NO reduction with ammonia employing Co/Pt supported on a mesoporous silica containing zirconium as a low temperature selective reduction catalyst

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Received 12 January 2004; received in revised form 17 March 2004; accepted 18 March 2004

Available online 1 June 2004

Abstract

Selective catalytic reduction (SCR) of NO with ammonia in an excess of oxygen was carried out over cobalt-platinum impregnated on a zirconium containing mesoporous silica (Si/Zr molar ratio of 5) with a 12 wt.% of Cobalt and Co/Pt molar ratios of 10, 20 and 30. These catalysts were compared with two catalysts containing 12 wt.% of Co and 1.5 wt.% of Pt, respectively. The presence of platinum improves the reducibility of Co(III) to Co(II) and at the same time the presence of cobalt ions impedes the reduction of Pt(II) to Pt(0). This gives rise to a synergetic effect, especially in the case of the catalyst with a Co/Pt molar ratio of 30, exhibiting a good performance in the SCR of NO by ammonia, even when water or SO2 are added to the feed on stream, and maintaining high conversion and selectivity at moderately low temperatures (250 °C). In fact, this catalyst maintains a conversion of 84% at 300 °C in the presence of water during 24 h.

Keywords: NO selective catalytic reduction; Platinum; Cobalt; SO2; Mesoporous silica; Zirconium

1. Introduction

The emission of nitrogen oxides (NOx) produced during high temperature combustion processes, from both mobile and stationary sources, is one of the most important current environmental issues that concerns the scientific community. The main problems emerging from NOx emissions into the atmosphere are their contribution to acid rain and photochemical smog. Currently, selective catalytic reduction (SCR) over catalysts based on vanadium [1] is the most widely used technology for purifying flue-gases from stationary sources. As this reaction takes place in an oxidant environment, ammonia is used as a reducing agent owing to its preferential selectivity for reacting with NO instead oxygen in the range of temperatures of maximum conversion of NO to N2. However, this reductor is not feasible for mobile sources because of the difficulty of handling ammonia.

For mobile sources, hydrocarbons [2,3] or CO [4] have been studied as reducing agents instead of ammonia in the presence of oxygen because they are present in the flue-gases. However, improvements are still needed in this field of research since the catalysts are ineffective in the presence of an excess of oxygen as is the case in the exhaust from diesel engines [5,6]. Since the first report of Li and Armor [7] who reported that NO could be reduced by CH4 over Co-catalysts, cobalt has been widely studied as a catalyst for the reduction of NO with CH4 [8,9]. However, in contrast to the catalysts using ammonia as a reducing agent, these Co containing cata-
lysats are active only at high temperatures [10]. In addition, these catalysts are not stable in the presence of water vapour or SO2 [11,12]. To overcome these problems, catal-
lysats with two or more metals as active phases have been developed, one of them usually being a noble metal, such as platinum or palladium [13,14]. The presence of Pt or Pd seems to produce an increase in the amount of NO adsorbed onto the Co-catalysts, and it may also be responsible for...
the water tolerance and the NO oxidation to NO₂, which is a known reaction intermediate for HC-SCR. On the other hand, there are some reports in which the second metal is not a noble metal. Ren et al. have shown that the presence of Zn in Co-ZSM-5 improves its catalytic activity by inhibiting the CH₄ combustion [15]. Stakheev et al. studied the effect of barium over Co-ZSM-5 [16], finding an considerable improvement in the NO conversion in the SCR of NO with propane. In general, this second metal induces a change in the catalytic activity by improving its stability in the presence of water [13] or SO₂ [17].

At the beginning of the 90s, Mobil scientists discovered a new mesoporous family, MCM–41 [18]. These materials have a hexagonal arrangement of cylindrical channels with diameters ranging between 16 and over a 100 Å whilst also displaying high BET areas. Moreover, they show high thermal stability, which is an issue of great importance owing to the reaction conditions of SCR. Since there were few papers published relating to the activity of cobalt oxides in the SCR of NO with ammonia, we were led to develop a new catalyst with cobalt as the active phase, based in a zirconium doped mesoporous silica, which is active in this reaction [19]. NO conversions of over 85% were achieved with negligible N₂O production and at temperatures lower than 200 °C. These results encouraged us to improve the catalytic activity of this catalyst by doping with Pt and assaying the resulting catalysts in the presence of H₂O and SO₂. Hence, in this work, we present the results of the addition of Pt, at three different loadings, to cobalt supported over a zirconium doped mesoporous silica for SCR of NO with NH₃ in wet conditions and in the presence of SO₂.

2. Experimental

2.1. Preparation of catalysts

A zirconium-doped mesoporous silica, with a Si/Zr molar ratio of 5, was prepared by following the method described in previous papers [19,20]. The material was calcined in air at 550 °C (1 °C min⁻¹ heating rate) for 6 h and was denoted as SiZr5. Catalysts with a cobalt loading of 12 wt.% and Co/Pt atomic ratios of 10, 20 and 30 were prepared by the incipient wetness method. Both metals were added simultaneously to the support. After impregnation, the samples were calcined at 550 °C for 4 h (1 °C min⁻¹ heating rate). For comparison, two monometallic catalysts with a cobalt loading of 12 wt.% and a platinum loading of 1.5 wt.% were prepared, following the same method. The monometallic catalysts were named Co-12 and Pt-1.5 and the bimetallic catalysts Co/Pt10, Co/Pt20 and Co/Pt30 depending on Co/Pt atomic ratios.

2.2. Characterisation methods

Powder XRD patterns were obtained with a Siemens D500 diffractometer, equipped with a graphite monochromator and using Cu Kα radiation. X-ray photoelectron spectra were collected using a Physical Electronics PHI 5700 spectrometer with non-monochromatic Mg Kα radiation (300 W, 15 kV, 1253.6 eV) for the analysis of photoelectronic signals of Si 2p, Zr 3d, O 1s, Co 2p and Pt 4f and with a multi-channel detector. For achieving a Wagner plot, the Co 2p photoelectron signal and the Co LMN Auger line were collected by using a non-monochromatic Al Kα radiation (300 W, 15 kV, 1486.6 eV) as an excitation source as an excitation source to avoid the overlapping of the O KLL Auger line with the photoelectron Co 2p signal observed when using Mg Kα radiation as an excitation source. Spectra of powdered samples were recorded with the constant pass energy values at 29.35 eV, using a 720 μm diameter analysis area. During data processing of the XPS spectra, binding energy values were referenced to the C 1s peak (248.8 eV) from the adventitious contamination layer. The PHI ACCESS ESCA-V6.0 F software package was used for acquisition and data analysis. A Shirley-type background was subtracted from the signals. Recorded spectra were always fitted using Gauss-Lorentz curves, in order to determine the binding energy of the different element core levels more accurately. The error in BE was estimated to be ca. 0.1 eV.

Textural parameters were obtained from N₂ adsorption–desorption isotherms (BET method) as determined using a glass volumetric apparatus at −196 °C, after outgassing the catalysts at 200 °C and 10⁻⁴ Torr overnight. Temperature-programmed reduction of H₂ (H₂-TPR) was performed between room temperature and 800 °C using a flow of Ar/H₂ (40 cm³ min⁻¹, 10 vol.% of H₂) and a heating rate of 10 °C min⁻¹. Water produced in the reduction was eliminated by passing the gas flow through a cold finger (−80 °C). The consumption of H₂ was monitored by an on-line gas chromatograph (Shimadzu GC-14A) provided with a TCD.

Temperature-programmed desorption of NO (NO-TPD) was performed by adsorbing NO onto the catalysts at room temperature (150 cm³ min⁻¹ flow rate and 0.05 vol.% NO balanced with He) for 1 h, and desorption between 40 and 550 °C, using a heating rate of 10 °C min⁻¹. Before the adsorption of NO, the catalysts were heated at 550 °C under a He flow for 1 h. During desorption, helium was flushed and the eluted gas phase was carefully monitored and quantified using an on-line quadrupole mass spectrometer, Balzer GSB 30002.

2.3. Catalysis

Catalysts were tested in the SCR of NO by using a Pyrex glass tube microreactor (0.27 m i.d.) working at atmospheric pressure in a steady-state flow mode and with a catalytic charge of 150 mg of pelleted solids, sieved to 0.3–0.4 mm, in all cases without dilution. Samples were pretreated at 350 °C in situ for 2 h under a He flow (30 cm³ min⁻¹). The gas reaction mixture was composed of 1000 ppm NO, 1000 ppm NH₃ and 2.5 vol.% O₂ (balanced
with helium). In some tests, 10 vol.% H2O, passing helium through a saturator with deionized water, and 150 ppm of SO2 was added to the feed stream. The flows were independently controlled by channel mass flowmeters (Brooks) and a total flow rate of 42 cm³ min⁻¹ was used in the feed. The space velocity (F/W) was 3300 h⁻¹; in these conditions, both external and internal diffusional limitations were absent. The reaction was studied from 100 to 500 °C. The analysis of reactants and products (NO, N₂O, N₂, NH₃, H₂O and SO₂) was monitored by using the on-line quadrupole mass spectrometer described above. At each temperature, conversions of NO and NH₃ were calculated using steady-state concentrations.

3. Results and discussion

3.1. Characterisation of catalysts

Three different catalysts with cobalt and platinum atomic ratios of 30, 20 and 10, but maintaining a cobalt loading of 12 wt.%, were prepared by using a zirconium doped mesoporous silica as a support. At the same time, two other catalysts with 12 wt.% of cobalt and 1.5 wt.% of platinum were prepared to compare with the CoPt catalysts. Table 1 shows the main characteristics of the support and the prepared catalysts. The specific surface area of the Pt-1.5 catalyst is very close to that of the support. However, when the metal loading is increased there is a decrease in the textural properties due to the blockage of some mesopores. The powder XRD patterns of the support and catalysts exhibit a diffraction peak centred at 2θ, although this signal appears as more broadened when the metal loading increases. In the higher angles region, the Co-12 and CoPt catalysts calcined at 550 °C clearly show the characteristic peaks of Co₃O₄ corresponding to the 220, 311 and 400 planes (Fig. 1). The Co-12 catalyst, with a cobalt loading of 12 wt.%, shows the best catalytic performance in the NO-SCR from among a set of catalysts with different cobalt loadings in spite of the presence of Co₃O₄ [10]. The Pt-1.5 catalyst exhibits two peaks in its XRD patterns at 39.5 and 46.2°, corresponding to the 111 and 200 planes of metallic Pt, respectively. It is noteworthy that in mixed CoPt catalysts these peaks do not appear, even in the sample with the highest loading of platinum, CoPt10. Thus, the presence of cobalt seems to impede the reduction and nucleation of the platinum atoms to form metallic particles. In the CoPt catalysts, the diffraction lines of neither PtO₂ or PtO are observed.

The XPS technique is largely used to study the nature of the surface species on the catalysts. Fig. 2 shows the XPS
spectrum of the Pt-1.5 catalyst, calcined at 550 °C. The Pt 4f7/2 signal is made up of two contributions at 71.0 (71%) and 72.3 eV (29%) which can be assigned to Pt(0) and to oxidised platinum species (Fig. 2A), respectively [21]. The later signal could be due to unreduced PtOxCly species. The reduced Pt particles are probably surrounded by layers of platinum oxidised species [22].

The core level Pt 4f spectra of CoPt calcined catalysts do not show the signal corresponding to Pt(0) (see Fig. 2B), this being in good agreement with the results obtained from XRD patterns. In contrast, a main signal at 74.3 eV assigned to PtO appears with a shoulder at 72.3 eV that corresponds to unreduced PtOxCly species. The percentages of both species are similar for CoPt10 and CoPt20, however for CoPt30 the percentage of PtOxCly species is higher (55%) (Table 1), clearly indicating that when platinum is in low concentration, it interacts strongly with the surface of the support or cobalt and as a consequence is more difficult to reduce by heating (Table 2).

In the spent catalysts, after a complete catalytic cycle between 100 and 500 °C, the Pt 4f signals are hardly modified for catalysts with the lower loading of platinum, CoPt20 and CoPt30. However, the core level Pt 4f spectrum of the spent CoPt10 catalyst (Fig. 2C) shows, together with the other signals, a new peak at 71.3 eV (22.6%) assigned to Pt(0), revealing that the excess of the Pt on this catalyst, possibly a fraction which is not interacting or is in the vicinity of cobalt ions, is segregated and reduced during the catalytic reaction, especially at the highest temperatures.

In the core level Co 2p3/2 spectra a broad and asymmetric signal appears in all cases at 780.1–781.1 eV, but, as is well known, it is difficult to assign because both Co(II) and Co(III) ions may originate this signal. For this reason the CoLMN Auger signal has been recorded to establish the presence of both ions. Two peaks, corresponding to CoLMN Auger lines, were observed at ~712.5 and ~717.0 eV, which allow us to calculate the modified Auger parameter (α’) by using the following equation:

\[
\alpha’ = 1486.6 + \text{KE(CoLMN)} - \text{KE(Co2p3/2)}
\]

where \(\text{KE(CoLMN)}\) is the kinetic energy of the CoLMN Auger electron, \(\text{KE(Co2p3/2)}\) is the kinetic energy of the Co 2p3/2 photoelectron and 1486.6 is the energy of the Al Kα X-ray excitation source in eV, and they are close to 1550 or 154 eV. Using a Wagner plot (Fig. 3), two sets of points can be observed, one in the CoO region (\(\alpha’ = 1550\) eV) and another in the region of Co3O4 region (\(\alpha’ = 1553\) eV). These results reveal the presence of both Co(II) and Co(III) in all samples containing cobalt.

Concerning the atomic ratios obtained by XPS, the Co/Zr atomic ratio is almost constant across the different samples. On the other hand, both the Pt/Zr and Pt/Co atomic ratios increase with platinum loading. These atomic ratios are higher than bulk atomic ratios, however, indicating that a good dispersion has been attained.

**Table 2**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Co 2p3/2 (eV)</th>
<th>KE CoLMN (eV)</th>
<th>(\alpha’) (eV)</th>
</tr>
</thead>
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<tr>
<td>Fresh catalysts</td>
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</tr>
<tr>
<td>Co-12</td>
<td>780.1</td>
<td>769.6</td>
<td>1540.7</td>
</tr>
<tr>
<td>CoPt30</td>
<td>780.6</td>
<td>769.7</td>
<td>1553.4</td>
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<td>1550.2</td>
</tr>
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<td>CoPt10</td>
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<td>1550.0</td>
</tr>
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<td>Spent Catalysts</td>
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</tr>
<tr>
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<td>780.8</td>
<td>769.3</td>
<td>1551.1</td>
</tr>
<tr>
<td>CoPt30</td>
<td>780.6</td>
<td>769.7</td>
<td>1553.9</td>
</tr>
<tr>
<td>CoPt20</td>
<td>780.8</td>
<td>769.5</td>
<td>1553.8</td>
</tr>
<tr>
<td>CoPt10</td>
<td>781.1</td>
<td>769.5</td>
<td>1554.1</td>
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</table>
The H₂-TPR curves of a supported phase depend on several factors such as the type of support, precursor salt and solvent used in the impregnation as well as the calcination temperature [23]. The H₂-TPR curve of the Pt-1.5 calcined catalyst, does not exhibit any significant features, confirming that after calcination metallic platinum is formed, as observed by XRD and XPS analysis (Fig. 4). Only a very small and negative peak at 197°C is observed due to the desorption of a small amount of hydrogen together to a very small reduction peak of hydrogen consumption at 367°C, which could be due to the reduction of the PtOₓClᵧ detected in the XPS spectrum (Fig. 4, insert). These results are different to those found by Shen et al. [24] for Pt impregnated on silica MCM-41, where one or two reduction peaks were detected. On the other hand, the H₂-TPR curves of the Co-12 catalyst show a H₂ consumption peak at low temperature, ca. 280°C, which can be assigned to the reduction of Co(III) ions formed during calcination at 550°C. The presence of these ions has also been detected by XRD and XPS studies. At higher temperatures, 420–750°C, a new band corresponding to Co(II)/Co(0) reduction appears [25,26]. The width of this band reveals that cobalt ions interact in a different way with the support. The formation during the calcination of a small amount of Co₂SiO₄ which is reduced at very high temperatures can not be discarded [27,28].

The H₂-TPR profiles for bimetallic catalysts (Fig. 4) are different to those of the Pt-1.5 and Co-12 monometallic catalysts, showing two H₂ consumption peaks between 95 and 400°C, but the temperature of the peaks shifted with the platinum loading. The higher the platinum loading, the lower the reduction temperature. The first peak can be assigned to platinum reduction together with Co(III)/Co(II) reduction. In fact, the XPS spectrum of the CoPt10 sample reduced at 200°C with H₂ reveals the presence of Pt(0) and a small peak of unreduced PtOₓClᵧ. It is noteworthy that the reduction of Co(III)/Co(II) takes place at a lower temperature than for the Co-catalyst. The temperature of the first peak increases from 94°C (CoPt10) to 177°C (CoPt30) in accordance with decreasing platinum loading. Thus, the presence of platinum increases the reducibility of Co(III). Perhaps this metallic particle spills over H₂ to the Co(III) ions located in the vicinity. It means that platinum and cobalt cations could be in intimate contact or possibly forming a mixed PtCoₓOᵧ oxide [29]. The influence of platinum on the reducibility of cobalt is also observed in the reduction step of Co(II)/Co(0), which appears in the H₂-TPR curves as the second peaks. The temperature of this peak ranges between 253 and 327°C, and increasing for samples with low platinum loading. In any case, the low temperatures for the reduction of Co(III)/Co(II) and Co(II)/Co(0) reveal that platinum influences the reduction of cobalt as has been reported by other authors on the subject of zeolite catalysts [30–32]. In fact, Boix et al. [31] only found Co(II) species as cations...
of Co(II) induced by the presence of Pt(II) oxide, with the in bimetallic catalyst could be related to a better dispersion of Co(II) together with the Pt(II) cations being responsible for the NO adsorption.

3.2 Catalytic performances

This set of catalysts prepared on zirconium doped mesoporous silica by impregnation was tested in the SCR of NO using ammonia as a reducing agent in the excess of oxygen, according to the reaction:

\[
4\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}
\]  

(1)

The NO conversion curves versus the reaction temperature are plotted in Fig. 6a. From these curves it can be deduced that monometallic and bimetallic catalysts show maximum conversions at very low temperatures, 200 °C. This result is of great interest because bimetallic catalysts exhibit a similar behaviour to that of Co-12, which was found to be one of the best reported cobalt containing catalysts [34–42]. On the other hand, the conversion is maximum for bimetallic samples with values ranging between 84 and 91%, whereas both monometallic catalysts show intermediate conversions with 85 and 88% for Pt-1.5 and Co-12, respectively. However, the yield of N₂, calculated according to the expression:

\[\text{Yield} = \frac{[\text{NO}]_{\text{initial}} - [\text{N}_2\text{O}]}{[\text{NO}]_{\text{initial}}} \times 100\]

is different for each sample (Fig. 6b), the highest values appearing for Co-12 (82%), whereas the lowest values correspond to catalysts with the maximum platinum loading, CoPt10 and Pt-1.5 (Table 3). The low N₂ yield values for these catalysts is due to the secondary reaction:

\[
4\text{NO} + 4\text{NH}_3 + 3\text{O}_2 \rightarrow 4\text{N}_2\text{O} + 6\text{H}_2\text{O}
\]  

(2)

which becomes more important, such that at 200 °C, 518 and 386 ppm of N₂O are formed (Table 3). In these experimental conditions, the catalysts forming the lowest amount of N₂O are Co-12 and CoPt30. The N₂O formation could also originate from the non-selective reaction:

\[
2\text{NH}_3 + \text{O}_2 \rightarrow \text{N}_2\text{O} + 3\text{H}_2\text{O}
\]  

(3)

Since the ammonia conversion at 200 °C ranges between 80 and 100% (Table 3), whereas the NO conversions are below these values. This means that some ammonia molecules are oxidised to N₂O. From this data, it is noteworthy that Co-12 and the bimetallic CoPt30 catalyst, with the lowest loading of platinum, exhibit excellent performances with high NO conversions, moderate formation of N₂O and high selectivity for N₂. Moreover, the CoPt30 catalyst has a broad temperature windows of operation, ranged between 130 and 280 °C.

On the other hand by comparing the experimental results corresponding to monometallic with those of bimetallic catalysts some important features can be deduced: the catalyst with the maximum platinum loading (CoPt10) shows quite a similar performance to Pt-1.5 (Table 3). This indicates that...
Fig. 6. (a) NO conversion as a function of reaction temperature for Co-12 (○), CoPt30 (●), CoPt20 (▲), CoPt10 (□) and Pt-1.5 (□) catalysts. Experimental conditions: NO (1000 ppm), NH₃ (1000 ppm), O₂ (2.5 vol. %); total flow rate: 42 cm³ min⁻¹; (b) N₂ yield as a function of temperature for Co-12 (○), CoPt30 (●), CoPt20 (▲), CoPt10 (□) and Pt-1.5 (□) catalysts. Experimental conditions: NO (1000 ppm), NH₃ (1000 ppm), O₂ (2.5 vol. %); total flow rate: 42 cm³ min⁻¹.

Table 3: Catalytic data

<table>
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<tr>
<th>Catalyst</th>
<th>Temperature of maximum conversion (°C)</th>
<th>NO conversion (%)</th>
<th>NH₃ conversion (%)</th>
<th>N₂O formation (ppm)</th>
<th>N₂ yield (%)</th>
<th>N₂ selectivity (%)</th>
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<td>10% (v/v) H₂O</td>
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<td>68.4</td>
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the presence of platinum in this catalyst has more influence on the catalytic performance than cobalt. In fact, XPS analysis of the spent CoPt10 catalyst showed the presence of superficial Pt(0) in a similar way to that for Pt-1.5. This result could be contrasted with the different NO adsorption capacities for both samples (Fig. 5), although TPD curves do not present the true surface coverage of NO under reaction conditions. However, it is necessary to take into account the different chemical species present in fresh CoPt10 and spent catalysts. The fresh catalyst contains essentially Pt(II) and cobalt, whereas used catalysts have at least 23% Pt(0). In consequence, the Pt(II)/Pt(0) redox pair may be responsible for the NO adsorption and oxidation to N₂O, which is later reduced to N₂ by ammonia. However, CoPt20 and CoPt30 catalysts have a catalytic behaviour closer to that of Co-12, although their performances are slightly lower. Since the NO adsorption capacity is enhanced by the presence of Pt(II), and the amount of Co(III) is lower, as shown by XPS in both bimetallic catalysts, owing to the presence of platinum increases the reducibility of Co(III), these data point to Co(II)/Co(III) redox pair could be responsible of the catalytic activity in both samples as was found in the case of Co-12 [10].

When 10% (v/v) of water is added to the feed, the catalytic performance of this group of catalysts is largely modified, changing not only the temperature of the maximum conversion but interestingly the yield of N₂. Fig. 7 depicted the evolution of conversion with temperature, where the maximum conversion of catalysts with the highest loading of platinum (Pt-1.5 and CoPt10) can be observed as shifted to lower temperatures, whereas Co-12 and CoPt30 are shifted to higher temperatures. The CoPt30 catalyst exhibits in these conditions a broad temperature window of operation ranged between 230 and 380 °C. Moreover, this catalyst maintains a
conversion of 84% at 300 °C in the presence of water during 24 h. Interestingly, all catalysts recover their initial activities when water is removed from the feed stream, as in the case for the SCR of NO with methane in Co-zeolites [30,32]. As mentioned above, the presence of water also affects the yield of N2. Only Co-12 and CoPt30 maintain their yield of N2, whereas the other catalysts show a considerable decay in the N2 yields, with values ranging between 38 and 47%, mainly due to the formation of N2O by the non-selective reactions. It is noteworthy that, in the presence of water, Co-12 and CoPt30 catalysts improve their selectivity to N2, which in these experimental conditions produce only 21 and 45 ppm of N2O, respectively. From these results we can divide this set of catalysts in two classes, one with behaviour similar to Pt-1.5 and another one with behaviour similar to Co-12. Only in the case that an excess of noble metal is loaded into these catalysts does the presence of water seem to affect the SCR of NO, possibly due to its competitive adsorption onto sites playing a role in this catalytic reaction [12,31,43].

4. Conclusions

Bimetallic CoPt catalysts, especially when platinum is present in a low loading, may be moderate catalysts for SCR of NO by ammonia in excess of oxygen. From the characterisation and catalytic results data is possible to conclude that the presence of platinum improves the reducibility of Co(III) to Co(II) and at the same time, the presence of cobalt ions impedes the reduction of Pt(II) to Pt(0). As a consequence of this synergetic effect bimetallic catalysts, especially CoPt30, a good performance in the SCR of NO by ammonia is exhibited, maintaining high conversion and selectivity at moderate temperatures (250 °C) even when water or SO2 are added to the feed on stream. On the other hand, this catalyst maintains a conversion of 84% at 300 °C in the presence of water during 24 h.

References