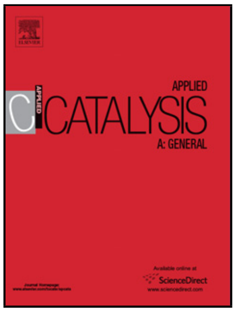

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Trifluoroacetic acid promoted hydration of styrene catalyzed by sulfonic resins: comparison of the reactivity of styrene, n-hexene and cyclohexene

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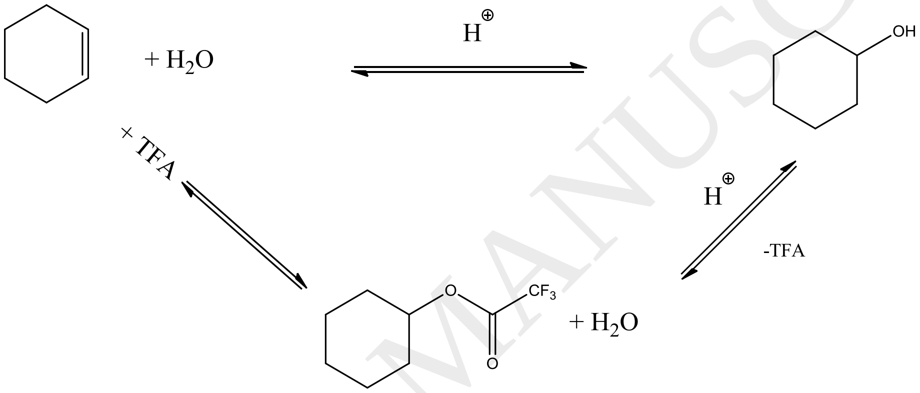
Graphical abstract



Cyclohexene hydration in TFA catalyzed by sulfonic resins

Research highlights

- Trifluoroacetic acid acts as promoter and catalyst in olefin hydration.
- Trifluoroacetic acid favors the displacement of equilibria to alcohol.
- Trifluoroacetic acid acts as initiator in polystyrene polymerization and in parallel promotes styrene hydration.
- Trifluoroacetic acid promotes cyclohexene hydration to cyclohexanol and can be easily recovered.
- The reactions can be carried out in the presence of a sulfonic resin as a catalyst, which increases the overall reaction rate.

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Abstract

Alcohol production by olefin hydration is an important reaction in the modern intermediate chemistry. The use of trifluoroacetic acid (TFA) could be a way to increase alcohol productivity by addition of the TFA to the double bond forming the corresponding ester. The product obtained by addition is then hydrolyzed to alcohol by sulfonic resins. The study of the overall multiphase equilibrium aqueous TFA solution/olefin ester cyclohexene is carried out together with the initial rate of reaction for cyclohexene hydration. Reaction profiles and a likely reaction path is also given. The influence of the operative variable on both equilibria and initial reaction rate are studied in the range of temperature typical of the sulfonic resin as catalysts (383-413K). The use of aqueous TFA allows fast reaction and high conversion as well as an easily separable aqueous system compared with other organic acid.

Keywords: trifluoroacetic acid, acid catalysis, olefin hydration, cyclohexanol.

1. Introduction

Hydration of olefins is an apparently trivial reaction; however, its practical implementation is seldom quite cumbersome. The acid catalysis is able to promote several reactions in the presence of olefins as substrate, such as hydration, condensation polymerization and so on [1-7]. The key intermediate in the acid catalytic reaction of olefin, it is an attack by nucleophilic molecules to a positively polarized species, in some cases a carbonium ion. This moiety may undergo an attack of nucleophilic molecules, such as water, olefin, alcohol and so on, all these reaction can concur to the various products and, if present simultaneously, they induce the selectivity to one product by following the reactivity of the nucleophile [8, 9]. In the case of olefin hydration, the presence of rather concentrated aqueous mineral acid (70%) allows high yields to alcohol. The reaction proceeds via an alkyl sulfate intermediate, which is hydrolyzed after dilution [10]. However, such a reaction is neither environmentally friendly, nor sustainable, because of its intrinsic necessity of using large amount of aqueous acid, which at the end must be disposed and/or concentrated. Other hydration methods are in any case complex and require solid acid catalysts to be employed in gas phase reaction such as those of ethene and propene to give ethanol and isopropanol, respectively [9, 11, 12]. Liquid/Liquid biphasic reactions in the presence of an aqueous and an organic phase are well known reactions employed in several industrial processes, nitrations, hydrogenations, carbonylations and hydroformylation [13-17]. The presence of two phases may create problems of mass and/or heat transfer because of the necessity of having reagents in the same phase to react, that can be attained by forming an emulsion. This allows to the system a sufficient exchange to have a kinetic of reaction useful for practical applications. Under this light, the rate of agitation is of paramount importance in multiphase processes [18, 19]. For instance, toluene nitration occurs in biphasic aqueous/organic environment, and the formation of non-homogeneous zones may cause risks of heat accumulation, thus causing dangerous hot-spot [17]. Other examples of multiphase liquid reaction is the selective hydrogenation of benzene to cyclohexene, in this case, the presence of an aqueous phase may help reaction regulation, both from a thermal point of view as well as for the selectivity control [14-16, 20]. In carbonylation reactions, the presence of an aqueous phase allows some interesting features especially in the co-polymerization of the carbon monoxide and ethene to polyketone [16]. As a matter of fact, both the limitation of organic solvent utilization, or the achievement of high molecular weight polymers are important goals that the presence of an aqueous phase may concur to accomplish [16]. The presence of acids or salts, in some cases, promotes reactions favoring a better interaction between reactants and catalyst, or by inducing desorption of products from catalyst surface [14, 20, 21]. For instance, in the hydrogenation of benzene to cyclohexene, in the presence of $ZnSO_4$ in the aqueous phase increases the selectivity to cyclohexene, by reducing the hydrogenation activity of the Ru, which is the actual hydrogenation catalyst [14, 20]. It is noteworthy that the $ZnSO_4$ action is obtained by the presence of the aqueous phase, which diminish the hydrogen availability on catalyst surface [14, 20]. The contact of the two liquid phases is guaranteed by strong agitation but no stable emulsion is formed. On the contrary, the use of a surfactant achieves stable micelles formation, it allows to take place carbonylations and hydroformylations in stable emulsions, by using either an organic solvent-soluble catalyst or a water-soluble one [22].

Hydration of olefins, from an industrial point of view, is strictly connected with alcohol production. For instance, an important intermediate for polymers and chemicals, is cyclohexanol, which is usually obtained by phenol hydrogenation or by cyclohexane oxidation with nitric acid forming the so called K/A oil (cyclohexanone and cyclohexanol mixture) [23]. These routes have some drawbacks from both economic and environmental point of view, that is phenol is a valuable intermediate (a greatly requested intermediate), while the oxidation with nitric acid of cyclohexane is a stoichiometric non-environmentally friendly process [23]. Under this light, cyclohexene hydration could be an interesting alternative for cyclohexanol production only if cyclohexene is an intermediate obtained from the selective hydrogenation of benzene, which is available in large amount from the petrol chemistry [24].

Among alcohols, interesting intermediates are phenyl carbinols, these compounds are commonly found in nature as fragrances but are also synthetized starting from bulk chemicals [25]. As already pointed out, phenyl carbinols and particularly 1-phenylethanol is interesting because of its several applications in the field of fine chemistry. The acetophenone reduction is a valuable route for obtaining this compound, and the reaction occurs under mild conditions in almost quantitative yields [26]. However, this reaction is industrially sustainable only if acetophenone is easily available, for instance as byproducts in phenol Hock process [27]. On the contrary, the hydration of styrene could be an interesting route being such a compound a commodity available in very large amounts (the annual production of styrene in the world is close to 20 millions of tons) [28].

An important feature of olefin hydration is its reversibility, then equilibrium influences conversion, for this reason the method of synthesis will determine the overall yield to the alcohol [29-33]. Gas phase hydration is extensively used for ethanol synthesis being olefin easily separated and recycled, on the contrary liquid phase reaction is normally used for heavier olefin such as cyclohexanol [34]. As regard cyclohexene hydration, it must be taken into account that the industrial synthesis of cyclohexene (the selective hydrogenation of benzene to cyclohexene [23]) gives a mixture cyclohexane, cyclohexene, and benzene and their separation is not easy and require specific extraction procedure [35]. The separation of the mixture, the mixtures of cyclohexene and cyclohexane could be achieved by addition/esterification with formic acid giving cyclohexyl formate, and then the saponification of the ester gives cyclohexanol [32, 36].

Styrene hydration is carried out, at high acid concentration (40-50% $HClO_4$), at low temperature (283-298K) and at concentration of 10^{-4} - 10^{-5} mol L^{-1}, in order to avoid the formation of polystyrene [37]. At such conditions no industrial application could be developed. However, starting from another point of view, and taking into account the large production and the various type of polystyrene, a small coproduction (in percentage term) of the alcohol could be of industrial interest if obtained as byproduct of the polymerization. This could occur if the polymer came from a reaction carried out in emulsion catalyzed by an acid or an acidic cationic initiator.

Many hydration methods in gas and liquid phase catalyzed by solid acid is extensively reported in literature and the sulfonated resins are important materials for these reactions. [29-34, 38-41]. For instance, ethers and esters are commonly obtained by using these type of materials as catalysts, such as in the synthesis of methyl tert-butyl ether (MTBE), or in transesterification of vegetal oil in biodiesel production. On the contrary, oligomerization of olefin is not generally achieved with this type of catalysts [40, 41]. The mechanism of the catalysis and the proton exchange, however, are not yet completely understood for these reactions [42]. In fact, O-alkylation of phenol with cyclohexene shows the need of a protic molecule thus allowing the proton exchange between the resin and the olefin in order to form a surface polarized adduct, which is responsible of the catalysis. As a matter of fact, the absence of phenol show negligible interaction between cyclohexene and the sulfonated resin, thus forming on the surface a negligible amount of electrophile, whose concentration does not allow oligomerization [42].

This work deals to some study on hydration reactions catalyzed by solid acid and promoted by trifluoroacetic acid (TFA) in aqueous solvent. The reaction is carried in biphasic condition where the olefin forms a phase and the water-TFA solution another one. Olefin results as a dispersion in the aqueous phase (due to agitation) and their reactivity is investigated by using several solid acid and three olefin, that is n-hexene, cyclohexene and styrene. In the case of styrene, the polymerization initiated by TFA occurs in high yields, but (4-8%) of 1-phenyl-ethanol is formed, too. The addition of TFA to the olefin and formation of the corresponding ester promotes the formation of the alcohol, thus increasing its yield compared with the reactions carried out in the absence of the TFA. The use of various sulfonated resins is investigated because of its ability to interact with oxygenated compound favoring hydration and saponification reaction.

2. Experimental

2.1 Materials and instruments

All solvents and products were employed as received without further purification, or by following the usual purification procedures for spectrophotometric analysis.

All the analysis were carried out by GC and GC-MS (Agilent 7890 A, equipped with HP-5 30 m long I.D. 250 µm, film 0.25 µm, coupled to a Agilent 5975 C mass spectrometer or to a flame ionization detector). Some reactions are analyzed also by HPLC (Perkin Elmer LC 250 pump coupled to a diode array detector 235C, equipped with a Merck licrosphere 100 C18 column with water acetonitrile mixtures as eluent) in order to verify if present in reaction mixture temperature sensitive intermediates or products.

^{1}H NMR, ^{13}C, and ^{19}F spectra were recorded at 400MHz, 100MHz, 376MHz, repectively, using $CDCl_3$ as a solvent on a Brucker Avance II nuclear magnetic resonance spectrometer.

All solids employed as catalyst were commercial products and used after desiccation for at least 20h at 383K in a ventilated oven.

Tab. 1. Main characteristic of solid catalysts employed in hydration reactions

Catalyst	Surface area ($m^2\ g^{-1}$)	Average pore diameter (nm)	Total exchange H^+ (meq g^{-1})
Amberlyst 15	36	180	4.9
Amberlyst 36	24	220	5.6
Amberlite IRC 50	/	/	10
Dowex D50	10	240	4.2
HZSM 5	280	2	0.2

2.2. Reaction set-up

All reactions were carried out in an isotherm multi-reactor system equipped with eight aisi 316 autoclave of 8 mL of inner volume. In each autoclave reactants and catalyst are loaded into a glass insert (a modified test tube) closed with a pierced polytetrafluoroethylene plug in order to avoid liquid dispersion outside the insert. The electric heating of an aluminum block ensures that the autoclave is maintained at constant temperature within 0.5 K, the control were achieved by PID regulator (CAL 9500P). Each autoclave could be purged with nitrogen, the maximal temperature and operative pressure are 523 K and 30 bar, respectively. The mixing of the biphasic system were achieved with a magnetic bar rotating at 5-20 Hz driven by a magnetic stirrer. The homogeneity of the emulsion were visually tested, by observing phase separation at a rate of rotation below 10 Hz.

2.3. Reactions methodology

In a typical, experiment a magnetic bar, 0.26-2.6 mmol of TFA, 2 mL of water, 2.6 mmol of substrate and 40mg of solid catalyst (if used) are added into the glass insert. The autoclave, after the loading of the stoppered vial, which fits almost exactly the autoclave volume, is closed, outgassed and filled with nitrogen at 1 bar. The aluminum block is now heated at the reaction temperature (383-403K), when the system heater is stabilized, all autoclaves are inserted in its seat. After 5 minutes without agitation, in order to allow temperature equilibration, agitation was turn on and the reaction starts. After the definite time the selected autoclave (or autoclaves) was cooled in a water bath and opened. The test tube was removed and the mixture diluted with 6.5 g of CH_2Cl_2, then 40 mg of tetradecane, as internal standard, was added to the slurry and stirred for 2 minutes. Finally, solid catalyst was filtered and the organic phase separated, from the mixtures, and dried with anhydrous Na_2SO_4.

2.4. 1-Phenylethanol, cyclohexanol and hexanols synthesis

The reactions are carried out in multiphase systems being styrene, cyclohexene and n-hexene not soluble in water, in additions, there could be the presence of a heterogeneous solid catalyst. In a typical reaction 2.62 mmol of substrate were placed into the reactor together with 1-3 mL of water, 0.87 mmol of promoter and 40 mg of a solid catalyst (if present). Tab. 2 shows the list of all catalytic systems.

Tab. 2. List of substrate and of the catalytic system employed

substrate	**Promoter**	**Solid catalyst**
Styrene	H_2SO_4	Amberlyst 15
Cyclohexene	CF_3COOH	Amberlyst 36
n-hexene	CH_3COOH	Amberlite IRC 50
		Dowex D50

All possible combinations of substrate, promoter and heterogeneous catalysts were tested in order to verify what were that gave the best results. As a matter of fact, the typical reaction conditions are: 4h of reaction, 393K, pressure are autogenous pressure of water, TFA and substrate, about 3 bar.

2.5. Analysis

GC and GC-MS analysis were carried by using GC or a GC-MS instruments with the following conditions: temperature program, 5 minutes isotherm at 333K, 20 K min^{-1} to 523K isotherm at such temperature for 5 minutes; nitrogen flow 1 mL min^{-1}, split ratio 10/1. Quantification of the products are carried out if possible by using calibration with standard (styrene and 1-phenylethanol), for dimers selectivities are calculated by using the same response factor of styrene and oxygenated isomers (mainly dimers of the 1-phenylethanol) are used the same response factor of the alcohol.

3. Result and discussion

The study is composed of two parts where the first one is a screening of aqueous acid, solid catalyst, and combination of them in the liquid phase hydration of styrene and cyclohexene as examples of olefins whose product of hydration is an interesting product from industrial point of view. The second part deals to the study of the rate of cyclohexene hydration in the presence of an aqueous solution of

TFA and a macroreticular styrene di-vinylbenzene sulfonated resins (Amberlyst 36) as a heterogeneous catalyst. All reactions are carried out in a large amount of water, and the concentration of the acid is less than 0.3-1.6 mol L^{-1}, at such a concentration the acid is solvated and the aqueous phase can be considered as an aqueous solution [43].

3.1. Styrene hydration

In table 3 we can observe, some results of styrene hydration promoted by various liquid acid. It is noteworthy that the absence of acid gives in very high yield polystyrene, small amount of unreacted styrene and traces of oligomers due to the thermal polymerization of styrene [45]. In the presence of aqueous acid only TFA is effective in the promotion of styrene hydration, thus allowing a selectivity of 10% after 4h of reaction. The composition of whole addition products is a mixture of styrene dimers and of the bis-(1-phenylethyl) ether, the latter obtained by condensation of 1-phenylethanol or by its addition to styrene, products of TFA esterification are not detected.

Tab.3. Styrene hydration promoted by homogeneous acid systems. Run conditions: T 393 K, P autogenous pressure of the system, styrene, 2.62 mmol water 2 mL, acid 1 mmol, time of reaction 4h.

Entry	**Acid promoter**	**Conversion (%)**	**1-phenylethanol (%)^{a}**	**Styrene dimers (%)^{a}**	**Condensation products (%)$^{a, b}$**	**Polymer (solid) (%)$^{a, c}$**
1	/	95	/	5	/	95
2	TFA	87	10	7	3	80
3	H_2SO_4	87	1	30	9	60
4	CH_3COOH	85	/	4	1	95

a) Selectivity. b) Oxygenated compounds observed by GC-MS. c) Calculated by weighing the solid.

These results are a clear indication of the high reactivity of styrene, which polymerizes in high yields, as can be observed in Tab.3 entry 1. The presence of organic acids TFA and acetic acid decreases the amount of solid polymer recovered at the end of the reaction. Such an evidence could be due to a partial dissolution of styrene in water favored by the presence of the organic acid. Hydration, however, it is likely to occur by catalytic step that involves the protonation of the olefin and the subsequent nucleophilic attack, which could be, in turn, either of another olefin molecule or one of water. The oligomerization of the substrate is clearly favored in the case of sulfuric acid as promoter thus causing a low selectivity for the hydration reaction. On the contrary, TFA allows a non-negligible selectivity to the alcohol thus suggesting a different reaction path in the presence of this acid. The reaction selectivity in the case of the TFA could be driven by the addition of TFA to the double bond, with a consequent hydrolysis of the TFA-Styrene ester giving 1-phenyl-ethanol [30, 31]. In detail, the strongest acid that is sulfuric acid, it immediately favors the oligomerization. In contrast, TFA is able to activate the substrate also for the subsequent hydration reaction to 1-phenylethanol, which was gained with a selectivity of 10% (entry 2). The main product was howsoever polystyrene. Finally, the use of acetic acid as a promoter do not activate the substrate for the hydration and only the polymerization occurs even though in lesser extent with respect to sulfuric acid.

Tab. 4 shows the hydration of styrene catalyzed by some solid acid. It is evident that the styrene di-vinyl benzene sulfonated resins are those that give the more interesting results. By the comparison of Tab. 3 with Tab. 4 entry 1-5, it is clear the lower tendency of the solid catalyst to promote styrene polymerization, but does not suppress oligomers formation. This suggests that the formation of a surface ionic intermediate which is easily attacked by the nucleophile which could be both water or the styrene itself. In such a conditions, polymerization at high molecular weight is not favored because of steric hindrance on the surface of the resins. In fact, the sulfonic group of the resin “protonates” (it is likely to be a surface interaction rather than a real protonation) forming a surface ionic couple, which is actually the reacting specie. The reduction of the degree of freedom strongly influences the attack of the nucleophile, especially if a growing chain hinders the center of reaction on the surface.

Tab. 4 entry 6-16 shows the results of styrene hydration in mixed catalysis using both solid acid and liquid acid as a promoter. The presence of TFA increases the selectivity towards 1-phenyethanol but the main products is in any case the polymer. As solid catalysts Amberlyst 15 and 36 give an evident improvement on the selectivity towards 1-phenyethanol, in agreement with the reactivity of Tab. 3, On the contrary, the mixed system solid acid/H_2SO_4 shows a negligible increase of the selectivity toward the alcohol, suggesting a preferential way for the polymerization.

Hydration of the styrene double bond appears to be a cumbersome problem because of its easy parallel polymerization reaction, which occur also by acid catalysis (radical polymerization it is likely to take place in parallel), a further problem is the reversibility of the hydration, which could give back styrene in the presence of acids. In fact, the reaction of 1-phenylethanol with TFA (entry 16) in aqueous media in the presence of Amberlyst 36 as a solid acid catalyst gives a products distribution similar to that obtained starting from styrene as a substrate, with traces of polystyrene.

Tab. 4. Styrene hydration promoted by homogeneous acid systems and catalyzed by solid acid. Run conditions: T 393 K, P autogenous pressure of the system, styrene 2.62 mmol, water 2 mL, acid 1 mmol, catalyst 40mg, and time of reaction 4h.

Entry	**Catalytic system**	**Conversion (%)**	**1-phenylethanol (%)[a]**	**dimers (%)[a]**	**Condensation products[a, b] (%)**	**Polymer (solid)[a, c] (%)**
1	Amberlyst 15	88	7	3	2	80
2	Amberlyst 36	87	7	3	1	81
3	Amberlite 50	87	/	12	2	86
4	HZSM5	89	/	2	1	97
5	D50	88	4	6	2	84
6	TFA/Amb15	65	22	20	6	52
7	TFA/Amb36	69	23	17	6	54
8	TFA/Amb50	67	16	13	6	65
9	TFA/HZSM5	70	/	25	7	78
10	TFA/ D50	66	8	10	4	78
11	H_2SO_4/Amb15	92	3	17	15	65
12	H_2SO_4/Amb36	91	3	40	14	67
13	H_2SO_4/Amb50	89	/	20	16	64
14	H_2SO_4/HZSM5	94	/	19	15	66
15	H_2SO_4/D50	93	/	26	7	67
16[d]	H_2SO_4/Amb36	50[e]	50	10	10	traces

a) Selectivity. b) Oxygenated compounds observed by GC-MS. c) Calculated by weighing the solid. d) The substrate is 1-phenylethanol. e) Styrene is the main product.

It is noteworthy the different composition of the polystyrene obtained in the presence of TFA because ^{1}H and ^{19}F NMR shows the presence of fluorinated ester terminal group (see more details in the supplementary materials), the study of the polystyrene obtained in the presence of TFA, even though interesting, is beyond the aim of the present work.

3.2 Cyclohexene hydration

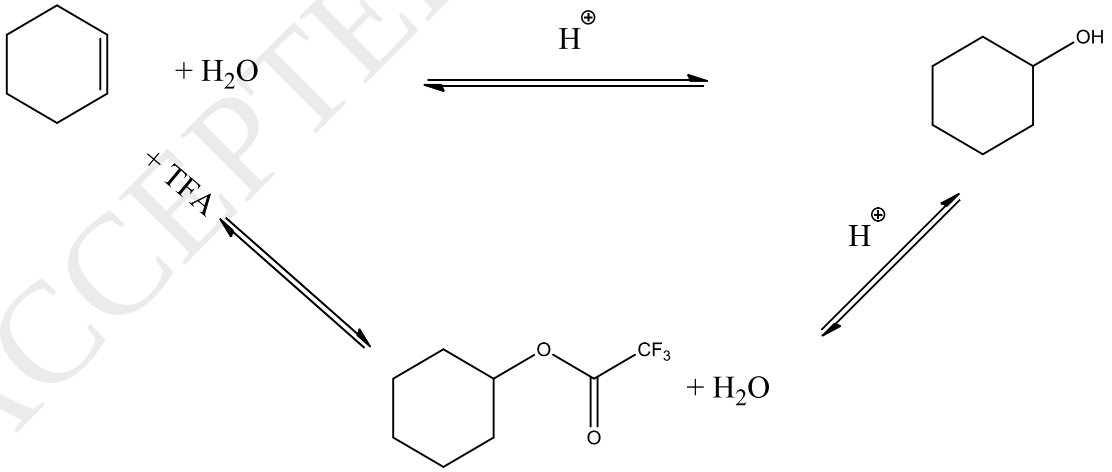
Cyclohexene hydration appears to be a problem easier than that of styrene, though, the reaction is not even and an accurate selection of the catalytic system needs. Typically, hydration is acid catalyzed and we test those employed in styrene hydration. In this case, the olefin does not polymerize as easy as styrene, and the main products are cyclohexanol and cyclohexyl trifluoroacetate (in the presence of

TFA), but, in the case of homogeneous promoters the amounts of condensation products are not negligible. Tab.s 5-7 shows some tests on the various catalytic systems. Liquid/liquid systems seem to be more effective in the multiphase batch hydrations of cyclohexene than liquid/solid ones, anyway, Amberlyst 15 and 36 show results close to that of the liquids systems. In addition, there is a neat decrease of the condensation byproducts whose presence in several percent of concentration may negatively affect a process.

Tab. 5. Cyclohexene hydration promoted by liquid acids. Run conditions: T 393 K, P autogenous pressure of the system, cyclohexene 2.62 mmol, water 2 mL, acid 1 mmol, time of reaction 4h.

Entry	**Acid promoter**	**Conversion (%)**	**Cyclohexanol selectivity (%)**	**Addition product (%)** [a]	**Condensation products (%)** [b]
1	TFA	12	48	36	8
2	H_2SO_4	12	92	/	8
3	CH_3COOH	2	/	1	1

a) Selectivity cyclohexyl trifluoroacetate. b) Calculated by difference.



Scheme 1. Cyclohexene hydration paths.

The reaction carried out in the presence of TFA shows the formation of addition products in 36% of selectivity. This product is of interest because could be converted to cyclohexanol by hydrolysis. The reactions occurring in this multiphase system are all equilibrium reactions as reported in scheme 1 and confirmed by entry 11 of Tab 7 in which the hydrolysis of cyclohexyl trifluoroacetate gives both cyclohexene and cyclohexanol as products.

Tab. 6. Cyclohexene hydration catalyzed by solid acids. Run conditions: T 393 K, P autogenous pressure of the system, cyclohexene 2.62 mmol, water 2 mL, catalyst 40mg, time of reaction 4h.

Entry	**Catalyst**	**Conversion (%)[a]**	**Cyclohexanol selectivity (%)**
1	Amb15	7	99
2	Amb36	8	99
3	Amb50	1	99
4	HZSM5	1	99
5	D 50	3	99

a) There are traces of condensation products

The best results in cyclohexanol yield are those obtained by the mixed liquid solid systems with sulfuric acid as promoter (entries 6-10). The main drawback of the system is the difficulty of achieving higher cyclohexanol yield by using reactive distillation equipment. For this reason this method with sulfuric appear to be not practical, on the contrary, a methodology based on formic acid has been proposed for the hydration of cyclohexene because of its possibility to be used in reactive distillation equipment [31, 36]. Analogously, the mixture water/TFA could be used in this type of apparatus; in addition, the sulfonated styrene/divinylbenzene resin catalyst is active in the ester hydrolysis. In Fact, the hydrolysis of the cyclohexyl trifluoroacetate (entry 11) gives cyclohexene and cyclohexanol thus suggesting that the system tends to reach an equilibrium composition. These evidences suggest that the system TFA/sulfonated resins could be a promising way for an industrial process, because of its potentiality in its use by a reactive distillation process.

Tab. 7. Cyclohexene hydration promoted by liquid acids and catalyzed by solid acids. Run conditions: T 393 K, P autogenous pressure of the system, cyclohexene 2.62 mmol, water 2 mL, acid 1 mmol, catalyst 40mg, time of reaction 4h.

Entry	**Catalytic system**	**Conversion**	**Cyclohexanol**	**Addition**

		(%)[a]	selectivity (%)	products selectivity (%)
1	TFA/Amb15	12	69	30
2	TFA/Amb36	12	68	31
3	TFA/Amb50	11	68	31
4	TFA/HZSM5	7	65	35
5	TFA/ DW50	10	66	33
6	H_2SO_4/Amb15	13	100	/
7	H_2SO_4/Amb36	12	100	/
8	H_2SO_4/Amb50	12	100	/
9	H_2SO_4/HZSM5	12	100	/
10	H_2SO_4/D50	12	100	/
11[b]	H_2SO_4/Amb36	60[c]	55	/

a) About 1-3% are traces of condensation products. b) Cyclohexyl trifluoroacetate as the substrate. c) Cyclohexene is formed in 42% of selectivity.

3.3 n-Hexene hydration

n-Hexene hydration occurs only in very low conversion, lower than that obtained with cyclohexene, this system seem to be useless for practical application especially with TFA as a liquid acid system. It is likely that the low conversion of this olefin is due to by two behaviors of the system:

i) the low solubility of the olefin in the aqueous phase; ii) the low protonation of the olefin in diluted acid. As expected, the main product of the reaction is the 2-hexanol similarly, of what already obtained in concentrated sulfuric acid [10]. Anyway, Tab. 8 shows some results suggesting that the best acid system for this reaction is sulfuric acid other acid systems give a negligible conversion. The mixed system appears to be not effective and only a negligible increase of the conversion is observed with TFA as a promoter. In sulfuric acid, the presence of the solid catalyst does not increase the conversion suggesting that is not effective compared to the neat sulfuric acid.

Tab. 8. n-Hexene hydration promoted by liquid acids and catalyzed by solid acids. Run conditions: T 393 K, P autogenous pressure of the system, n-hexene 2.62 mmol, water 2 mL, acid 1 mmol, catalyst 40mg, time of reaction 4h.

Entry	Catalytic system	Conversion (%)	2-hexanol selectivity (%)[1]
1	TFA	2	99
2	H_2SO_4	8	95
3	Amb15	<1	100
4	Amb36	<1	100
5	TFA/Amb15	3	99
6	TFA/Amb36	3	99
7	H_2SO_4/Amb15	8	95
8	H_2SO_4/Amb36	8	95

1) Traces of isomers

3.4 Cyclohexene hydration: reaction rate, profiles and equilibria

In previous chapters, we have verified the ability of various aqueous system to promote the formation of alcohol from olefins, the presence of the solid catalyst favors the formation of the latter, increasing the rate of additions of the nucleophiles. It is well known, that in cyclohexene hydration, which is an important reaction from industrial point of view, it is quite difficult achieving high yields because of its reversibility. As a matter of fact, about 10-20% of overall yield can be achieved under the conventional hydration conditions in Batch type reactor [29, 45, 46]. Reactive distillation is necessary to achieve high yield in the cyclohexanol [29, 32]. The use of an organic acid to promote the hydration it is known, in particular, the addition of formic acid to the double bond and its further hydrolysis allow the formation of the alcohol [31]. The use of a sulfonated resin in combination with the TFA as acid promoter seems to be the most promising system to achieve high yield of cyclohexanol, taking into account problem of the reversibility of the reaction. In Fig. 1 is reported a typical reaction profile of cyclohexene hydration catalyzed by sulfonated resins (Amberlyst 36 is the solid catalyst chosen for the study of the rate of reaction throughout the rest of the work) and promoted by aqueous TFA.

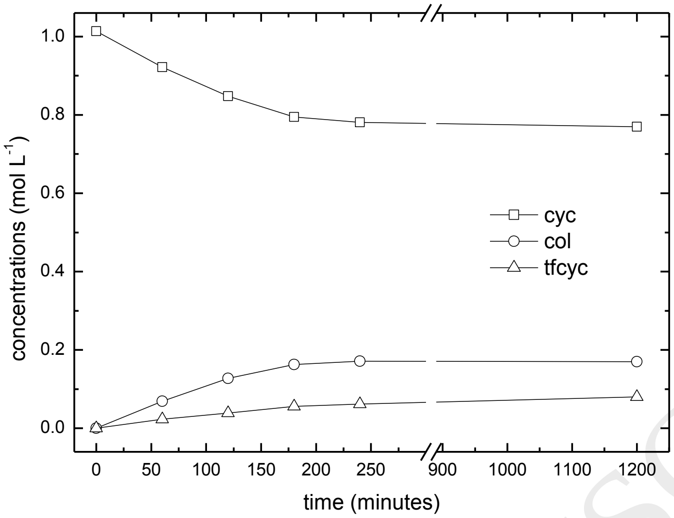
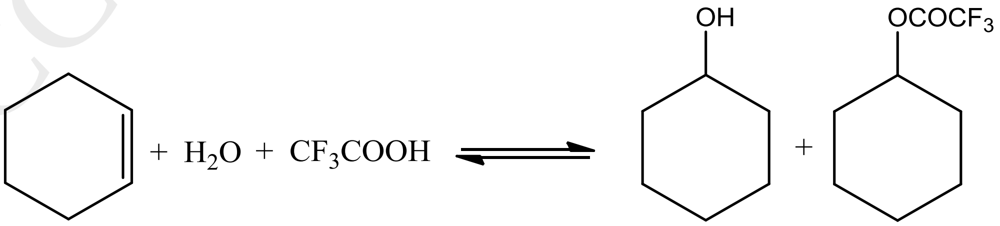


Fig. 1. Reaction profile. Run conditions: T 403 K, P autogenous pressure of the system, cyclohexene 1.14 mol L^{-1}, water 2 mL, TFA 1.32 mol L^{-1}, Amberlyst 36 40mg.

As already pointed out, the reaction occurs in two phases an aqueous phase and an organic one and, as clearly appear in Fig.1, the reaction does not go to completion but reach a value determined by the multiphase equilibria of the reaction environment. At 403K equilibrium is reached in about 4 h, but at lower temperature the system needs up to 80 h to get it. This system is affected by several equilibria, such as liquid/liquid equilibria (of all the species), acid dissociation, olefin protonation, hydration, addition equilibrium. This is a really complex system, whose study is clearly beyond the purposes of the present work, we consider, however, the overall multiphase equilibrium shown in scheme 2.

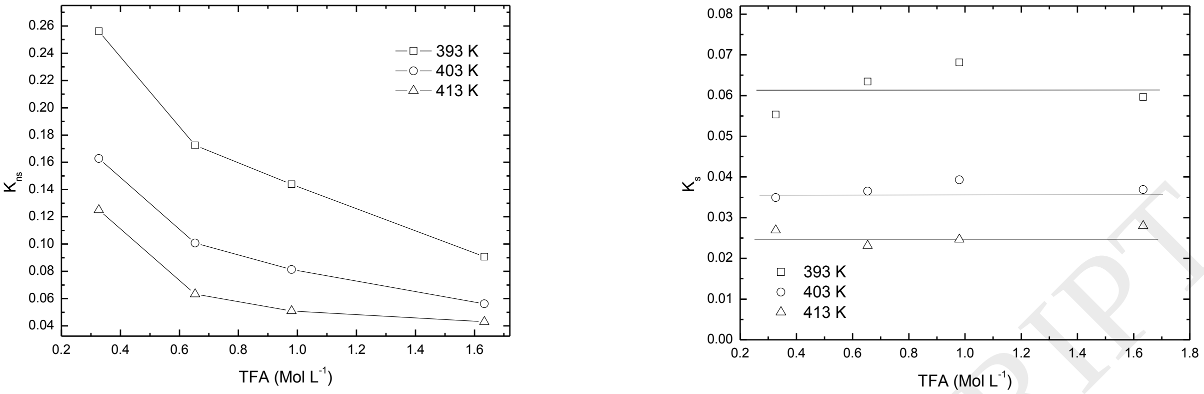


Scheme 2 Overall multiphase equilibrium

In order to try a determination of some reaction parameter we neglect the interphase equilibria by supposing that these equilibria give only proportional constant that can be embedded in the overall constant. In addition, we suppose that activities of all the non-ionic species can be considered as concentrations referred to the volume of both phases. This approximation could hold because the activity of the non-charged molecule are generally proportional to the concentration of the specie itself as well as to the charged species, by following the Setchenow equation [47, 48]. Under these limits, Equation 1 can describe the overall equilibrium. All equilibria in solution are calculated by the GC analysis of solutions obtained from the sample extracted with CH_2Cl_2, except for TFA for which the literature dissociation degree are used and employing the values of the activity coefficient calculated for the ionic species [49, 50].

$$K_{sn}(w) = \frac{[CyTf][Ol]}{[Cy]\,[TFA]} \qquad \text{Equation 1}$$

It is clear from Fig. 2 A, however, that this over-simplified hypothesis does not hold, because there is a clear dependence of this pseudo-equilibrium constant (K_{sn}) obtained from Equation 1 from total TFA concentration. This effect could be caused by the salting out effect, which diminish the concentration of cyclohexene in the aqueous phase, thus affecting the equilibrium in function of the amount of the charged species. As a matter of fact, in Equation 2 we take into account the activity of the hydrogen ions in order to compensate the increase of the charged species in solution whose effect cause a reduction of the solubility of the cyclohexene. The correction introduced in Equation 2 allows one to obtain a K_s as a constant over the range of TFA concentration studied in the present work and at 3 different temperatures as can be observed in Fig. 2 B.



A

B

Fig. 2 Overall equilibrium constant obtained by varying temperature and TFA concentrations.

$$K_s(w) = \frac{[CyTf][Ol]a_{H^+}}{[Cy]\,[TFA]}$$ Equation 2

A linear Van't Hoff plot (Fig. 3) is obtained from the average of the *K*$_s$ obtained at different TFA concentration and an overall exothermic effect with a value of ΔH° = -57kJ mol^{-1}, and ΔS° = 175 J K^{-1} mol^{-1}. The values are in agreement with thermodynamic data of individual reactions carried out in much ideal condition, thus suggesting a good reliability of the parameter proposed [51 52].

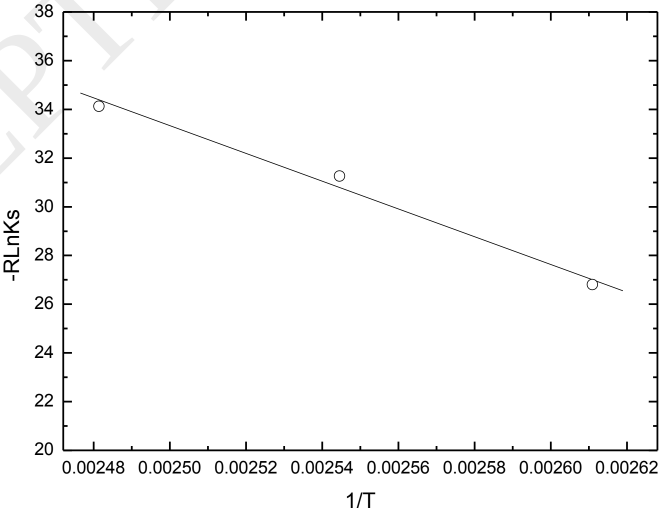


Fig. 3 Van't Hoff plot. Equilibrium constant variations with temperature: ΔH° = -56kJ mol^{-1} and ΔS° = 175 J K^{-1} mol^{-1}.

3.4.1 Influence of the amount of the aqueous phase on the initial reaction rate

Initial reaction rate is a complex parameter because is a combination of the various process occurring in the reaction, however, it gives a reliable value on the overall behavior of the reaction. The presence of two immiscible liquid phase clearly indicate the presence of mass transfer between the two phases, these process are seldom determining the overall reaction rate. The amount of aqueous phase seems to influence faintly the initial reaction rate also at two different acid concentrations. This suggests the two phases are mixed together homogenously at different substrate aqueous phase ratio.

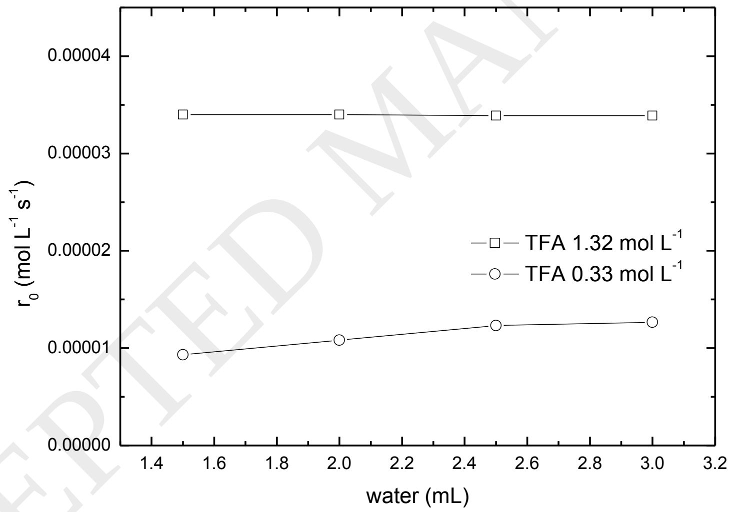


Fig. 4. Influence of the amount of the aqueous phase on the initial reaction rate. Run conditions: T 393 K, P autogenous pressure of the system, cyclohexene 1.14 mol L^{-1}, water 2 mL, Amberlyst 36 40mg.

3.4.2 Influence of cyclohexene amount on the initial reaction rate

The variation of the amount of cyclohexene does not influence the initial reaction rate, actually, the biphasic conditions allows a constant concentration in the aqueous solution of the substrate. This is an evidence that the reactions occurs in the aqueous phase for this reason the amount of cyclohexene faintly influence the rate of reaction, being the concentration of substrate almost constant in the aqueous phase at low conversions. The constancy of the initial rate of reaction observed in Fig. 5 for two different concentrations of TFA confirms the homogeneity of the emulsion induced by the agitation visually observed at room temperature for the same reaction system.

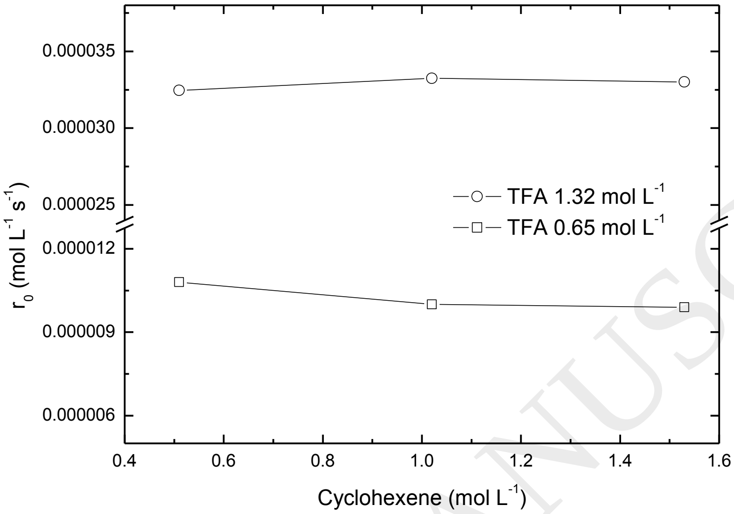


Fig. 5. Influence of cyclohexene amount on initial reaction rate. Run conditions: T 393 K, P autogenous pressure of the system cyclohexene 1.14 mol L^{-1}, water 2 mL, Amberlyst 36 40mg.

3.4.3 Influence of TFA concentration on the initial reaction rate

Fig. 6 shows the influence of the TFA concentration on the initial reaction rate, the when TFA concentration is 0 the reaction proceed by the acid catalysis of the sulfonated resins, achieving a conversion of 8% after 4h of reaction and with an initial rate of reaction of 6 10^{-6} mol L^{-1} s^{-1}. The increase of the rate appear to initially low but after 0.6 mol L^{-1} s^{-1} the increasing is stiff with a neat slowing down after 1.5 mol L^{-1}s^{-1}. This trend looks like a titration suggesting the formation of a TFA-cyclohexene adduct, a further indication of the formation an active adduct TFA-cyclohexene, as the key intermediate is the fact that the flex of the curve coincide with the concentration of the olefin. Anyway, such an evidence allow only a mere hypothesis, because of the complexity of the system. More thermodynamics and mechanistic researches are necessary for the determination of the reaction steps.

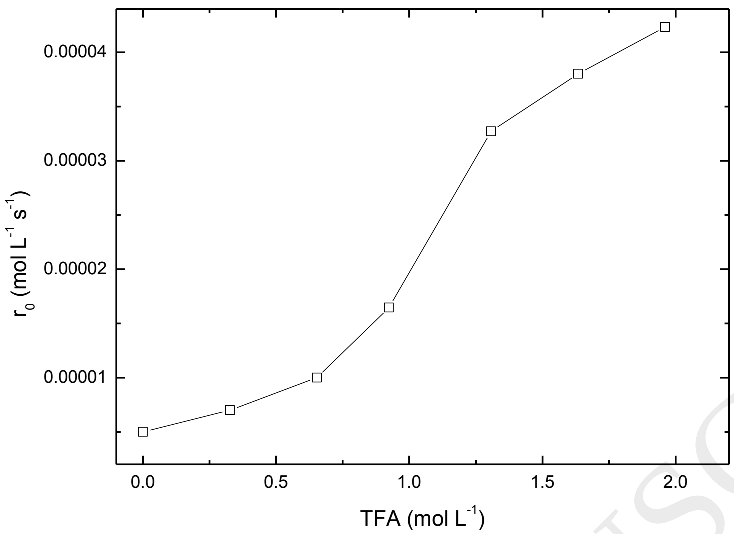


Fig. 6. Influence of the TFA amount on the initial reaction rate. Run conditions: T 393 K, P autogenous pressure of the system, cyclohexene 1.14 mol L^{-1}, water 2 mL, Amberlyst 36 40mg.

3.4.4 Influence of the sulfonated resin amount (Amberlyst 36) on the initial reaction rate

Fig. 7 shows the trend obtained between the initial reaction rate and the sulfonated resin amount. It is clear that in both cases with and without TFA the initial reaction rate increase linearly, what is interesting is the fact that the slope of the two straight line are quite similar suggesting that the increase of the initial rate is due to the same phenomenon. It is likely that the solid catalyst, at the initial stage of the reaction, promotes hydration of the olefin as and it is not influenced by the presence of TFA, similarly TFA addition to the cyclohexene is not promoted by the resins. Actually, the slope of the TFA promoted reaction is only 0.54 10^{-7} higher than that of the unprompted one. The intercept of the reactions without TFA is very close to 0 which imply the necessity of the catalyst to achieve the reaction. On the contrary, reactions carried out in the presence of 1.32 mol L^{-1} of TFA show an intercept close to the initial rate of the reaction carried out without catalyst (filled point at 0 sulfonated resins amount). The black filled circle represent the experimental data at 0 resin concentration, in agreement with the intercept of the straight line of the fitting.

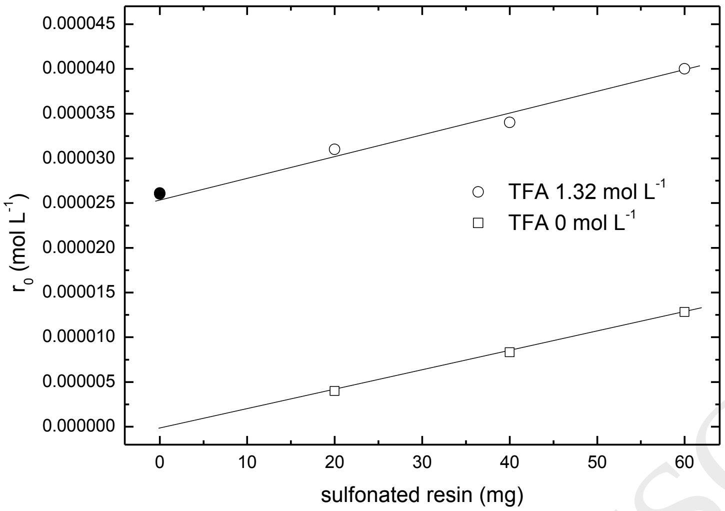


Fig. 7. Influence of the catalyst amount on the initial reaction rate. Run conditions: T 393 K, P autogenous pressure of the system, cyclohexene 1.14 mol L^{-1}, water 2 mL. TFA=0 slope = 2.21 10^{-7}, intercept = -4.4 10^{-7}; TFA = 1.32 mol L^{-1} Slope = 2.45 10^{-7}, Intercept = 2.59 10^{-5}.

3.4.5 Influence of Temperature on the initial reaction rate

The influence of temperature on initial reaction rates are reported in Figs 8 and 9. The initial trends of the reactions are almost linear with time but the overall kinetics is not of first order as can be observed in Fig. 1 for the complete reaction, as a matter of fact, the multiphase system allow a constant composition especially at low conversion, showing a zero order like reaction path. In addition, as observed in figs 2 and 3 the variation of the ration of the two liquid phases does not alter initial reaction rate. Starting from these evidences, we calculate an overall temperature factor by the Arrhenius plot of Fig. 9. The values of ΔE_{ft}=84 kJ mol^{-1} has been calculated with a pre-exponential factor of ΔS_{ft}=151 J mol^{-1} K^{-1}. The value of the temperature factor are quite high suggesting no limitation of the diffusion on the reaction rate [18, 19, 52]. In addition, such a value suggest that the increase the temperature favors the attainment of the equilibrium, but reactions are exothermic, than the equilibrium is shifted to the left as the temperature increase. These parameters are the starting point for the realization of a reactive distillation process in order to achieve high conversion to cyclohexanol by using TFA as an easily recoverable non-toxic organic acid [53, 54].

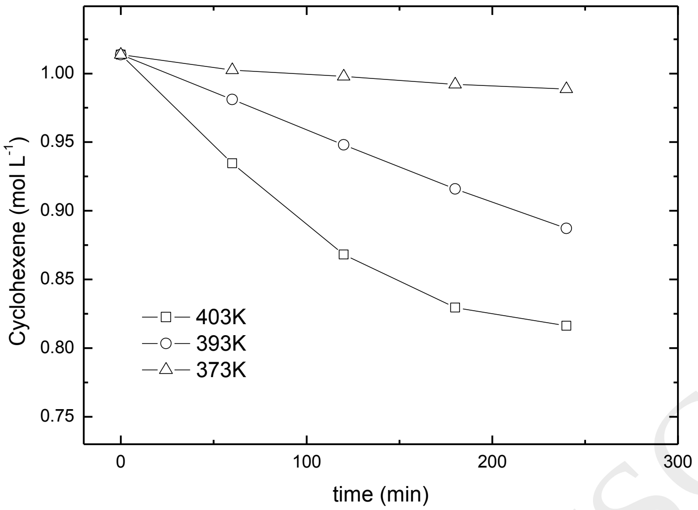


Fig. 8 Influence of Temperature on the initial reaction rate. Run conditions: T 373-403 K, P autogenous pressure of the system, cyclohexene 1.14 mol L^{-1}, water 2 mL, TFA 1.32 mol L^{-1}, Amberlyst 36 40mg.

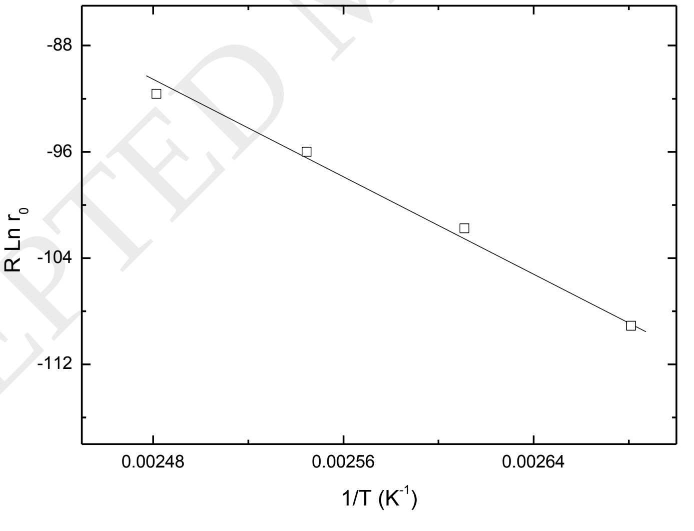


Fig. 9. Arrhenius Plot. Run conditions: T 373-403 K, P autogenous pressure of the system, cyclohexene 1.14 mol L^{-1}, water 2 mL, TFA 1.32 mol L^{-1}, Amberlyst 36 40mg. ΔE_{ft}=84 kJ mol^{-1}, ΔS_{ft} =151 J mol^{-1} K^{-1}

3.4.5 Catalyst recycling

The experimental observation above descripted suggest that the presence of the TFA is main factor that influence the yield to cyclohexanol, however the presence of the acid resin favors the attainment of the equilibrium. This may help in the development of a process based on this reaction. The increase of the reaction rate due to the presence of the resin could be considered as not determining for the practical development of a process. In fact, the increases of the reaction rate, in the presence of 40 mg of catalyst is only 30% (see Fig. 7) with respect of the reaction rate in the absence of the solid acid. However, the absence of an evident deactivation after 4 recycles it suggests that could be practically employed in a process. In addition, because of its ability in the reaction of hydrolysis it could be used in a second stage of cyclohexyl trifluoroacetyl ester saponification to give acid and alcohol.

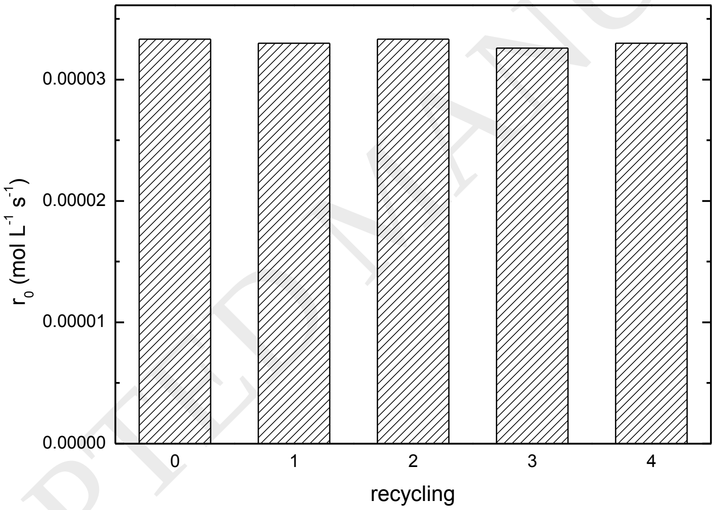


Fig. 10 Catalyst recycling. Run conditions: T 393K, P autogenous pressure of the system, cyclohexene 1.14 mol L^{-1}, water 2 mL, TFA 1.32 mol L^{-1}, Amberlyst 36 40 mg

As regard TFA recovery, the acid can be easily separated from the reaction environment since it is in the aqueous phase, however, the reuse of the acid phase depend on the hydrolysis step of the cyclohexyl trifluoroacetate, whose study is beyond the aim of the present work. Besides, it is noteworthy that the recovery of the TFA has been studied in the Beckmann rearrangement of oximes, in which there were no needs of neutralization but a simple distillation [54]. In this case, separation is even simpler, since the acidic phase can be reused directly as a liquid aqueous phase.

4. Conclusions

In this work, we show the potentiality of TFA in the promotion of the hydration olefin to alcohol. It acts by forming the ester intermediate, which reaches an equilibrium with olefin and alcohol, together with traces of condensation products (ether and light oligomer). The reactions occurring to reach the equilibrium are acid catalyzed, for this reasons TFA acts also as catalyst, but a further increases of the rate of the processes are achieved by using sulfonic resins as acid catalysts. The thermodynamic parameter of the overall equilibrium are calculated, and it shows a strictly dependence from TFA dissociation suggesting a firm relationship between equilibria and the ionic species in solution. The Van't Hoff plot gives enthalpy and entropy in quite good agreement with the literature values. The temperature factor of the initial reaction rate are in agreement with those of similar reaction. The solid catalyst Amberlyst 36, which is those largely employed during kinetics and equilibrium experiments, shows at temperature of 393K a negligible loss in activity after 4 recycling.

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