



Investigating the Influence of Fe Speciation on N₂O Decomposition Over Fe–ZSM-5 Catalysts

Nia Richards¹ · Ewa Nowicka¹ · James H. Carter¹ · David J. Morgan¹ · Nicholas F. Dummer¹ · Stanislaw Golunski¹ · Graham J. Hutchings¹

© The Author(s) 2018

Abstract

The influence of Fe speciation on the decomposition rates of N₂O over Fe–ZSM-5 catalysts prepared by Chemical Vapour Impregnation were investigated. Various weight loadings of Fe–ZSM-5 catalysts were prepared from the parent zeolite H-ZSM-5 with a Si:Al ratio of 23 or 30. The effect of Si:Al ratio and Fe weight loading was initially investigated before focussing on a single weight loading and the effects of acid washing on catalyst activity and iron speciation. UV/Vis spectroscopy, surface area analysis, XPS and ICP-OES of the acid washed catalysts indicated a reduction of ca. 60% of Fe loading when compared to the parent catalyst with a 0.4 wt% Fe loading. The TOF of N₂O decomposition at 600 °C improved to $3.99 \times 10^3 \text{ s}^{-1}$ over the acid washed catalyst which had a weight loading of 0.16%, in contrast, the parent catalyst had a TOF of $1.60 \times 10^3 \text{ s}^{-1}$. Propane was added to the gas stream to act as a reductant and remove any inhibiting oxygen species that remain on the surface of the catalyst. Comparison of catalysts with relatively high and low Fe loadings achieved comparable levels of N₂O decomposition when propane is present. When only N₂O is present, low metal loading Fe–ZSM-5 catalysts are not capable of achieving high conversions due to the low proximity of active framework Fe³⁺ ions and extra-framework α -Fe species, which limits oxygen desorption. Acid washing extracts Fe from these active sites and deposits it on the surface of the catalyst as Fe_xO_y, leading to a drop in activity. The Fe species present in the catalyst were identified using UV/Vis spectroscopy and speculate on the active species. We consider high loadings of Fe do not lead to an active catalyst when propane is present due to the formation of Fe_xO_y nanoparticles and clusters during catalyst preparation. These are inactive species which lead to a decrease in overall efficiency of the Fe ions and consequentially a lower TOF.

Keywords Nitrous oxide · Iron zeolites · Fe–ZSM-5 · N₂O decomposition · Acid washing · Iron species · Chemical vapour impregnation · UV/Vis · XPS

1 Introduction

Nitrous oxide (N₂O) is a highly potent greenhouse gas, having a global warming potential of roughly 300, therefore the effect on the atmosphere is far more devastating than carbon dioxide [1–3]. N₂O is produced by both natural and anthropogenic sources [4–6]. There are many sources of anthropogenic N₂O such as sewage treatment, fuel and biomass combustion, industrial chemical processes, and contributions from the agriculture sector [4]. Agricultural processes lead to around 60% of the global emissions. The main industrial

processes that lead to the formation of N₂O such as adipic and nitric acid production [1], with adipic acid production leading to around 80% of the global industrial emission of N₂O (~ 10% total) [6, 7]. There are also small industrial uses such as hospital and dental surgeries [8]. Therefore it is extremely important to decompose N₂O before it is released into the atmosphere. Decomposition of N₂O takes place through dissociation into O₂ and N₂ (Eq. 1, [9, 10]).



There are many types of catalysts that can be used for N₂O decomposition including perovskites [11–15], ceria-based catalysts [16–18], spinels [19–21] and iron containing zeolites [22]. In the latter case, H-ZSM-5 has been frequently used as a support [23–25]. Xie et al. reported 100% conversion at 450 °C using 7.46 wt % Fe [26] while Wood

✉ Nia Richards
RichardsN8@cardiff.ac.uk

¹ Cardiff Catalysis Institute, School of Chemistry, Cardiff University, Cardiff CF10 3AT, UK

and co-workers [27] reported 84% conversion at 500 °C using an Fe/ZSM-5 catalyst with a loading of 0.57 wt%. Sobalik et al. showed that when using Ferrierite (FER) a Si:Al ratio of 8.5 outperformed Si:Al 10.5 when the same Fe loading is prepared for N₂O decomposition [28]. Rauscher et al. reported that low Si:Al ratios are more effective for N₂O decomposition catalysts [23]. Fe-ZSM-5 (Si:Al = 11.4) exhibited 95% conversion of N₂O at 500 °C in contrast to Fe-BEA (93) achieving just 20% conversion of N₂O at 575 °C [29]. The work of both these groups show that Si/Al ratio is an important factor for activity of an N₂O decomposition catalyst.

Furthermore, it was shown that zeolites with different framework structures can be used for the decomposition of N₂O with MFI (ZSM-5), beta (BEA) and ferrierite (FER) zeolites acting as supports for Fe [29–31]. Jisa et al. reported that low loaded Fe-FER was the most active, achieving 85% conversion at 450 °C [32]. FER had the lowest Si/Al ratio (8.6) out of all the zeolites tested compared to 15.5 for BEA and 13.4 for MFI. Supporting the earlier findings that a low Si:Al ratio is necessary for high N₂O conversion. As the active Fe site is considered to form on the Al moiety in the zeolite framework, low Si:Al ratio zeolites can facilitate a higher concentration of active species [26].

The rate-limiting step in the decomposition of N₂O is typically the recombination of oxygen to form O₂. Specifically, the dissociation of N₂O on the active Fe species is facile and leaves an oxidised Fe active site. The surface oxygen must then recombine with another oxygen atom to form O₂. It has been demonstrated that the addition of a reductant can facilitate the abstraction of oxygen from the oxidised active site, significantly increasing the observed rate of N₂O decomposition at lower temperatures [27, 33–38]. Propane [26, 39–42] has been used as a reductant, in addition to ethane, methane and CO [26, 43–47].

Fe-ZSM-5 can be prepared by various ion-exchange methods, including via wet [48–51] or solid state [23, 50, 52], or sublimation [28, 32, 53–56] methodologies. Wet ion exchange includes the use of solvents, while solid state includes solventless mechanical mixing. Sublimation makes use of low evaporation temperature salts, usually FeCl₃, as precursors. One challenge with this preparation method is that Cl[−] ions tend to remain after sublimation and a post-preparation washing step may be required. To combat this we have used a variation of this preparation method: chemical vapour impregnation (CVI). In this method, Fe(acac)₃ is used instead of FeCl₃, as acetylacetonate precursors are easily removed under vacuum [57–59].

During the deposition of Fe on zeolites it is possible to form various types of Fe species such as framework Fe³⁺ (formed during isomorphous substitution), isolated Fe³⁺ or Fe²⁺ anchored to the zeolite framework by either Si–O–Fe or Al–O–Fe bridges, di-nuclear Fe–O–Fe species either in

the framework or in the channels, oligomeric Fe oxo-species, and both small nanoparticles and bulk FeOx particles [26, 59–61]. Determination of the active Fe species for N₂O decomposition remains a challenge; thus far nano-particulate iron [26, 62] and extra-framework Fe have been suggested to catalyse the decomposition of N₂O. However, most suggest that extra framework Fe is the active species due to enabling the formation of α-oxygen, [38, 63–68] which is formed by decomposing N₂O over reversible redox α-Fe sites that switch between Fe²⁺ and Fe³⁺ [69, 70].

Treatment of catalysts with acids was reported to increase both their activity and stability, due to the removal of spectator Fe species (Fe_xO_y nano-particulates and clusters), with extended periods of time for acid washing not required to remove Fe species, with Fe being removed almost immediately [59]. Due to the stability of the zeolites, acid washing does not greatly affect the pore channels and new mesopores were not created. During mild acid washing only a small quantity of surface Al is removed [71]. This stability implies that only the Fe species present will be affected by the acid washing and the zeolite will remain unchanged [72]. Alternatively literature shows that steaming pre-treatments can be used to extract iron from the pores and into the extra-framework sites [53, 73–76], however we will not consider this technique in this work.

In this work we have investigated the importance of different Fe species in Fe-ZSM-5 for the decomposition of N₂O in the presence and absence of a reductant, propane. In addition to comparing different Fe loadings, we have evaluated the efficacy of acid washing to increase the efficiency of the Fe in the active catalyst and we have used UV/Vis spectroscopy to identify the different Fe species.

2 Experimental

2.1 Catalyst Preparation

A series of Fe-ZSM-5 catalysts (0.4, 1.25, 2.5 wt%) were prepared by CVI following the procedure described by Forde et al. [58]. Prior to catalyst preparation, ZSM-5 (23) and (30) (Zeolyst, 2 g) were dried under vacuum, and then placed into a Schlenk flask and evacuated at room temperature using a vacuum line, followed by heating at 150 °C for 1 h under continuous vacuum to remove any surface water species. ZSM-5 (23 or 30) (Zeolyst, 0.975–0.996 g) and iron acetylacetonate Fe(acac)₃ (Sigma Aldrich, 0.0253–0.1582 g) were placed into a glass vial and mixed by manual shaking. The obtained mixture was then transferred to a 50 mL Schlenk flask fitted with a magnetic stirrer bar and sealed. The flask was then evacuated at room temperature using a vacuum line followed by heating at 150 °C for 2 h under continuous vacuum conditions with stirring to induce sublimation and

deposition of the organometallic precursor onto the support. The flask was then brought up to atmospheric pressure with air and the sample removed and calcined at 550 °C in static air for 3 h.

Acid washing was performed by heating 10 v/v% HNO_{3(aq)} (50 mL) to 50 °C, adding the catalyst (0.25 g) and stirring for 10 min. The solution was filtered and washed with deionised water (1 L g⁻¹) followed by drying in an oven at 110 °C for 16 h. The samples obtained using this method were denoted as Acid Washed (AW).

2.2 Catalyst Testing

All reactions were performed at atmospheric pressure in a continuous-flow fixed-bed reactor. A 35 cm length of 1/4 in outer diameter stainless steel tubing was packed with 0.0625 g of catalyst that was sandwiched between two layers of quartz wool. The reaction temperature was tested in the range 200–600 °C. The total flow for all reactions was 100 mL min⁻¹ (GHSV of 45,000 h⁻¹) and the gas feed was 5 v/v% N₂O in He or 5 v/v% N₂O, 5 v/v% C₃H₈ in He. All outgoing gaseous products were analysed online using an Agilent 7890B Gas Chromatograph (GC) [columns: Hayesep Q (80–100 mesh, 1.8 m) MolSieve 5A (80–100 mesh, 2 m)] fitted with a thermal conductivity detector.

Here we define Turnover Frequency (TOF) based on the total moles of Fe present by ICP (Eq. 2) as it is a challenge to determine the concentration of surface active sites.

$$\text{Turnover frequency (TOF)} = \frac{\text{mol of N}_2\text{O converted per second}}{\text{total mol of Fe}} \quad (2)$$

2.3 Catalyst Characterisation

Diffuse reflectance UV/Vis spectra was collected using an Agilent Cary 4000 UV/Vis spectrophotometer. Samples were scanned between 200 and 800 nm (150 nm min⁻¹).

X-ray photoelectron spectroscopy (XPS) was performed on a Thermo Fisher Scientific K-alpha⁺ spectrometer. Samples were analysed using a micro-focused monochromatic Al X-ray source (72 W) over an area of approximately 400 microns. Data were recorded at pass energies of 150 eV for

survey scans and 40 eV for high resolution scan with 1 eV and 0.1 eV step sizes respectively. Charge neutralisation of the sample was achieved using a combination of both low energy electrons and argon ions. Data analysis was performed in CasaXPS using a Shirley type background and Scofield cross sections, with an energy dependence of -0.6.

Nitrogen adsorption isotherms were collected on a Micrometrics 3Flex. Samples (0.050 g) were degassed (250 °C, 9 h) prior to analysis. Analyses was carried out at -196 °C with P₀ measured continuously. Free space was measured post analysis with He. Pore size analysis was carried out using DFT (N₂-Cylindrical Pores-Oxide surface) via the Micrometrics 3Flex software.

Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES) was performed by Exeter Analytical Services using HF digestion to get an accurate Fe loading. The sample was digested by Anton Paar Multiwave 3000 microwave with nitric and HF acids—then the HF was neutralised with the addition of boric acid. A reagent blank was carried out. An internal standard was added to the resulting solutions, and the blank and sample were run against Fe standards by ICP-OES using Thermo Fisher iCAP Duo 7400.

3 Results and Discussion

Although iron-containing zeolites catalyse N₂O decomposition, [24–27, 48–50, 72, 78] high reaction temperatures (> 450 °C) are typically required. The effect of varying the Si:Al ratio has been investigated previously [23, 29], the Fe:Al ratio is also an important parameter, as the maximum population of α-Fe sites is directly proportional to the Al content of the zeolite [27, 50, 79]. Additionally, the presence of spectator or extraneous Fe species remains a challenge with respect to calculating real TOF values.

Fe–ZSM-5 Catalysts were prepared with Fe loadings of 0.4 and 1.25 wt% with two different Si:Al ratios. It is clear that the lower Si:Al ratio exhibits higher relative activity (Table 1). The addition of propane enhances the decomposition of N₂O by reducing the oxidised α-Fe sites that remain on the surface of the catalysts, preventing turnover of N₂O

Table 1 Influence of Fe:Al ratio on 0.4 wt% Fe and 1.25 wt% Fe–ZSM-5 for N₂O Decomposition both with and without propane present

Catalyst	Fe:Al ratio	N ₂ O conversion at 550 °C without propane (%)	N ₂ O conversion at 550 °C with propane (%)
0.4 wt% Fe–ZSM-5 (23)	0.072	20	90
0.4 wt% Fe–ZSM-5 (30)	0.092	12	81
1.25 wt% Fe–ZSM-5 (23)	0.224	35	81
1.25 wt% Fe–ZSM-5 (30)	0.288	29	68

Reaction Conditions: Total flow rate 100 mL min⁻¹, 0.06 g catalyst, temperature range 400–600 °C, GHSV 45,000 h⁻¹, either 5 v/v% N₂O in He or 5 v/v% N₂O, 5 v/v% C₃H₈ in He

[27, 33–38]. Due to the higher activity of the Fe–ZSM-5 (23) parent zeolite catalyst, further investigation was carried out on this Si:Al ratio zeolite [26].

In order to understand the effect of Si:Al ratio, UV/Vis spectroscopy of the various catalysts was performed (Fig. 1). When Fe is added to ZSM-5, four UV-active species can be differentiated. These absorb at: 200–250 nm (isolated Fe^{3+} in framework sites), 250–350 nm (isolated or oligomeric extra framework Fe species in zeolite channels), 350–450 nm (iron oxide clusters) and > 450 nm (large surface oxide species) [61, 80]. UV/Vis shows how higher Al content leads to high absorbance in the region 250–350 nm due to the presence of more extra-framework α -Fe.

An additional Fe–ZSM-5 (23) catalyst was prepared with an Fe weight loading of 2.5% and contrasted to the 0.4 and 1.25 wt% catalysts. Figure 2 (closed symbols) illustrates the conversion of N_2O over the four Fe–ZSM-5 (23) catalysts across the temperature range of 400–600 °C. The increasing weight loading of Fe in ZSM-5 increased the conversion of N_2O , up to ca. 70% conversion over the 1.25 wt% catalyst, compared to 40% conversion over the 0.4 wt% Fe–ZSM-5 catalyst. Increasing the Fe loading to 2.5 wt% did not increase the N_2O conversion further (Fig. 2). The 0.4% Fe catalyst exhibited limited activity despite the presence of active extra-framework α -Fe species. Therefore, when N_2O decomposition takes place at these sites oxygen recombination is limited due to the oxygen species proximity

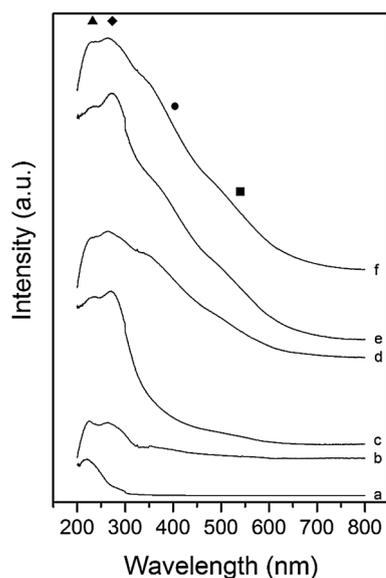


Fig. 1 UV/Vis spectra of a series of Fe–ZSM-5 (23 or 30) catalysts and H-ZSM-5 support. *Filled triangle* framework Fe^{3+} , *filled diamond* extra framework species, *filled circle* Fe_xO_y clusters, *filled square* large Fe_xO_y species. *a* H-ZSM-5 (23), *b* H-ZSM-5 (30), *c* 0.4 wt% Fe–ZSM-5 (23), *d* 0.4 wt% Fe–ZSM-5 (30), *e* 1.25 wt% Fe–ZSM-5 (23), *f* 1.25 wt% Fe–ZSM-5 (30)

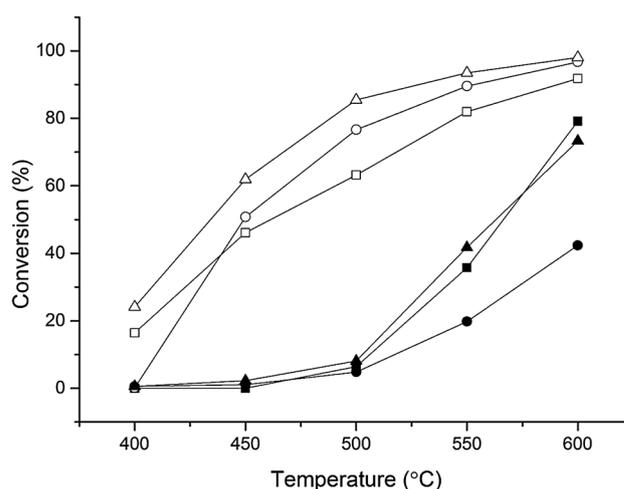


Fig. 2 The influence of Fe weight loading on N_2O conversion over Fe–ZSM-5 catalysts. Closed symbols: N_2O present 5 v/v% N_2O in He, open symbols: N_2O +Propane present: 5 v/v% N_2O , 5 v/v% C_3H_8 in He, *circle* 0.4 wt% Fe–ZSM-5 (23), *square* 1.25 wt% Fe–ZSM-5 (23), *triangle* 2.5 wt% Fe–ZSM-5 (23). Conditions; total flow rate 100 mL min^{-1} , 0.06 g catalyst, temperature range 200–600 °C, GHSV $45,000 \text{ h}^{-1}$

to combine to form molecular oxygen and, therefore, effectively blocking active sites.

High loadings of Fe lead to a high proportion of active framework and extra-framework species and due to the increased density of these species, the rate of oxygen recombination is higher, leading to a higher conversion. UV/Vis spectroscopy (Fig. 3) shows that there are a number of distinct Fe species present in the high loaded catalysts, with both Fe_xO_y nanoparticle and cluster species present, indicating that not all the Fe is efficiently utilised. Therefore, while a significant proportion of Fe is not necessarily active, there is a high concentration of extra-framework α -Fe sites that can facilitate oxygen recombination and high N_2O conversion.

When propane is added to the reaction feed-stream, the onset of activity shifts from 400 to 450 °C to a much lower temperature (Fig. 2 open symbols). In this context, propane acts as a reductant [26, 39, 40, 42, 81] and limits the formation of site blocking oxygen species on the surface of the catalyst. The rate-limiting step without propane is oxygen recombination. Propane can activate the oxidised α -Fe site forming CO and CO_2 , which regenerates the active site and allows the reaction to proceed [27, 33–36]. At lower temperatures (< 500 °C) minor quantities of propene, ethene and ethane are produced, however, at higher temperatures the selectivity shifts to exclusively CO and CO_2 .

Comparing the reaction data (Fig. 2) to the UV/Vis spectroscopy (Fig. 3), it is possible to observe that the more active catalysts have a higher proportion of framework and extra framework α -Fe species. This is the case in

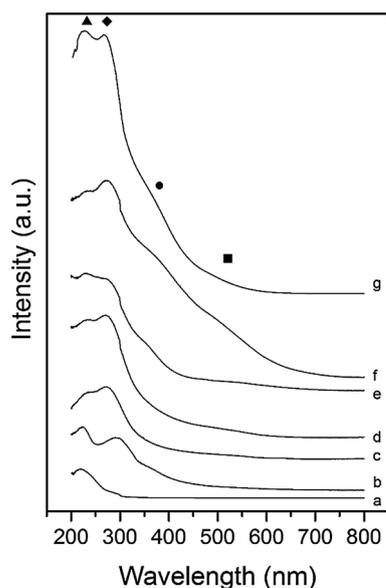


Fig. 3 UV/Vis spectra of a series of Fe-ZSM-5 (23) catalysts and H-ZSM-5 support. Filled circle framework Fe^{3+} , filled diamond extra framework species, filled circle Fe_xO_y clusters, filled square Large Fe_xO_y species. a H-ZSM-5 (23), b H-ZSM-5 (23) AW, c 0.16 wt% Fe-ZSM-5 (23), d 0.4 wt% Fe-ZSM-5 (23), e 0.4 wt% Fe-ZSM-5 (23) AW, f 1.25 wt% Fe-ZSM-5 (23), g 2.5 wt% Fe-ZSM-5 (23)

the 0.4 wt% Fe-ZSM-5 catalyst, where UV/Vis spectroscopy (Fig. 3) shows that framework and extra-framework species are present, with only a small absorbance due to Fe_xO_y nano-particles and clusters. By contrast, the poor activity of 1.25 wt% Fe-ZSM-5 correlates with the high proportion of nanoparticles and clusters of Fe_xO_y present,

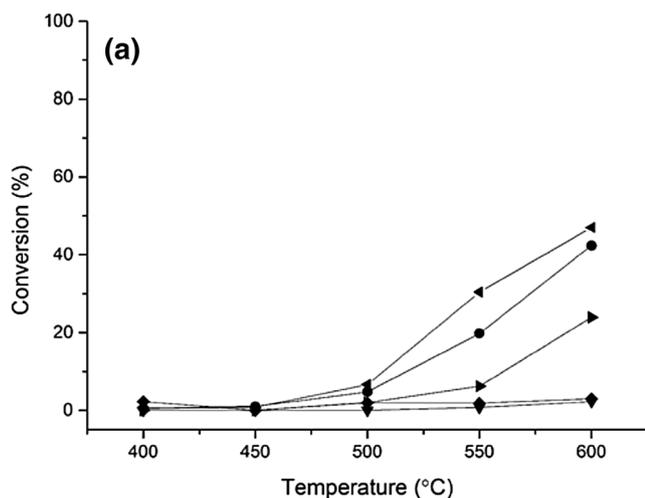
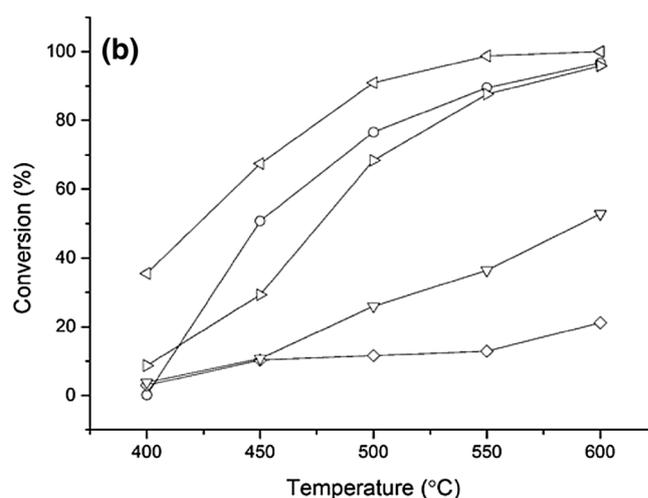


Fig. 4 a Influence of Fe loading and acid washing over Fe-ZSM-5 catalysts for N_2O conversion (closed symbols); Left pointed triangle 0.16 wt% Fe-ZSM-5 (23), circle 0.4 wt% Fe-ZSM-5 (23), right pointed triangle 0.4 wt% Fe-ZSM-5 (23) acid washed, diamond H-ZSM-5 (23), inverted triangle H-ZSM-5 (23) acid washed. Con-

ditions: 5 v/v% N_2O in He, total flow rate 100 mL min^{-1} , 0.06 g catalyst, temperature range 400–600 °C, GHSV 45,000 h^{-1} .

which limit the number of Fe ions available to form the active species. Peneau et al. demonstrated that using dilute HNO_3 , it is possible to remove excess iron and spectator species from the catalyst, which was investigated for the selective oxidation of ethane by H_2O_2 [59]. Here, 0.4 wt% Fe-ZSM-5 (23) was identified as a suitable catalyst formulation for acid washing, due to the presence of extra-framework $\alpha\text{-Fe}$ species and minor levels of spectator Fe_xO_y nano-particulates and clusters. Previous work within the group has shown that it is difficult to distinguish between the Fe species present at higher weight loadings, therefore lower weight loadings were selected for acid washing to enable changes to be noted [82, 83]. After acid washing the calcined catalyst, ICP-OES analysis of the digested samples revealed that the weight loading had reduced to 0.16%. Figure 4a illustrates the activity of the as-prepared parent catalyst, the acid washed 0.4 wt% Fe-ZSM-5 catalyst, a 0.16 wt% Fe-ZSM-5 (prepared by CVI for comparison to the AW catalyst) as well as the analogous H-ZSM-5 catalysts, which were tested to confirm that the support alone was not active for the reaction. The 0.4 wt% Fe-ZSM-5 (23) sample has an N_2O conversion of 40% at 600 °C, however, over the acid washed catalyst the conversion was lower at 600 °C at 25%.

UV/Vis Spectroscopy (Fig. 3) supports the hypothesis that the decrease in activity observed after acid washing was due to the removal of framework Fe^{3+} ions which are extracted and deposited onto the surface of the catalyst as nanoparticles of Fe_xO_y (270 nm). UV/Vis Spectroscopy of 0.16 wt% Fe-ZSM-5 suggests that the Fe is present as framework Fe^{3+} and extra-framework $\alpha\text{-Fe}$ species only



ditions: 5 v/v% N_2O in He, total flow rate 100 mL min^{-1} , 0.06 g catalyst, temperature range 400–600 °C, GHSV 45,000 h^{-1} . **b** N_2O conversion with propane present; open symbols. Conditions: 5 v/v% N_2O , 5 v/v% C_3H_8 in He total flow rate 100 mL min^{-1} , 0.06 g catalyst, temperature range 400–600 °C, GHSV 45,000 h^{-1}

(Fig. 3). The lower activity of this catalyst further suggests that the proximity of the Fe sites to each other is crucial to achieve high activity in N_2O decomposition. When propane is present (Fig. 4b) however, the relative proximity of active sites does not affect activity as propane can abstract oxygen from a single oxidised Fe site.

UV/Vis Spectroscopy was further used to understand the contrasting influence of the Fe loading concentration on N_2O decomposition with and without propane. The spectrum of H-ZSM-5 (23) shows that framework Fe^{3+} species are present in the parent zeolite due to the absorbance at 220 nm (Fig. 3) and are likely to be impurities introduced during manufacture [84]. However, acid washing the H-ZSM-5 has the effect of re-dispersing the Fe species and forming Fe with extra-framework character. The 0.16 wt% Fe-ZSM-5 catalyst appears to possess both framework (< 250 nm) and extra-framework Fe (280 nm) only. Both the 1.25 wt% Fe-ZSM-5 and 2.5 wt% Fe-ZSM-5 catalysts contains all species present, with framework (< 250 nm), extra-framework Fe (280 nm), iron oxide nanoparticles (400 nm) and large clusters of iron oxide (> 450 nm). The spectrum of 0.4 wt% Fe-ZSM-5 (23) shows that there are three species of Fe present, framework Fe^{3+} , extra-framework α -Fe and large Fe_xO_y clusters. In contrast, the spectrum of 0.4 wt% Fe-ZSM-5 (23) acid washed sample shows that there are all four species of Fe present. Most notably, a reduced absorbance due to extra-framework α -Fe being extracted and an increased absorbance from deposited Fe_xO_y nanoparticles and clusters.

Further characterisation was performed on the 0.4 wt% Fe-ZSM-5 and acid washed samples with XPS (Table 2). XPS measurements revealed a significant loss of Fe from the surface of the catalyst following acid washing, as the atomic % of Fe dropped from 2.02 to 0.28%, in addition to a decrease in the intensity of the Fe peak (Fig. 5). Consideration of the surface and bulk Fe content, as determined using XPS and ICP-OES showed a drop in the surface:bulk Fe ratio after acid washing (5.05 and 1.75 for the as-prepared and acid washed 0.4 wt% Fe-ZSM-5 catalysts, respectively). This confirmed that Fe was preferentially removed from the

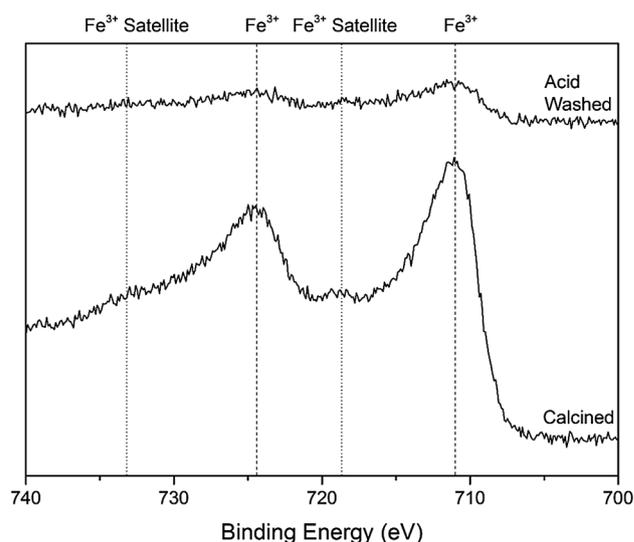


Fig. 5 XPS data of the Fe region of 0.4 wt% Fe-ZSM-5 (23) calcined and acid washed

surface of the catalyst rather than within the micro-porous channels. Furthermore, XPS showed that the binding energy of Fe is 711 eV in the calcined and acid washed catalysts, this alongside the satellite at 719 eV indicates that there is Fe^{3+} species present [85, 86]. After the addition of iron to the ZSM-5 the binding energy of both the Al and Si shift to slightly higher binding energies. Shifts in the Al spectrum from 102.9 eV in ZSM-5 to 103.4 eV in the calcined and acid washed catalyst, with Si shifting from 74.1 to 74.9 eV were observed in both catalysts. This shift to a higher binding energy indicates that Fe has substituted into the lattice, [87–89] and corresponds with the UV/Vis spectroscopy as there is a larger absorption in the framework Fe^{3+} region indicating that Fe has substituted into the framework.

Surface area measurements for all catalysts remained constant at around $430 \text{ m}^2 \text{ g}^{-1}$. This is consistent with the parent zeolite, which has a surface area of $423 \text{ m}^2 \text{ g}^{-1}$. The micropore volume of H-ZSM-5 (23) is $0.167 \text{ cm}^3 \text{ g}^{-1}$, this varies by $\pm 0.003 \text{ cm}^3 \text{ g}^{-1}$ when iron is added and calcined

Table 2 Surface composition, Fe binding energies, surface area and micropore volume of a series of 0.4 wt% Fe-ZSM-5 (23) catalysts and H-ZSM-5 (23) support as reported by XPS analysis. Degas conditions—9 h at 250 °C prior to analysis

Catalyst	Al 2p (at.%)	Na 1s (at.%)	O 1s (at.%)	Si 2p (at.%)	Fe 3p (at.%)	Fe binding energy (eV)	Fe satellite binding energy (eV)	Surface area ($\text{m}^2 \text{ g}^{-1}$)	Micropore volume ($\text{cm}^3 \text{ g}^{-1}$)
H-ZSM-5 (23)	3.17	0.41	62.52	33.90	—	—	—	423	0.167
0.4 wt% Fe-ZSM-5 (23)	3.77	0.12	49.35	44.74	2.02	711.2	719	437	0.169
0.4 wt% Fe-ZSM-5 (23) AW	3.22	0.28	49.87	46.63	0.28	711.0	719	428	0.164

and then acid washed, (Table 2). The consistency of surface area and micropore volume during the catalyst preparation, calcination, and acid washing indicates that H-ZSM-5 (23) is stable under the pre-treatment conditions.

Due to the complexity in resolving the active Fe species, the TOF over the catalysts samples was calculated for N_2O decomposition (Fig. 6a) using the total moles of Fe present in the sample. The low loaded Fe-ZSM-5 sample with 0.16 wt% Fe achieved a TOF of ca. $3.99 \times 10^3 s^{-1}$ at 600 °C. The TOF of the acid washed H-ZSM-5 catalyst at 600 °C is an order of magnitude greater than the Fe based catalyst, when propane is present at 600 °C (Fig. 6b). This is due to the zeolite achieving 52% conversion (Fig. 6b) and only having trace amounts of iron present (245 ppm) typically in framework positions. This results in an extremely high TOF based on the ppm of iron present, however in reality a very low yield of nitrogen was observed. The activity of the H-ZSM-5 after acid washing is due to the formation of active extra-framework α -Fe from Fe that has been removed from the framework [63, 64, 90]. The TOF of the acid washed catalyst was calculated to be $0.94 \times 10^3 s^{-1}$, which compares to $0.69 \times 10^3 s^{-1}$ achieved over the parent catalyst at 600 °C (Fig. 6a). When comparing the activity of the parent and acid washed catalyst in the presence of propane, the difference in activity is less significant and at higher temperatures (> 550 °C) the activity is comparable: both catalysts achieved 95% N_2O conversion at 600 °C (Fig. 4b). In terms of TOF, the activity of the acid washed Fe-ZSM-5 catalyst was two and a half times that of the calcined equivalent catalyst (Fig. 6b). However, the TOF over the 0.16 wt% Fe-ZSM-5 catalyst is ca. $8.5 \times 10^3 s^{-1}$ at > 550 °C, with

propane present. Park et al. reported a TOF of $1.8 \times 10^3 s^{-1}$ for N_2O decomposition at 550 °C using 1.96 wt% Fe-ZSM-5 (27) [50] compared to $2.59 \times 10^3 s^{-1}$ achieved by 0.16% Fe-ZSM-5 (23) at 550 °C under similar conditions, demonstrating the superior activity of the catalyst prepared herein.

4 Conclusions

At low Fe loadings, Fe-ZSM-5 (23) catalysts prepared by CVI have two species of Fe present, Framework Fe^{3+} and isolated extra-framework Fe_xO_y in the pores, as shown by UV/Vis spectroscopy. However, when high-loading Fe-ZSM-5 is prepared by this method there are two additional species of Fe present: Fe_xO_y nanoparticles and large clusters. The species of iron present in low loaded catalysts, framework and extra-framework Fe, are the active species for N_2O decomposition, which lead to high conversion when propane is present, however without propane the activity of these catalysts is limited by slow oxygen desorption, due to the low proximity of active Fe sites. Therefore, the oxygen desorption step becomes rate limiting. At higher weight loadings with only N_2O present the activity of the catalyst is increased as the density of the active sites increase, therefore, increasing the rate of oxygen desorption. When acid washing is performed it is not possible to selectively remove the Fe_xO_y nanoparticles and clusters, but instead extra-framework Fe is extracted from the pores and deposited on the surface, leading to a decrease in conversion, but increase in TOF.

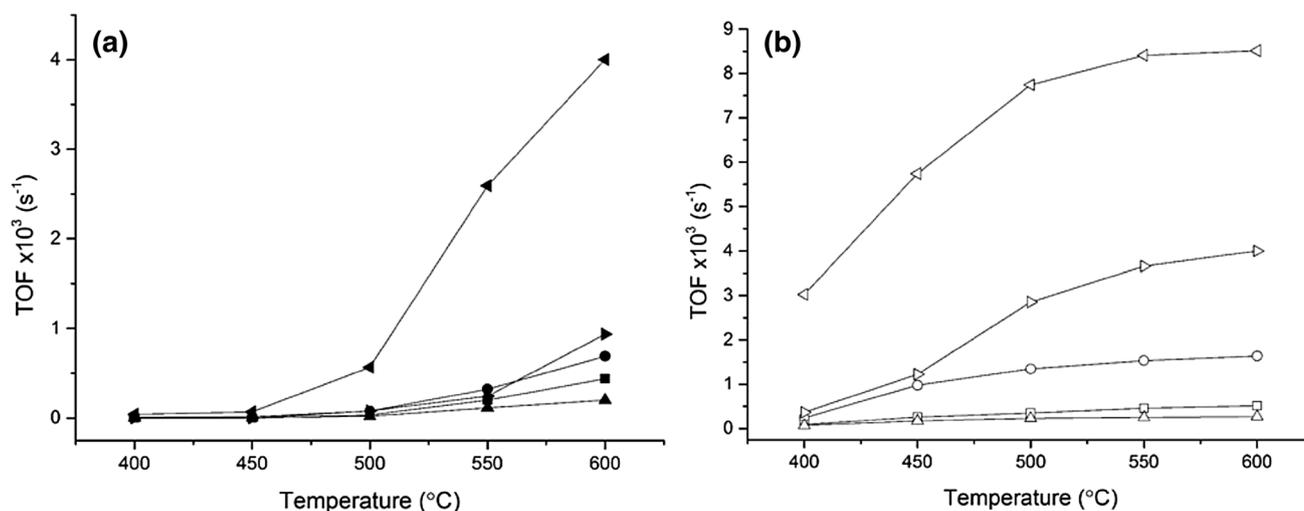


Fig. 6 **a** TOF of N_2O decomposition over a series of Fe-ZSM-5 catalysts that have been calcined or acid washed, closed symbols. *Left pointed triangle* 0.16 wt% Fe-ZSM-5 (23), *circle* 0.4 wt% Fe-ZSM-5 (23), *square* 1.25 wt% Fe-ZSM-5 (23), *triangle* 2.5 wt% Fe-ZSM-5 (23) *right pointed triangle* 0.4 wt% Fe-ZSM-5 (23) AW. Condi-

tions: 5 v/v% N_2O in He, total flow rate $100 mL min^{-1}$, 0.06 g catalyst, temperature range 400–600 °C, GHSV $45,000 h^{-1}$. **b** TOF of N_2O decomposition with propane present, open symbols; Conditions: 5 v/v% N_2O , 5 v/v% C_3H_8 in He, total flow rate $100 mL min^{-1}$, 0.06 g catalyst, temperature range 400–600 °C, GHSV $45,000 h^{-1}$

Acknowledgements ERC Funding ‘After the GoldRush’ code, ERC-AtG-291319. Cardiff Catalysis Institute would like to thank Exeter Analytical for the ICP-OES data. The authors would like to thank Dr. Robert Armstrong for fruitful discussion.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Pérez-Ramírez J, Kapteijn F, Schöffel K, Moulijn JA (2003) Formation and control of N₂O in nitric acid production: where do we stand today? *Appl Catal B* 44:117–151. [https://doi.org/10.1016/S0926-3373\(03\)00026-2](https://doi.org/10.1016/S0926-3373(03)00026-2)
- Weimann J (2003) Toxicity of nitrous oxide. *Best Pract Res Clin Anaesthesiol* 17:47–61
- Grace P, Barton L (2014) <http://theconversation.com/meet-n2o-the-greenhouse-gas-300-times-worse-than-co2-35204>. In: <http://theconversation.com/meet-n2o-the-greenhouse-gas-300-times-worse-than-co2-35204>. Accessed 12 June 2017
- IPCC (2007) Climate change 2007: synthesis report. In: The Core Writing Team, Pachauri RK, Reisinger A (eds), Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, p 104
- Li L, Xu J, Hu J, Han J (2014) Reducing nitrous oxide emissions to mitigate climate change and protect the ozone layer. *Environ Sci Technol* 48:5290–5297. <https://doi.org/10.1021/es404728s>
- IPCC (2013) Climate Change 2013: The physical science basis. Contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
- UNEP (2013) Drawing down nitrous oxide to protect climate and the ozone layer. United Nations Environment Programme, Nairobi
- Maroufi SS, Gharavi MJ, Behnam M, Samadikuchaksaraei A (2011) Nitrous oxide levels in operating and recovery rooms of Iranian hospitals. *Iran J Public Health* 40:75–79
- Space Propulsion Group (2012) <http://www.spg-corp.com/nitrous-oxide-safety.html>. In: <http://www.spg-corp.com/nitrous-oxide-safety.html>
- Kapteijn F, Rodriguez-Mirasol J, Moulijn JA (1996) Heterogeneous catalytic decomposition of nitrous oxide. *Appl Catal B* 9:25–64. [https://doi.org/10.1016/0926-3373\(96\)90072-7](https://doi.org/10.1016/0926-3373(96)90072-7)
- Kumar S, Teraoka Y, Joshi AG et al (2011) Ag promoted La_{0.8}Ba_{0.2}MnO₃ type perovskite catalyst for N₂O decomposition in the presence of O₂, NO and H₂O. *J Mol Catal A* 348:42–54. <https://doi.org/10.1016/j.molcata.2011.07.017>
- Kumar S, Vinu A, Subrt J et al (2012) Catalytic N₂O decomposition on Pr_{0.8}Ba_{0.2}MnO₃ type perovskite catalyst for industrial emission control. *Catal Today* 198:125–132. <https://doi.org/10.1016/j.cattod.2012.06.015>
- Dacquín JP, Lancelot C, Dujardin C et al (2009) Influence of preparation methods of LaCoO₃ on the catalytic performances in the decomposition of N₂O. *Appl Catal B* 91:596–604. <https://doi.org/10.1016/j.apcatb.2009.06.032>
- Kartha KK, Pai MR, Banerjee AM et al (2011) Modified surface and bulk properties of Fe-substituted lanthanum titanates enhances catalytic activity for CO + N₂O reaction. *J Mol Catal A* 335:158–168. <https://doi.org/10.1016/j.molcata.2010.11.028>
- Russo N, Mescia D, Fino D et al (2007) N₂O decomposition over perovskite catalysts. *Ind Eng Chem Res* 46:4226–4231. <https://doi.org/10.1021/ie0612008>
- Zabilskiy M, Erjavec B, Djinović P, Pintar A (2014) Ordered mesoporous CuO-CeO₂ mixed oxides as an effective catalyst for N₂O decomposition. *Chem Eng J* 254:153–162. <https://doi.org/10.1016/j.cej.2014.05.127>
- Zhou H, Hu P, Huang Z et al (2013) Preparation of NiCe mixed oxides for catalytic decomposition of N₂O. *Ind Eng Chem Res* 52:4504–4509. <https://doi.org/10.1021/ie400242p>
- Zhou H, Huang Z, Sun C et al (2012) Catalytic decomposition of N₂O over Cu_xCe_{1-x}O_y mixed oxides. *Appl Catal B Environ* 125:492–498. <https://doi.org/10.1016/j.apcatb.2012.06.021>
- Abu-Zied BM, Soliman SA, Abdellah SE (2015) Enhanced direct N₂O decomposition over Cu_xCo_{1-x}Co₂O₄ (0.0 ≤ x ≤ 1.0) spinel-oxide catalysts. *J Ind Eng Chem* 21:814–821. <https://doi.org/10.1016/j.jiec.2014.04.017>
- Stelmachowski P, Maniak G, Kaczmarczyk J et al (2014) Mg and Al substituted cobalt spinels as catalysts for low temperature deN₂O-evidence for octahedral cobalt active sites. *Appl Catal B* 146:105–111. <https://doi.org/10.1016/j.apcatb.2013.05.027>
- Amrousse R, Tsutsumi A, Bachar A, Lahcene D (2013) N₂O catalytic decomposition over nano-sized particles of Co-substituted Fe₃O₄ substrates. *Appl Catal A* 450:253–260. <https://doi.org/10.1016/j.apcata.2012.10.036>
- Konsolakis MI (2015) Recent advances on nitrous oxide (N₂O) decomposition over non-noble metal oxide catalysts: catalytic performance, mechanistic considerations and surface chemistry aspects. *ACS Catal*. <https://doi.org/10.1021/acscatal.5b01605>
- Rauscher M, Kesore K, Mönnig R et al (1999) Preparation of a highly active Fe-ZSM-5 catalyst through solid-state ion exchange for the catalytic decomposition of N₂O. *Appl Catal A* 184:249–256. [https://doi.org/10.1016/S0926-860X\(99\)00088-5](https://doi.org/10.1016/S0926-860X(99)00088-5)
- Abu-Zied BM, Schwieger W, Unger A (2008) Nitrous oxide decomposition over transition metal exchanged ZSM-5 zeolites prepared by the solid-state ion-exchange method. *Appl Catal B* 84:277–288. <https://doi.org/10.1016/j.apcatb.2008.04.004>
- Sklenak S, Andrikopoulos PC, Boekfa B et al (2010) N₂O decomposition over Fe-zeolites: structure of the active sites and the origin of the distinct reactivity of Fe-ferrierite, Fe-ZSM-5, and Fe-beta. A combined periodic DFT and multispectral study. *J Catal* 272:262–274. <https://doi.org/10.1016/j.jcat.2010.04.008>
- Abdulhamid H, Fridell E, Skoglundh M (2004) Influence of the type of reducing agent (H₂, CO, C₃H₆ and C₃H₈) on the reduction of stored NO_x in a Pt/BaO/Al₂O₃ model catalyst. *Top Catal* 30/31:161–168. <https://doi.org/10.1023/B:TOCA.0000029745.87107.b8>
- Reimer R Wood B, Bell J AT (2002) Studies of N₂O adsorption and decomposition on Fe-ZSM-5. *J Catal* 209:151–158. <https://doi.org/10.1006/jcat.2002.3610>
- Sobalík Z, Novakova J, Dedecek J et al (2011) Tailoring of Ferrierite for N₂O decomposition: on the decisive role of framework Al distribution for catalytic activity of Fe species in Ferrierite. *Microporous Mesoporous Mater* 146:172–183. <https://doi.org/10.1016/j.micromeso.2011.05.004>
- Melián-Cabrera I, van Eck ERH, Espinosa S et al (2017) Tail gas catalyzed N₂O decomposition over Fe-beta zeolite. On the promoting role of framework connected AlO₆ sites in the vicinity of Fe by controlled dealumination during exchange. *Appl Catal B* 203:218–226. <https://doi.org/10.1016/j.apcatb.2016.10.019>
- Mauvezin M, Delahay G, Coq B et al (2001) Identification of iron species in Fe-BEA: influence of the exchange level. *J Phys Chem B* 105:928–935. <https://doi.org/10.1021/jp0021906>
- Øygarden AH, Pérez-Ramírez J (2006) Activity of commercial zeolites with iron impurities in direct N₂O decomposition. *Appl Catal B* 65:163–167. <https://doi.org/10.1016/j.apcatb.2006.03.002>

32. Jiřa K, Nováková J, Schwarze M et al (2009) Role of the Fe-zeolite structure and iron state in the N₂O decomposition: comparison of Fe-FER, Fe-BEA, and Fe-MFI catalysts. *J Catal* 262:27–34. <https://doi.org/10.1016/j.jcat.2008.11.025>
33. Guesmi H, Berthomieu D, Kiwi-Minsker L (2008) Nitrous oxide decomposition on the binuclear [Fe II (μ-O)(μ-OH)Fe II] center in Fe-ZSM-5 zeolite. *J Phys Chem C* 112:20319–20328. <https://doi.org/10.1021/jp808044r>
34. Sang C, Kim BH, Lund CRF (2005) Effect of NO upon N₂O decomposition over Fe/ZSM-5 with low iron loading. *J Phys Chem B* 109:2295–2301. <https://doi.org/10.1021/jp048884m>
35. Hansen N, Heyden A, Bell AT, Keil FJ (2007) A reaction mechanism for the nitrous oxide decomposition on binuclear oxygen bridged iron sites in {Fe-ZSM-5}. *J Phys Chem C* 111:2092–2101. <https://doi.org/10.1021/jp065574q>
36. Bulushev DA, Kiwi-minsker L, Renken A (2004) Dynamics of N₂O decomposition over Fe/ZSM-5 catalysts: effects of. 211:2004
37. Sun K, Xia H, Hensen E et al (2006) Chemistry of N₂O decomposition on active sites with different nature: effect of high temperature treatment of Fe/ZSM-5. *J Catal* 238:186–195. <https://doi.org/10.1016/j.jcat.2005.12.013>
38. Pirngruber GD (2003) The surface chemistry of N₂O decomposition on iron containing zeolites (I). *J Catal* 219:456–463. [https://doi.org/10.1016/S0021-9517\(03\)00220-3](https://doi.org/10.1016/S0021-9517(03)00220-3)
39. Ohtsuka H, Tabata T, Okada O et al (1997) A study on selective reduction of NOx by propane on Co-Beta. *Catal Lett* 44:265–270
40. Ohtsuka H, Tabata T, Okada O et al (1998) A study on the roles of cobalt species in NOx reduction by propane on Co-Beta. *Catal Today* 42:45–50. [https://doi.org/10.1016/S0920-5861\(98\)00075-3](https://doi.org/10.1016/S0920-5861(98)00075-3)
41. Van Den Brink RW, Booneveld S, Verhaak MJFM, De Bruijn FA (2002) Selective catalytic reduction of N₂O and NOx in a single reactor in the nitric acid industry. *Catal Today* 75:227–232. [https://doi.org/10.1016/S0920-5861\(02\)00073-1](https://doi.org/10.1016/S0920-5861(02)00073-1)
42. Centi G, Vazzana F (1999) Selective catalytic reduction of N₂O in industrial emissions containing O₂, H₂O and SO₂: behavior of Fe/ZSM-5 Catalysts. *Catal Today* 53:683–693. [https://doi.org/10.1016/S0920-5861\(99\)00155-8](https://doi.org/10.1016/S0920-5861(99)00155-8)
43. Djéga-Mariadassou G, Fajardie F, Tempère JF et al (2000) A general model for both three-way and deNO(x) catalysis: dissociative or associative nitric oxide adsorption, and its assisted decomposition in the presence of a reductant. Part I. Nitric oxide decomposition assisted by CO over reduced or oxidized rhodium. *J Mol Catal A* 161:179–189. [https://doi.org/10.1016/S1381-1169\(00\)00334-4](https://doi.org/10.1016/S1381-1169(00)00334-4)
44. He L, Wang LC, Sun H et al (2009) Efficient and selective room-temperature gold-catalyzed reduction of nitro compounds with CO and H₂O as the hydrogen source. *Angew Chem Int Ed* 48:9538–9541. <https://doi.org/10.1002/anie.200904647>
45. Teramura K, Tanaka T, Ishikawa H et al (2004) Photocatalytic reduction of CO₂ to CO in the presence of H₂ or CH₄ as a reductant over MgO. *J Phys Chem B* 108:346–354. <https://doi.org/10.1021/jp0362943>
46. Yogo K, Ihara M, Terasaki I, Kikuchi E (1993) Selective reduction of nitrogen monoxide with methane or ethane on gallium ion-exchanged ZSM-5 in oxygen-rich atmosphere. *Chem Lett* 22:229–232. <https://doi.org/10.1246/cl.1993.229>
47. Burch R, Loader PK (1994) Investigation of Pt/Al₂O₃, and Pd/Al₂O₃ & catalysts for the combustion of methane at low concentrations. *Appl Catal B* 5:149–164
48. Pieterse JAZ, Booneveld S, Van Den Brink RW (2004) Evaluation of Fe-zeolite catalysts prepared by different methods for the decomposition of N₂O. *Appl Catal B* 51:215–228. <https://doi.org/10.1016/j.apcatb.2004.02.013>
49. Li L, Shen Q, Li J et al (2008) Iron-exchanged FAU zeolites: preparation, characterization and catalytic properties for N₂O decomposition. *Appl Catal A* 344:131–141. <https://doi.org/10.1016/j.apcata.2008.04.011>
50. Park JH, Choung JH, Nam IS, Ham SW (2008) N₂O decomposition over wet- and solid-exchanged Fe-ZSM-5 catalysts. *Appl Catal B* 78:342–354. <https://doi.org/10.1016/j.apcatb.2007.09.020>
51. Chen B, Liu N, Liu X et al (2011) Study on the direct decomposition of nitrous oxide over Fe-beta zeolites: from experiment to theory. *Catal Today* 175:245–255. <https://doi.org/10.1016/j.catto.2011.04.010>
52. Christoforou SC, Efthimiadis EA, Vasalos IA (2002) Catalytic conversion of N₂O to N₂ over metal-based catalysts in the presence of hydrocarbons and oxygen. *Catal Lett* 79:137–147
53. Zhu Q, Hensen EJ, Mojet BL et al (2002) N₂O decomposition over Fe/ZSM-5: reversible generation of highly active cationic Fe species. *Chem Commun*. <https://doi.org/10.1039/B202843C>
54. Kucherov A V, Montreuil CN, Kucherova TN, Shelef M (1998) In situ high-temperature ESR characterization of FeZSM-5 and FeSAPO-34 catalysts in flowing mixtures of NO, C₃H₆, and O₂. *Catal Lett* 56:173–181
55. Lee H-T, Rhee H-K (1999) Stability of Fe/ZSM-5 De-NOx catalyst: effects of iron loading and remaining Brønsted acid sites. *Catal Lett* 61:71–76. <https://doi.org/10.1023/A:1019044032219>
56. Lobree LJ, Hwang I, Reimer J, Bell AT (1999) An in situ infrared study of NO reduction by C₃H₈ over Fe-ZSM-5. *Catal Lett* 63:233–240
57. Forde MM, Armstrong RD, Hammond C et al (2013) Partial oxidation of ethane to oxygenates using Fe- and Cu-containing ZSM-5. *J Am Chem Soc* 135:11087–11099. <https://doi.org/10.1021/ja403060n>
58. Forde MM, Armstrong RD, McVicker R et al (2014) Light alkane oxidation using catalysts prepared by chemical vapour impregnation: tuning alcohol selectivity through catalyst pre-treatment. *Chem Sci*. <https://doi.org/10.1039/c4sc00545g>
59. Peneau V, Armstrong RD, Shaw G et al (2017) The low-temperature oxidation of propane by using H₂O₂ and Fe/ZSM-5 catalysts: insights into the active site and enhancement of catalytic turnover frequencies. *ChemCatChem* 9:642–650. <https://doi.org/10.1002/cctc.201601241>
60. Ates A, Hardacre C, Goguet A (2012) Oxidative dehydrogenation of propane with N₂O over Fe-ZSM-5 and Fe-SiO₂: influence of the iron species and acid sites. *Appl Catal A* 441–442:30–41. <https://doi.org/10.1016/j.apcata.2012.06.038>
61. Pérez-Ramírez J, Groen JC, Brückner A et al (2005) Evolution of isomorphously substituted iron zeolites during activation: comparison of Fe-beta and Fe-ZSM-5. *J Catal* 232:318–334. <https://doi.org/10.1016/j.jcat.2005.03.018>
62. Kapteijn F, Mul G, Moulijn J, Pérez-Ramírez J (2002) Highly active SO₂-resistant ex-framework FeMFI catalysts for direct N₂O decomposition. *Appl Catal B* 35:227–234
63. Sun K, Zhang H, Xia H et al (2004) Enhancement of α-oxygen formation and N₂O decomposition on Fe/ZSM-5 catalysts by extraframework Al. *Chem Commun*. <https://doi.org/10.1039/B408854A>
64. Hensen EJM, Zhu Q, Hendrix MMRM et al (2004) Effect of high-temperature treatment on Fe/ZSM-5 prepared by chemical vapor deposition of FeCl₃: I. Physicochemical characterization. *J Catal* 221:569–583. <https://doi.org/10.1016/j.jcat.2003.09.024>
65. Pérez-Ramírez J (2003) Active site structure sensitivity in N₂O conversion over FeMFI zeolites. *J Catal* 218:234–238. [https://doi.org/10.1016/S0021-9517\(03\)00087-3](https://doi.org/10.1016/S0021-9517(03)00087-3)
66. Sobolev V (1993) Catalytic properties of ZSM-5 zeolites in N₂O decomposition: the role of iron. *J Catal* 139:435–443
67. Panov GI, Kharitonov AS, Sobolev VI (1993) Oxidative hydroxylation using dinitrogen monoxide: a possible route for organic synthesis over zeolites. *Appl Catal A* 98:1–20. [https://doi.org/10.1016/0926-860X\(93\)85021-G](https://doi.org/10.1016/0926-860X(93)85021-G)
68. Panov GI, Sobolev VI, Kharitonov AS (1990) The role of iron in N₂O decomposition on ZSM-5 zeolite and reactivity of the

- surface oxygen formed. *J Mol Catal* 61:85–97. [https://doi.org/10.1016/0304-5102\(90\)85197-P](https://doi.org/10.1016/0304-5102(90)85197-P)
69. Panov GI, Starokon EV, Pirutko LV et al (2008) New reaction of anion radicals O⁻ with water on the surface of FeZSM-5. *J Catal* 254:110–120. <https://doi.org/10.1016/j.jcat.2007.12.001>
70. Parfenov MV, Starokon EV, Pirutko LV, Panov GI (2014) Quasicatalytic and catalytic oxidation of methane to methanol by nitrous oxide over FeZSM-5 zeolite. *J Catal* 318:14–21. <https://doi.org/10.1016/j.jcat.2014.07.009>
71. Fernandez C, Stan I, Gilson JP et al (2010) Hierarchical ZSM-5 zeolites in shape-selective xylene isomerization: role of mesoporosity and acid site speciation. *Chemistry* 16:6224–6233. <https://doi.org/10.1002/chem.200903426>
72. Wu M, Wang H, Zhong L et al (2016) Effects of acid pretreatment on Fe-ZSM-5 and Fe-beta catalysts for N₂O decomposition. *Cuihua Xuebao/Chinese J Catal* 37:898–907. [https://doi.org/10.1016/S1872-2067\(15\)61052-X](https://doi.org/10.1016/S1872-2067(15)61052-X)
73. Sun K, Zhang H, Xia H et al (2004) Enhancement of α -oxygen formation and N₂O decomposition on Fe/ZSM-5 catalysts by extraframework Al. *Chem Commun* 216:2480–2481. <https://doi.org/10.1039/B408854A>
74. Dubkov KA, Ovanesyan NS, Shteinman AA et al (2002) Evolution of iron states and formation of α -sites upon activation of FeZSM-5 zeolites. *J Catal* 207:341–352. <https://doi.org/10.1006/jcat.2002.3552>
75. Ribera A, Arends IWCE, De Vries S et al (2000) Preparation, characterization, and performance of FeZSM-5 for the selective oxidation of benzene to phenol with N₂O. *J Catal* 195:287–297. <https://doi.org/10.1006/jcat.2000.2994>
76. Panov GI, Uriarte AK, Rodkin MA, Sobolev VI (1998) Generation of active oxygen species on solid surfaces. Opportunity for novel oxidation technologies over zeolites. *Catal Today* 41:365–385. [https://doi.org/10.1016/S0920-5861\(98\)00026-1](https://doi.org/10.1016/S0920-5861(98)00026-1)
77. Forde MM, Kesavan L, Bin Saiman MI et al (2014) High activity redox catalysts synthesized by chemical vapor impregnation. *ACS Nano* 8:957–969. <https://doi.org/10.1021/nn405757q>
78. Li G, Pidko EA, Filot IAW et al (2013) Catalytic properties of extraframework iron-containing species in ZSM-5 for N₂O decomposition. *J Catal* 308:386–397. <https://doi.org/10.1016/j.jcat.2013.08.010>
79. Wood BR, Reimer JA, Bell AT et al (2004) Nitrous oxide decomposition and surface oxygen formation on Fe-ZSM-5. *J Catal* 224:148–155. <https://doi.org/10.1016/j.jcat.2004.02.025>
80. Kumar MS, Perez-Ramirez J, Debbagh MN et al (2006) Evidence of the vital role of the pore network on various catalytic conversions of N₂O over Fe-silicalite and Fe-SBA-15 with the same iron constitution. *Appl Catal B* 62:244–254. <https://doi.org/10.1016/j.apcatb.2005.07.012>
81. Van Den Brink RW, Booneveld S, Verhaak MJFM, De Bruijn FA (2002) Selective catalytic reduction of N₂O and NO_x in a single reactor in the nitric acid industry. *Catal Today* 75(1–4):227–232
82. Chow YK, Dummer NF, Carter JH et al (2018) A kinetic study of methane partial oxidation over Fe-ZSM-5 using N₂O as an oxidant. *ChemPhysChem* 19:402–411. <https://doi.org/10.1002/cphc.201701202>
83. Xu J, Armstrong RD, Shaw G et al (2016) Continuous selective oxidation of methane to methanol over Cu- and Fe-modified ZSM-5 catalysts in a flow reactor. *Catal Today* 270:93–100. <https://doi.org/10.1016/j.cattod.2015.09.011>
84. Hammond C, Forde MM, Ab Rahim MH et al (2012) Direct catalytic conversion of methane to methanol in an aqueous medium by using copper-promoted Fe-ZSM-5. *Angew Chem Int Ed* 51:5129–5133. <https://doi.org/10.1002/anie.201108706>
85. Biesinger MC, Payne BP, Grosvenor AP et al (2011) Resolving surface chemical states in XPS analysis of first row transition metals, oxides and hydroxides: Cr, Mn, Fe, Co and Ni. *Appl Surf Sci* 257:2717–2730. <https://doi.org/10.1016/j.apsusc.2010.10.051>
86. Graat PCJ, Somers MAJ (1996) Simultaneous determination of composition and thickness of thin iron-oxide films from XPS Fe 2p spectra. *Appl Surf Sci* 100–101:36–40. [https://doi.org/10.1016/0169-4332\(96\)00252-8](https://doi.org/10.1016/0169-4332(96)00252-8)
87. Södergren S, Siegbahn H, Rensmo H et al (1997) Lithium intercalation in nanoporous anatase TiO₂ studied with XPS. *J Phys Chem B* 101:3087–3090. <https://doi.org/10.1021/jp9639399>
88. Chen W, Xu Q, Hu YS et al (2002) Effect of modification by poly(ethylene oxide) on the reversibility of insertion/extraction of Li⁺ ion in V₂O₅ xerogel films. *J Mater Chem* 12:1926–1929. <https://doi.org/10.1039/b203056j>
89. Stakheev AY, Shpiro ES, Apijok J (1993) XPS and XAES study of titania-silica mixed oxide system. *J Phys Chem* 97:5668–5672. <https://doi.org/10.1021/j100123a034>
90. Pérez-Ramírez J, Kapteijn F, Brückner A (2003) Active site structure sensitivity in N₂O conversion over FeMFI zeolites. *J Catal* 218:234–238. [https://doi.org/10.1016/S0021-9517\(03\)00087-3](https://doi.org/10.1016/S0021-9517(03)00087-3)