NO reduction by hydrocarbons and oxygenated compounds in O₂ excess over a Pt/Al₂O₃ catalyst. A comparative study of the efficiency of different reducers (hydrocarbons and oxygenated compounds).

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Abstract:

A 1% Pt/Al₂O₃ catalyst was prepared by wet impregnation of a δ -alumina with an aqueous solution of Pt(NH₃)₂(NO₂)₂. Metal particle sizes were centered around 20 nm. Twenty-seven reducers (12 hydrocarbons and 15 oxygenated compounds) were tested in NO reduction in O₂ excess while keeping the same experimental conditions (inlet gas: 5% O₂ and 5% H₂O; space velocity: 14100 h⁻¹; same temperature program from 150 to 600°C). To compare the reducers between them, two criteria were used: (i) the catalyst behavior at the maximum NO_x conversion, and (ii) the efficiencies in NO_x conversion and N₂, N₂O, NO₂ production taking into account the temperature integrated performances of the reducers between 150 and 600°C. Among the hydrocarbons tested, cyclic C₆ compounds show the highest efficiency in NO_x conversion while, among the oxygenated compounds, diols and particularly butane-diols are the most efficient reducers. However, the selectivity to N₂ is extremely dependent on the structure of the molecule. For instance, cyclohexadiene is very selective to N₂ while aromatics are not. Moreover, the position of the two OH groups in diols can largely control the selectivity: butane-1,3-diol is very selective to N₂ while butane-1,4-diol produces a great amount of N₂O. The best ten reducers in terms of NO_x reduction efficiency are: cyclohexadiene, 292 > butane-1,4-diol, 234 > benzene, 221 > butane-1,3-diol, 212 > cyclohexene, 209 > propane-1,3-diol, 161 > propene, 153 $\approx$ propan-1-ol, 149 > ethanol, 124 > propanoic acid, 114. If these data are coupled with a criterion of selectivity, cyclohexadiene, butane-1,3-diol, propan-1-ol, propanoic acid and to a lesser extent ethanol would be the best candidates for the selective NO_x reduction.

Key-words: catalytic NO reduction, Pt/alumina catalyst, hydrocarbons, C₆ hydrocarbons, cyclohexadiene, aromatics, oxygenated compounds, diols, butane-1,3-diol, alcohols, aldehydes, ketones, carboxylic acids.

Introduction

Surface transportation is a source of huge emissions of pollutants, CO, HC and NO_x which are now treated in catalytic converters placed in the exhaust line of cars and trucks. Though converters based on three-way catalysts appear as a mature technology for gasoline engine at the stoichiometry, NO_x abatement in Diesel engines and gasoline lean-burn engines is a challenge for Catalysis since NO_x should be globally reduced in a large O₂ excess. The catalytic reduction of NO_x in O₂ excess has largely been investigated in the 90's [1]. Since mid-90's, the passive DeNO_x catalysis using reducers normally present in the exhaust gas has been replaced by active DeNO_x systems like those based on the NO_x-trap concept [2,3,4], and more generally cyclic addition of reducers not normally present in the exhaust gas. These technologies are more efficient than those based on passive DeNO_x catalysis. However, whatever the technology employed, both car and catalyst makers need more information on the reducer efficiency for the conception of modern converters.

Numerous reducers have been investigated: hydrocarbons [5,6,7,8,9,10,11,12,13], oxygenated compounds (mainly alcohols, more rarely aldehydes, ketones, ethers,...) [13,14,15] and nitrogen containing compounds (ammonia, urea, nitrocompounds,...) [15,16,17,18,19]. Nevertheless, most studies were carried out on very different catalysts so that the comparison between reducer efficiencies in such conditions is difficult. Although recent studies have shown that silver catalysts could have promising properties in selective NO_x reduction by heavy HC in the presence of hydrogen [1,20], Pt remains a reference catalyst having a broad spectrum of potential applications with very different reducers. The objective of this work was to acquire data on a large number of reducers (i) by using the same Pt catalyst throughout the study and (ii) while performing the DeNO_x reaction under similar conditions with an excess of O₂ and in the presence of water. Some of the reducers investigated in this study are present in the Diesel exhaust gases, specially ethylene, propene and aromatics (HC), ketones, aldehydes and carboxylic acids (oxygenates) [21,22].

1. Experimental

The catalyst used throughout this study was a 1 wt-%Pt/Al₂O₃ prepared by impregnation of a δ -alumina (Rhône-Poulenc SCS79; 80 m² g⁻¹ ; main impurities in ppm : Na, 590 ; Ca, 490 ; Fe, 315 and S, 400) with an aqueous solution of Pt(NH₃)₂(NO₂)₂. Prior to impregnation, the support was crushed and sieved to 0.1-0.3 mm. The suspension was evaporated to dryness and

the catalyst was dried at 120°C, calcined for 4h at 700°C in air and reduced for 3h in H₂ at 450°C. The Pt dispersion measured by H₂ chemisorption, DRX and TEM was close to 5 %. This low dispersion allowed to maintain a high catalyst stability whatever the reaction conditions and the reagent processed.

The reaction was carried out in the following conditions: gas hourly space velocity: 14100 h⁻¹, 300-800 ppm NO, 120-600 ppm reducer, 5%O₂, 5%H₂O. The reducer to NO ratio ("richness") can be characterized by the ratio R defined as follows:

$$R = \frac{P_{\text{red}}}{P_{\text{NO}}} \times n_C \quad (1)$$

where n_C is the number of atoms of carbon in the molecule of reducer. For instance, $R = 1.9$ for experiments with 800 ppm NO and 500 ppm propene.

The catalyst was initially heated at 150°C (starting temperature) before admission of the reaction gas mixture. The temperature was then increased by steps of 25 or 50°C at 10°C min⁻¹ from 150°C to 600°C. The catalyst performances were evaluated at each temperature after stabilization for 40 minutes. This was sufficient to reach a stable conversion. Moreover, when the reaction was carried out at decreasing temperatures from 600 down to 150°C gave, the same curves "conversion vs T°C were obtained". At the reactor outlet, the gases were dried by water elimination on a permeation membrane. Nitrogen oxides were analyzed by means of specific analyzers: chemiluminescence for NO and NO₂ (Cosma Topaze 2020) and IR for N₂O (Cosma Beryl 100). Dinitrogen could only be analysed in the upper range of concentration (200-400ppm) and [N₂] was most often obtained by difference from the N-balance. Carbon oxides (TCD) and organics (FID) were analyzed by GC.

The conversion X_{NOx} (%) is calculated from the disappearance of the NOx (NO+NO₂):

$$X_{\text{NOx}} = \frac{[\text{NOx}]_i - [\text{NOx}]_T}{[\text{NOx}]_i} \times 100 \quad (2)$$

where $[\text{NOx}]_i$ and $[\text{NOx}]_T$ are the inlet NOx concentration and the outlet NOx concentration at T°C, respectively. The yield X_Z (%) and the selectivity S_Z (%) of a product Z is defined as follows:

$$X_Z = \frac{n ([Z]_T - [Z]_i)}{[\text{NOx}]_i} \times 100 \text{ and } S_Z = \frac{n ([Z]_T - [Z]_i)}{[\text{NOx}]_i - [\text{NOx}]_T} \times 100 \quad (3)$$

where n is the number of nitrogen atoms in the molecule of Z. According to the definitions of Eq. (3), $X_{\text{NOx}} = X_{\text{N}_2} + X_{\text{N}_2\text{O}}$ and $S_{\text{N}_2} + S_{\text{N}_2\text{O}} = 100\%$, while X_{NO_2} may be higher than X_{NOx} . An example is given below for the NOx reduction by ethane in the presence of 5% O₂ and 5% H₂O. For $[\text{NO}]_i = 420$ ppm NO and $[\text{red}] = 400$ ppm ($R = 1.9$), the outlet concentrations at 225°C

and 14100 h⁻¹ are: [NO] = 165 ppm, [NO₂] = 169 ppm, [N₂O] = 1.0 ppm and [CO₂] = 36 ppm. The calculated conversions are then: X_{NOx} = 20.3%, X_{N₂} = 19.8%, X_{N₂O} = 0.5% and X_{NO₂} = 40.3%.

A similar definition can be given for X_{CO₂}, a 100% yield being obtained for a complete oxidation of the reducer into CO₂:

$$X_{CO_2} = \frac{[red]_i - [red]_T}{n_C [red]_i} \quad (4)$$

[red]_i and [red]_T being the inlet and the outlet HC concentrations at T°C and n_C is the number of C atoms in the reducer molecule.

2. Results and discussion

2.1 Hydrocarbons

The same temperature program having being applied for every reducer, a comparative evaluation of the reducer efficiency can be given by the temperature integrated conversion, i.e. the sum of the conversions at 150, 200, 225, 250, 300 and so on by step of 50°C up to 600°C.

$$\sum X_{NOX} = \sum_{T=150}^{600^\circ C} X_{NOX} \text{ and } \sum X_Z = \sum_{T=150}^{600^\circ C} X_Z \quad (5)$$

An example corresponding to the NO reduction by ethane is given in Table 1.

Table 1: NO reduction by ethane in the 200-400°C range of temperature. Inlet composition: 420 ppm NO + 400 ppm C₂H₆ + 5% O₂ + 5% H₂O diluted in He (R = 1.9). Space velocity: 14100 h⁻¹.

T °C	X _{NO_x} %	X _{N₂} %	X _{N₂O} %	X _{NO₂} %	X _{red} %	X _{CO₂} %	S _{N₂} %	S _{N₂O} %
200	21.8	21.3	0.5	25.8	4.2	4.0	98	2
225	20.3	19.8	0.5	40.3	9.8	4.5	98	2
250	16.8	16.3	0.5	49.3	10.7	5.7	97	3
300	6.8	6.3	0.5	52.0	13.7	7.6	93	7
350	1.3	0.8	0.5	47.5	21.8	19.1	60	40
400	0	0	0	34.8	45.2	41.0		
Efficiency	Σ= 67	Σ= 65	Σ= 3	Σ= 329				

The temperature range in the Table is limited to 200-400°C, the NO reduction being nil at 150°C, at 400°C and above. This illustrates the classical behaviour of Pt catalysts in NO reduction by HC with a maximal conversion around 200-250°C and an irremediable decrease of activity at higher temperatures. The catalyst efficiencies are given in the last line of Table 1. Except for NO₂ (whose formation goes on above 400°C), catalyst efficiencies in NO_x, N₂ and N₂O conversion are the same in the 150-600°C range as in the 200-400°C range.

Other parameters are considered for evaluating the catalyst performances with a given reducer:

- the maximum NO_x conversion, $X_{\text{NO}_x \text{ max}}$, and the temperature, T_{max} , at which this $X_{\text{NO}_x \text{ max}}$ is reached,
- the width at half height of NO_x conversion. This is the temperature range in which a significant NO_x conversion (at least $X_{\text{NO}_x \text{ max}}/2$) is maintained.
- The temperature T_{50} of half conversion and the lowest temperature T_{100} of full conversion of the reducer.

This is illustrated in Fig. 1 for NO reduction by n-hexane and in Fig. 2 for NO reduction by cyclohexane.

Fig. 1: NO reduction by n-hexane. Inlet gas composition: 800 ppm NO + 450 ppm C₆H₁₄ + 5% O₂ + 5% H₂O in He (R = 3.3). Space velocity: 14100 h⁻¹.

Fig. 2: NO reduction by cyclohexane. Inlet gas composition: 800 ppm NO + 440 ppm C₆H₁₂ + 5% O₂ + 5% H₂O in He (R = 3.4). Space velocity: 14100 h⁻¹.

The maximum NO_x conversion $X_{\text{NO}_x \text{ max}}$ in the reduction by n-hexane is 40% reached at 250°C (Fig. 1) while it is of 37% at 300°C in the reduction by cyclohexane (Fig. 2). Although very close $X_{\text{NO}_x \text{ max}}$ are obtained with both C₆ compounds, X_{NO_x} profiles are quite different with a relatively narrow peak for n-hexane (width at 20% conversion: 75°C) and a rather broad peak for cyclohexane (width at 18.5% conversion: 130°C).

Before comparing the different reducers, the impact of several reaction parameters were investigated. Fig. 3 shows the effect of the R ratio on the NO_x conversion profile for ethene (Fig. 3a) and propene (Fig. 3b).

As expected, an increase of the richness R improves the NO_x conversion. Nevertheless, no significant change in the width of the NO_x conversion peak with propene can be observed. As $X_{\text{NO}_x \text{ max}}$ is observed at temperature where the reducer is fully oxidized (see for instance Fig 1 and 2), this means that NO_x are reduced in the very first part of the catalytic bed with hydrocarbon adsorbed species or with organic intermediates issued from the partial oxidation of the reducer. These intermediates (CH_x or CH_xO_y) should survive, even at high temperature, over a large distance in the catalytic bed. The change of X_{NO_x} with the reducer concentration (ethene and propene) is shown in Fig. 4.

Fig. 3: Effect of the richness R (see Eq. 1) on the NO_x conversion profile with ethene (a) and with propene (b) as reducers. NO and HC composition are given in the tables inserted below the figures. Other gases: 5% O₂ and 5% H₂O in He. Space velocity: 14100 h⁻¹.

Fig. 4: Effect of the reducer concentration on the NO_x conversion: a) ethene; b) propene. Reactions conditions are given in Fig. 3.

Fig. 5: Effect of the reducer concentration on the N_2O formation at 225°C: a) ethene; b) propene. Reactions conditions are given in Fig. 3.

A continuous increase of X_{NOx} with $P_{C_2H_4}$ and $P_{C_3H_6}$ can be observed. Worthy of note also is the small NOx conversion in absence of reducer which could originate from homogeneous radical reactions or from NO_2 adsorption (or more likely, NO_2 -water co-adsorption) on the apparatus walls or in the analyzers. The formation of N_2O depends linearly on the reducer concentration (Fig. 5).

Moreover, there is no N_2O formed in the absence of reducer, which proves that the small NOx abatement observed at zero concentration in reducer is probably not a NOx reduction. The effect of the oxygen concentration was also investigated (Fig. 6).

The results confirm the prominent role of O_2 in NOx reduction with virtually no NOx conversion when O_2 is absent. There is a parallelism between the NOx reduction and the HC oxidation. X_{NOx} reaches its maximum when the hydrocarbon becomes fully oxidized. Within the concentration range used for most hydrocarbons, this maximum of NOx conversion can be observed at 5% O_2 , which justifies the O_2 concentration adopted for a general comparison of the different reducers. The data for the 12 hydrocarbons tested in NOx reduction are reported in Table 2.

Fig. 6: Effect of the oxygen concentration on the performance of the 1% Pt/Al₂O₃ in NO_x reduction by ethene (a) or propene (b) at 225°C. R = 1.9. Other conditions as in Fig. 3.

Table 2: Summary table of the performances of 12 hydrocarbons in NO_x reduction over the 1%Pt/Al₂O₃ catalyst.

Reducer	R	X _{NO_x max} % T (°C)	Width at half conversion X _{NO_x max} /2 (°C)	T ₅₀ (°C)	T ₁₀₀ (°C)	Efficiency (Temperature integrated conversion)			
						ΣX _{NO_x}	ΣX _{N₂}	ΣX _{N₂O}	ΣX _{N₂O₂}
CH ₄	2.2	29 (225)	105	550	650	80	75	5	294
C ₂ H ₄	1.9	42 (225)	75	200	225	105	42	63	216
C ₂ H ₂	1.9	42 (250)	90	225	250	92	56	36	206
C ₂ H ₆	1.9	22 (200)	115	410	550	67	64	3	328
C ₃ H ₆	1.9	55 (225)	90	210	225	153	73	80	198
C ₃ H ₄	1.3	31 (250)	90	225	250	75	47	28	157
C ₃ H ₈	2.5	13 (200)	55	365	500	18	17	1	263
C ₆ H ₁₄	3.3	40 (250)	75	210	250	84	39	45	203
C ₆ H ₁₂	3.4	37 (300)	130	225	250	110	90	20	168
C ₆ H ₆	3.8	65 (200)	125	165	200	221	90	131	203
C ₆ H ₈	5.2	70 (200)	160	165	200	292	219	73	181
C ₆ H ₁₀	5.2	70 (250)	125	220	250	209	119	90	183

From these results, the following rules can be drawn:

- light alkanes are poor NO_x reducers but they are very selective in N₂. Methane is surprisingly rather active compared to ethane and propane probably because it is difficult to oxidize so that it can be active over a relatively large window of temperature. The behaviour of light alkanes contrasts with that of C₆ saturated hydrocarbons (n-hexane and cyclohexane) slightly more active but also much less selective into N₂. A good compromise occurs with cyclohexane rather active and not too selective in N₂O.
- light alkenes are better reducers than are alkanes in the order C₃H₆ > C₂H₄ > C₂H₆ >> C₃H₈. A similar ranking was observed over Cu-MFI catalysts by the group of Iwamoto [23] and by Gaudin et al. [24] while Maunula et al. reported the same activity for ethene and propene over In catalysts [25]. However, unsaturated C₆ hydrocarbons are by far much more active with cyclohexadiene being the best reducer of the twelve hydrocarbons tested. The

- selectivity to N₂O remains generally high specially with propene and benzene. Compared to its high activity, cyclohexadiene shows an interestingly low selectivity to N₂O.
- c- the relatively high activity of aromatic hydrocarbon coupled with a poor selectivity to N₂ has already been reported by Bourges et al. in NO_x reduction by toluene in a gas mixture containing water [26]. On the contrary, Burch and Ottery did not observe the same tendency in NO_x reduction by benzene in the absence of water. As already suggested by one of us [27], H₂O could play a decisive role in N₂O formation via the Neff reaction [28].
 - d- although they are fully oxidized at very low temperature, cyclic C₆ compounds maintain a significant NO_x activity over a large temperature range. This can be explained by the formation of organic intermediates, partially oxygenated, present over a long distance in the catalyst bed, even when the initial hydrocarbon is almost totally oxidized.
 - e- the rate of NO₂ formation is the highest with alkanes and apparently decreases with the degree of insaturation and when the number of carbon in the molecule increases. There is certainly a competition between the reducer and NO at the Pt surface, thus inhibiting the NO oxidation reaction when the hydrocarbon is too strongly adsorbed.

2.2 Oxygenated compounds

This study was performed with alcohols (methanol, ethanol, propan-1-ol, propan-2-ol), diols (propane diols and butane diols), aldehydes (ethanal, propanal), ketone (propanone), C₃ carboxylic acids. It was completed with propene oxide and tetrahydrofurane (THF) which may be formed intermediary in the transformation of diols. The reaction was carried out in the following conditions: 800 ppm NO, 500 ppm reducer (except ethanal, 310 ppm and THF 300 ppm), 5% O₂, 5% H₂O in He, 14100 h⁻¹. The temperature programme was the same as in NO_x reduction by hydrocarbons. To take into account the presence of O atoms in the reducer molecule, the definition of R (Eq. 1) was modified as follow:

$$R = \frac{P_{\text{red}}}{P_{\text{NO}}} \times \left(n_{\text{C}} - \frac{n_{\text{O}}}{2} \right) \quad (6)$$

where n_{C} and n_{O} are the numbers of C and O atoms in the molecule.

Compared to hydrocarbons, one of the most interesting feature of the alcohols is their good selectivity to N₂ in NO_x reduction. This is illustrated in Fig. 7a (propan-1-ol) and 7b (propan-2-ol) where it can be seen that the N₂O production is remarkably low, particularly with the secondary alcohol.

Fig. 7: NO reduction by propan-1-ol (a) and propan-2-ol (b) over 1% Pt/Al₂O₃. Inlet gas: 800 ppm NO, 500 ppm alcohol, 5% O₂, 5% H₂O in He. Space velocity: 14100 h⁻¹.

Fig. 8: NO reduction by butane-1,3-diol (a) and butane-1,4-diol (b) over 1% Pt/Al₂O₃. Inlet gas: 800 ppm NO, 500 ppm diol, 5% O₂, 5% H₂O in He. Space velocity: 14100 h⁻¹.

This feature cannot be extrapolated to all the diols as shown on Fig. 8a (butane-1,3-diol) and Fig. 8b (butane-1,4-diol).

Though butane-1,3-diol produces little N₂O (and resembles alcohols), butane-1,4, diol leads to a great amount of N₂O which makes this diol comparable to most of the hydrocarbons. With this diol, nitrogen production is shifted to higher temperatures so that the selectivity to N₂O is very high in the 200-250°C range of temperature.

When the two OH are in adjacent position as in propane-1,2-diol, the NO reduction is limited to less than 20%. This diol can lead to propene oxide by internal dehydration. Interestingly, there is a close parallelism between the behaviour of the two reducers (Fig. 9).

Fig. 9: Comparison of the NOx conversion profile with propane-1,2-diol and propene oxide.

A similar result was obtained with butane-1,4-diol which can be cyclized into THF by internal dehydration. Both reducers (diol and furane) gives very close NO_x conversion profiles at low temperature (<250°C). Above 250°C, the diol is more active than THF which does no longer seem to be an intermediate in the transformation of butane-1,4-diol. A comparison of the NO_x conversion profiles between the different alcohols and diols is given on Fig. 10.

The reducers can be ranked in the following order: butane-1,3-diol $\approx$ butane-1,4-diol > propane-1,3-diol > propan-1-ol > ethanol > methanol > propan-2-ol > propane-1,2-diol with maximum NO_x conversion ranging between 20 and 44%.

Fig. 10: NO_x conversion profiles obtained with alcohols and diols over the 1%PtAl₂O₃ catalyst. Inlet gas: 800ppm NO, 500 ppm reducer, 5% O₂, 5% H₂O in He. Space velocity: 14100 h⁻¹.

Five carbonyl and carboxylic compounds were finally investigated over the 1%Pt catalyst. As a rule, these reducers are very, sometimes fairly, selective to N_2 and show a behaviour close to that of alcohols. Their NO_x conversion profiles are compared in Fig. 11.

Carboxylic acids are more active than carbonyl compounds, the order of X_{NO_x} efficiency being: acrylic acid > propanoic acid > propanal > ethanal > acetone.

Fig. 11: NO_x conversion profiles obtained with carbonyl and carboxyl compounds over the 1%PtAl₂O₃ catalyst. Inlet gas: 800ppm NO, 500 ppm reducer, 5% O₂, 5% H₂O in He. Space velocity: 14100 h⁻¹.

The performances of the 15 oxygenated compounds tested in NO_x reduction are summarised in Table 3.

Table 3: Summary table of the performances of 15 oxygenated compounds in NO_x reduction over the 1%Pt/Al₂O₃ catalyst.

Reducer	R	X _{NO_x max} % T(°C)	Width at X _{NO_x max} /2 °C	T ₅₀ °C	T ₁₀₀ °C	Efficiency (Temperature integrated conversion)			
						ΣX _{NO_x}	ΣX _{N₂}	ΣX _{N₂O}	ΣX _{NO₂}
Methanol	0,5	23 (250)	180	<150	<150	107	99	8	353
Ethanol	1,3	27 (225)	150	220	250	124	91	36	271
Propan-1-ol	1,9	31 (250)	145	185	225	149	124	25	217
Propan-2-ol	1,9	24 (250)	100	180	250	91	75	16	300
Propane-1,2-diol	1,9	10 (225)	200	-	-	88	52	36	299
Propane-1,3-diol	1,9	41 (250)	145	210	250	161	115	46	206
Butane-1,3-diol	2,5	44 (250)	210	240	300	212	174	38	136
Butane-,1,4-diol	2,5	44 (250)	223	225	300	234	118	116	114
Ethanal	0,9	21,5 (300)	185	200	300	96	84	12	275
Propanal	1,7	28 (225)	130	170	225	106	65	41	257
Acetone	1,7	25 (250)	125	185	230	88	76	12	295
Propanoic acid	1,7	30 (250)	160	210	225	114	100	14	191
Acrylic acid	1,7	39 (250)	160	220	250	149	95	54	194
Propene oxide	1,9	21 (225)	140	-	-	89	64	25	236
THF	1,5	36 (200)	75	170	200	100	47	53	216

From these data, some conclusions can be drawn:

- a- primary alcohols are relatively good NO_x reducers. Among the C1-C3 alcohols tested, methanol shows the better selectivity to N₂. Secondary alcohols would be less active than the corresponding primary alcohols.
- b- diols and specially butane-diols are very active in NO_x reduction. However, the selectivity to N₂ depends strongly on the relative position of the two OH groups: though butane-1,3-diol has both a high activity and a good selectivity to N₂, butane-1,4-diol is active but produces a great amount of N₂O.

- c- aldehydes are slightly less active than the corresponding primary alcohols. On the contrary, carboxylic acids are rather more active.
- d- NO oxidation into NO₂ seems to be correlated with the adsorption strength of the reducer: those molecules which are subject to strong adsorption decrease the NO oxidation properties of Pt.

3. Conclusions

The objective of this work was to compare a series of reducers in NO_x conversion on the same 1%Pt/Al₂O₃ catalyst and under similar conditions (space velocity, gas composition including O₂ and H₂O, temperature program from 150 to 600°C). Instead of the maximum NO_x conversion, a criterion based on the performance of the reducer over the entire range of temperature (NO_x conversion and product formation efficiencies) was preferred to compare the reducers. If one combines the NO_x conversion and the selectivity to N₂, cyclohexadiene, butane-1,3-diol, propan-1-ol, propanoic acid and to a lesser extent ethanol are good candidates for the selective NO_x reduction. Molecular structures, specially in diols, alcohols and C₆ hydrocarbons were proved to have a strong impact on both the NO_x reduction and the selectivity to nitrogen.

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