinating the substrate and intermediates. This hypothesis is in a good agreement with the results shown in the figure on right. In this case, effect of the presence BHT was expressed as the conversion of cyclohexanone in the function of molar ratio of BHT and catalyst. Here, BHT influences the conversion more significantly for the tests carried out using high amount of the catalysts, in fact loading traces amount of catalyst, the conversion is not influences by the presence of radical scavenger, and really high molar ratio of BHT/catalyst has to be used to detect any changes in the reaction rate.

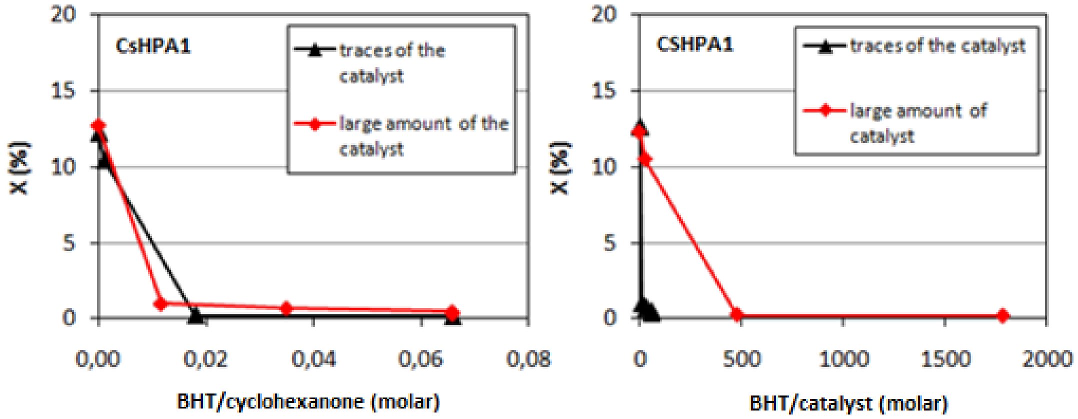


Figure 6.24: Effect of the presence of radical scavenger, effect of the BHT on the conversion in the function of the ratio of BHT and cyclohexanone (left), effect of the BHT on the conversion in the function of the ratio of BHT and catalyst (right).

Effect of the presence of the radical scavenger, was completely different in the case of CsHPA1. The results are shown in the figure 6.24. For both cases, traces of the catalyst and large amount of the catalyst, BHT caused rapid decline of the conversion of cyclohexanone, more readily compared to HPA1. This can be explained by the fact, which was already discussed above, that in the case of CsHPA1, the true catalyst is the dissolved part of CsHPA1, thus indicating the real ratio of BHT/catalyst is much higher than the theoretical one.

Thus after these studies which were carried out in the presence of the radical scavenger, it was possible to make a final hypothesis about the reaction mechanism. According to these results, there are two different mechanisms involved:

1. redox type mechanism and
2. radicalic chain-reaction autoxidation

Redox type mechanism prevails using high catalyst-to-cyclohexanone molar ratio in the presence of equivolumetric solution of H_2O and acetic acid. In this case POMs are directly involved in the reaction, which is shown in the figure 6.25.

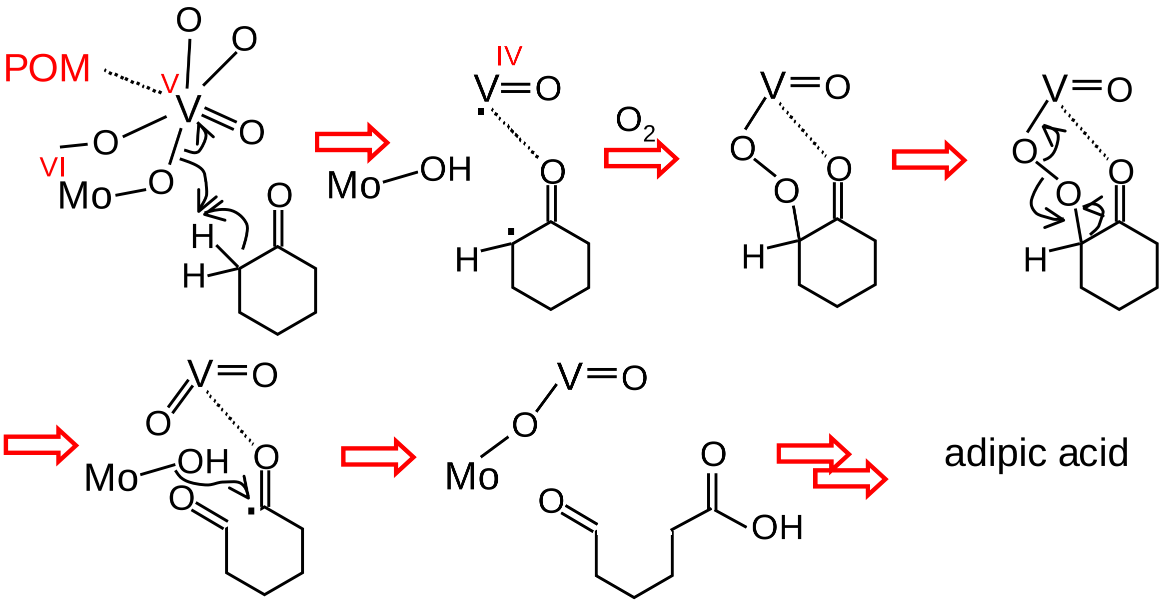


Figure 6.25: Proposed redox mechanism for oxidation of cyclohexanone using HPA as a catalyst.

Radicalic chain-reaction autoxidation occurs performing the reaction using acetic acid/water solvent but loading small amount of the catalyst (working with low molar ratio of catalyst/cyclohexanone). Figure 6.26 shows how can the mechanism of autoxidation proceed in the presence of POM. As can be seen from the figure, almost all the radicalic intermediate could act as a radical initiator.

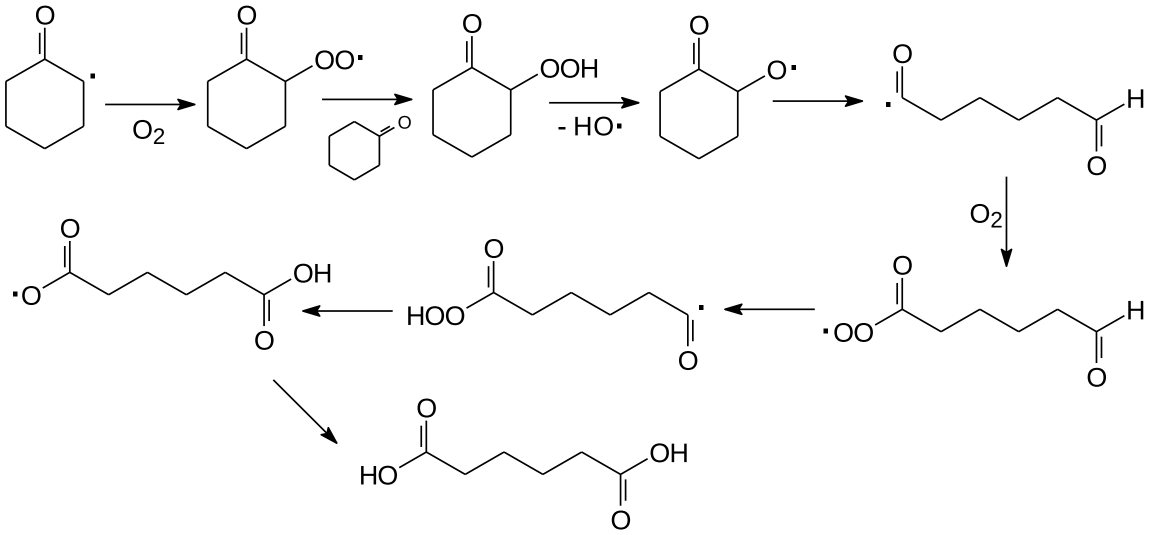


Figure 6.26: Proposed radicalic mechanism for the oxidation of cyclohexanone with molecular oxygen

6.2.8 Tests of leaching

Tests of leaching were done with the CsHPA1 catalyst in order to verify our hypothesis, that the theoretically heterogeneous catalyst CsHPA1 would be partially soluble in our reaction media and the soluble part of the catalyst was the active specie. For this purpose, the catalyst after the reaction was separated by the filtration from the reaction mixture. The solution was loaded in the reactor and the reaction was performed, moreover also the filtrated catalyst was loaded in the reactor and again the reaction was performed. In this case the amount of cyclohexanone and the solvent was adjusted to have the same ratio of all the substrate as in the original reaction. The results are shown in the table 6.1.

Table 6.1

catalyst	X cyclohexanone (%)
CsHPA1 fresh	10
CsHPA1 recovered by filtration	13.7
Solution after the filtration	18.1

From the results reported in the table 6.1 it is clear, that the catalyst CsHPA1 does not act as a heterogeneous catalyst. The conversion of cyclohexanone with the fresh catalyst is 10 % while the conversion of cyclohexanone with the solution reloaded in the reactor has increase a lot – to 18.1 %. That means that during the first reaction part of the catalyst has been dissolved in the solution, the part of the catalyst which is responsible for the catalytic activity. Also the catalyst which was reloaded in the reactor after the reaction gave higher conversion of cyclohexanone. This could be explained by the higher solubility of the catalyst in the reaction media, which would be in a good agreement with the observation done after the FTIR characterization, in fact the amount of the Cs determines the solubility of the HPC. Thus the higher is the amount of the Cs, the smaller is the solubility of the sample.

References

[1] J. K. Lee, J. Melsheimer et al., Appl. Catalysis A 214 (2001) 125

[2] D. Casarini, G. Centi et al., J. Catal. 143 (1993) 325

[3] N. Mizuno, D.J. Sun, W. Han, T. Kudo, J. Mol. Catal. A 114 (1996) 309

[4] A. Frattini, Tesi di dottorato, Facolta di Chimica Industriale, Universita degli studi Bologna XX ciclo (2008)

[5] I. Belkhir, A. Germain et al., J. Chem. Soc., Faraday Trans. 94 (1998) 1761

- SECOND PART -

Oxidation of cyclohexanone with hydrogen peroxide: Baeyer-Villiger oxidation

7. Baeyer – Villiger reaction

7.1 Description of the reaction

Baeyer -Villiger is one of the most well known and widely applied reactions in organic synthesis [1]. First the reaction was described by Adolf Baeyer and Victor Villiger in 1899, when they performed the oxidation of menthone to the corresponding lactone using a mixture of sodium persulfate and concentrated sulfuric acid [2].

The big success of this reaction is mainly due to its versatility:

- A variety of carbonyl compound can be oxidized, ketones are converted into esters, cyclic ketones to lactones, benzaldehydes into phenols, or carboxylic acids and R-diketones into anhydrides
- A large number of functional groups are tolerated
- The regiochemistry is highly predictable with the migratory aptitude being tertiary alkyl> cyclohexyl> secondary alkyl> benzyl> phenyl> primary alkyl> CH3
- The reaction is generally stereoselective; that is, the migrating group retains its configuration
- A wide range of oxidants may be used, their activity is decreasing in order: CF_3CO_3H > monopermaleic acid > monoperphthalic acid > 3,5-dinitroperbenzoic acid > p-nitroperbenzoic acid > m-CPBA~ HCO_3H> $C_6H_5CO_3H$ > CH_3CO_3H » H_2O_2 > t-BuOOH [1].

Generally accepted mechanism for the Baeyer - Villiger oxidation is shown in the figure 7.1. It consists of initial nucleophilic attack of the peroxy acid at the carbonyl carbon (step a) to form an intermediate species (highlighted in the red) known as the Criegee adduct. This step is followed by the migration of one of the alkyl groups onto the peroxygen and the concomitant release of the carboxylate anion (step b). Of these, step b is the more important in determining the properties of the overall reaction [3].

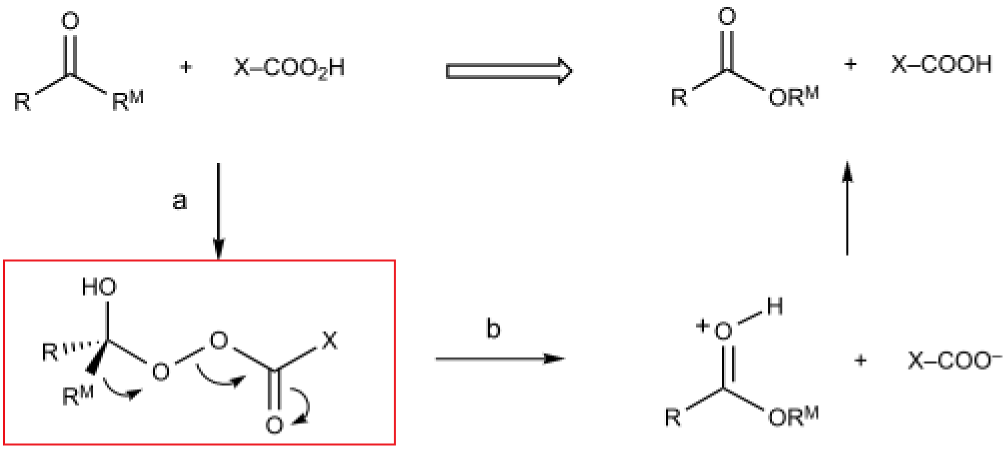


Figure 7.1: Baeyer-Villiger oxidation via formation of Criegee intermediate, taken from [3]

Unfortunately Baeyer-Villiger oxidation suffers from some drawbacks such as: the use of organic peracids which are expensive and hazardous and moreover which results in the formation of one equivalent of the corresponding carboxylic acid salt as waste. One possibility how to solve this problem is the use of the spent carboxylic acid to regenerate the peracid, but this process would increase the cost of the whole reaction. Thus a great attention has been devoted to finding greener oxidant agents, such as H_2O_2 and a lot of studies deal with the oxidation of cyclohexanone to caprolactone. The main advantages of the H_2O_2 oxidants would be:

- It simplifies greatly the workup to allow the use of simpler reaction conditions and avoid the separation of the carboxylic acid
- It has a higher active oxygen content (defined as the % active oxygen with respect to the molecular weight), which is economically advantageous as chemicals are sold by weight
- As a consequence, it produces a lower amount of by-product (water) and is the most environmentally friendly among peroxidic oxidants. [3]

However, there are also some disadvantages regarding using hydrogen peroxide as oxidizing agent with respect to organic peracids:

- Water is always present either as a co-solvent or in any case as a reaction product. Hydrolysis of the ester products may result, and incompatibility with the solvent/substrate system may hamper the substrate/oxidant interaction.

- It has a lower stability towards radical decomposition
- It is kinetically more inert and requires the use of a suitable catalyst [3].

Because my research deals with the oxidation of cyclohexanone with hydrogen peroxide as oxidizing agent, I will discuss only this reaction. The product of the Baeyer-Villiger oxidation of cyclohexanone is ε–caprolactone (from now on: caprolactone). Anyway according to our results, the product is the function of the reaction condition; this fact will be discussed in the chapter devoted to the results of Baeyer-Villiger oxidation.

7.2 Caprolactone

7.2.1 Production and use of caprolactone

Caprolactone is a colorless to yellow liquid with a perceptible odor. It is soluble in water [5].

Currently, the main industrial process for the production of caprolactone is the oxidation of cyclohexanone with m-chloroperbenzoic acid and peracetic acid. The unreacted cyclohexanone is separated by distillation and recycled to the oxidation stage. The Baeyer – Villiger oxidation of cyclohexanone with acetic acid is shown in the figure 7.2.

$$CH_3COOH + H_2O_2 \longrightarrow CH_3COOOH + H_2O$$

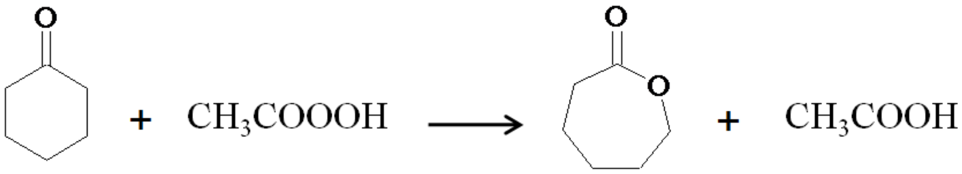


Figure 7.2: Baeyer-Villiger oxidation with acetic acid

In 2003, the estimated world-wide production of caprolactone was 40,000 – 60,000 tones. In recent years the world-wide production was growing slowly (<5 % per year) [4].

The main producers of caprolactone are BASF in the USA, Daicel in Japan and the largest Perstorp in the UK.

Caprolactone is mainly used as an intermediate for production of:

- Adhesives
- Modifier in resins and polymers
- Paints
- Polycaprolactone
- TPU (thermoplastic polyurethane) [5]

7.2.2 Studied alternatives for the production of caprolactone

As mentioned before, there is a great interest to replace the conventional oxidizing agent with another environmentally friendlier oxidizing agent; the possible solution would be using molecular oxygen or hydrogen peroxide. In past years several procedures for preparation of caprolactone from cyclohexanone using molecular oxygen and aldehyde catalyzed by transition metal salts or complexes had been patented, however, the selectivity of caprolactone described in most of these patents was not satisfactory (70–80% selectivity) and the conversions of cyclohexanone were generally low (3–30%) [11].

The studied systems for the oxidation of cyclohexanone with hydrogen peroxide can be divided in the four groups in the function of the used catalyst:

a) Brønsted-type acid catalysts [6,7], alumina [8] and polyoxometalates [9],

b) catalysts showing Lewis-type acid behavior, based on Sn (IV) (Sn-β, Sn-hydrotalcite, Sn-clay) [10-14,23], Sb(V) [15,16] or supported Pt complexes [17,3]

c) basic oxides [18,19]

d) catalysts based on elements capable of providing the formation of Me-OOH species, for example Ti (IV) incorporated in silicalite or β zeolite. [20, 21]

Some examples of studied heterogeneous systems for Baeyer-Villiger oxidation of cyclohexanone with hydrogen peroxide is given in the table 7.1.

Table 7.1: Some studied system for the Baeyer-Villiger oxidation of cyclohexanone

catalyst	**T (°C)**	**solvent**	**$C_6H_{10}O$/HP**	**X $C_6H_{10}O$ (%)**	**S $C_6H_{10}O_2$ (%)**	**other products**	
TS 1	80	/	1/1	31	20	Hydroxy ketone Diketone	[20]
SnBeta	90	dioxane	1/1.5	54	98	/	[21]
Al_2O_3	90	ethylacetate	1/4 (anhydrous HP)	53	98	6-hydroxohexanoic acid	[8]
H-BEA	45	1,2-DCE	1/1	78	21	6-hydroxohexanoic acid dicyclohexylidene peroxide	[7]
Sb-HT	85	acetonitrile	1/6	79	94	not reported	[16]
Sn-MCM41	56	MTBE	1/1.2	36	97	/	[18]
Mg/Al HT	70	benzonitrile	1/0.3, 1/2	100	100	/	[22,18]
Ti-β	56	MTBE	1/1.5	4	98	/	[23]
Sn(dendritic)/ cellulose	70	1,2-DCE	1/2	70	100	/	[24]

Because a great part of my research deals with titanium silicalite, next chapter will describe this kind of material and its use in catalysis.

References:

[1] J.J. ten Brink et al., Chem. Rev. 104 (2004) 4105

[2] A. Baeyer, V. Villiger, Ber. Dtsch. Chem. Ges. 32 (1899) 3625

[3] G.Strukul Angew. Chem. Int. Ed., 37 (1998) 1198

[4] http://www.chem.unep.ch/irptc/sids/OECDSIDS/502443.pdf

[5]http://worldaccount.basf.com/wa/NAFTA/Catalog/ChemicalsNAFTA/doc4/BASF/PRD/30062055/.pdf?title=&asset_type=pds/pdf&language=EN&urn=urn:documentum:eCommerce_sol_EU:09007bb280063b37.pdf

[6] J. Fischer, W. Hoelderich, Appl. Catal. A 180 (1999) 435

[7] M. Lenarda, M. Da Ros et al., Inorg. Chim. Acta 349 (2003) 195

[8] R.A. Steffen, S. Teixeira et al., J. Mol. Catal. A 287 (2008) 41

[9] L. Balbinot, U. Schuchardt et al., Catal. Commun. 9 (2008) 1878

[10] A. Corma, M.T. Navarro et al., Chem. Commun. (2001) 2190

[11] P. Zhang, M. Yang et al., Chem. Eng. Journal 121 (2006) 59

[12] U.R. Pillai, E. Sahle-Demessie, J. Mol. Catal. A 191 (2003) 93

[13] C. Jimenez-Sanchidrian, J.M. Hidalgo et al., Appl. Catal. A 312 (2006) 86

[14] C Li, J. Wang et al., Catal. Commun. 8 (2007) 1202

[15] A. Lambert, D.J. Macquarrie et al., New J. Chem. 24 (2000) 485

[16] C. Chen, J. Peng et al., Catal. Lett. 131 (2009) 618

[17] C. Palazzi, F. Pinna et al., J. Mol. Catal. A 151 (2000) 245

[18] R. Llamas, C. Jimenez-Sanchidrian et al., Tetrahedron 63 (2007) 1435

[19] R. Llamas, C. Jimenez-Sanchidrian et al., Appl. Catal. B 72 (2007) 18

[20] A. Bhaumik, P. Kumar et al., Catal. Lett. 40 (1996) 47

[21] A. Corma, L.T. Nemeth Nature 412 (2001) 423

[22] J.R. Ruiz, C. Jimenez-Sanchidrian et al., Tetrahedron 62 (2006) 11697

[23] M. Renz, T. Blasco et al., Chem. Eur. J. 8(2002) 4708

[24] C Li, J. Wang et al., Catal. Commun. 8 (2007) 1202

8. Titanium silicalite (TS-1)

Titanium silicalite-1 is a medium pore titanium substituted silicalite in a framework of MFI type. First synthesized in 1983 by the researchers from Enichem and since that great attention has been devoted to this material.

8.1 Structure and properties

TS-1 is a zeolites with MFI structure whose topology is formed by a two-channel system with diameters of 0,53x0,56 and 0,51x0,41 nm respectively [1]. TS-1 contains only Si and Ti in the tetrahedral structure, without any Al. Consequently, the framework of TS-1 has no charge, no Brønsted acidity. Its remarkable activity in oxidation with H_2O_2 is due to site isolation of Ti (IV) centers in the hydrophobic pores of silicalite which allows the simultaneous adsorption of the hydrophobic substrate and the oxidant [2]. According to the literature, there is a maximum of titanium atoms per cell unit which can be incorporated in the framework (it is 2,4 Ti atoms).

Following the synthesis of the original patent [3], the resulting TS-1 is typically a material with regular [$Ti(SiO)_4$] and sites showing some internal defects such as the lack of one or more adjacent T (Si or Ti) which is compensated by the presence of hydroxylated nanocavities, also referred as hydroxyl nests [4]. It is well known, that the presence of OH groups in TS-1 improves the framework interaction with guests molecules and increases the adsorption capacity.

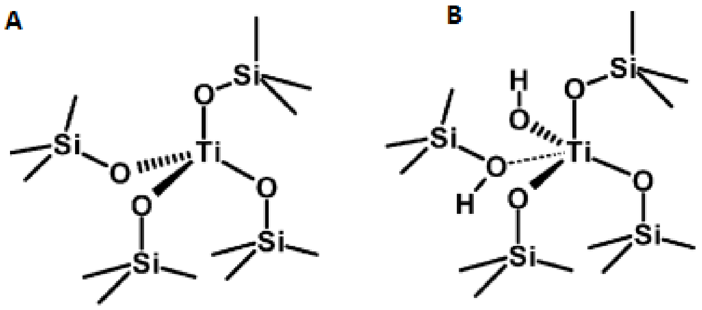


Figure 8.1: Structure of TS-1, A) regular “closed” [$Ti(SiO)_4$], B) defective “open” [$Ti(SiO)_3OH$], taken from [4]

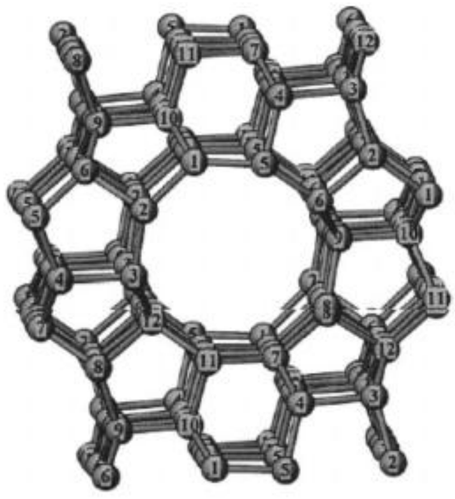


Figure 8.2: Independent T sites in MFI lattice, taken from [12]

In the titanium silicalite there are 12 crystallographically inequivalent silicon sites, which could be substituted by titanium, see figure 8.2. Although it has been almost 30 years since the discovery of TS-1, the distribution of titanium is still not known. Some researchers believe that the location of titanium is purely random [6,7], another groups of researchers are convinced that there are some preferentially occupied sites [8-10]. Anyway still there is no agreement upon which sites are the preferred ones.

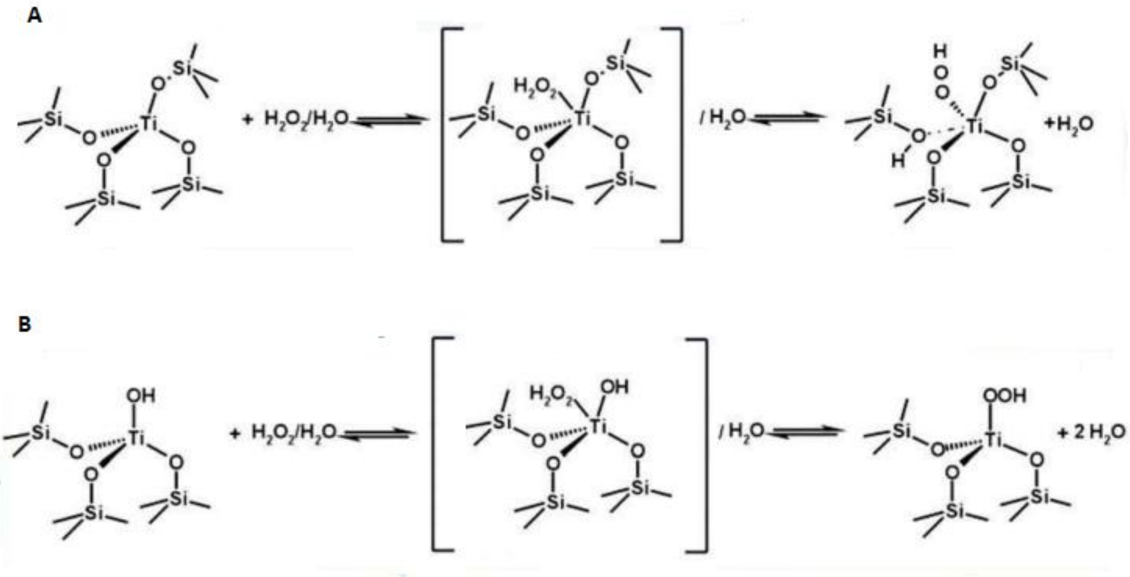


Figure 8.3: Scheme of equilibrium between TiO_4 framework species and corresponding hydroperoxo species in H_2O_2-H_2O solution. Formation of Ti-hydroperoxo species upon hydrolysis of a Ti-O-Si bridge (A) and upon reaction with a pre-existing defective Ti-OH species (B), taken from [4]

According to the literature the reaction of the aqueous solution of hydrogen peroxide with TS-1 could result in the formation of some species, which can have neutral (coordinated H_2O_2), peroxidic, superoxidic and hydroperoxidic character. The preferred hypothesis is that active species are Ti-hydroperoxide, which can be formed upon deprotonation of HP on Ti (IV) site itself, either on a perfect [Ti $(SiO)_4$], site by rupture of one out of the four Ti-O-Si bridges or on defective [(H-O)-Ti-$(O\text{-}Si)_{30}$] site by elimination of a water molecule [4].

8.2 Catalyzed reaction

TS-1 is very well studied catalytic system; by the year 1990 most of the catalytic reactions with TS-1 have been discovered. The figure 8.4 shows the most studied reactions with this catalyst, among them are epoxidation of olefins, hydroxylation of aromatics, oximation of ketones, oxidation of primary alcohols to aldehyde and subsequently to acids, secondary alcohol to ketones, alkanes to secondary alcohols and ketones.

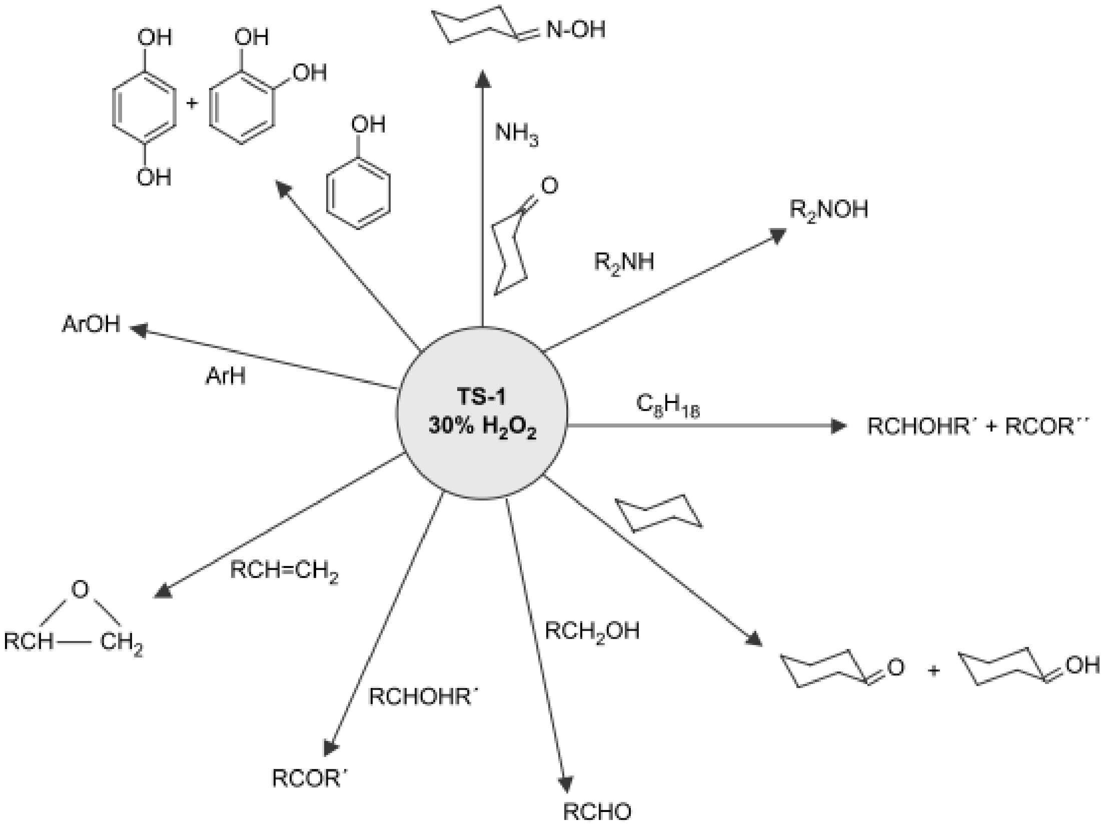


Figure 8.4: Oxidation reactions involving TS-1 as a catalyst, taken from [5]

8.3 TS-1 as a catalyst in industry

The big success of TS-1 is also given by the fact that there have been some processes already put in the industrial application. Among them are: hydroxylation of phenol with the capacity of 10 000 ton per year (in 1986), ammoximation of cyclohexanone to cyclohexanoxime, capacity of 12 000 tons per year, both processes developed by Enichem.

In the year 2003 Japanese corporation Sumitomo started the production of cyclohexanoxime with the capacity 60 000 tons per year [4] and recently, in 2008 BASF together with Dow Chemical started the production of propylene oxide with the capacity of 300 000 per year [1] environmentally friendlier alternative to traditional synthesis such as the chlorohydrin process and the propylene/styrene or propylene/tert-butyl alcohol routes.

References

[1] A. Corma, E. Garcia, Chemical Reviews 102 (2002) 3837

[2] R. A. Sheldon, M. Wallau, et al., Accounts of chemical research 31 (1998) 485

[3] M. Taramasso, G. Perego et al., US Patent 4410,501, (1983) (assigned to EniChem)

[4] S.Bordiga, F. Bonino et al., Phys. Chem. Chem. Phys. 9 (2007) 4854

[5] C. Jimenez-Sanchidrian, J.R. Ruiz, Tetrahedron 64 (2008) 2011

[6] G. Sankar, J.M. Thomas, Top. Catalysis 8 (1999) 1

[7] R. Millini, G. Prego et al., Stud. Surf. Sci. Catal 84 (1994) 2123

[8] C.A. Hijar, R.M. Jacubinas et al., J. Phys. Chem. B, 104 (2000) 12157

[9] C. Lamberti, S. Bordiga et al., J Am. Chem. Soc 123 (2001) 2204

[10] P.P. Henry. M.T. Weller et al., J. Phys. Chem. B 105 (2001) 7452

[11] P. Bassler, H.G. Gobbel et al., Chem. Ing. Transaction 21 (2010) 571

[12] P.Ratnasamy, D.Srinivas et al., Adv. Catalysis 48 (2004) 1

9. Experimental part

9.1 Synthesis of TS-1

TS-1 was synthesized following the procedure described in the literature [1] with small modifications, such as the TPAOH-to-TEOS ratio in the synthesis sol. In a typical procedure, tetraethylorthotitanate (TEOTi) was dissolved in tetraethylorthosilicate (TEOS); the clear yellow solution obtained was stirred for 15–20 min, then TPAOH (20% aqueous solution) was added. After further stirring, the resulting synthesis gel had the following composition: $1SiO_2{-}aTiO_2{-}bTPAOH{-}23H_2O$ (a = 0.0149, or 0.026 or 0.046; b = 1.63, or 2.5 or 3.0). In order to hydrolyze TEOS, the batch was kept in a water bath at 80 °C for 4 h. After the hydrolysis the mixture was topped up to its original volume with deionized water, transferred into a Teflon-lined, stainless-steel autoclave, and subsequently heated at 180 °C for 24 h under autogeneous pressure. After the cooling of the autoclave the white gelatinous solution formed was centrifuged at 10,000 rpm for 10 min. The supernatant liquid was discarded, deionized water was added, and the process was repeated 4–5 times until the pH of the supernatant solution was close to neutral. Samples were activated by thermal treatment at 550 °C in air.

9.2 Synthesis of silica bounded decatungstate

Silica bound decatungstate was prepared by university of Parma following the literature [2]. First step of the synthesis was the preparation of $Na_4W_{10}O_{32}$.

To synthesize $Na_4W_{10}O_{32}$ 260 ml of a boiling aqueous 1 M HCl solution was added to a boiling solution containing $Na_2WO_4 \cdot 2H_2O$ (44 g) in distilled water (250 ml). The resulting solution was allowed to boil for 40 s, after which it was transferred to a 2-l beaker and rapidly cooled to 0 °C in a liquid nitrogen/acetone bath under stirring. Solid NaCl was added to saturation while the temperature was maintained at 0 °C. A formed precipitate was collected on a fritted funnel; washed in a small amount of cold water, ethanol, and diethyl ether; and transferred to a 250-ml beaker. This precipitate was suspended in hot acetonitrile (130 ml); then the suspension was filtered, and the filtrate was placed in a freezer overnight. Large pale-lime crystals of sodium decatungstate were collected on a fritted funnel and dried (9.4 g). From the mother liquor, it was possible to obtain more crystals on concentration.

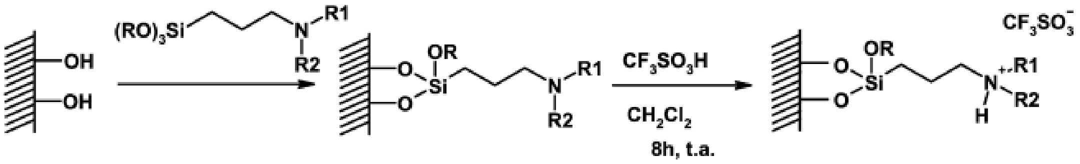
The preparation of silica bound decatungstate involved two main steps:

(a) silica functionalization anchoring ammonium salts to surface silanols and
(b) anion exchange with sodium decatungstate.

Silica was activated by refluxing in concentrated HCl for 4 h, followed by washing until neutral with distilled water and then drying. Anchoring tertiary ammonium salt was prepared by refluxing 5g of activated silica and 10 mmol of (alkylaminopropyl)triethoxysilane in 30 ml of toluene under stirring for 1 h. After distillation of a toluene fraction containing ethanol, the refluxing was continued. After 1 h, this second procedure was repeated and refluxing continued for 0.5 h. The cooled functionalized silica was filtered off; washed with toluene, diethyl ether, and dichloromethane (2 × 25 ml each); and then dried under high vacuum at 60 °C for 3 h to give the surface-bound alkylamine groups with a loading of 0.8–0.9 mmol/g. The resulting materials in dry dichloromethane (5 g in 25 ml) were reacted with trifluoromethane sulfonic acid (two equivalents with respect to the supported amino group) for 8 h at room temperature; filtered off; washed successively with dichloromethane, ethanol, and diethyl ether (2 × 25 ml each); and then dried under vacuum at 60 °C for 3h, affording the corresponding alkylammonium salts bound to the solid.

The process is schematically shown in the figure 9.1.

(A) heterogenisation of ammonium salts



(B) decatungstate anchoring

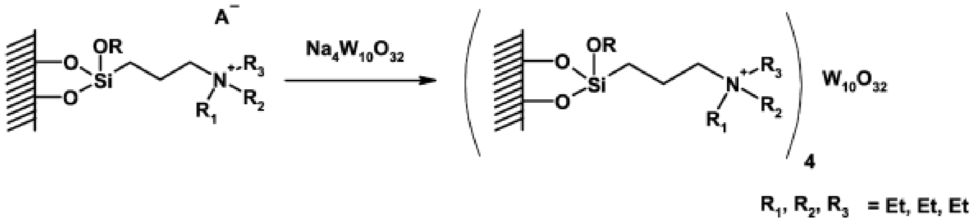


Figure 9.1: Synthesis of silica bounded decatungstate, taken from [2]

9.3 Catalytic measurement

Typical conditions for the thermal, uncatalyzed oxidation of cyclohexanone with HP were the following: in a 10 ml pyrex reactor with screw stopper, a mixture of 0,1 ml of H_2O, 3 mmol (0.304 ml) of 30% H_2O_2 and 1 mmol (0.103 ml) cylohexanone; were stirred at 90 °C for the required time. In the catalyzed reactions, the procedure was the same, but different amount of catalyst was added, in the case of TS-1 it was 0,077 g and in the case of silica bound decatungstate it was 0,0163 g.

9.4 Treatment of the reaction mixture

After the cooling of the reaction mixture to the room temperature, the catalyst was simply removed by Büchner filtration, washed with H_2O (5 ml) and then with CH_3CN (5 ml). The solution was then diluted with 10 mol of equivolumetric mixture of H_2O and CH_3CN. Hydrogen peroxide conversion was determined by iodometric titration.

9.5 Analysis of the products

Products concentration was determined by UPLC-MS analysis. UPLC analysis was performed using an Acquity Ultra Performance Waters UPLC System equipped with autosampler. UPLC separation was conducted on a Acquity UPLC BEH C18 Column (1.7µm, 2.1 x 100 mm) at a flow rate of 0.3 ml/min using an elution gradient: eluent A H_2O (0.2% HCOOH), eluent B (0,2% HCOOH); elution: 0-2 min isocratic 100% A, 2-10 min linear gradient to 65% A-35% B, 10-10.5 min linear gradient to 100% B, 10.5-13.5 min isocratic 100% B, 13.5-14 min linear gradient to 100% A, 14-19 min isocratic 100% A; flow rate 0.3 mL/min. Both the column and the autosampler were maintained at 25°C. MS conditions in positive ion mode: capillary voltage 3.0 kV, cone voltage 28.0 V, source temperature 100°C, desolvation temperature 200°C, cone gas flow (N_2) 100 L/h, desolvation gas flow (N_2) 600 l/h.

Reference

[1] M. Taramasso, G. Perego et al., US Patent 4410,501 (1983) (assigned to EniChem)

[2] F. Bigi, A. Corradini, et al., J. Catalysis 250 (2007) 222

10. Results and discussion

10.1 Uncatalyzed thermally activated Baeyer-Villiger oxidation of cyclohexanone

First we studied the uncatalyzed thermally activated Baeyer-Villiger oxidation of cyclohexanone, an aspect which is usually overlooked in the literature.

10.1.1 Effect of the presence of the solvent, effect of the temperature

Figures 10.1 and 10.2 show the results obtained performing the oxidation of cyclohexanone in the absence of the catalyst at 90 °C, with a molar ratio of H_2O_2/cyclohexanone of 3. The first figure shows the data from the oxidation in the absence of the solvent (water), the second figure reports the results from the reaction which was carried out in the presence of water. The conversion of cyclohexanone in both cases reached about 40 % in 6 hours.

The primary product was caprolactone (capro). Secondary products were 6-hydroxyhexanoic acid (6OH), AA, and lower diacids (glutaric + succinic); also small amount of 6-oxohexanoic acid (6oxo) formed. In both cases caprolactone underwent consecutive reaction forming adipic acid and 6-hydroxyhexanoic acid. Glutaric and succinic acid were very probably formed as the lasts one by consecutive transformation from 6-hydroxyhexanoic acid or AA. According to the data, the secondary products 6-hydroxyhexanoic acid and AA were not kinetically related; they were formed by direct transformation of the caprolactone, but 6-hydroxyhexanoic acid by hydrolysis and the AA by direct oxidation. Moreover, at these conditions the hydroxyacid was stable and was not extensively transformed to AA

The difference in these two studies was the different reaction rate of the transformation of the intermediate caprolactone. This transformation was more rapid in the presence of water and mainly led to formation of AA

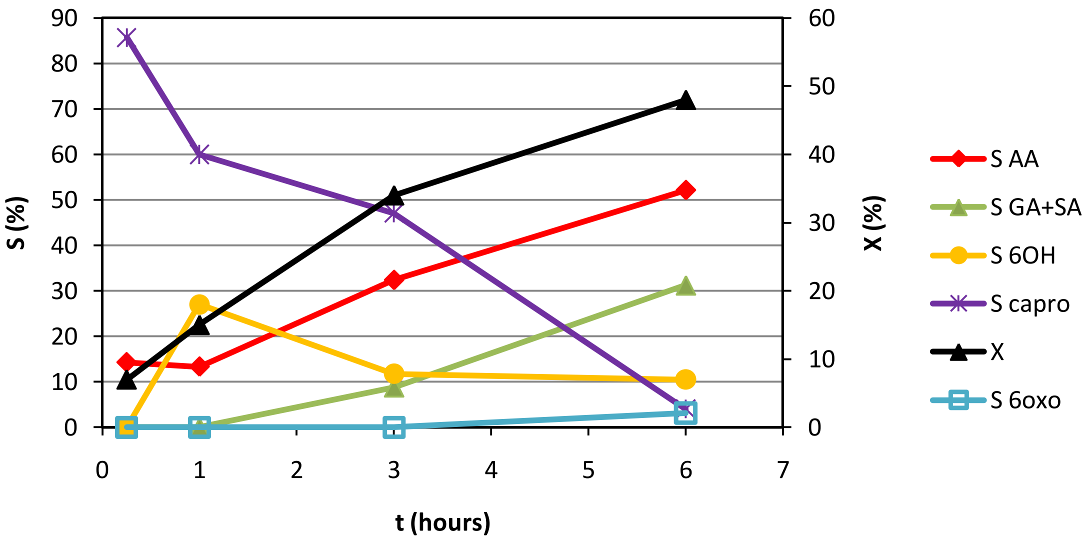


Figure 10.1: Uncatalyzed thermally activated oxidation of cyclohexanone with H_2O_2 in the absence of solvent, selectivities and conversion in function of time. Reaction conditions: T = 90 °C, 1 mmol cyclohexanone (0.103 ml), 3 mmol H_2O_2 (30% aqueous solution; overall volume 0.304 ml).

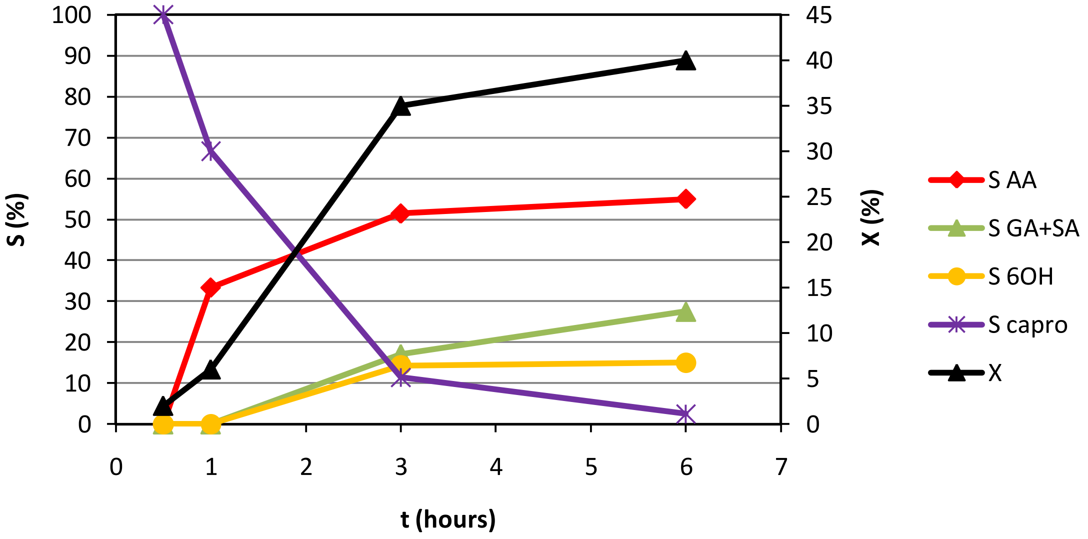


Figure 10.2: Uncatalyzed thermally activated oxidation of cyclohexanone with H_2O_2 in the presence of solvent, selectivities and conversion in function of time. Reaction conditions: T = 90 °C, 1 mmol cyclohexanone (0.103 ml), 3 mmol H_2O_2 (30% aqueous solution; overall volume 0.304 ml) solvent: water (0.100 ml).

Figure 10.3 reports the behavior of the hydrogen peroxide. It reports its decomposition during the time for the thermally activated oxidation of cyclohexanone and its decomposition in the absence of cyclohexanone. From the results it is evident that the consumption of H_2O_2 was slightly faster in the presence of cyclohexanone. This means, that the presence of ketone, does not influence significantly the decomposition of hydrogen peroxide. This would mean also, that in the absent of the catalyst, the formation of the lactone and consequently of adipic acid occurs by reaction with the radicalic species formed by hydrogen peroxide decomposition.

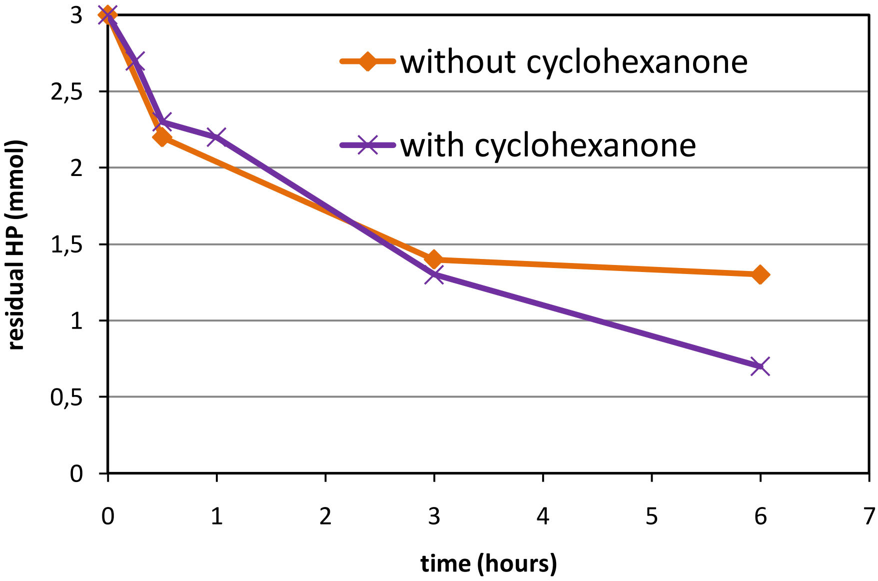


Figure 10.3: Hydrogen peroxide decomposition in the presence and in the absence of cyclohexanone. Reaction conditions: T = 90 °C, 1 mmol cyclohexanone (0.103 ml), 3 mmol H_2O_2 (30% aqueous solution; overall volume 0.304 ml) solvent: water (0.100 ml).

The oxidation of cyclohexanone in the absence of the catalyst was also studied at the lower temperature, at 50 °C; the time of the reaction was 6 hours. Also at this low temperature it was possible to obtain high selectivity to adipic acid (56%). Contrary to the results obtained at 90 °C, the selectivity to caprolactone was relatively high (44 %) and no 6-hydroxyhexanoic, 6-oxohexanoic and glutaric and succinic acid were detected. This means that at the low temperature the hydrolysis of caprolactone is kinetically unfavored.

Table 10.1: Uncatalyzed thermally activated oxidation of cyclohexanone, effect of the temperature. Reaction conditions: 6 hours of the reaction, 1 mmol cyclohexanone (0.103 ml), 3 mmol H_2O_2 (30% aqueous solution; overall volume 0.304 ml) solvent: water (0.100 ml).

T (°C)	X (%)	S capro (%)	S AA (%)	S 6-OH (%)	S 6-oxo (%)	S GA + SA (%)
50	9	44	56	0	0	0
90	40	3	55	15	0	27

10.1.2 Effect of the presence of radical scavenger

In order to confirm the hypothesis, that the transformation of cyclohexanone to caprolactone and then to acids occurs via radical mechanism with radicalic species formed from hydrogen peroxide, tests in the presence of radical scavenger were carried out. For this study two different radical scavengers were chosen: t-butanol and dioxane. T-butanol was chosen for the following reasons: i) it is soluble in water; (ii) it generates *t*-butylhydroperoxide by reaction with HP a hydroperoxide that is stable and does not react with cyclohexanone in the absence of TS-1 (see below experiments using TS-1 catalyst). With t-butanol the reaction was carried out with equimolar ratio of radical scavenger/cyclohexanone. The results are reported in the figure 10.4. The presence of radical scavenger caused the fall of the conversion: after 3 hours of the reaction the conversion of cyclohexanone was 18% versus 34% without *t*-butanol but also caused the change of the distribution of the products. Meanwhile the selectivity to adipic acid was the same as in the absence of radical scavenger, selectivity to caprolactone increased (23 % vs. 11%), selectivity to 6-hydroxyhexanoic acid decreased a little bit 9% vs. 14%.

T-butanol had a main effect on the rate of transformation of cyclohexanone into caprolactone (the only primary reaction, see figure 10.2), which was definitely lower than without *t*-butanol.

The second radical scavenger was dioxane, which should be also soluble in water. With this scavenger only one reaction was carried out – using equimolar ratio of dioxane/cyclohexanone and reaction time of three hours. The results are also shown in the same figure. Dioxane had a higher inhibiting effect on the reaction, the conversion of cyclohexanone dropped from 34% to 6%, reaction gave 71% selectivity to lactone and low selectivity (18%) to adipic acid.

These results confirm the hypothesis, that in our reaction conditions, hydrogen peroxide decomposes by forming radical species which are further involved in the non-catalyzed transformation of cyclohexanone into lactone and subsequently into adipic acid.

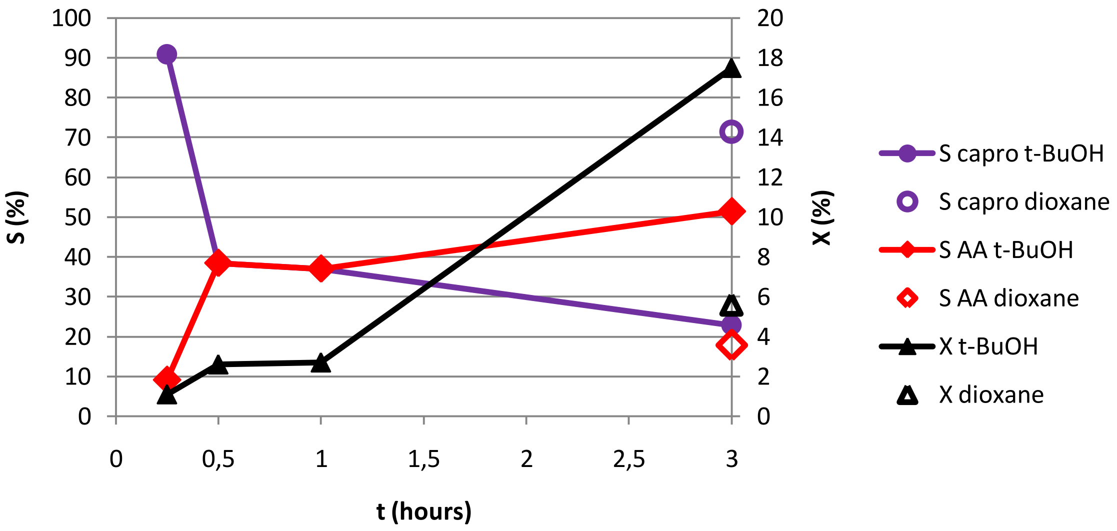


Figure 10.4: Uncatalyzed thermally activated oxidation of cyclohexanone with radical scavengers: t-butanol and dioxane, t-butanol/cyclohexanone = 1/1 (molar), dioxane/cyclohexanone = 1/1 (molar). Reaction conditions: T = 90°C, 1 mmol cyclohexanone (0.103 ml), 3 mmol HP (30% aqueous solution; overall volume 0.304 ml); solvent water (0.100 ml).

To rule out the possible role of molecular oxygen as a reactant for a radicalic autooxidation, the oxidation of cyclohexanone was carried out in nitrogen atmosphere. The reaction conditions were the same as in the case of oxidizing in the air atmosphere, 90 °C, 3/1 molar ratio of hydrogen peroxide and cyclohexanone, the reaction time was 6 hours, the reaction was carried out in the presence of water as a solvent. The results are shown in the table 10.2, as can be seen the presence of molecular oxygen does not contribute to the reaction by forming radical species.

Table 10.2

	X (%)	S AA (%)
Air	40	55
N_2	42	58

10.1.3 Effect of the cyclohexanone/hydrogen peroxide molar ratio

Because the stoichiometric for the formation of lactone is 1/1, it was decided to carry out the reaction using this ratio in the same reaction condition as in the precedent cases (90 °C, using water as a solvent). The results are shown in the figure 10.5.

Remarkably also in this condition high conversion of cyclohexanone (30%) was achieved. Meanwhile the selectivity to adipic acid dropped from 55% to 43% the selectivity to 6-hydroxyhexanoic acid was higher than that achieved with excess HP (37% vs. 15%), selectivities to lighter acids were also lower (13% vs. 28%). This means, that using high ratio of H_2O_2 and cyclohexanone, the consecutive degradation to light acids is kinetically more probable.

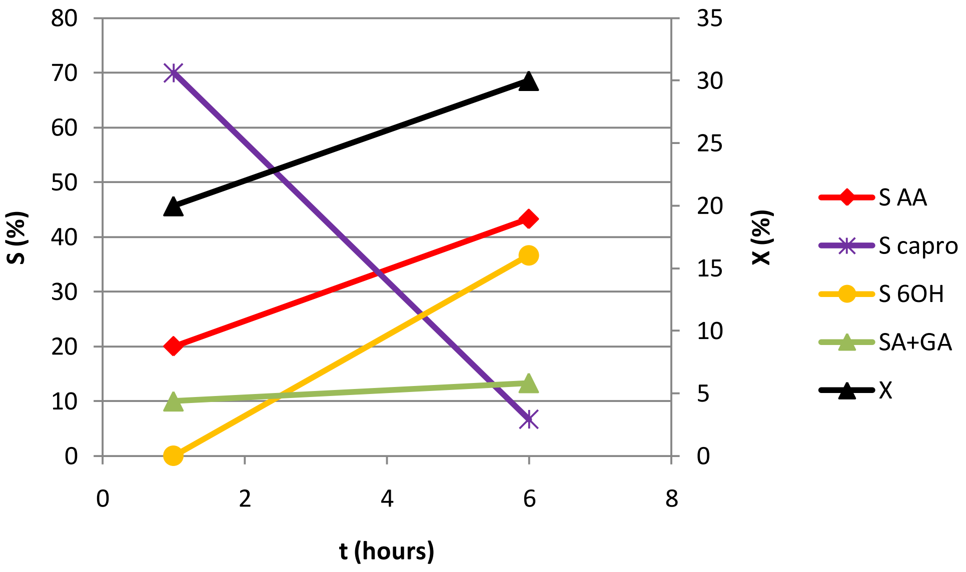


Figure 10.5: Uncatalyzed thermally activated oxidation of cyclohexanone. Reaction conditions: T = 90 °C, 1 mmol cyclohexanone (0.103 ml), 1 mmol HP (30% aqueous solution; overall volume 0,103 m1); solvent water (0.100 ml)

10.1.4 Reactivity of caprolactone and 6-hydroxyhexanoic acid

The results of the uncatalyzed thermally activated oxidation of cyclohexanone showed, that the intermediates of the reaction are 6-hydroxyhexanoic acid, caprolactone and 6-oxohexanoic acid. To see how these intermediates are reactive in the reaction media, reactions using caprolactone and 6-hydroxyhexanoic acid were carried out using the same reaction conditions.

The results are reported in the table 10.3.

Table 10.3: Uncatalyzed thermally activated oxidation of caprolactone and 6-hydroxyhexanoic acid

Reactant	(h)	X (%)	S AA (%)	S 6OH (%)	S 6oxo (%)	S GA + SA (%)
capro	3	78	28	44	-	28
capro	6	99	56	9	-	35
6OH	3	13	62	-	4	34

The results obtained by performing the oxidation of caprolactone confirmed the hypothesis, that caprolactone is very rapidly transformed to 6-hydroxyhexanoic acid, which is subsequently converted to AA, its conversion after 3 hours was 78 % and after 6 hours the conversion was almost complete (99%).

On the other hand, 6-hydroxyhexanoic acid was not as reactive as caprolactone, after three hours of the reaction, the conversion was only 13%, the main product was adipic acid with the selectivity of 62%.

These were the results from the uncatalyzed thermally activated oxidation of cyclohexanone with hydrogen peroxide, which showed that in the absence of the catalyst cyclohexanone is very easily transformed to caprolactone, which further undergoes the different paths. It can be oxidized to give adipic acid or it can undergo hydrolysis to form 6-hydroxyhexanoic acid. Moreover, it was found out, that these reactions occur via radicalic reaction with radical species which are formed by decomposition of hydrogen peroxide:

$H_2O_2 \rightarrow 2\ HO\bullet$

$HO\bullet + H_2O_2 \rightarrow H_2O + HO_2\bullet$

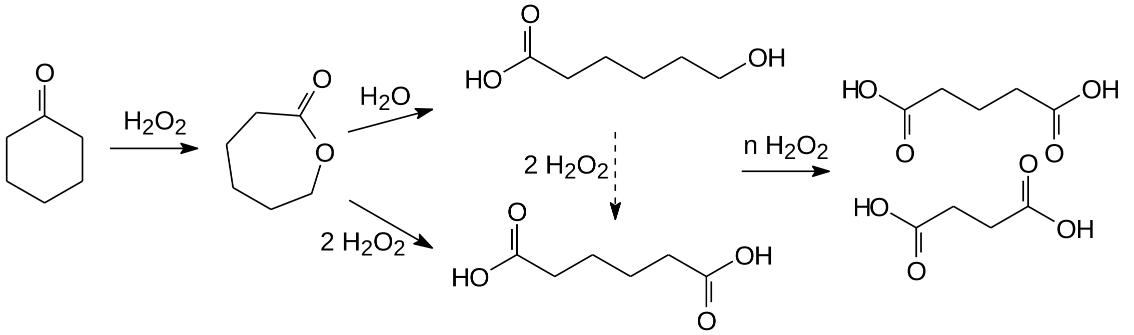


Figure 10.6: Reaction scheme of uncatalyzed thermally activated oxidation of cyclohexanone

Generally accepted mechanism of the transformation of caprolactone from cyclohexanone is via Criegee intermediate, our results suggested that Criegee intermediate may be also formed via radicalic reaction as is shown in the figure 10.7.

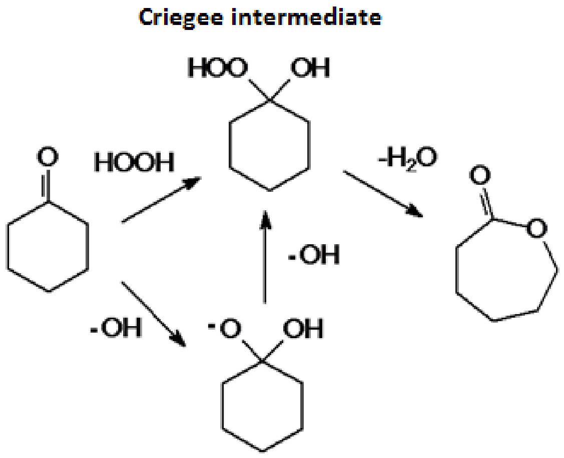


Figure 10.7: Two possible pathways of formation caprolactone: via Criegee intermediate by electrophilic addition to the carbonyl and via radicalic mechanism, also involving Criegee intermediate.

Further studies have been made with two different catalysts: TS-1 and silica-grafted decatungstate. First, results obtained with TS-1 will be discussed.

10.2 Catalyzed oxidation of cyclohexanone with TS-1 catalyst

Oxidation of cyclohexanone with TS-1 was studied in the same reaction conditions as in the uncatalyzed thermally activated oxidation, temperature 90 °C, molar ratio of H_2O_2/cyclohexanone 3/1, the amount of the catalyst was 0,077 gram which corresponded to 0,032 mmol of titanium.

10.2.1 Effect of the reaction time, temperature, study of the decomposition of HP

The effect of the reaction time on the catalytic activity is shown in the figure 10.8.

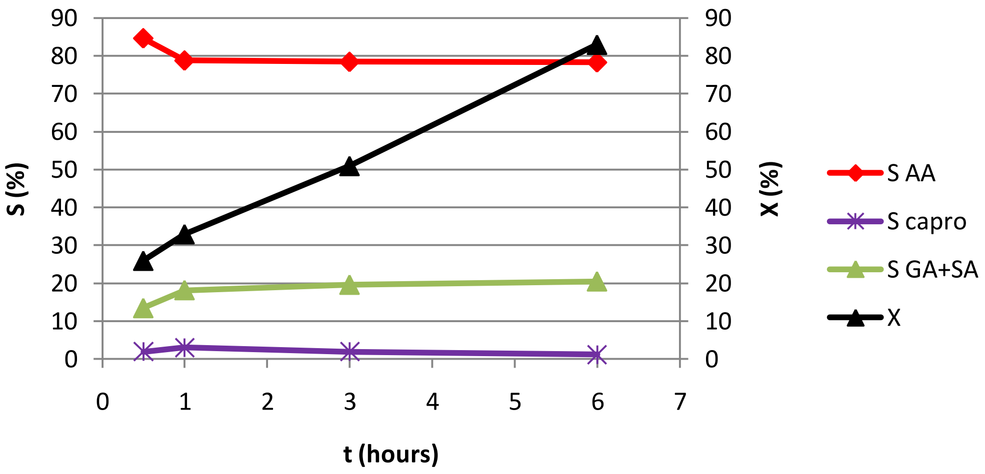


Figure 10.8: Oxidation of cyclohexanone with TS-1 catalyst. Reaction conditions: T = 90 °C, 1 mmol cyclohexanone (0.103 ml), 3 mmol HP (30% aqueous solution; overall volume 0,304 ml); solvent water (0.100 ml), m(catalyst) = 0,077 g

Comparing the results from the catalyzed and non catalyzed (figure 10.2) oxidation of cyclohexanone, it is evident that conversion is greatly enhanced in the presence of the catalyst. After 6 hours 83 % of cyclohexanone was converted (vs. 40 % in the absence of the catalyst). The distribution of the products changes a lot, there is no 6-hydroxyhexanoic and 6-oxohexanoic acid, and moreover, the main product is adipic acid with the selectivity about 80 % with very low selectivity to caprolactone. Lower acids, glutaric and succinic were also formed in non negligible amount. These results indicate, that once formed caprolactone, it is very efficiently transformed to adipic acid inside the hydrophilic pores of TS-1 before it may diffuse in the bulk liquid phase.

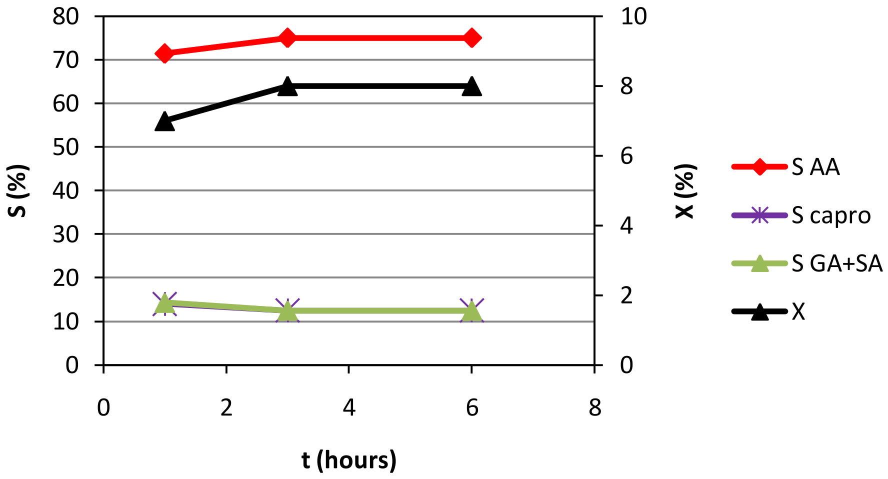


Figure 10.9: Oxidation of cyclohexanone with TS-1 catalyst. Reaction conditions: T = 50 °C, 1 mmol cyclohexanone (0.103 ml), 3 mmol HP (30% aqueous solution; overall volume 0,304 ml); solvent water (0.100 ml), m(catalyst) = 0,077 g

Performing the oxidation of cyclohexanone at 50 °C, the conversion drastically drops, after 6 hours being only 8 %, the distribution of the products is very similar to the reaction at 90 °C (see figure 10.9). The selectivity to adipic acid is little bit lower, it is about 70%, the selectivities to caprolactone and light acids are equal, about 13%.

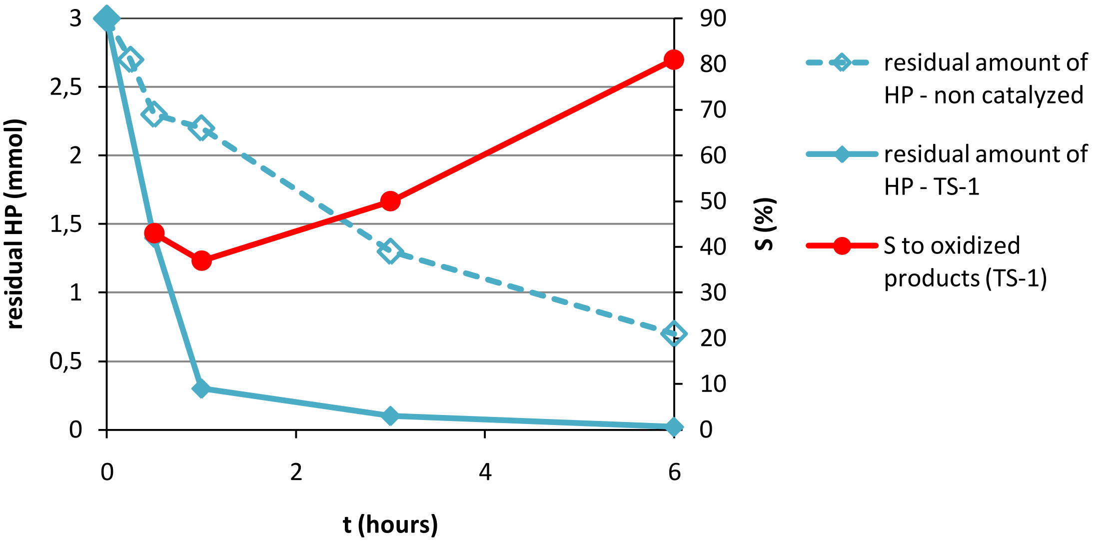


Figure 10.10: Decomposition of HP and selectivities to oxidized products in the function of the reaction time. Reaction conditions: T = 90 °C, 1 mmol cyclohexanone (0.103 ml), 3 mmol HP (30% aqueous solution; overall volume 0.304 ml); solvent water (0.100 ml), m(catalyst) = 0.077 g

Figure 10.10 shows the decomposition of hydrogen peroxide in the function of the reaction time compared to the decomposition of hydrogen peroxide in non catalyzed reaction and also selectivities to diacids with respect to converted hydrogen.

The presence of the catalyst greatly enhances the consumption of hydrogen peroxide, already after half an hour there was less than 0.5 mmol HP rest in the reaction mixture. Surprisingly, although the residual amount of hydrogen peroxide in the reaction mixture was very low and decreasing with the time, the conversion of cyclohexanone and selectivities to diacids were slowly increasing. The explanation for this phenomenon would be the hypothesis that the rate determining step of the process is not the generation of the TiOOH species but its subsequent reaction with cyclohexanone. Considering the limited number of Ti sites, the molar ratio Ti^{IV}/cyclohexanone was equal to 0.032; these Ti sites could act as a reservoir of hydroxy radicals for the oxidant species:

$$H_2O_2 + \text{-O-Ti}^{IV} \rightarrow \text{(HO)-Ti-OOH} \leftrightarrows \text{(HO)-Ti-O}\bullet + \bullet OH$$

$$\text{(HO)-Ti-O}\bullet + H_2O_2 \rightarrow \text{(HO)-Ti-OH} + HO_2\bullet$$

(HO)-Ti-O• + $C_6H_{10}O \rightarrow$ (HO)-Ti-OH + •C_6H_9O

$C_6H_{10}O$ + •OH $\rightarrow$ •C_6H_9O + H_2O

(HO)-Ti-OH + $H_2O_2 \rightarrow$ (HO)-Ti-OOH + H_2O

Thus, because of the high reactivity of caprolactone with respect to cyclohexanone and high concentration of radicals •OH and HO_2•, once formed rapidly caprolactone it is transformed into adipic acid and lighter acids inside the pores.

10.2.2 Effect of the presence of radical scavenger

To confirm that radical species were involved in the catalytic oxidation of cyclohexanone, the reaction was carried out in the presence of t-butanol using the equimolar ratio of cyclohexanone and t-butanol.

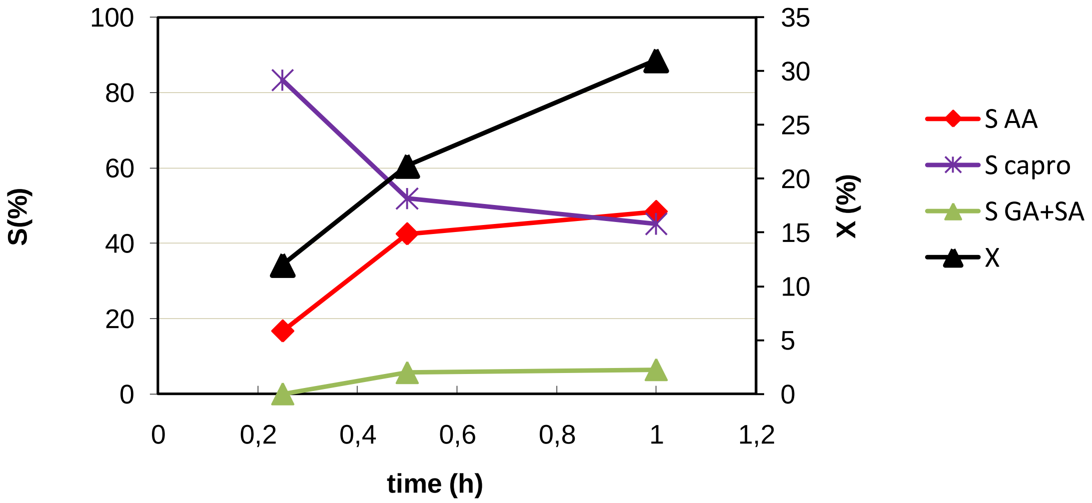


Figure 10.11: Oxidation of cyclohexanone in the presence of radical scavenger (t-BuOH). Reaction conditions: cyclohexanone/*t*-butanol 1/1 molar ratio), T = 90 °C, 1 mmol cyclohexanone (0.103 ml), 1 mmol HP (30% aqueous solution; overall volume 0.304 ml); solvent water (0.100 ml), m(catalyst) = 0.077 g

Figure 10.11 shows that conversion of cyclohexanone is not almost influenced by the presence of radical scavenger (31% vs. 33% in the absence of radical scavenger). However there is a difference in the distribution of the products. The selectivity to caprolactone is clearly higher than in was in the absence of the radical scavenger. That means that the consecutive transformation of caprolactone to adipic acid is inhibited by the presence of t-butanol. Table 10.4 reports the results obtained after 6 hours of the reaction using higher amount of t-butanol (6/1 molar ratio of t-butanol/cyclohexanone). Using high amount of the radical scavenger, the conversion of cyclohexanone is greatly influenced being only 8%. Selectivity to caprolactone is still relatively high compared to the selectivity obtained in the absence of the radical scavenger. These data suggest that radical scavenger has a major effect on the rate of oxidation of the lactone into adipic acid thanks to its high reactivity compared to cyclohexanone. Using high amount of radical scavenger its inhibitory effect also extends to less reactive cyclohexanone.

Table 10.4: Effect of the radical scavenger on the oxidation of cyclohexanone. Reaction conditions: cyclohexanone/*t*-butanol 1/6 (molar), T = 90 °C,6 hours of the reaction, 1 mmol cyclohexanone (0.103 ml), 1 mmol HP (30% aqueous solution; overall volume 0.304 ml); solvent water (0.100 ml), m(catalyst) = 0.077 g

	t (hours)	**X (%)**	**S AA (%)**	**S capro (%)**	**S GA+SA (%)**
Without t-BuOH	6	83	78	1	20
With t-BuOH	6	8	42	34	23

Also in this catalyzed oxidation of cyclohexanone study, we carried out the reaction in the N_2 atmosphere in order to rule out the possibility of involvement of molecular oxygen as radicalic initiator. The results are reported in the table 10.5. The reaction confirmed that O_2 atmosphere does not have any additional effect on the behavior of the reaction.

Table 10.5: Effect of the nitrogen on the reaction

	t (h)	**X (%)**	**S AA (%)**
Air	3	51	78
N_2	3	51	82

Catalytic oxidation of caprolactone was studied in two different reaction times, 30 min and 1 hour (see table 10.6). This test confirmed the high reactivity of caprolactone, the conversion after 1 hour of the reaction was 84%, with high selectivity to adipic acid (87%). When the reaction was carried out in the presence of radical scavenger, using equimolar ratio of radical scavenger/caprolactone, after 1 hour of the reaction, the conversion of caprolactone was only 22%. The selectivity to adipic acid was 59% and to 6-hydroxyhexanoic acid was 27%. This results means that radical scavenger inhibited the further transformation of caprolactone to adipic acid; on the other hand the hydrolysis of caprolactone to 6-hydroxyhexanoic acid was not affected by the presence of t-butanol. The same table also reports the data obtained by oxidation of 6-hydroxyhexanoic acid, the reaction time was 6 hours. This experiment confirmed the low reactivity of this acid, after 6 hours the conversion of the acid was only 17%, the major product was adipic acid with the selectivity of 83%.

Table 10.6: Oxidation of caprolactone and 6-hydroxyhexanoic acid in different reaction conditions.

	t (h)	X (%)	S AA (%)	S oxo (%)	S OH (%)	S GA+SA (%)
capro	0,5	40	93	2	3	2
capro	1	84	87	2	7	4
capro + t-BuOH	1	22	59	0	27	14
6OH	6	17	83	5	/	12

10.2.3 Effect of controlled dosage of HP

All the described experiments were carried out loading the substrate, water, catalyst and hydrogen peroxide once together. To see what effect would have the controlled input of hydrogen peroxide, experiment was performed loading in the reactor cyclohexanone, water, catalyst together, whereas hydrogen peroxide has been added to the reaction mixture continuously during first three hours of the reaction. The overall time of the reaction was 6 hour, the comparison between controlled additions of HP and "at once" addition of HP is reported in the table 10.7. Conversion of cyclohexanone drastically dropped from 83 to 38%, the distribution of the product did not change. The explanation for the low conversion of cyclohexanone would be that controlled addition of hydrogen peroxide caused low concentration of OH, OOH radicals during the first three hours and thus cyclohexanone did not have sufficient radicalic species to react with.

Table 10.7: Effect of the addition of HP into reaction mixture on the catalytic activity. Reaction conditions: 90 °C, 1 mmol cyclohexanone (0.103 ml), 1 mmol HP (30% aqueous solution; overall volume 0.304 ml); solvent water (0.100 ml), m(catalyst) = 0.077 g

	X (%)	S AA (%)	S capro (%)	S GA+SA (%)
HP from the beginning of the reaction	83	78	1	20
HP added during first 3 hours	38	79	3	18

10.2.4 Quantification of isolated yield and deactivation of the catalyst

In order to quantify isolated yield, the reaction was carried out using higher amount of the starting compound, all the reagents and the catalyst weights were loaded in the reactor 50 times higher with respect to the experiments described herein. Thus 5 ml of cyclohexanone, 5 ml H_2O was loaded in the reactor; the amount of the catalyst was 3.83 g. The reaction was carried out for 3 and 6 hours. Hydrogen peroxide could not be loaded in the reactor already from the beginning of the reaction, because its decomposition would lead to high concentration of O_2 and to rapid increase of the pressure. For this reason hydrogen peroxide was added continuously during the first hour of the reaction, the volume of the hydrogen peroxide was 15.2 ml H_2O_2 (35%), which corresponded to molar ratio of HP/cyclohexanone 3/1. The results are shown in the figure 10.12.

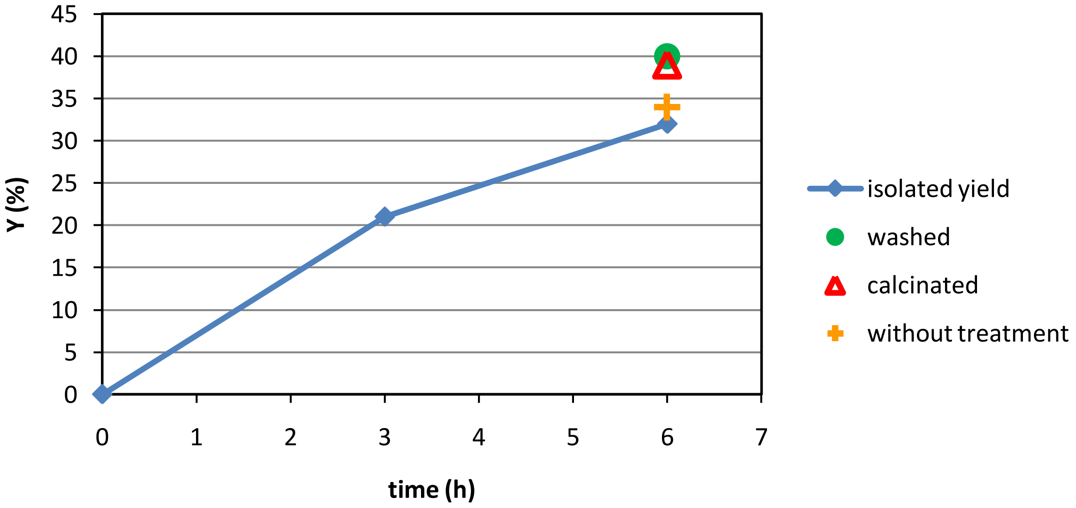


Figure 10.12: Oxidation of cyclohexanone with TS-1 catalyst. Reaction conditions: T = 90 °C, 50 mmol cyclohexanone (5 ml), 150 mmol HP (30% aqueous solution; overall volume 15,2 ml); solvent water (5ml), m(catalyst) = 3.83 g

To see if the catalyst underwent any deactivation during the reaction, after the experiments the catalyst was recovered and again loaded in the reactor. Before the loading two different treatments were performed i) the catalyst was washed with distilled water and acetone and ii) the spent catalyst was calcinated for 3 hours at 450 °C. Moreover one experiment was carried out with the spent catalyst but without any treatment. As the figure 10.12 clearly shows, the catalyst did not lost any of its activity and surprisingly the recovering of the catalyst by washing or by thermal treatment slightly increased the activity.

10.3 Catalytic oxidation of cyclohexanone with silica-grafted decatungstate

This part of the results will also begin with the comparison between catalyzed and non catalyzed thermally activated cyclohexanone. The results from non catalyzed reaction were already shown in the figure 10.2. Figure 10.13 reports the result obtained from oxidation of cyclohexanone catalyzed by silica-grafted decatungstate.

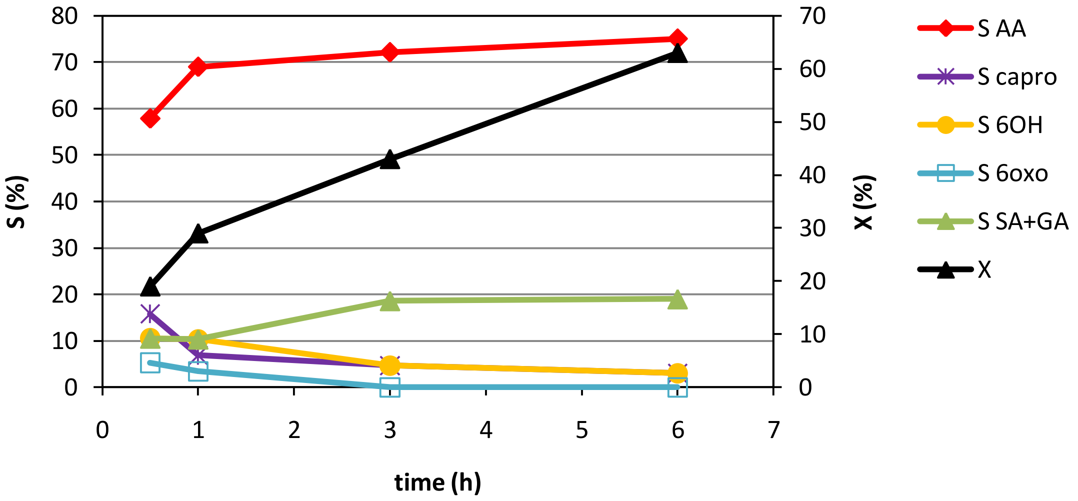


Figure 10.13: Oxidation of cyclohexanone with silica-grafted decatuntgstate. Reaction conditions: T = 90 °C, 1 mmol cyclohexanone (0.103 ml), 3 mmol hydrogen peroxide (30% aqueous solution; overall volume 0.304 ml), solvent water (0.100 ml), m (catalyst) = 0.0163 g

Presence of the catalyst greatly enhanced the activity compared to non catalyzed reaction (compare the figures 10.2 and 10.13). Anyway the activity was not as high as in the case of TS-1. After six hours of the reaction the conversion of cyclohexanone was about 60%. Very similarly to the case of TS-1, the selectivity to AA was much higher than the selectivity to caprolactone. The fact that the selectivity to AA compared to selectivity to caprolactone was so high could be explained by the hypothesis that caprolactone was very easily converted to AA via 6-oxohexanoic acid, or possibly by intermediate 6-hydroxyhexanoic acid (which was formed by hydrolysis of lactone) into 6-oxohexanoic acid first and then to AA. But the more probable one will be the first hypothesis due to the very low reactivity of 6-hydroxyhexanoic acid as shown in the precedent part.

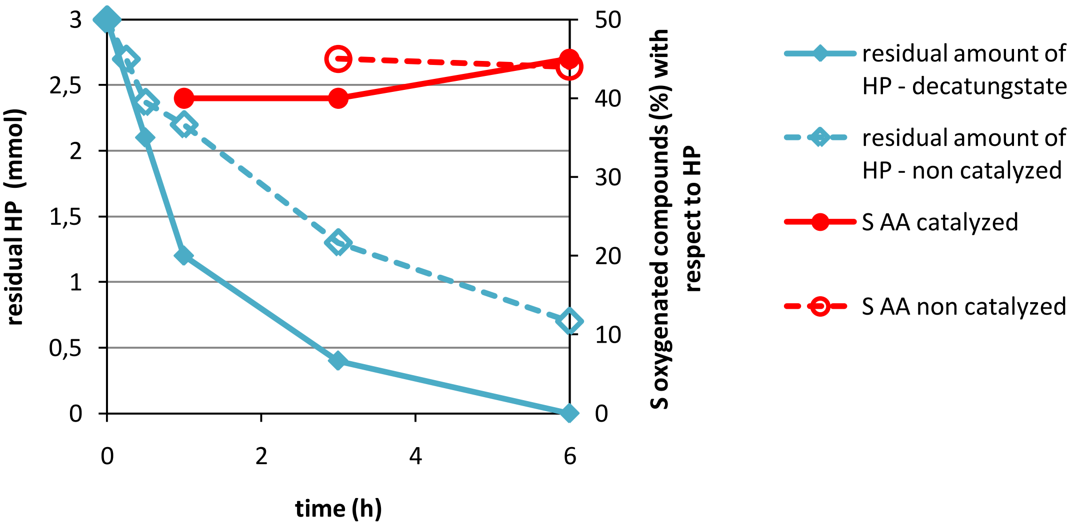


Figure 10.14: Decomposition of HP in the absence and in the presence of the silica grafted decatungstate

Figure 10.14 shows the conversion of hydrogen peroxide, in the absence of the catalyst (already showed above viz. figure 10.10) and in the presence of catalyst. The conversion of hydrogen peroxide is higher in the case of catalyzed reaction. This means that W activates hydrogen peroxide and the formed active species contributes to cyclohexanone conversion. The selectivities to oxygenated products are very similar in the case of non-catalyzed and catalyzed reaction indicating that the nature of generated active species is the same in these two cases.

Thus it seems that after the formation of W-OOH species, these species are further decomposed to WO• + •OH; the hydroxyl radical then reacts as described in the non-catalyzed reaction.

Figure 10.15 reports the results obtained in the difference reaction condition after 1 hour of the reaction at

i) 90 °C and HP/cyclohexanone = 3

ii) 50 °C and HP/cyclohexanone = 3

iii) 90 °C and HP/cyclohexanone = 1

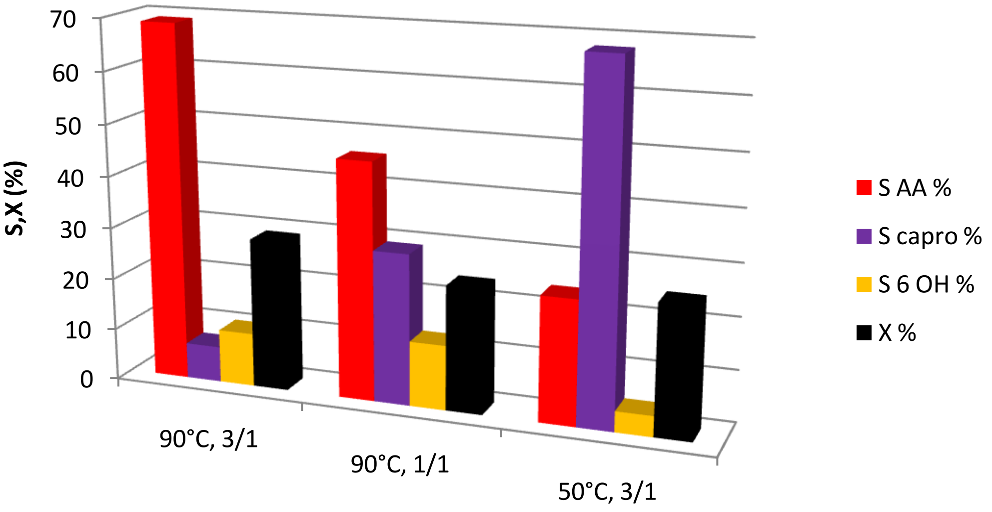


Figure 10.15: Catalyzed oxidation of cyclohexanone with silica grafted decatungstate, effect of the reaction temperature and molar ratio of HP and cyclohexanone

Decreasing the amount of hydrogen peroxide or the reaction temperature causes the fall of the selectivity to adipic acid, the fall of selectivity is more pronounced in the case of lower reaction temperature. Because the conversion of cyclohexanone is not much affected by these changes in the reaction condition (the difference is 5%) the changes of the selectivity cannot be attributed to the changes in the conversion, rather it would be caused by lower rate for consecutive transformation of the lactone into AA (as compared to the primary reaction of lactone formation), consequence of an higher activation energy for the secondary reaction, and of a lower concentration of the oxidant.

The conversion of cyclohexanone was almost proportional to the amount of the catalyst, as is shown in the figure 10.16. This figure reports the results obtained after 1 hour of the reaction loading different amount of the catalyst. Increasing amount of the catalyst caused the enhancement of the conversion and selectivity to AA, and fall of selectivity to caprolactone.

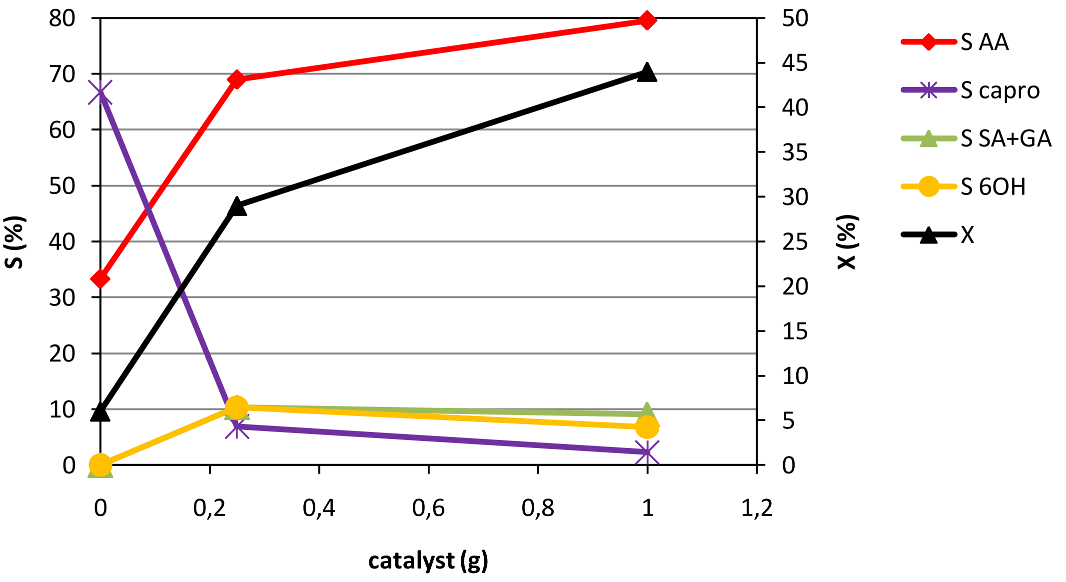


Figure 10.16: Catalyzed oxidation of cyclohexanone with silica grafted decatungstate, effect of the amount of the catalyst. Reaction conditions: T = 90 °C, 1 mmol cyclohexanone (0.103 ml), 3 mmol hydrogen peroxide (30% aqueous solution; overall volume 0.304 ml), solvent water (0.100 ml)

Also in this case, deactivation of the catalyst during the reaction has been studied. For this purpose the same procedure as mentioned in the case of TS-1 was used. But in this case, no treatment of the recovered catalyst was done. The table 10.8 clearly shows that the samples are during the reaction drastically deactivated. The distribution of the product is not affected by this deactivation.

Table 10.8: Study of the deactivation of the catalyst

	X (%)	S AA (%)	S capro (%)	S GA+SA (%)	S 6OH (%)
fresh catalyst	63	75	3	19	3
reloaded catalyst 1st time	37	76	3	13	8
reloaded catalyst 2nd time	33	82	3	9	6

10.3.1 The reactivity of ε-caprolactone

Silica-grafted decatungstate was also employed in the oxidation of caprolactone in order to reveal the reaction scheme. The results are reported in the figure 10.17.

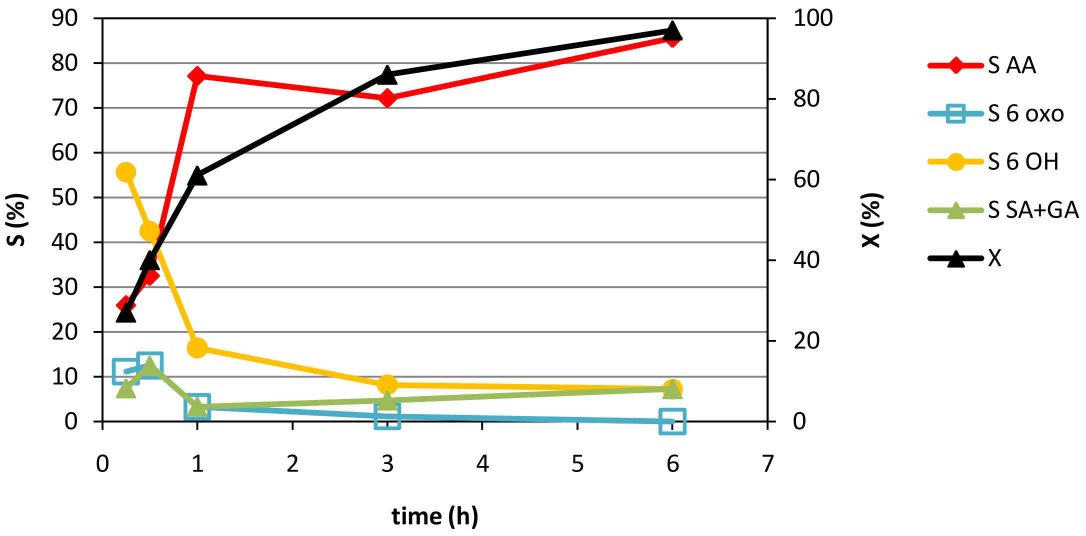


Figure 10.17: Oxidation of caprolactone catalyzed by silica grafted decatungstate. Reaction conditions: 1 mmol caprolactone (0.110 ml), T = 90 °C, 3 mmol hydrogen peroxide (30% aqueous solution; overall volume 0.304 ml), solvent water (0.100 ml)

The primary product was 6-hydroxyhexanoic acid, 6-oxohexanoic acid was formed in minor quantity. This acid is likely to be formed by direct transformation of caprolactone and by consecutive reaction via 6-hydroxyhexanoic acid. As already stated in the chapter devoted to the oxidation with TS-1, 6-hydroxyhexanoic acid is formed by hydrolysis of the lactone, whereas a direct transformation of the lactone into 6-oxohexanoic acid involves radicalic attack / ring opening by the •OH species. According to the results, both acids undergo subsequent transformation to AA and lighter diacids.

10.3.2 The reactivity of 6-hydroxyhexanoic acid

The final tests were carried out using 6-hydroxyhexanoic acid as a starting material. The results reported in the table 10.9 confirm the results already obtained in the uncatalyzed reaction and catalyzed reaction with TS-1, that this acid is less reactive than both cyclohexanone and caprolactone. After six hours of the reaction only 31 % of acid was converted mainly to AA, in the case of uncatalyzed reaction acid was converted to AA but also in high quantities to lighter acids (34 % after 6 hours of the reaction)

These results indicates that i) the catalyst accelerates the transformation of 6-hydroxyhexanoic into 6-oxohexanoic acid and then into AA, and (ii) the formation of GA and SA likely occurs thermally, starting either from the hydroxyacid or from the oxoacid

Table 10.9: Oxidation of 6-hydroxyhexanoic acid

	X (%)	S AA (%)	S GA+SA (%)	S 6oxo (%)
6OH 3 hours	18	88	5	7
6OH 6 hours	31	90	7	3

In the conclusion it can be said that the study of the uncatalyzed thermally activated oxidation of cyclohexanone and catalyzed oxidation of cyclohexanone showed that it is possible perform uncatalyzed oxidation of cyclohexanone and obtain non negligible amount of the product (caprolactone). In the case of catalyzed reaction it is possible, by changing the reaction conditions, to selectively convert cyclohexanone to caprolactone or to adipic acid. This study was so far the first one to explain the influence of the reaction conditions (namely the solvent) on the distribution of the products.

- THIRD PART -

Two step synthesis of adipic acid, starting from cyclohexene via 1,2-cyclohexanediol

11. Two step synthesis of adipic acid

The third part of my thesis is devoted to the two step synthesis of adipic acid starting from cyclohexene via 1,2 - cyclohexanediol. This research was done together with Radici Chimica, Spa and resulted in the patent [1].

11.1 General overview

As was already discussed in the chapter Alternative ways for synthesis of AA, two step synthesis of AA is one of the possibilities for the production of AA. Two step synthesis is done via 1,2 – cyclohexanediol.

Typically, the hydroxylation of olefins is carried out in the presence of following oxidants: $KMnO_4$, OsO_4, tert-butyl hydroperoxide or acids such as m –chlorobenzoic acid or peracetic acid. Because of the poor efficiency of these oxidants, it would be convenient to perform the oxidation with other oxidant, such as hydrogen peroxide. Hydrogen peroxide is an ideal solvent, because of its atom efficiency and the fact that water is the only by-product.

The scope of our study was to find such a reaction condition, where it would be possible to selectively oxidize cyclohexene to 1,2-cyclohexanediol and subsequently continue with another catalytic system to selectively obtain adipic acid. In our research we used two different oxidants and two different catalysts. For the first step of the synthesis of adipic acid, we used hydrogen peroxide together with H_2WO_4 as the catalyst. For the second step, molecular oxygen was the oxidizing agent and ruthenium supported on alumina was used as a catalyst.

11.1.2 First Step: oxidation of cyclohexene

Cyclohexene can be selectively oxidized to 1,2 – cyclohexanediol either with hydrogen peroxide or tert-butyl hydroperoxide. The small overview of the studied system is given in the table 11.1. As can be seen from the table it is quite difficult to obtain high conversion of olefin with high selectivity to alcohol.

Table 11.1: Studied system for the oxidation of cyclohexene (c.ene) to 1,2 cyclohexanediol (1,2-c.diol)

	oxidant	**ox/c.ene (molar)**	**T (°C)**	**X (%) c.ene**	**S (%) 1,2-c-diol**	**other products**	
$WO(O_2)_2$ 2QOH	H_2O_2	5,4	90	/	84 [a]	not reported	[2]
OsO_4 + NNMO*	H_2O_2	1,5	n.r.	/	91 [a]	not reported	[3]
resin supported sulfonic acid	H_2O_2	2	0	/	98 [a]	not reported	[4]
ZrO_2-SiO_2	H_2O_2	2	70	35	95	not reported	[5]
Ti-MCM-48	H_2O_2	0,2	50	38,5	59,4	cyclohexene oxide cyclohexanol cyclohexanone	[6]
Ti-MMM-2	H_2O_2	1,2	80	100	50	adipic acid cyclohexanone 1-ol	[7]
Cr-MCM-41	TBHP	2	120	51	8,2	2-cyclohexene-one cyclohexene oxide	[8]

*** NNMO = N-methylmorpholine N-oxide, used for reoxidation of reduced Os (VI), [a] – yield of 1,2 cyclohexanediol**

11.1.3 Second Step: oxidation of trans-1,2-cyclohexanediol

Possible catalytic systems for the oxidation of 1,2-t cyclohexanediol were also already mentioned in the precedent chapter. We investigated the second step of the synthesis using ruthenium supported on alumina as a heterogeneous catalytic system.

11.2 Catalyst – ruthenium supported on alumina

This recently studied catalyst was reported to be a highly active and selective in the oxidation of benzylalchol to benzaldehyd and other substrates such as cyclopentanol, 2-octanol, 1-phenylethanol and so on [9-12]. This system belongs to the class of supported materials, which is very popular class of catalyst, advantageous from the economical and practical point of view. Assuming the hypothesis that the supported catalyst behave heterogeneously, they would be considerably cheaper than the conventional materials and also environmentally friendly, because, after the reaction, the catalyst would have to simply separate from the products and recycled.

Ruthenium as the supported metals was chosen on the basis of its ability to behave as active specie on the oxidation reaction. According to the literature ruthenium was employed in a vast variety of oxidation of alcohols with molecular oxygen: tetrapropylammonium perruthenate (TPAP)/MCM-41 [13], Ru–Co(OH)$_2$ –CeO$_2$ [14], RuO$_2$ [15] Ru-hydroxyapatite [16], Ru/CeO$_2$ [17], Ru-hydrotalcite, [18], [RuCl$_2$(p-cymene)]$_2$/activated carbon [19], Ru-based mixed oxides ($Ru_{0.35}MnFe_{1.65}O_4$ and $Ru_{0.45}MnFe_{1.4}Cu_{0.15}O_x$) [20,21], RuO$_2$ in faujasite [22], Ru-substituted silicotungstate, $[(n\text{-}C_4H_9)_4N]_4H[SiW_{11}Ru(H_2O)O_{39}]$ $2H_2O$ [23], oxidation of 1,2 - cyclohexanediol to adipic acid was studied with already mentioned one of the precedent chapter pyrochlores [24] and also with ruthenium complex covalently linked to silica by 2-(phenylazo)pyridine [25]. Ruthenium is a unique chemical element; Ru complexes display the widest range of oxidation states of all the elements. It is characterized by complex chemistry, its external electronic structure is $4d^75s^1$, which gives it nine stable oxidation states lying between 0 and +VIII, and even a –II oxidation state [26,27].

References

[1] Italian patent, application number: MI2009A001842, assigned to Radici Chimica SPA

[2] H. Li, W. Zhu, React. Kinet. Catal. Lett. 92 (2007) 319

[3] K.Bergstad, S. Y. Jonsson et al., J. Am. Chem. Soc. 121 (1999) 10424

[4] Y. Usui, K. Sato et al., Angew. Chemie Int. Ed. 42 (2003) 5623

[5] M. Morandin, R. Gavagnin, J. Catalysis 212 (2002)193

[6] T. Tatsumi, K.A. Koyano et al., Chem. Commun. (1998) 325

[7] M.N. Timofeeva , O.A. Kholdeeva et al., Appl. Catal. A. 345 (2008) 195

[8] A. Sakthivel, S.E. Dapurkar et al., Appl. Catalysis A 246 (2003) 283

[9] N. Mizuno, K. Yamaguchi, Catal. Today 132 (2008) 18

[10] K. Yamaguchi, N. Mizuno, Chem. Eur. J. 9 (2003) 4353

[11] K. Yamaguchi, T. Koike et al., Chem. Eur. J. 14 (2008) 11480

[12] K. Yamaguchi, N. Mizuno, Angew. Chem. Int. Ed. 41 (2002) 4538

[13] A. Bleloch, B. F. G. Johnson, Chem. Commun. (1999) 1907

[14] H. Ji et al., Tetrahedron Letters 43 (2002) 7179

[15] M. Matsumoto, N. Watanabe, J. Org. Chem. 49 (1984) 3436

[16] K. Yamaguchi, K. Mori et al., J. Am. Chem. Soc. 122 (2000) 7144

[17] F. Vocanson, Y. P. Guo et al., Synth. Commun. 28 (1998) 2577

[18] T. Matsushita, K. Ebitani et al., Chem. Commun. (1999) 265

[19] E. Choi, C. Lee et al., Org. Lett. 4 (2002) 2369

[20] H.B. Ji, T. Ebitani et al., Catal. Commun. 3 (2002) 511

[21] H.B. Ji, T. Ebitani et al., React. Kinet. Catal. Lett. 78 (2003) 73

[22] B. Z Zhan, M.A. White et al., J. Am. Chem. Soc. 125 (2003) 2195

[23] K. Yamaguchi, N. Mizuno, New J. Chem. 26 (2002) 972

[24] T. R. Felthouse, J. Am. Chem. Soc., 109 (1987) 7566

[25] A.M.J. Jorna, A. E.M. Boelrijk et al., React. & Funct. Polymers 29 (1996) 101

[26] P. Pascal, Nouveau traité de chimie minérale Tome XIX (1958)

[27] M. Pagliaro, S. Campestrini, Chem. Soc. Rev. 34 (2005) 837

12. Experimental part

12.1 Synthesis of the catalyst

Catalyst for the first step of the synthesis H_2WO_4 (purity 99.999%) and the phase transfer catalyst PTC were both commercial products from Sigma Aldrich.

All the samples for the second step of the synthesis were prepared following the literature [1]. In order to obtain the catalyst with 4.9 wt % Ru the procedure was as follows:

γ - Al_2O_3 was calcined for 3 hours at 550 °C, subsequently the 8.3 mM solution of $RuCl_3$ was prepared, and to this solution 2 g of γ - Al_2O_3 was added. The mixture was stirred for 15 minutes and then the pH of the solution was adjusted to 13.2 by adding 1 M NaOH. The resulting slurry was stirred for 24 h at room temperature, then the solid was filtered and the dark green powder was obtained. The rest of the samples were prepared following the same method, the only difference was the different concentration of the solution of $RuCl_3$.The summary of the samples is given in the table 12.1.

Table 12.1: The list of the prepared samples

sample (Ru wt)	mol of Ru
Ru/Al_2O_3 6.2 %	1.311E-03
Ru/Al_2O_3 4.9 %	1.024E-03
Ru/Al_2O_3 3.7 %	7.647E-04
Ru/Al_2O_3 2.5 %	5.091E-04
Ru/Al_2O_3 1.3 %	2.560E-04
Ru/Al_2O_3 0.8 %	1.582E-04
Ru/Al_2O_3 0.4 %	8.154E-05
Ru/Al_2O_3 0.2 %	4.138E-05

12.2 Catalytic measurement: oxidation of cyclohexene

The reaction was carried out in the three neck flask (the volume 250 ml), equipped with refrigerator and thermometer, immersed in water bath. Typically, hydrogen peroxide (7.5 wt %) was loaded in the reactor together with the catalytic system: H_2WO_4 in the presence of phosphoric acid and Aliquat 336 (a quaternary ammonium salt of octyl and decyl chains) which act as a phase transfer agent. After 15-30 minutes of stirring at the temperature of 50 °C the feeding of cyclohexene started. The feeding of cyclohexanone caused an increase of the temperature, thus the temperature of the reactor was lowered until the modulation of the exothermity (this lasted cca 1 hour). When the temperature was stabilized at 70 °C the reaction was further carried for 1 hour.

12.3 Treatment of the reaction mixture

After the reaction the reaction mixture was filtrated and divided in two parts.

First part was diluted in order to be analyzed by means of GC and potentiometric titration with $KMnO_4$ for determining the consumption of hydrogen peroxide.

Second part was put in the rotating evaporator in order to evaporate the rest of the water. After the evaporation the resulting solid was dissolved in methanol and subsequently analyzed in GC capillary in order to evaluate the yield of 1,2 cyclohexanediol.

12.4 Catalytic measurement: oxidation of trans-1,2-cyclohexanediol

Catalytic tests were carried out following the same procedure as described in the chapter 5.1.

Typically the reaction measurements were carried out as follows: the substrate (trans-1,2-cyclohexanediol), solvent (25 ml of H_2O) and NaOH (1.5 g) were put in the reactor and 0.1 g of the catalyst was added. The mixture was stirred with magnetic stirrer; the reactor was heated to the temperature of the reaction (90 °C). When the temperature was reached the valve of oxygen was opened, and the reaction started. The reaction was stopped by closing the valve of the oxygen.

12.5 Treatment of the reaction mixture

After the reaction, catalyst was separated from the reaction mixture by filtration. The mixture was further treated in the same way as already described in detail in the chapter 5.2.

12.6 Characterization of the catalyst

12.6.1 Characterization by XRD

Powder X-ray diffraction (XRD) experiments of the catalysts were performed with Ni-filtered CuKα radiation ($\lambda = 1.54178$ Å) on a Philips X'Pert vertical diffractometer equipped with a pulse height analyzer and a secondary curved graphite-crystal monochromator. A °2θ range from 5° to 80° was investigated at a scanning speed of 70°/h.

12.6.2 Characterization by XPS

XPS was measured by the Institute of Chemical Technology together with Polytechnic University of Valencia.

12.6.3 Characterization by HRTEM

HRTEM was measured by University of Torino, Department of inorganic chemistry, physics and materials.

Reference

[1] N. Mizuno, K. Yamaguchi, Catal. Today 132 (2008) 18

13. Results and discussion

13.1 First step of the synthesis – catalytic performance

The results from the oxidation of cyclohexene are reported in the table 13.1. The main product of the reaction was the mixture of cis and trans 1,2 - cyclohexanediol. Adipic acid was formed in very low amount. Also very negligible amount of the non identified products was detected.

Conversion of cyclohexene varied between 93.7 and 96.8 %. The obtained selectivities to cyclohexanediol were very high, the lowest one being 88.7 and the highest 99.5 %. The factor which influenced the catalytic performance was mainly the molar ratio between the phase transfer catalyst and the catalyst. Because of the limited solubility of cyclohexene in water, the presence of the phase transfer catalyst was indispensable.

Table 13.1: Oxidation of cyclohexene (c.ene) to 1,2 cyclohexanediol (c.diol)

	time of reaction (min)	S (%) with respect to c.ene		X (%)	molar ratio of reagents				
entry		**1,2 - c.diol**	**AA**	**c.ene**	**H_2WO_4**	**H_3PO**	**PTC**	**c.ene**	**H_2O_2**
1	86	99.5	0.2	96.8	1.00	0.50	1.00	100.0	116.5
2	85	99.4	0.2	95.6	1.00	0.50	0.50	100.2	110.1
3	62	99.0	0.4	94.8	1.00	0.49	0.47	100.2	109.0
4	77	98.8	0.7	93.7	1.00	0.51	0.23	99.8	109.1
5	112	88.7	1.0	94.4	1.00	0.48	0.13	100.2	110.7
6	92	89.4	0.8	95.5	1.00	0.52	0.16	101.3	110.3
7	63	93.6	0.8	96.2	1.00	0.51	0.20	103.0	112.3

The best result was obtained using equimolar ratio of H_2WO_4 and PTC and the molar ratio H_2WO_4/H_2O_2/cyclohexene equal to 1/116.5/100 (entry 1). The conversion of cyclohexene was 96.8 % with 99.5 % selectivity to 1,2 cyclohexanediol. The amount of the hydrogen peroxide did not have any marked effect on the selectivity of alcohol, decreasing the amount of oxidizing agent (using the ratio of H_2O_2/cyclohexene 110.1/100) the conversion dropped to 95.6 % anyway the selectivity remained almost the same (99.4 %) (entry 2). Remarkably, the amount of the phase transfer catalyst had very pronounced effect on the catalytic activity. Decreasing the amount of PTC, from the molar ratio H_2WO_4/PTC ratio 1/0.5 to 1/0.13 led caused the fall of the selectivity from 99.4 to 88.7 % with increase of the selectivity to AA (entry 5). This is caused by the higher solubility of 1,2- cyclohexanediol in water with respect to cyclohexene and thus the oxidation of formed alcohol is favored in this condition.

These results are very good considering the fact that in the literature has never been reported high selectivity to 1,2-cyclohexanediol in the epoxidation of cyclohexene with stoichiometric amount of hydrogen peroxide. In a kinetically complex reaction scheme, any consecutive reaction on the intermediate compound (in this case 1,2-cyclohexanediol) may occur provided there is enough unconverted reactant left (in this case, hydrogen peroxide) and the concentration of the intermediate is high enough to make the consecutive reaction kinetically relevant: considerations that indicate the possible occurrence of oxidative reactions upon the formed cyclohexanediol. On the opposite, in our case the oxidation of cyclohexanediol into AA was found to be negligible. This may be attributed to the fact that the temperature of reaction used (70 °C) was lower than that reported in the literature for the one-step transformation of cyclohexene into AA, that allows avoiding the oxidative cleavage via intermediate formation of 2-hydroxycyclohexanone, hydroxycaprolactone, the α-ketolactone and final ring opening to the diacid via hydrolysis.

13.2 Second step of the synthesis

13.2.1 Characterization of the catalyst

In order to understand to the structure of the catalyst and to verify that alumina was able to bond all the metal on its surface, we decided to characterize the samples by HRTEM, XRD, XPS and ICP analysis.

13.2.1.1 ICP analysis

ICP analysis was done only for three chosen samples (samples with the following amount of ruthenium: 3.7 %, 2.5 % and 0.4 %). The results are given in the table 13.2. According to the ICP results, synthesis of the sample is very precise in the case of low concentration of metal, moving to higher amount of the metal only part of the metal is able to bond to alumina.

Table: 13.2: ICP analysis of the samples

	amount of Ru wt %	
	theoretical	experimental
Ru/Al_2O_3 3.7 %	3.7	3.09
Ru/Al_2O_3 2.5 %	2.5	2.22
Ru/Al_2O_3 0.4 %	0.4	0.37

13.2.1.2 Characterization by XRD

All the prepared samples were characterized by XRD. We found out that no signals due to Ru metal clusters and RuO were observed. These facts suggest that ruthenium species are highly dispersed on the surface of supports. We also studied the structure of the catalyst after the reaction. Both of the diffractograms are reported in the figure 13.1.

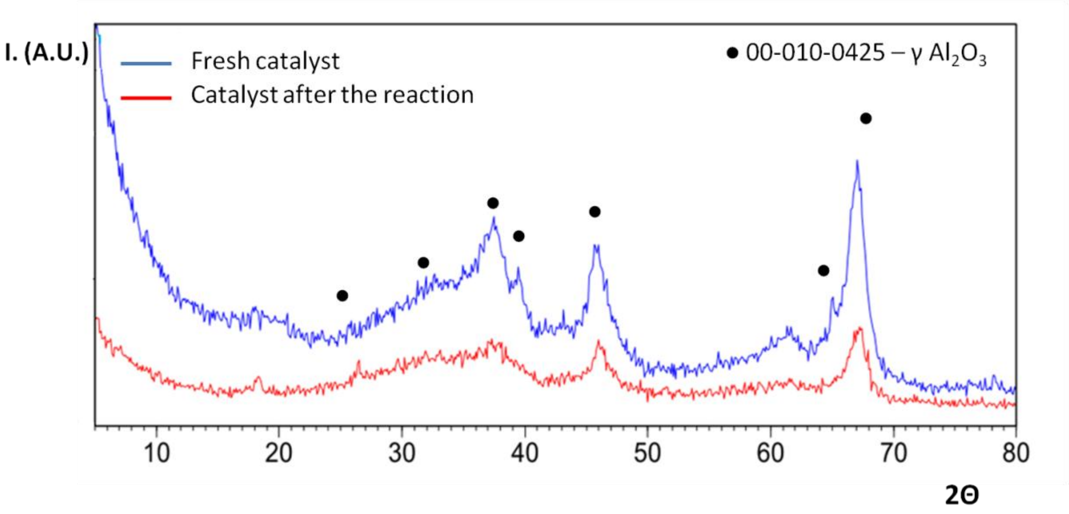


Figure 13.1: XRD of the sample Ru/Al_2O_3 4.9 % before and after the reaction

By comparing these graphs, it is evident, that catalyst during the reaction does not undergo any substantial differences in his structure. We also measured XRD spectra of other samples with different amount of ruthenium, and the only visible signals belonged to gamma alumina. For the sake of the brevity they are not reported.

13.2.1.3 Characterization by XPS

XPS analysis was carried out with the scope to reveal the oxidation state of ruthenium in the studied catalyst. Although in the literature there are many reports on XPS spectra of 3d lines of ruthenium, in our case it was not possible to analyze 3d lines because of their complexity and overlapping with C1s line. For this reason, our samples were analyzed describing 3p lines. The XPS spectrum for 3p 3/2 line is shown in the figure 13.2.

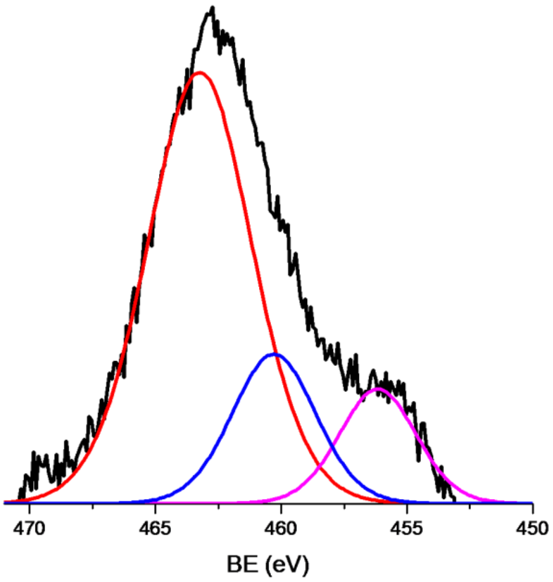


Figure 13.2: XPS spectrum of Ru/Al_2O_3 4.9 %

According to the spectra ruthenium is present in two different oxidation states. A high intense component observed at binding energy of 463.2 eV and the less intensive one at binding energy of 460.28 eV (the small signal at the binding energy of 456,1 eV does not belong to the signal of ruthenium, it is due to the XPS instrument). Unfortunately, due to the scarce information about 3p signals of ruthenium in the literature, it is quite difficult to explicitly assign these to peaks to the two different oxidation state of ruthenium. Most likely, these two signals could belong to Ru^{3+} and ruthenium in its lower oxidation state

[1]. The detected amount of ruthenium 3+ is four times higher than of ruthenium in lower oxidation state. This means, that during the synthesis, small amount of ruthenium is being reduced. It can be supposed that the samples with different amount of ruthenium have also different percentage content of different oxidation states of ruthenium, which also will influence the catalytic activity (see the chapter 13.2.2.1).

13.2.1.4 Characterization by HRTEM

Transition electron microscopy characterization of Ru/Al_2O_3 showed that ruthenium is highly and homogeneously dispersed. According to the images, particles exhibit roundish shape and their size is around 2 nm. Analysis of this sample did not reveal any presence of big agglomerates. This result is in a good agreement with the observation from XRD analysis, confirming the high dispersion of ruthenium on alumina. Also particle size distribution has been determined and it was found out that the average size of the particle was 1.17 nm, the figure 13.4 shows the particle size distribution graph.

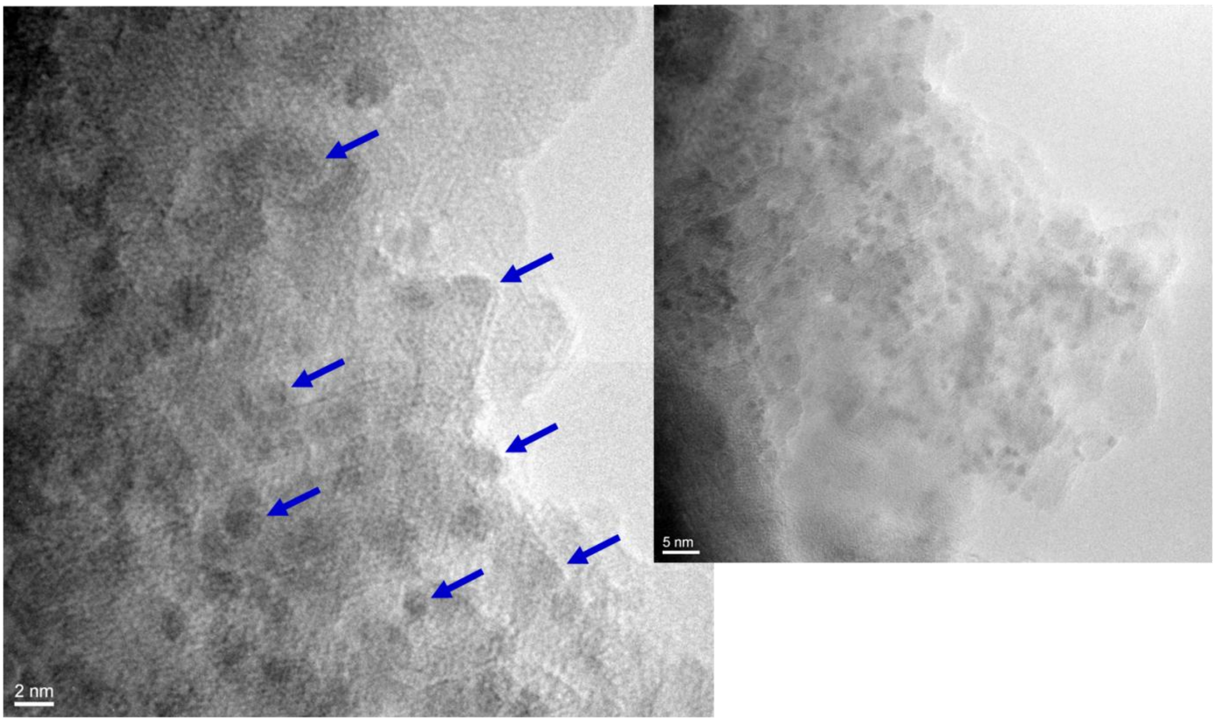


Figure 13.3 TEM picture of Ru/Al_2O_3 4.9 %

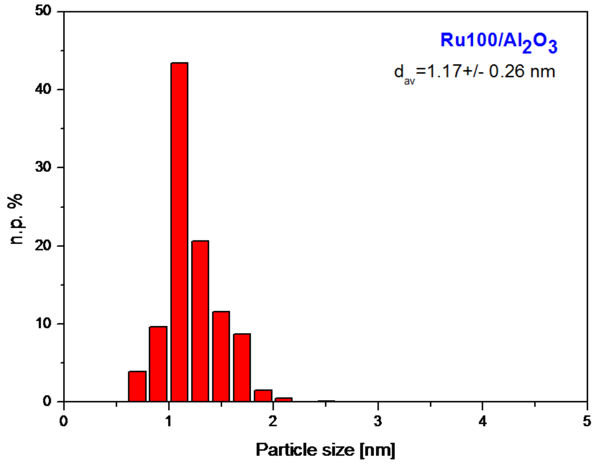


Figure 13.4: Particle size distribution for of Ru/Al_2O_3 4.9 %

13.2.2 The second step: the oxidation of trans-1,2-cyclohexanediol to adipic acid with oxygen – catalytic activity

The products of this reaction were adipic acid, glutaric acid, succinic acid, oxalic acid (OA), propandioic acid (PA) and an intermediate 1-hydroxycyclopentane carboxylic acid.

13.2.2.1 The effect of Ru content

All set of the samples were studied in the oxidation of trans-1,2 -cyclohexanediol to adipic acid under the reaction condition describe above in order to see the effect of the ruthenium on alumina on the catalytic activity. The results are shown in the figure 13.5.

An increase of Ru content in catalysts led to an increase of cyclohexanediol conversion, even though the increase was not monotonous; apparently, in the Ru content range of 0.2-1.3% the increase of activity was proportional to the Ru content; then, from 1.3 to 4.9 wt % the activity was constant, and then it further increased again. There are two possible hypothesis for the conversion trend experimentally observed; the first one is that in the range 0 to 1.5 wt % Ru, the alumina coverage increases, and a monolayer coverage of the alumina surface is obtained at about 1.5 wt % Ru (that however does not allow us excluding that a fraction of the alumina surface still remains uncovered even at high Ru loading). Therefore, higher Ru content did not cause any further increase of cyclohexanediol conversion because the number of active Ru species exposed did not increase inside the 1.5-4% Ru content. However, even larger amounts of Ru caused an increase of conversion because at high Ru content (4, 9%) leaching phenomena led to the overlapping of homogeneous oxidation by dissolved Ru^{3+} species (see the chapter test of leaching). The second hypothesis is that the nature of the Ru species may vary in function of the Ru content, especially for high Ru loadings.

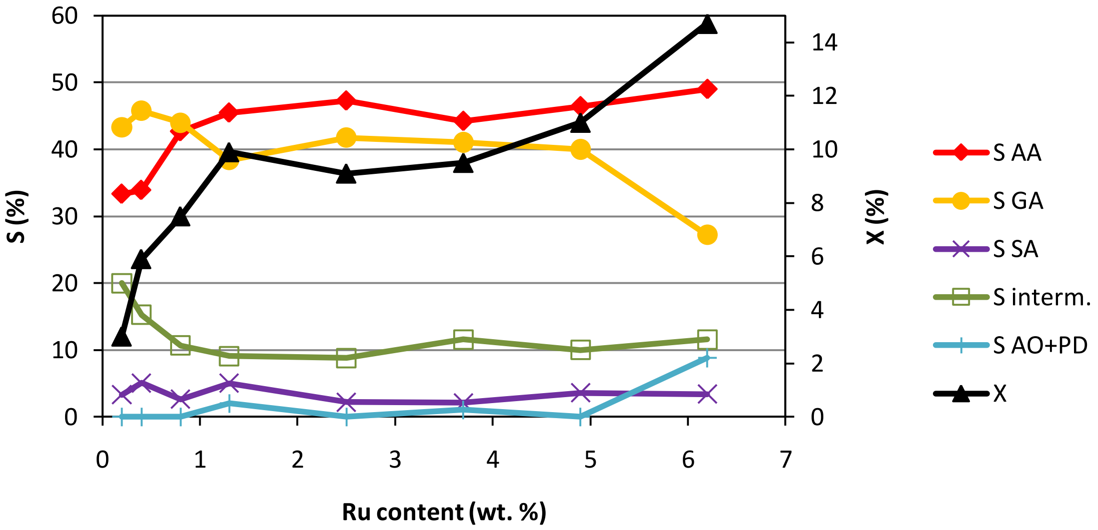


Figure 13.5: Effect of the amount of ruthenium on the catalytic activity. Reaction conditions: T = 90 °C, p = 3 bar, 3 hours, 25 ml H_2O, 1.5 g NaOH, 0.1 g catalyst, 0.3 g t-1,2 c.diol

An important effect on selectivity was also observed in function of the Ru content. An increase of Ru content led to an increase of selectivity to AA and to oxalic + propandioic acids, with a decline of selectivity to glutaric acid; selectivity to succinic acid was not much affected. Worth noticing, because of the increased reactant conversion, we would have expected a decrease of selectivity to AA and a corresponding increase of selectivity to lighter diacids, especially glutaric acid, that form by consecutive oxidative degradation of AA. On the opposite, we observed that the selectivity to AA was enhanced, despite the higher conversion achieved with catalysts containing the greater amount of Ru, and a corresponding lower selectivity to glutaric acid. This means that an increase of alumina coverage by $Ru(OH)_3$ leads to a modification of the reactivity properties of the catalyst. Yet, two possible hypothesis can be made; either the nature of Ru active species is changed in function of the Ru loading (as mentioned above), or alumina itself may play a role in the formation of glutaric acid in catalysts having the lower Ru content, which may hold a fraction of alumina which is still uncovered.

Besides dicarboxylic acid, we also observed a non negligible amount of 1-hydroxycyclopentane carboxylic acid, the selectivity of which was substantially constant (around 10%), regardless of the Ru content. We shall deal with the formation of this compound in the following section.

13.2.2.2 The role of the basic medium

Catalyst containing 4.9 wt % Ru has been tested by varying the amount of NaOH added to the reaction medium. Results are plotted in figure 13.6.

In the absence of any added NaOH, the conversion was low, but non-negligible (0.5%; this point has not been reported in the figure, because of the great uncertainty in the measurement of selectivity). Moreover, remarkably there was no formation of by-products; therefore, the selectivity to AA was very high, namely 100%, but indeed it was likely less, because the amount of GA and SA produced were less that the detection limit for the analytical tool used.

After addition of 0.5 g NaOH, instead, on one hand there was a relevant increase of cyclohexanediol conversion, on the other hand a large amount of both GA and 1-hydroxycyclopentane carboxylic acid compound. This compound plays a key role; from literature, it forms under basic medium by cyclohexandione hydrolysis [2,3]. The hypothesis can be made, that this compound is the precursor for glutaric acid (that would explain why such a great amount of the latter acid is formed in the reaction), because of its structure that makes it prone to easily loose a CO_2 molecule by decarboxylation, and that it forms from 1,2-cyclohexandione in large amount when the reaction conditions are strongly basic.

The data clearly indicate that the basic medium accelerated the overall reaction rate, that agrees with the literature about the role of the basic medium in alcohols oxidation to aldehydes or ketones [4,5], but also favored the formation of 1-hydroxycyclopentane carboxylic acid (likely by 1,2-cyclohexandione hydrolysis and rearrangement), and then of glutaric acid. However, when even greater amounts of NaOH were added, the consecutive transformation of the intermediate acid into both glutaric and adipic acid acids occurred, as evident from the opposite trend of the selectivity to the mentioned products. Finally, an excessively basic environment disfavored the consecutive transformation of the intermediate acid, with a corresponding lower selectivity to glutaric acid.

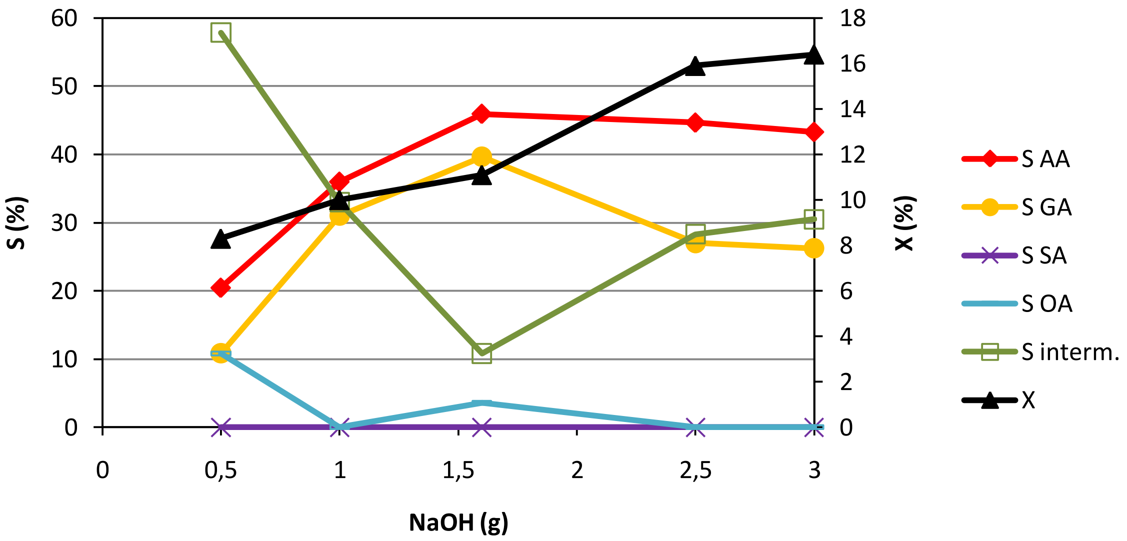
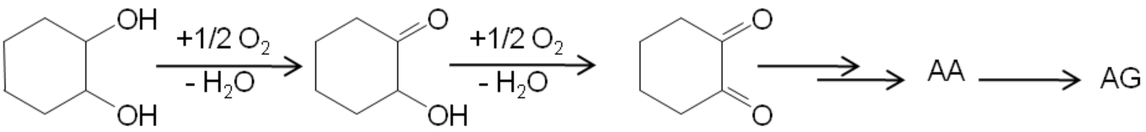


Figure 13.6: Effect of the amount of NaOH on the catalytic activity, reaction conditions: T = 90 °C, p = 3 bar, 3 hours, 25 ml H_2O, 1.5 g NaOH, 0.1 g catalyst, 0.3 g t-1.2-c.diol

We would like now to draw a hypothetical reaction mechanism that changes in function of the NaOH amount added.

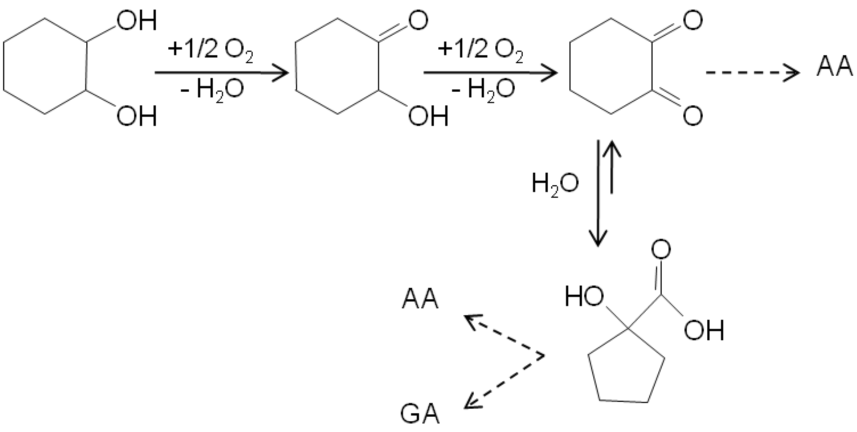
1. With **0 g NaOH added** (scheme 1), the reaction rate is very low, because the hydroxyl groups needs the basic medium in order to be activated. Therefore the conversion is low, and there is prevailing formation of AA, because the consecutive oxidation of AA to GA (a reaction typically observed in oxidation of cyclohexanone with oxygen) is negligible. We did not detect the formation of intermediates, 2-hydroxycyclohexanone and 1,2-cyclohexandione, but it cannot be excluded that low amounts of these compounds are also formed.



Reaction scheme 1

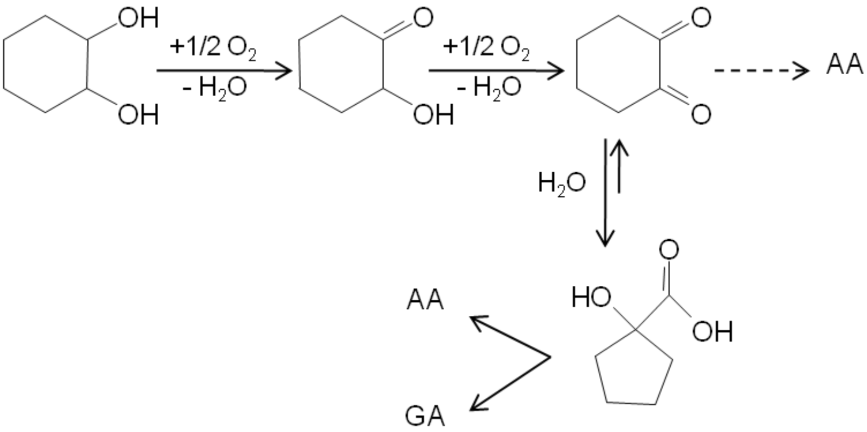
2. With 0.5 g NaOH added (scheme 2), the reaction is accelerated, because of the activation of the hydroxy groups. However, the main effect is that 1,2-cyclohexandione, once formed, is rapidly transformed into the 1-hydroxycyclopentane carboxylic acid; this compound is the precursor for the formation of both AA and AG (the latter by

decarboxylation). At these conditions, however, the intermediate acid is relatively stable, and its selectivity is high.



Reaction scheme 2

3. With **1.0 and 1.5 g NaOH added** (scheme 3), the transformation of the intermediate acid into AA and AG is favored, both because of an increased pH and increased reaction time. Therefore, in this interval of NaOH amount, the selectivity to 1-hydroxycyclopentane carboxylic acid decreases, and that to AA and GA increases.



Reaction scheme 3

4. Finally, with **2.5 and 3.0 g NaOH added**, again there is an increase in selectivity to 1-hydroxycyclopentane carboxylic acid and a corresponding decrease of selectivity to GA; at the same time, the conversion is not much changed. It seems that in this strongly basic

pH, the transformation of the intermediate acid into AG is slowed down. However, an alternative explanation is that the reversible transformation of cyclohexandione into 1-hydroxycyclopentane carboxylic acid becomes less favored (therefore, also the transformation of the intermediate acid into AA and GA becomes slower), and that therefore the contribution to AA formation also derives from the direct oxidation of cyclohexandione (as shown in scheme 1).

In order to confirm the above mentioned hypothesis on the reaction scheme, we have performed tests in function of the reaction time, with the catalyst containing 4.9 wt % Ru, using 1.5 g of NaOH, that is, at conditions at which the selectivity of the intermediate acid is the lower. We also carried out some experiments by directly reacting 1,2-cyclohexandione.

13.2.2.3 The reaction scheme in 1,2-cyclohexanediol oxidation

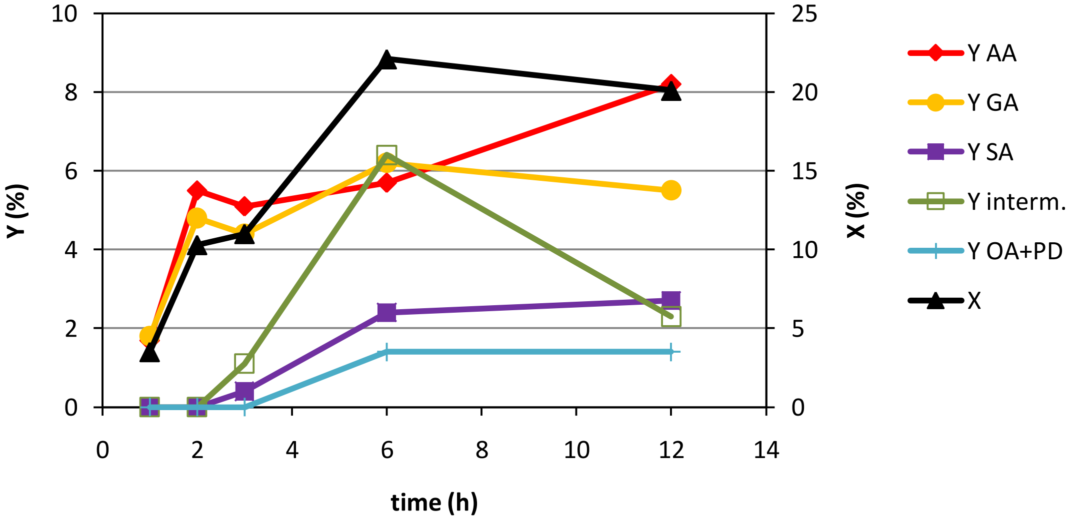


Figure 13.7: Effect of the reaction time on the catalytic activity. Reaction conditions: T = 90 °C, p = 3 bar, 25 ml H_2O, 1,5 g NaOH, 0,1 g catalyst, 0,3 g t-1,2- c.diol

Figure 13.7 plots the effect of the reaction time on catalytic behavior, for the catalyst containing 4.9 wt % Ru, with 1.5 g NaOH added (0.038 moles; an excess with respect to 0.3 cyclohexanediol, corresponding to 0.0026 moles). We have reported the yield to products, and not the selectivity, because this allows better understand the effect of reaction time on parallel and consecutive reactions.

The initial behavior, when still the yields to diacids (AA+GA) are low, is similar to that one observed in the previous figure in correspondence of 1.5 g NaOH added, with the network being similar to that shown in scheme 3: formation of the intermediate acid and quick transformation of the latter compound into AA and GA (in fact, the yield to 1-hydroxycyclopentane carboxylic acid is zero).

When the reaction time is increased (in the range 2-6 h), we move towards a situation closer to that shown in reaction scheme 2: the intermediate acid is formed, but its transformation into AA and GA is slower. Therefore the yield (and selectivity) to the intermediate acid increases. Finally, in the range 6 to 12 h there is no further variation of cyclohexanediol conversion, and therefore no additional intermediate acid is formed; however, because of the long reaction time, the latter undergoes consecutive transformation into AA, and GA has time to transform into SA and OA.

13.2.2.4 Test of leaching

In order to verify that our catalyst behaves truly heterogeneously we decided to carry out test of leaching proposed by Sheldon [6]. According to Sheldon the truly heterogeneous catalyst should not lose any of its active sites and the only reliable method to confirm it, is to separate the catalyst from the reaction mixture by filtration and again loaded the reaction mixture in the reactor and carry out the reaction. This study was carried out with 4.9 wt % Ru catalyst. The table 13.3 shows the results obtained from three different reactions, before and after the filtration of the catalyst. As can be seen, the differences of the conversions of cyclohexanediol are not crucial considering the experimental error of the measurements. Thus it can be concluded, that the catalyst did not undergo the leaching of the active specie in the solution and the heterogeneous character of the catalyst has been confirmed.

Table 13.3: Test of leaching

	X c.diol (%) original reaction	X c.diol (%) reloaded solution
1.	7,8	7,3
2.	16,1	14
3.	16,6	18,6

13.2.2.5 Reactivity of 1,2-cyclohexandione

A key role in the reaction scheme is likely played by cyclohexandione. We have never found it amongst the reaction products; however, its formation is evident because of the formation of 1-hydroxycyclopentane carboxylic acid. We probably did not find it because of its high reactivity. In order to confirm the role of this compound, we carried out selected reactivity experiments; the results are summarized in Table 13.4.

Table 13.4: Reactivity of cyclohexandione in the different reaction conditions

entry	catalyst (g)	p O_2 (bar)	NaOH (g)	X (%)	S AA (%)	S GA (%)	S SA (%)	S OA (%)	S HC (%)
1	0,1	3	/	5	24	76	0	0	0
2	0,1	/	1,5	8,6	9	3	0	0	88
3	0,1	3	1,5	12.3	18	8	0	25	49

* HC: 1-hydroxycyclopropane carboxylic acid
Other conditions: T = 90 °C, O_2 300 mL/min, 3 bar,3 hours, catalyst: 4.9 wt % Ru, 0.3 g cyclohexandione; H_2O 25 ml

These experiments demonstrate the following:

1. Without NaOH (entry 1), 1,2-cyclohexandione conversion was 5 %, whereas at same conditions, cyclohexandiol conversion was only 0.5 % (with apparently the only formation of AA, see above). This indicates that 1,2-cyclohexandione is more reactive than 1,2-cyclohexandiol, that explains why the former compound is not found during the oxidation of cyclohexandiol. Concerning the products formed, there was no formation of 1-hydroxycyclopropane carboxylic acid; this supports the hypothesis shown in Scheme 1 that the latter compound only forms when the reaction is done at basic conditions. In this case, however, the selectivity to GA is higher than selectivity to AA; this can be due either to the fact that under these conditions there is a relevant contribution of the consecutive transformation of AA into GA (this might be demonstrated by carrying out experiments in function of time and without NaOH added), or that the reaction network shown in Scheme 1 is not correct.
2. With NaOH, but without oxygen, cyclohexandione hydrolyzed and rearranged into 1-hydroxycyclopentane carboxylic acid (entry 2), that forms with very high selectivity. There is also some formation of AA and GA, that may be due to some oxygen which is

captured from the gas phase (we fed neither oxygen nor nitrogen in the liquid phase, but there was air in the reaction dome).

3. When both NaOH and oxygen were added, the conversion was higher than that achieved both without O_2 and without NaOH, but similar to that obtained at the same experimental conditions from cyclohexandiol. This experiment shows that in the presence of oxygen, 1-hydroxycyclopentane carboxylic acid is oxidized into AA and GA. We notice also the relevant formation of OA and PA.

In conclusions, the experiments demonstrate that the reaction schemes 1-3 are probably correct. Without NaOH, the reaction rate is slow, because 1,2-cyclohexandiol is not activated; however, after 1,2-cyclohexandione has formed, it readily reacts to yield AA; the latter then undergoes a quick consecutive degradation into GA and lighter diacids (probably, basic medium is necessary to protect AA and limit consecutive oxidative degradations; in fact, AA is in the form of Na carboxylate). 1,2-cyclohexandione is a key intermediate; in basic medium it is very quickly transformed by hydrolysis into 1-hydroxycyclopentane carboxylic acid, and the latter is oxidized (when oxygen is present) into AA and GA. The intermediate acid is not formed from cyclohexandione when the reaction medium is not basic.

References:

[1] L. Guczi, R. Sundararajan et al., J. Catalysis 167 (1997) 482

[2] O. Wallach, Jus. Lieb. Annalen der Chemie 437 (1924) 193

[3] O. Wallach, Jus. Lieb. Annalen der Chemie 414 (1918) 332

[4] T. Mallat, A. Baiker, Chem. Rev. 104 (2004) 3037

[5] M. Besson, P. Gallezot, Catal. Today 57 (2000) 127

[6] H.E.B. Lempers, R.A. Sheldon, J. Catalysis 175 (1988) 62

14. Concluding remarks

My thesis was devoted to the study of the new catalytic processes for the synthesis of adipic acid. Different substrates (cyclohexanone, cyclohexene) have been studied with different oxidizing agents (molecular oxygen and hydrogen peroxide) with homogeneous (Keggin heteropolycompounds) or heterogeneous catalysts (silica grafted decatungstate, TS-1, tungstic acid).

It was found out, that the oxidation of cyclohexanone with molecular oxygen in the presence of Keggin polyoxometalates is possible; however the conversions of cyclohexanone were rather low. The main product of the oxidation was adipic acid, which subsequently underwent consecutive reaction to form lower acids – glutaric and succinic acid. Performing the oxidation of cyclohexanone in the presence of radical scavenger it was found out, that there are two different reaction mechanisms involved – redox mechanism and radicalic chain-reaction autoxidation. Their presence is influenced by the reaction condition, namely the amount of the catalyst.

The problematic part of this process was the recovery of the catalyst because also in the case of oxidation of cyclohexanone in the presence of cesium salts of heteropolyacids, which should behave as heterogeneous system, partial solubility of the catalyst was detected.

In the case of Baeyer-Villiger oxidation of cyclohexanone with hydrogen peroxide, uncatalyzed thermally activated oxidation of cyclohexanone showed to be the key aspect for the understanding of the reaction mechanism. We found out that the reaction occurs via radicalic mechanism involving radical species which were formed by the decomposition of hydrogen peroxide.

Catalyzed Baeyer-Villiger oxidation of cyclohexanone with TS-1 or silica grafted decatungstate gave very good results; high conversions of cyclohexanone were reached. The products of the reaction were caprolactone, adipic acid, lower acids – glutaric and succinic acids and 6-hydroxyhexanoic and 6-oxohexanoic acid. Their formation was influenced by the reaction condition, namely by the solvent, which could act as a radical scavenger. This research showed that it is possible to selectively convert cyclohexanone to caprolactone or to adipic acid.

Two step oxidation of cyclohexene via 1,2 – cyclohexanediol gave very promising results mainly regarding the first step of the synthesis – oxidation of cyclohexene with stoichiometric amount of hydrogen peroxide. High yields of 1,2-cyclohexanediol could be obtained with minimum amount of by-products. On the other hand, the second step of the synthesis – oxidation of trans-1,2-cyclohexanediol to adipic acid with molecular oxygen did not give selectivities to adipic acid as was expected. But as the employed catalytic system has never been studied for this kind of reaction, it can be supposed that in the future this catalyst would achieve better results.

Acknowledgement

I would like to thank professor Cavani for giving me the opportunity to do the PhD in his research group. I appreciated his incredible enthusiasm for the research, his ideas and his kindness.

Special thanks go to ISA Institute of Advanced Studies (IAS) of the University of Bologna and to Radici Chimica, Spa for their financial support.

Thanks to all my colleagues from the laboratory that helped me not only with the research, but also with the language. Thanks to them my PhD study was really nice period. Namely I would like to thank Auruška, Alessandro, Irene, Giuseppe, Carlo, Saurino, Silvia, Stefania, Rosa, Stefano, Fede, Riccardo, Laura and Andrea .