Waste-reducing catalysis for acylation of a secondary amine: synthesis of DEET

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Mixed oxide catalysts were studied for a model acylation – *m*-toluic acid reacting with diethylamine to *N,N*-diethyl-3-methylbenzamide (DEET) – and compared to standard homogeneous catalysts such as titanium chelates. More acidic catalysts such as hydroxyapatites and supported 12-tungstophosphates were active, stable in a gas phase, and selective with stoichiometric feeds. Optimal results (long-term MTA conversion of 78 ± 6%, DEET selectivity of 86 ± 3% at WHSV = 3–9 h^{-1}, no deactivation over 100 h) were obtained with a supported 12-tungstophosphate at 573 K, 0.1 MPa.

KEY WORDS: *N,N*-diethyl-3-methylbenzamide; DEET; catalytic acylation; heteropolyacid; hydroxyapatite.

1. Introduction

N,N-diethyl-3-methylbenzamide (DEET) is a synthetic amide widely used as the most effective ingredient in repellents for mosquitoes and other blood-sucking insects. Soluble titanium alkyl and acetyl complexes, chelated with amines (DuPont Tyzor©, e.g., the bis(triethanolamine) diisopropoxide titanate), are commercial catalysts for DEET synthesis by the acylation (or amidation) of *m*-toluic acid (MTA) and diethylamine (DEA) [1]. The conversion of MTA to DEET is about 90% with 91–95% selectivity when the acylation is conducted at 493–508 K at autogeneous pressure for about 24 h with a stoichiometric (1/1 mole ratio) feed. The catalyst is not recyclable and the catalyst/MTA ratio is high, about 1 g/mol MTA. The product water must be removed continuously in order to reach this high conversion [1]. Alternatives such as the hydroamidation reactions (carbonylation of an alkene in the presence of an amine or NH_3) are effective for production of formamides and primary amides, but are far less effective with secondary amines; excess ligand or organic solvent are required [2].

Several heterogeneous catalysts have been studied as potential replacements for Ti-amines in DEET synthesis [3–6]. However, excess amine or very long reaction times were required to obtain high MTA conversions. For example, a boron phosphate catalyst gave 88% MTA conversion with 88% selectivity to DEET at 550 K, atmospheric pressure, with a 1/4 MTA/DEA (molar ratio) feed [3]. Alumina-supported inorganic acids also gave conversions up to 90% at ~590 K when the pKa range of the initial acids was 6.5–7.5 [4]. For mildly acidic calcium hydroxyapatites [$Ca_{10-x-y}H_{x+y}(PO_4)_6(OH)_{2-x-y}$ $((x+y) \leq 2)$], the optimum (90–95% MTA conversion, >90% selectivity) conditions were MTA/DEA = 1/5–1/7, 573–593 K, and WHSV (weight hour space velocity on a total feed basis) of only 0.1–1.3 h^{-1}. Other partially dehydrated metal (Zr, Ti and Sn) hydroxides have been studied for acylations of secondary amines with similar results [5]; some yields were high, but only at acid/amine ratios of 1/10, and long residence times (~5 h).

The literature on acylation reactions suggests that strongly (but not super-) acidic solid catalysts with both Lewis and Brønsted sites may be good catalysts for sec-amine acylations. Example materials include the hydroxyapatites and other structured phosphates [3,4,7], 12-tungstophosphoric acid and its salts [8,9], and 12-molybdophosphoric acid and its salts [9]. The last two are especially attractive because their Bronsted acid strengths and Lewis/Bronsted site ratios can be greatly affected by substituting Cs-ions for protons and/or by altering the hydration states of the cations [8,10–13]. They can also be supported in high dispersion on high surface area carriers such as mesoporous silicas without completely disrupting the α-Keggin structure of the anions by decomposition to WO_3 and P_2O_5 [8–11,13]. Finally, the literature also suggests that weakly basic (or amphoteric) oxides such as ZnO, ZrO_2, Y_2O_3/ZrO_2 and CeO_2 may also be selective sec-amine acylation catalysts [5,14–16].

Our goal was to develop long-lived and selective heterogeneous catalysts as potential replacements for the homogeneous catalyst, while still operating with stoichiometric feeds to minimize the operational problems associated with excess amine. From a separation cost and safety standpoint, it is easier to recycle DEET

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than amine. Considering the unstable nature of the Ti–amine complexes, we wished to compare several types of strong supported acids, and weakly basic metal oxides, to the supported Ti–amine complexes. We have characterized the product slates of the different catalyst classes, and explored their deactivation behavior, a subject seldom discussed in the amine acylation literature.

2. Experimental

2.1. Catalyst preparation

Supported Tyzor TE [titanium bis(triethanolamine) isopropoxide, 80 wt% in propanol, Aldrich] catalysts of different loadings were prepared by incipient wetness impregnation. The desired quantity of support (Davison 57 silica gel, 8 mesh; Vista 1.6 mm extrudate Al_2O_3; LaRoche TiO_2, with 15 wt% Al_2O_3) was dried under vacuum at 573 K and contacted under N_2 with Tyzor TE further diluted in 2-propanol to give 15.0, 11.4 and 4.6 atom% Tyzor (on a metal atom basis) for SiO_2, Al_2O_3 and TiO_2, respectively. The loadings were chosen to give ~0.015 mmol/m^2 of Tyzor complex on each support. The catalysts were dried under vacuum at 523 K overnight.

Calcium hydroxyapatite ($Ca_{10-x-y}H_{x+y}(PO_4)_6(OH)_{2-x-y}$, $x+y \leq 2$) catalysts were prepared according to Bett *et al.* [17], by titrating a saturated $Ca(OH)_2$ solution with concentrated phosphoric acid (85%, Mallinckrodt) under N_2. The gelatinous precipitate was filtered and washed several times until the washings were pH ~7.0, then dried at 448 K and calcined in air at 773 K for 1 h. The final solids were pelletized and sieved to 20~40 mesh.

Silica-supported 12-tungstophosphoric acid (TPA) was obtained from ExxonMobil research (40 wt% TPA on silica gel). Supported catalysts of the cesium salts of 12-tungstophosphoric acid of different Cs/H ratio were prepared according to a two-step impregnation method [10]. First, MCM-41 prepared according to the literature [18,19] was impregnated with Cs_2CO_3 (Aldrich, 99.9%) by incipient wetness, dried at 383 K and calcined at 773 K for 2 h. The TPA (α-12-tungstophosphoric acid hydrate, reagent) was dissolved in solvent (1 gTPA/1 mL, water for Cs/H = 2.5/0.5 and 1-butanol for Cs/H = 1/2) and impregnated similarly. The Cs–TPA catalysts were dried at 383 K and calcined at 573 K in 100 mL/min air for 2 h.

2.2. Catalyst characterization

Catalyst surface areas were determined by the BET method using an Omnisorp 360. For thermogravimetric analysis (TGA, Perkin–Elmer 7), the catalysts (12–17 mg) were first ground to >100 mesh. The sequence of treatments for coke analyses was:(1) dry (100mL/min He) at 823 K; (2) oxidize at 823 K with 50% air/50% He for 120 min.

Investigation of total and Bronsted acid contents of the catalysts was by TPD of 1-propanamine (1-PA) in the TGA [20,21]. The sequence of treatments was: (1) dry (100mL/min He), 32–48 K at 10 K/min, hold 10 min; (2) adsorb at 323 K by bubbling He through 1-PA for 10 min; (3) desorb 1-PA and its elimination products C_3H_6 and NH_3 at 50–823 K, 5 K/min. For most of the catalysts a peak associated with very strong acid sites appear at ~570–650 K. For the hydroxyapatites, total proton concentrations were also estimated by TGA in He, assuming the following reaction occurs at 77–173 K [17]:

$$\begin{aligned} &Ca_{10-n}(PO_4)_{6-2n}(HPO_4)_{2n}(OH)_2 \\ &\quad \rightarrow Ca_{10-n}(PO_4)_{6-2n}(P_2O_7)_n(OH)_2 + nH_2O \end{aligned} \tag{1}$$

The Ca^{2+}/H^+ ratios were 7.9 (HEA00) and 6.3 (HEA01).

2.3. Reaction studies

Kinetic experiments were performed in 316 stainless steel tubular reactors (1.25 cm ID, 15 cm length). Typical catalyst loadings were 0.5–2.0 g. Reactor temperatures varied between 518 and 593 K, pressures between 0.1 and 3.5 MPa. The temperature was controlled using a 1/16″ K-thermocouple in contact with the catalyst bed, and controlled to within ± 1 K. The pressure was controlled with a diaphragm-type backpressure regulator (Grove Mitey Mite).

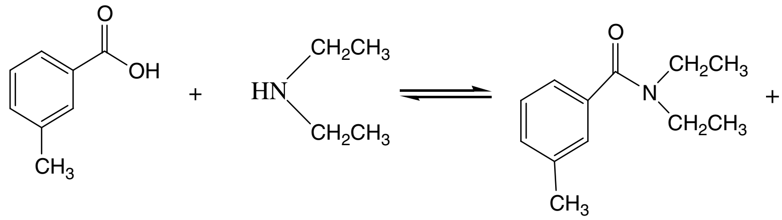
Feeds were prepared from *m*-toluic acid (Aldrich, 99%), diethylamine (DEA, Aldrich, 99.5 + %), and DEET itself (MGK, 95 + %). Product samples of 0.1 mL were collected and diluted with 0.9 mL of 10% (vol) toluene internal standard in methanol. The organic phase was analyzed by FID-GC on an Alltech EC-1 column (30 m×0.32 mm). Peak identifications were made using a similar column in an H-P 5900 GC with mass-selective detector (H-P 5972). The overall mass balance based on these GC results closed to !2%. Further details may be found in a thesis [22].

3. Results and discussion

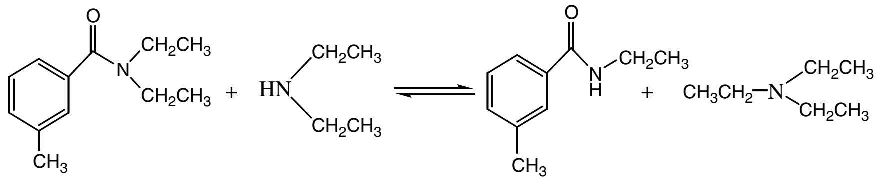
3.1. Thermodynamic analysis

The primary reaction is (2). The principal decomposition reaction of DEET produces *N*-ethyltoluamide (ETA) and triethylamine (4):

The equilibrium constant K_e for reaction (2) can be written as:



(3-1)



(3-2)

$$K_e = (\alpha + X)X/(1 - X)(\beta - X)$$

α = [DEET]/[MTA] molar ratio in feed,
β = [DEA]/[MTA] molar ratio in feed,
X, MTA fractional conversion.

The only published data for K_e of (2) are based upon maximum conversions in aqueous acid from 533 to 593 K [4]:

$$K_e = \exp(8.81 - 3019.25/T) \quad (5)$$

The K_e values for the gas phase reactions were calculated from both tabulated and estimated (DEET and ETA, by both the Joback and Reid [23] and the Cohen and Benson [24] methods) values of the Δ H_f, Δ G_f, and C_p[22]. For the Δ H_f of DEET a value of −140 kJ/mol at standard conditions was calculated from a heat of reaction of (2) [4], because the values given by the estimation methods differ by more than 70%. Otherwise the two methods give similar property estimates for both DEET and ETA. The results for equilibrium MTA conversion, summarized in table 1 for a typical feed, are compared with those calculated from equation (5) and those estimated from maximum conversion data with [4]. According to these data, it should be possible to obtain MTA conversions to DEET of ~80% at about 573 K using a feed of 1/1/0.4 MTA/DEA/DEET molar ratio (feed B), which forms a single liquid phase at ambient temperature after stirring for several hours. Feed A (1/1/0.75 MTA/DEA/DEET) forms a single liquid phase rapidly. Feed C (1/1 MTA/DEA) is two liquid phases. The side reaction is more irreversible, so it is possible to obtain even higher conversions of MTA when there is less than 100% DEET selectivity.

Table 1
Maximum MTA conversions[a], total pressure = 0.1 MPa

T K	Max. MTA conversions of Ref. [4], solid catalysts	From equation (5) [4]	From thermodynamic data [22]
533	48	80	79
573	55	83	81
593	62	84	82

[a] Feed B, DEA/MTA/DEET = 1/1/0.4, molar ratios.

3.2. Control experiments

Without a catalyst, the reaction occurred very slowly (2% conversion at 1.6 h^{-1} liquid hourly space velocity) but with >90% selectivity to DEET. Conversely, with a plain support such as Davison 57 silica gel (300 m^2/g) the DEET selectivity is only ~80% but a maximum conversion of 55% is possible at 573 K, 0.1 MPa pressure. The main by-product is ETA. Other products at trace level included *m*-tolunitrile, ethyl *m*-methyl benzoate, *N,N*-diethylbenzamide, *o*-DEET, *p*-DEET, *N*-ethylbutyltoluamide, substituted trimethylbiphenyls and other heavy compounds. The only products above trace level other than DEET and ETA are triethylamine and *N,N′*-diethyl-1-butanamine; both are clearly associated with ETA production.

The silica gel catalyst does lose activity for DEET production; there is a 10% loss of selectivity in <20 h time-on-stream, and regeneration is not possible. This correlates with a doubling (0.04–0.08 mmol/g) in high temperature 1-PA desorption, which is associated with very strong acid sites.

There are two possible ETA sources when DEET is added to the feed. One source is the reaction of MTA with the disproportionation products of DEA, monoethylamine and triethylamine (TEA). The other is from the reaction of DEET itself with DEA, to give ETA and TEA. We used feeds of DEA/tetrehydronaphathalene (inert) at typical reaction conditions to check for the disproportionation of DEA, and found no TEA product and little reaction of DEA, proving that ETA was formed mainly by the serial decomposition of DEET.

3.3. Anchored Ti-complex catalysts

Tyzor TE was mounted onto the oxide supports SiO_2, TiO_2or Al_2O_3in ~0.015 $mmol/m^2$ support surface area. Table 2 gives optimal (maximum yield) results, obtained prior to deactivation. The conversions at low pressure

Table 2
Reaction to DEET on supported Tyzor© catalysts

Catalyst	*T*, K	*P*, Mpa	Feed[a]	WHSV[b]	MTA Conv., %	Selectivity to DEET, wt. %
TE/TiO_2, 46 m^2/g	518	2.14	A	1.4–3.2	45 ± 5	93 ± 3
	523	2.14	A	0.8–1.4	38 ± 5	85 ± 3
TE/Al_2O_3, 72 m^2/g	518	2.14	A	1.2–1.8	28 ± 2	92 ± 5
	523	0.85	A	1.0–1.9	30 ± 2	88 ± 3
	523	2.14	A	0.9–1.2	40 ± 5	85 ± 3
	533	2.14	B	1.2–1.8	43 ± 3	88 ± 2
TE/SiO_2, 89 m^2/g	528	2.14	A	3	45 ± 9	84 ± 3

[a] Feed A, DEA/MTA/DEET = 1/1/0.75; Feed B, DEA/MTA/DEET = 1/1/0.4, molar ratios.
[b] Weight hourly space velocity, weight of feed/h/gcat.

were about 10% less than at high pressure, but with almost the same selectivity. The calculated saturation vapor pressure at 523 K is 1.1 MPa for Feed A [22]. Therefore, the reactor contents are mostly gas phase at 0.85 MPa but mostly liquid phase at 2.14 MPa. Generally, the selectivity using Tyzor TE/TiO_2 or Al_2O_3 catalysts could reach 95%, which is the same as that obtained using homogeneous Tyzor TE catalysts [1]. The maximum MTA conversions using supported Tyzor catalysts were far less than the typical homogeneous MTA conversion of 93%, and they are well below the equilibrium conversions estimated from thermodynamic data (table 1), even at quite low space velocities. However, the higher conversions using homogeneous catalysts are obtained by removing a product (water) continuously, and the reaction times here are long – about 1 day at 493–508 K.

For these catalysts, air regeneration is not possible because the triethanolamine ligands are slowly oxidized in air when the temperature is greater than 563 K [25]. Our TPD results also showed that in high temperature air, the supported Ti–amine was oxidized to TiO_2 gradually [22]. While such Ti–amine complexes are more stable in inert gas, we found triethanolamine ligand loss of up to 1.6 ligands per Ti atom after extensive treatment in N_2 at 523 K. Although treatment at 523 K with N_2 restored some activity to the spent catalysts, they still deactivated rapidly, losing 20–30% of their activity in 12 h. Use of higher reaction temperatures also resulted in destruction of the complex, and so both lower conversion and selectivity.

Further experiments with higher loadings on these supports did not improve upon these findings. Weakly basic or amphoteric materials such as ZnO, ZrO_2, CeO_2 and TiO_2 are less active than supported Tyzor complexes for sec-amine acylation. More typical basic oxides such as supported MgO (on SiO_2, TiO_2 or ZrO_2), SrO_2 or La_2O_3 did not give selectivities >85%, even with lower activity, and deactivated rapidly. The same was true of acid zeolites such as H-MFI and Ga-MFI. One problem here was excessive decomposition to ETA, the more stable product. Coupling reactions of DEET to substituted biphenyl and heavier products were also detected, along with increased amine coupling and disproportionation reactions. Selectivities were even worse with basic zeolites such as CsK-MFI or BaK-L, for similar reasons. Therefore these catalysts offer few advantages even over a plain SiO_2 support.

3.4. *Hydroxyapatites and heteropoly oxometalates*

The surprising results for SiO_2, and the indications that supported phosphates were in the correct acid strength range for DEET production, led us to examine both hydroxyapatites and the (generally) more strongly acidic 12-tungstophosphates. In previous work with calcium hydroxyapatites, low conversions were found except at very low WHSV [4]; we believed based on the literature for hydroxyapatites that careful precipitation to control particle size and suitable variation of the Ca^{2+}/H^+ ratio might overcome this limitation [7,17].

The series of Ca-defective hydroxyapatites was of general formula $Ca_{10-x-y}H_{x+y}(PO_4)_6(OH)_{2-x-y}$, with $x + y$ kept low to maintain thermal stability. These were tested catalytically at 53–93 K, 0.1–3.5 MPa. We also used these experiments to clarify the effects of liquid versus gas phase operation, i.e., gross pressure effects, for the acidic solids. The estimated saturation vapor pressure of Feed B at 573 K is 1.87 MPa [22], which suggests that the feed was all gas at 0.44 and 0.78 MPa

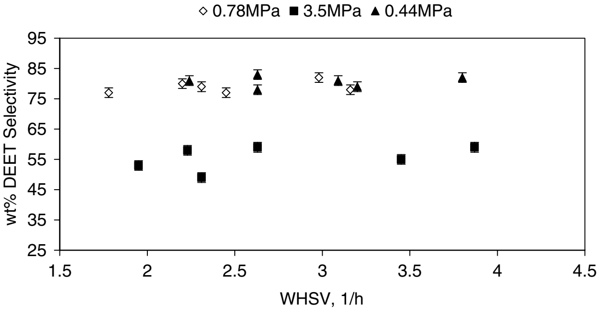


Figure 1. Pressure effects on hydroxyapatite catalyst (HEA00, $Ca^{2+}/H^+ = 7.9$), 573 K, feed B (DEA/MTA/DEET = 1/1/0.4).

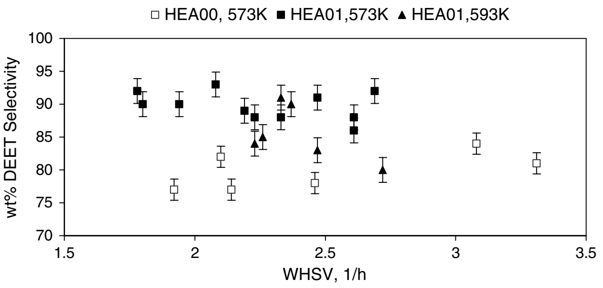


Figure 2. Effects of Ca^{2+}/H^+ ratio for hydroxyapatite catalysts (HEA00, $Ca^{2+}/H^+ = 7.9$, HEA01, $Ca^{2+}/H^+ = 6.3$), 0.1 MPa, feed B.

but mostly liquid at 3.5 MPa. The results of figure 1 demonstrate that low pressure, gas-phase operation is superior, as the conversions at the highest pressure were only ~5% higher at comparable WHSV. DEA is a stronger base than DEET, and when both are in the gas phase DEA should be adsorbed preferentially. The increased pressure probably resulted in less discrimination between the two, and so more DEET was present on the surface to decompose. There may also be a phase distribution effect here; the temperature is higher than the critical temperature of DEA (493 K) but lower than the critical temperature of DEET (766 K). Therefore, as a liquid phase wets the catalyst more efficiently than the gas when two phases are present, the DEET/DEA molar ratio in contact with the catalyst would increase with pressure, also resulting in more decomposition of DEET.

The Ca^{2+} /H^+ ratio varied within a typical range for hydroxyapatites in order to optimize the selectivity. From figure 2, it is seen that a lower Ca^{2+}/H^+ ratio favored higher selectivity. It was also more active by ~5% higher conversion (65% maximum at 0.1 MPa, 573 K), even though this catalyst had lower surface area (37 m^2/g versus 79 m^2/g for HEA00). This trend in surface area is consistent with previous results for porous hydroxyapatites [17]. HEA01 shows far more acid sites of moderate strength (1-PA desorption from 47–73 K), 0.12 versus 0.01mmol/g for HEA00, but fewer very strong acid sites (>573 K 1-PA desorption), 0.072 versus 0.16mmol/g for HEA00. In other words, decreasing the Ca^{2+}/H^+ ratio eliminated stronger acid sites that apparently lead to DEET decomposition to ETA. Hydroxyapatites exhibit three types of acid sites: those associated with P–OH groups, those formed by the interaction of water with Ca^{2+}, and weak sites associated with water adsorption elsewhere [7]. From the above results it would appear that the second type is stronger and more likely to result in DEET decomposition.

The optimal reaction temperature for hydroxy apatites is ~573 K (see figure 2), but offline treatment at this temperature is not sufficient to recover lost activity. The hydroxyapatites were stable (tested for >140 h) with periodic air regeneration at 773 K. Subsequent TGA analysis for coke showed ~0.08% oxidizable material after such regeneration. While high temperature air also removes some structural water from hydroxyapatites, this effect is only temporary in the water-rich environment of the DEET reaction; the initial selectivity is recovered rapidly. However, from table 1 it is clear that the activities of hydroxyapatites at 0.1 MPa are still below the thermodynamic equilibrium limit.

Tungsten heteropolyacids and their salts (TPAs, $A_xH_{3-x}PW_{12}O_{40}$, A is generally an alkali ion, and the anion has the α-Keggin structure) are highly uniform oxides useful for both acid-catalyzed and redox reactions. The stability of the α-Keggin structure in the solid state is good, up to 723–773 K, above which temperatures bulk dehydration occurs [8,13]. This means that TPAs can be regenerated with air, if necessary, at temperatures where the heavy byproducts from DEET manufacture are decomposed (~773 K).

A series of TPA catalysts were prepared by supporting TPA at high loadings on either silica gel or on MCM-41. The three used in reaction experiments are described in table 3; a more heterogeneous acid site density (than crystalline $H_3PW_{12}O_{40}$) is typical of supported TPAs [8,13]. The supported TPAs are more active, selective and resistant to deactivation than the hydroxyapatites. For 40 wt% TPA/SiO_2 ($H_3PW_{12}O_{40}$), the best long-term results were obtained when the acylation reaction was conducted at WHSV 3–9 h^{-1}, 573 K, 0.1–0.95 MPa. There was little change upon raising the temperature to 593 K; selectivity is adversely affected only at the lower space velocities (WHSV $< 3\ h^{-1}$). The catalyst showed no sign of permanent deactivation in >250 h of operation if there were periodic overnight air treatments at 723 K; in fact, some

Table 3
Properties of supported 12-tungstophosphates (TPAs)

Cs^+/H^+	Loading (wt.%)	Total 1-PA adsorbed (mmol/g)	Strong acid sites[a] (mmol/g)	Very strong acid sites[a] (mmol/g)	Surface area (m^2/g)
2.5/0.5	40	1.61	0.21	0.19	130
1/2	50	1.51	0.15	0.13	290
0	40	0.98	0.13	0.10	150

[a] Strong: 1-PA desorption <473 K; very strong: 1-PA desorption >573 K, almost all between here and 650 K.

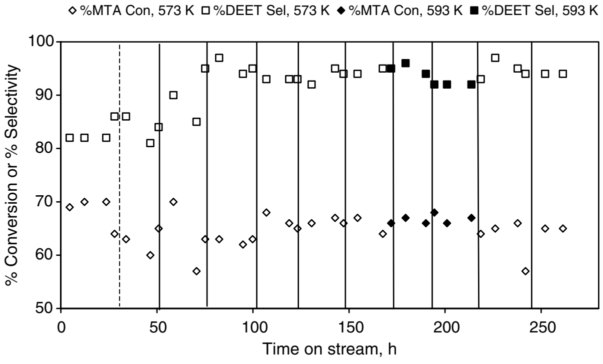


Figure 3. MTA conversion and wt% DEET selectivity, 40 wt% TPA/silica, 0.1 MPa, feed B. Dotted vertical line: offline treatment, N_2, 573 K. Solid vertical line: offline treatment, air, 773 K. The WHSV is 2–3 h^{-1} prior to first air treatment, 3–5 h^{-1} afterward.

activation occurred over the first few days (figure 3). Without such air treatments, some deactivation was noted at 30–40 h run time, at the optimal conditions.

In order to better understand cation substitution effects on the catalytic behavior of supported TPA catalysts, Cs-exchanged salts of 12-tungstophosphoric acid supported on MCM-41 were investigated. Figure 4 gives comparison results for two materials with almost the same number of total sites for 1-PA adsorption. The TPA with $Cs^+/H^+ = 1/2$ showed excellent selectivity and stability (no deactivation in over 100 h time on stream), but relatively low initial activity. As with the the supported acid catalyst, the activity increased over the first few days of use, to give a long-term conversion of 78 ± 6% and DEET selectivity of 86 ± 3% at WHSV = 3–9 h^{-1}. Such increased activity over long periods of thermal treatments is probably associated with the gradual breakup of large crystallites and, for Cs–TPAs, more uniform distribution of Cs [26]. While long-term data for the $Cs^+/H^+ = 2.5$ catalyst are lacking, all three supported TPA catalysts initially appear to follow the trend of increasing activity with total (strong + very strong) acid sites and Cs^+ content, but decreasing selectivity with Cs^+ content and increasing density of very strong acid sites. Given that the maximum proton content of a 40 wt% TPA (no Cs) is only 0.42 mmol/g, some of the acid sites measured in table 2 may actually be Lewis sites which can be converted to proton-donor sites in the water-rich environment of the reaction to DEET. The TPAs also interact with and break siloxane bonds in MCM-41, leading to additional acid sites [11]. Another factor favoring higher activity is the much higher microporosity of Cs-exchanged salts of TPAs versus the TPA acid [13]. The observed trend of decreasing selectivity with respect to increasing density of very strong sites (from 1-PA desorption) was also found for the hydroxyapatite and the silica gel catalysts.

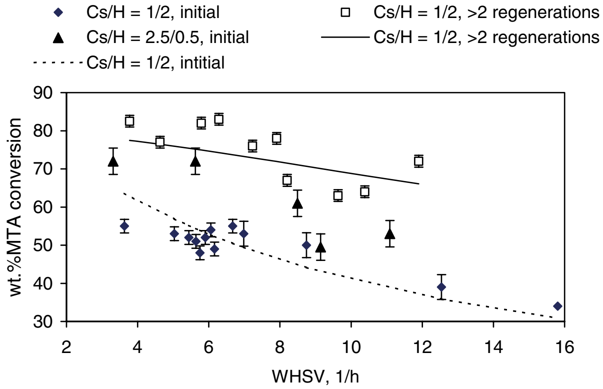


Figure 4. Effects of Cs^+/H^+ ratio for 12-tungstophosphate catalysts, 0.1 MPa, 573 K, feed B. The curves are the fits to the data using the kinetics model of Section 3.5.

3.5. Comparative discussion

For the more active TPA catalysts, the highest MTA conversions are close to the predicted value of 8–3% at 573 K, estimated using thermodynamic calculations (table 1). These highest conversions are equivalent to ones previously associated with a 1/3 or lower MTA/DEA feed ratio and very low (0.3 h^{-1}) WHSV [4]; catalyst stability was in this case associated with 1/5 MTA/DEA or higher. When the space velocity for these previous (hydroxyapatite) catalysts was increased, the MTA conversion decreased rapidly, to only about 40% at 0.9 h^{-1} [4]; this was not the case for the hydroxyapatite catalysts used here, which maintained essentially the same activity to at least 3.5 h^{-1} WHSV.

The long-term selectivities here are similar to the best reported values for solid catalysts, which were at low MTA/DEA feed ratios. The selectivities of the acid (no Cs) TPA catalyst and the hydroxyapatite HEA01 actually equal those of the homogeneous (Tyzor) catalysts and their heterogenized analogs (table 2). The higher conversions associated with the homogeneous catalysts are obtainable only in a batch system where the product water is removed continuously, using reaction times of ~24 h [1]. We also tested our supported Tyzor catalysts of Section 3.3 in batch mode and obtained MTA conversions slightly >80% with >90% DEET selectivity. This was possible with reaction times in the range of ~4–8 h and continuous water removal.

The stabilized $Cs^+/H^+ = 1/2$ catalyst (>2 regenerations) showed no apparent deactivation at 573 K in over 100 h operation. After air regeneration at 773 K, TGA analysis for coke gave <0.01 wt% oxidizable material. However, after a few weeks of use and more air treatments, there was significant (>50%) loss of the less strong acid sites, according to 1-PA desorption. This was not the case for the hydroxyapatites. Therefore, very long-term usage of the supported TPAs in secondary amine condensations is still open to question.

The data of figures 1,2, and 4, showing essentially no effects of residence time on kinetics over a wide range, are possible only for a system of high overall reaction order, and near equilibrium. If we model the primary (reversible DEET formation) and principal secondary (irreversible DEET decomposition to ETA) reactions only, and assume equivalent orders for the two reactants in all individual reactions, the relationships between WHSV ($1/\theta$), DEET/MTA molar ratio in feed (α), conversion (X) and DEET selectivity (S) are:

$$\frac{\mathrm{d}X}{\mathrm{d}\theta} = \delta\left[(1-X)^m - \frac{1}{K_\mathrm{e}}(\alpha + XS)^m\right] \tag{6}$$

$$\frac{\mathrm{d}(XS)}{\mathrm{d}\theta} = \frac{\mathrm{d}X}{\mathrm{d}\theta} - \delta\frac{k_2}{k_1}(\alpha + XS)^{m/2}(1-X)^{m/2} \tag{7}$$

$$\delta = k_1 C_{\mathrm{Mo}}^m \frac{C_{\mathrm{feed}}}{C_{\mathrm{Mo}}} MW_{\mathrm{feed}} \tag{8}$$

where K_e is the equilibrium constant, C_{Mo} and C_{feed} are the feed concentrations of DEET, and total feed, respectively, MW_{feed} is the molecular weight of the feed, and m is the overall reaction order. Using the estimated thermodynamic equilibrium constants, all the gas phase (low pressure) data for the hydroxyapatite and TPA catalysts can be fit adequately (e.g., see figure 4) by this simple model for $m \sim 2$, with δ and k_2/k_1 as the other regressed parameters. Both the DEET selectivities and the total conversions were used with equal weighting in constructing an objective function for the parameter regression.

These results suggest that adsorption of the gas phase (low pressure) reactants on the true active sites is relatively weak. The ratio k_2/k_1 was ~0.1 for these catalysts, and the activation of the TPA catalysts over the first few days of their operation corresponded to an increase in k_1 of 350–400%.

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References

[1] E.H. Hull, US Patent 4,133,833 (1979).
[2] P.P. Nicholas, US Patent 5,312,984 (1994).
[3] G.F. van Stryk, US Patent 3,198,831 (1965).
[4] A.V. de Vekki and T.N. Mozzhukhina, Petrol. Chem. 37 (1997) 320.
[5] M.H.N. Tabako, T. Kyoko and S.M.N. Tabako, EP 0,239,954 (1987).
[6] R. Nomura, T. Wada, Y. Yamada and H. Matsuda, Chem. Lett., 11 (1986) 1901.
[7] J.B. Moffat, Catal. Rev.–Sci. Eng., 18 (1978) 199, and references therein.
[8] I.V. Kozhevnikov, Catal. Rev.–Sci. Eng., 37 (1995) 311 and references therein.
[9] L. Pizzio, P. Vazquez, C. Caceres and M. Blanco, Catal. Lett., 77 (4) 2001233.
[10] Y. Wang, C.H.E. Peden and S. Choi, Catal. Lett. 75 (2001) 169.
[11] A. Molnar, T. Beregszaszi, A. Fudala, P. Lentz, J.B. Nagy, Z. Konya and I. Kiricsi, J. Catal., 202 (2001) 379.
[12] N. Essayem, A. Holmqvist, P.Y. Gayraud, J.C. Vedrine and Y. Ben Taarit, J. Catal., 197 (2001) 273.
[13] J.B. Moffat, *Metal–Oxygen Clusters:The Surface and Catalytic Properties of Heteropoly Oxometalates, Ch. 4–7* (Kluwer Academic, NewYork, 2001).
[14] P. Kumar, R.K. Pandey, M.S. Bodas, S.P. Dagade, M.K. Donagre and A.V. Ramaswamy, J. Mol. Catal. A, 181 (2002) 207.
[15] J.F. Day, US patent 5,496,959 (1996).
[16] E.E. McEntire, US Patent 4,613,673 (1986).
[17] J.A.S. Bett, L.G. Christner and W. Keith Hall, J. Am. Chem. Soc., 89 (1967) 5535.
[18] J.S. Beck, J.C. Vartuli, W.J. Roth, M.E. Leonowiez and C.T. Kresge, J. Am. Chem. Soc., 114 (1992) 10834.
[19] C.T. Kresge, M.E. Leonowiez, W.J. Roth, J.C. Vartuli and I.S. Beck, Nature 359 (1992) 710.
[20] T.J. Gricus Kofke, R.J. Gorte and W.E. Farneth, J. Catal. 114 (1988) 34.
[21] V. Kanazirev, K.M. Dooley and G.L. Price, J. Catal., 146 (1994) 228.
[22] Yujun Song, *Development of Catalytic Processes for Aromatic Amides and Carboxylic Acids*. M.S. Thesis, (Louisiana State University, Baton Rouge, LA, 2002).
[23] K.G. Joback and R.C. Reid, Chem. Eng. Commun. 57 (1987) 233.
[24] N. Cohen and S.W. Benson, Chem. Rev. (1993) 2419.
[25] C.F. Cullis and D.J. Waddington, Proc. R. Soc. (Lond.), A244 (1958) 110.
[26] T. Yamada, Y. Yoshinaga and T. Okuhara, Bull. Chem. Soc. Jpn. 71 (1998) 2727.