

Understanding the origins of N₂O decomposition activity in Mn-Co-Al-O_x hydrotalcite derived mixed metal oxides.

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Abstract

The catalytic decomposition of N₂O was studied over a series of calcined (Mn,Fe)-Co-Al hydrotalcite-like compounds. The precursors were prepared by coprecipitation and characterized by XRD and TGA. While the mixed metal oxides derived after calcination at 600 °C were characterized by XRD, N₂ adsorption, H₂-TPR and XPS. Moreover, *in situ* XAFS measurements over selected mixed metal oxides were performed. Such investigations under reaction conditions are rare, while a comprehensive understanding of the involved active species may facilitate a knowledge-based catalyst optimization. The activity of the Co-Al (Co/Al = 3/1, mol.%)

catalyst varied depending on the loading of Mn or Fe (0.0575, 0.0821, 0.1150, 0.1725, 0.2300, mol.%). In the investigated series, $\text{Mn}_{0.1725}\text{Co}_3\text{Al}$ mixed metal oxides reached the highest activity with T_{50} of about 305 and 376 °C under $\text{N}_2\text{O}/\text{N}_2$ and $\text{N}_2\text{O}, \text{NO}, \text{O}_2/\text{N}_2$ feed, respectively. *In situ* X-ray absorption experiments over $\text{Mn}_{0.1725}\text{Co}_3\text{AlO}_x$ suggested that $\text{Mn}_x\text{Co}_y\text{O}_4$ spinel undergo reduction to CoO and MnO upon heating up to 600 °C in He. Under $\text{N}_2\text{O}/\text{He}$ conditions, initial reoxidation of cobalt species began at 350 °C. The lower activity obtained for $\text{Fe}_{0.1725}\text{Co}_3\text{AlO}_x$ is explained by the fact that the majority of Fe was not incorporated into the Co_3O_4 structure but instead formed less reactive iron oxide clusters.

Keywords: hydrotalcite-like compounds, mixed metal oxides, cobalt, N_2O decomposition, *in situ* XAFS.

1. Introduction

The catalytic decomposition of N_2O (de N_2O) can be considered one of the best available technologies for N_2O abatement from nitric acid production, which is one of the major industrial sources of N_2O . A broad collection of catalysts have been applied at temperatures below 450-500 °C [1]. As implied by the published results, hydrotalcite derived mixed metal oxides present high activity for de N_2O even in the presence of H_2O , O_2 , SO_2 and/or NO_x . The hydrotalcite-like compounds with a general formula of $\text{M}^{2+}_{1-x}\text{M}^{3+}_x(\text{OH})_2(\text{A}^{n-})_{x/n} \cdot m\text{H}_2\text{O}$, where M^{2+} and M^{3+} – bi- and trivalent metal cations, respectively, A^{n-} – an interlayer anion, and $x = \text{M}^{3+}/(\text{M}^{3+}+\text{M}^{2+})$ with a value between 0.17 - 0.50 [2,3], serve as excellent precursors for the preparation of the catalysts of the desired chemical and phase composition for de N_2O . Thermal decomposition of hydrotalcite-like compounds at middle temperatures (≤ 600 °C) results in the formation of the relatively high surface mixed metal oxides, with a high dispersion of introduced transition oxide metal species [4–6]. Recently, Jabłońska and Palkovits [1,7] reviewed hydrotalcite derived mixed metal oxides in de N_2O , and concluded that the activity of the mixed metal oxides varied depending on the type and loading of the catalytically active metal, its oxidation state as well as dispersion and aggregation state, etc. The research of hydrotalcite derived mixed metal oxides focusses mainly on cobalt-based materials: Co-Al- O_x (e.g. [8,9]), Co-(Mg)-Mn-(Al)- O_x (e.g. [10–12]), Co-Mg-Al- O_x or Co-Cu-Mg-Al- O_x (e.g. [13]), etc. Kannan et al. [14–16] and furthermore Pérez-Ramírez et al. [8]

found Co/Al with 3/1 molar ratio as optimal hydrotalcite derived catalyst dedicated to deN₂O among catalysts varied between Co/Al = 3-1/1, mol.%. The Co₃Al₁ mixed metal oxides reached 84-100% conversion at 450 °C. Kannan et al. [15,16] reported that the activity of Co-Al mixed metal oxides correlated with the Co/Al bulk composition, but, an even better correlation in the activity was obtained with the Co²⁺ (generated by surface reduction and reconstruction) of mixed metal oxides, as determined by XPS. Obalová et al. [10,11,17] investigated numerous combinations of Co(Mg)-Mn(Al), and found Co₄Mn₁Al₁O_x as optimum catalyst for deN₂O (82-97% conversion at 450 °C). The authors reported an optimum surface amount of Co²⁺/Co³⁺ and Mn²⁺/Mn³⁺ molar ratios at 1.13 and 2.27 by XPS. Moreover, as determined from H₂-TPR, Co₄Mn₁Al₁O_x possessed an optimum number of components reducible in the temperatures of the maximum conversion of N₂O (between 350-450 °C) [11]. We note that to date there have been no previous studies on hydrotalcite-derived catalysts under reaction conditions and as such insight into the active form of the catalyst is currently absent. Such information however, often provides a better understanding of what makes for a good or poor catalyst. Thus, the above studies were the inspiration for Our present investigation focused on identifying the exact nature and behaviour of metal species in Mn(Fe)CoAl hydrotalcite derived mixed metal oxides applied to deN₂O using *in situ* XAFS supported by *ex situ* characterisation of precursors and/or mixed metal oxides using XRD, TG, N₂ adsorption and H₂-TPR, in order to explore additional structure-activity correlations.

2. Experimental

2.1. Catalysts preparation

A series of Mn(Fe)_xCo₃Al₁ (x = 0.0575, 0.0821, 0.1150, 0.1725, 0.2300, mol.%) hydrotalcite-like compounds was prepared by coprecipitation. An aqueous solution containing appropriate amounts of following metal nitrates: Co(NO₃)₂·6H₂O (Roth), Al(NO₃)₃·9H₂O (Sigma), Mn(NO₃)₂·4H₂O (Roth), Fe(NO₃)₃·9 H₂O (Roth) and 1 M NaOH (Chemsolute) was dropped simultaneously into a vigorously stirred at 60 °C aqueous solution containing a slight over-stoichiometric excess of Na₂CO₃ (Sigma). The pH of the reaction mixture was maintained constant at 10.0 ± 0.2 throughout the whole synthesis by NaOH addition. The obtained suspension was aged at 60 °C for another 0.5 h after complete coprecipitation. The solid was filtered, washed carefully

with distilled water and dried at room temperature. Finally, the prepared hydrotalcite-like compounds were crushed and calcined at 600 °C for 6 h with a heating ramp of 10 K/min and in static air. The hydrotalcite derived mixed metal oxides were kept in a desiccator in order to avoid the reconstruction of the hydroxide-like structure. For catalytic experiments, a fraction of particle size in the range of 0.250-0.500 mm was used.

2.2. Catalyst characterization

The X-Ray diffraction (XRD) measurements of the all as-synthesized hydrotalcite-like compounds and mixed metal oxides formed by their thermal decomposition was performed applying a Siemens D5000 XRD diffractometer using Cu-K α radiation ($\lambda = 1.54056 \text{ \AA}$, 45 kV, 40 mA). The difference thermogravimetric analysis (DTG) of the hydrotalcite-like compounds (~20 mg) was carried out using a Netzsch STA 409C/CD operated under a flow of air (10 cm³/min) in the temperature range of 30-1000 °C with a linear heating rate of 5 °C/min. The specific surface area (S_{BET}) of the mixed metal oxides was determined by low-temperature (-196 °C) N₂ sorption using a Quantachrome Quadrasorb SI. Prior to nitrogen adsorption the samples were outgassed at 250 °C for 12 h using a Quantachrome Flovac degasser. The specific surface area (S_{BET}) was calculated using the Brunauer-Emmett-Teller (BET) multiple point method in the p/p_0 range from 0.05 to 0.3. The chemical analysis of mixed metal oxides was determined by ICP-MS using an Agilent Technologies 8800 Triple Quad spectrometer. Prior to measurement, sample (50 mg) was dissolved in 6 cm³ mixture of concentrated acids (HCl:HNO₃, 1:1), and afterwards the resultant mixture was diluted with 64 cm³ deionized water before warming up to 40 °C for 24 h. The redox properties of the selected mixed metal oxides were studied by the temperature-programmed reduction (H₂-TPR) using Quantachrome ChemBET Pulsar TPR/TPD. H₂-TPR runs for the samples (30 mg) were carried out starting from room temperature to 1000 °C, with a linear heating rate of 10 °C/min and in a flow (25 cm³/min) of 5.0 vol.% H₂/Ar. Water vapour was removed from effluent gas by the means of a cold trap placed in an ice-water bath. The H₂ consumption was detected and recorded by TCD detector. The X-ray photoelectron spectra (XPS) of selected mixed metal oxides were measured on a VSW spectrometer equipped with a hemispherical analyzer. The photoelectron spectra were measured using a magnesium Mg K α source ($E = 1253.6 \text{ eV}$). The base pressure in the analysis chamber during the measurements was $3 \cdot 10^{-6} \text{ Pa}$ and the spectra were calibrated on a main carbon C 1s peak at 284.6 eV. The

composition and chemical surrounding of the sample surface were investigated based on the areas and binding energies of Co 2p, Mn 2p, Fe 2p, Al 2p, O 1s and C 1s photoelectron peaks. Mathematical analyses of the XPS spectra were carried out using the XPSpeak 4.1 computer software (RWM. Kwok, The Chinese University of Hong Kong).

The X-ray absorption spectra (XAS) of selected samples were collected *in situ* using the quartz capillary flow reactor cells, and gas delivery systems available on the beamline, on station B18 at the Diamond Light Source synchrotron facility. The measurements were carried out using a Si(111) monochromator at the Co K-edge, Mn K-edge or Fe K-edge with the respective Co, Mn or Fe monometallic foils (10 μm) used as an energy calibrant for the monochromator. The catalyst diluted with SiO_2 (1:5) was sieved into 0.200-0.250 mm and placed into the reactor. Prior to the reaction the catalyst was outgassed at 600 $^\circ\text{C}$ for 1 h in a flow of pure He (10 cm^3/min), and subsequently cooled down to 100 $^\circ\text{C}$. The reactant concentrations at the reactor inlet composed of $[\text{N}_2\text{O}] = 0.1 \text{ vol.}\%$ and $[\text{He}] = 99.9 \text{ vol.}\%$ (10 cm^3/min). The temperature was raised in steps of 50-100 $^\circ\text{C}$ up to 600 $^\circ\text{C}$. Each temperature was held for 30 min. X-ray absorption spectra at appropriate K-edges were collected in fluorescence mode for 240 s for Co, Fe or Mn K-edges. At least three spectra for each sample were taken (and averaged) at room temperature, appropriate temperatures and after reaction at room temperature. CoO, Co_3O_4 , FeO, Fe_2O_3 , MnO_2 references were measured only at room temperature. The data were analysed using the Demeter software package [18,19]); the edge position was determined as the first maximum – after the pre-edge peak – of the derivative of the XANES spectra.

2.3. Catalytic tests

The catalytic performance of the mixed metal oxides was evaluated in the N_2O decomposition. The catalytic experiments were carried out under atmospheric pressure in a fixed-bed flow microreactor. Prior to the reaction the catalyst (350 mg) was outgassed at 600 $^\circ\text{C}$ for 1 h in a flow of pure N_2 (100 cm^3/min). The reactant concentrations at the reactor inlet composed of: (i) $[\text{N}_2\text{O}] = 0.1 \text{ vol.}\%$, N_2 balance, (ii) $[\text{N}_2\text{O}] = 0.1 \text{ vol.}\%$, $[\text{NO}] = 0.03 \text{ vol.}\%$, $[\text{O}_2] = 4.5 \text{ vol.}\%$, N_2 balance (100 cm^3/min ; $\text{WHSV} = 17 \text{ L (h g)}^{-1}$), were analyzed by infrared spectroscopy using a Perkin Elmer Spectrum Two equipped with a Pike 5 m heated gas cell. The temperature was raised in steps of 50 $^\circ\text{C}$ starting from 100 up to 600 $^\circ\text{C}$. Each temperature was set constant for 0.5 h.

For selected material, additional tests were carried out in the presence of water vapour. Such catalytic experiments were carried out under atmospheric pressure in a fixed-bed flow microreactor. Prior to the reaction, the catalyst (70-150 mg) was activated at 580 °C for 0.5 h in a flow of pure He (75 cm³/min). After reactor cooled down, the following composition was applied: [N₂O] = 0.1 vol.%, ([H₂O] = 3.5 wt.%), He balance (75 cm³/min; WHSV = 30-64 L (h g)⁻¹), were analyzed by a Pfeiffer Omnistar quadrupole mass spectrometer equipped with Channeltron and Faraday detectors (0-200 amu).

The conversion of N₂O (X(N₂O)) was estimated according to $X(N_2O) = ([c(N_2O)_{in} - c(N_2O)_{out}] / c(N_2O)_{in}) \times 100\%$, where: $c(N_2O)_{in}$ and $c(N_2O)_{out}$ – concentration of N₂O in the inlet gas, and concentration of N₂O in the outlet gas.

3. Results and discussion

Fig. 1 presents the XRD patterns of Mn(Fe)_xCo₃Al₁ (x = 0.0575, 0.0821, 0.1150, 0.1725, 0.2300, mol.%) hydrotalcite-like compounds, exhibiting rhombohedral symmetry (space group R3m, 3R₁ polytype) [20] with sharp and symmetrical reflections (0 0 3), (0 0 6), (1 1 0) and (1 1 3), and broad and asymmetrical reflections (0 1 2), (0 1 5) and (0 1 8). The intensity of the reflection corresponding to the hydrotalcite-like phase were very weak for samples with 0.0575 mol.% of Mn or Fe. However, the intensity of such phases increased with increasing loading of both transition metals. Table 1 summarizes the unit cell parameters of the hydrotalcite-like compounds and their derivatives. The cell parameters were calculated using a position of (1 0 1) reflection: $a = 2(d_{1\ 0\ 1})$ and positions of basal reflections: $c = [3(d_{0\ 0\ 3}) + 6(d_{0\ 0\ 6})]/2$. The lattice parameter a depends on the size of the cation in the brucite-like layers, while the parameter c refers to the interlayer thickness. The a values for Mn(Fe)_xCo₃Al₁ (x = 0.0575, 0.0821, 0.1150, 0.1725, 0.2300, mol.%) hydrotalcite-like compounds varied only slightly with increasing Mn or Fe content and were close to that obtained for Co₃Al₁. The a values depends mainly on the ionic radii of the cations in octahedral coordination (0.070 nm Co²⁺, 0.070 nm Mn²⁺ and 0.070 nm Fe³⁺ [21], as cations of metal precursors). The c values of about 2.3 nm stay characteristic for hydrotalcite-like compounds containing carbonates located in the interlayer space [2]. The interlayer distances increased upon decreasing electronegativity of the cations: Co (1.70) > Fe (1.64) > Mn (1.60) > Al (1.47) (according to

Allred-Rochow scale) [22]. The crystal sizes were calculated from the Scherrer equation $D = 0.89 \cdot \lambda / \beta \cdot \theta$, where D is the crystallite size, λ is the X-ray wavelength, β is the line broadening and θ is the Bragg angle. The Fe-containing materials revealed overall higher crystal size (with the exception of $\text{Fe}_{0.0575}\text{Co}_3\text{Al}_1$) than the corresponding MnCo_3Al_1 compounds.

Fig. 2 presents the DTG profiles of $\text{Mn}(\text{Fe})_x\text{Co}_3\text{Al}_1$ ($x = 0.0575, 0.0821, 0.1150, 0.1725, 0.2300$, mol.%) hydrotalcite-like compounds, while Table 2 gathers total mass loss of these materials. DTG profiles revealed the presence of two stages of weight loss, providing an additional proof of the presence of the hydrotalcite-like structure. The thermal decomposition of Mn(Fe)-Co-Al precursors proceeded in two main stages with total mass losses of about 30-33%. The first DTG minimum centered at about 190-200 °C corresponded to the removal of interlayer and weakly adsorbed water without collapse of the structure. The second peak located at about 230-235 °C appeared due to the dehydroxylation of the brucite-like layers and thermal decomposition of interlayer carbonates and nitrates (e.g. [5,6,20]). The temperatures and peak intensities did not change significantly among studied precursors, possibly due to small differences in the Mn or Fe loading as well as similar size of Mn^{2+} and Fe^{3+} (as cations of metal precursors) in octahedral coordination of ~~0.058 and 0.055~~ 0.070 nm, respectively [21].

Fig. 3 shows the XRD patterns of calcined Mn(Fe)CoAl hydrotalcite-like compounds. The hydrotalcite-like structure was completely destroyed upon heating at 600 °C resulting in the formation of a spinel phase with a range of possible composition, namely $\text{Co}_3\text{O}_4/\text{CoAl}_2\text{O}_4/\text{Co}_2\text{AlO}_4$ (with Bragg reflections located at 2θ at 19, 31, 37, 39, 45, 56, 59, 65, 77°) (e.g. [8,16]), exhibiting cubic symmetry (space group $\text{Fd}\bar{3}\text{m}$) [24]. The lattice parameter a in the range of 0.8073-0.8099 nm was close to Co_3O_4 ($a = 0.8084$ nm). Mn- or Fe- containing materials did not reveal any diffraction characteristic for transition metal oxides in the XRD patterns, which confirmed the absence of bigger crystallites. Crystal sizes of 26-33 nm were calculated from (3 1 1) Bragg reflection in the XRD patterns using the Scherrer equation.

Fig. 1, Fig. 2, Fig. 3

Table 1. Lattice parameters of (Mn,Fe)-Co-Al hydrotalcite-like compounds and corresponding mixed metal oxides.

Hydrotalcite-like compounds	Cell parameter	Cell parameter	Crystallite size	Crystallite size	Mixed metal oxides	Cell parameter	Crystallite size
	<i>a</i> [nm]	<i>c</i> [nm]	<i>D_a</i> [nm]	<i>D_c</i> [nm]		<i>a</i> [nm]	<i>D_a</i> [nm]
Co ₃ Al ₁	0.3079	2.2956	29	20	Co ₃ Al ₁ O _x	27	0.8093
Mn _{0.0575} Co ₃ Al ₁	0.3085	2.3065	33	22	Mn _{0.0575} Co ₃ Al ₁ O _x	32	0.8076
Mn _{0.0821} Co ₃ Al ₁	0.3086	2.3060	34	21	Mn _{0.0821} Co ₃ Al ₁ O _x	32	0.8083
Mn _{0.1150} Co ₃ Al ₁	0.3085	2.3006	25	24	Mn _{0.1150} Co ₃ Al ₁ O _x	27	0.8099
Mn _{0.1725} Co ₃ Al ₁	0.3080	2.2800	33	24	Mn _{0.1725} Co ₃ Al ₁ O _x	26	0.8079
Mn _{0.2300} Co ₃ Al ₁	0.3078	0.2790	27	24	Mn _{0.2300} Co ₃ Al ₁ O _x	26	0.8099
Fe _{0.0575} Co ₃ Al ₁	0.3085	2.3215	22	22	Fe _{0.0575} Co ₃ Al ₁ O _x	30	0.8073
Fe _{0.0821} Co ₃ Al ₁	0.3086	2.3100	39	26	Fe _{0.0821} Co ₃ Al ₁ O _x	33	0.8076
Fe _{0.1150} Co ₃ Al ₁	0.3085	2.3065	39	28	Fe _{0.1150} Co ₃ Al ₁ O _x	33	0.8093
Fe _{0.1725} Co ₃ Al ₁	0.3081	2.2839	34	28	Fe _{0.1725} Co ₃ Al ₁ O _x	30	0.8083
Fe _{0.2300} Co ₃ Al ₁	0.3081	2.2790	42	30	Fe _{0.2300} Co ₃ Al ₁ O _x	31	0.8096

Table 2 lists the specific surface areas (S_{BET}) of the (Mn,Fe)-Co-Al mixed metal oxides. S_{BET} for Co-Al-O_x of 82 m²/g, significantly decreased after introduction of Mn or Fe within its structure. A similar trend was observed for both series, i.e. decrease for materials with 0.0821 mol.% then increase up to 0.1725 mol.%, and finally a drop in S_{BET} for materials with the highest loading of transition metal (0.2300 mol.%). However, slightly higher values for S_{BET} were reached over Mn-containing mixed metal oxides. Chemical analysis identified by ICP-MS evidenced sodium residual from preparation procedure up to 2.3 wt.%.

Table 2. Total mass losses of (Mn,Fe)-Co-Al hydrotalcite-like compounds, specific surface areas (S_{BET}), sodium residuals of mixed metal oxides, and T_{50} of mixed metal oxides in N₂O/N₂, N₂O,NO,O₂/N₂* and N₂O,H₂O/He** gas mixtures.

Hydrotalcite-like compounds	Total mass loss [%]	Mixed metal oxides	S_{BET} [m ² /g]	Na [wt.%]	T_{50} [° C]
Co ₃ Al ₁	32.62	Co ₃ Al ₁ O _x	82	1.4	352 ^a *409 ^a **549 ^b
Mn _{0.0575} Co ₃ Al ₁	31.90	Mn _{0.0575} Co ₃ Al ₁ O _x	59	0.7	317 ^a
Mn _{0.0821} Co ₃ Al ₁	31.54	Mn _{0.0821} Co ₃ Al ₁ O _x	57	1.3	332 ^a
Mn _{0.1150} Co ₃ Al ₁	30.53	Mn _{0.1150} Co ₃ Al ₁ O _x	61	1.0	320 ^a
Mn _{0.1725} Co ₃ Al ₁	30.89	Mn _{0.1725} Co ₃ Al ₁ O _x	76	2.3	305 ^a *376 ^a **528 ^b
Mn _{0.2300} Co ₃ Al ₁	31.03	Mn _{0.2300} Co ₃ Al ₁ O _x	65	0.8	316 ^a
Fe _{0.0575} Co ₃ Al ₁	31.43	Fe _{0.0575} Co ₃ Al ₁ O _x	56	0.8	356 ^a
Fe _{0.0821} Co ₃ Al ₁	31.34	Fe _{0.0821} Co ₃ Al ₁ O _x	53	0.8	325 ^a
Fe _{0.1150} Co ₃ Al ₁	31.10	Fe _{0.1150} Co ₃ Al ₁ O _x	54	1.6	333 ^a
Fe _{0.1725} Co ₃ Al ₁	30.27	Fe _{0.1725} Co ₃ Al ₁ O _x	54	0.9	327 ^a *380 ^a **549 ^b
Fe _{0.2300} Co ₃ Al ₁	31.00	Fe _{0.2300} Co ₃ Al ₁ O _x	50	0.9	355 ^a

^a350 mg of catalyst, 100 cm³/min total flow; ^b70 mg of catalyst, 75 cm³/min total flow.

Fig. 4 presents the H₂-TPR profiles for the Co₃Al₁ and selected Mn(Fe)_xCo₃Al₁ (x = 0.1725, 0.2300, mol.%) mixed metal oxides. The H₂-TPR profile for Co₃Al material revealed the presence of two main reduction peaks, with maxima centered at around 465 and 839 °C. The peak at lower temperatures appeared due to the complete reduction of Co₃O₄ to metallic cobalt [25–27]. While the high temperature reduction peak was related to the reduction of cobalt in Co₂AlO₄/CoAl₂O₄ [28]. Mn(Fe)_xCo₃Al (x = 0.1725, 0.2300, mol.%) revealed similar H₂-TPR profiles to Co₃Al₁. However, the modification of Co₃Al with Mn or Fe

influenced its redox properties, i.e. the position of the first reduction peaks shifted to higher temperatures for Mn- or Fe-doped materials than for Co_3Al_1 , while the position of the second peak shifted to lower temperatures, indicating depressed reducibility of Co_3O_4 and improved reducibility of cobalt in Co_2AlO_4 and CoAl_2O_4 . Such an effect was more visible for FeCoAlO_x . Additionally, for the Fe-containing samples a broad shoulder appeared at about 700 °C possibly due to reduction of iron oxide species [4,5].

Table 3 summarizes H_2 -TPR data of the studied materials. The H_2 uptake varied in the range of 5.22-6.64 mmol/g in the temperature range of 50-530 °C (where N_2O decomposition proceeded). Furthermore, analysis of reduction peak areas (A^b/A^c , estimated from the integrated areas of the respective H_2 -TPR peaks) revealed a comparable ratio (0.29 to 0.35) across the samples. Due to different oxidation states of metal oxide species in spinel forms, the calculations of the H_2 uptake based on materials composition are at best speculative. Fig. 5 shows the Co 2p, O 1s, Mn 2p and Fe 2p XPS spectra of $\text{Co}_3\text{Al}_1\text{O}_x$ and $\text{Mn}(\text{Fe})_{0.1725}\text{Co}_3\text{Al}_1\text{O}_x$, while Table 3 summarizes the peaks positions, their binding energies, peak areas, full width at half maximum (FWHM) and $O_\alpha/(O_\beta+O_\gamma)$ molar ratio. The Co 2p XPS spectra exhibited two main peaks characterized by binding energies in the ranges of 781.6-779.6 and 796.9-795.0 eV corresponding to the $\text{Co}2p_{3/2}$ and $2p_{1/2}$ spin-orbit peaks, respectively [29]. Thus, since the spin-orbit values for the tested materials have varied in the range of 15.3-15.4 eV, we concluded that mainly Co_3O_4 (spin-orbit value of 15.2 eV) together with CoAl_2O_4 (as minor compound; spin-orbit value of 15.9 eV) was present on the catalyst surface [29–31]. Considering that Mn or Fe are present only in small amounts, determination of their chemical state in the measured $\text{Mn}(\text{Fe})_{0.1725}\text{Co}_3\text{Al}_1\text{O}_x$ based on the position of the binding energy is again largely speculative. Furthermore, Mn or Fe may be present in several chemical states with the overlapping spectra, which are close in energy [11,32]. The O 1s spectra were deconvoluted to lattice oxygen – O_α , surface adsorbed oxygen, OH groups and oxygen vacancies – O_β and adsorbed molecular water – O_γ [33]. Additional low peaks at about 527-528 eV appeared possibly due to the differential charging of the materials [34]. The molar ratio of $O_\alpha/(O_\beta+O_\gamma)$ varied in the range of 0.21-0.32.

Fig. 4, Fig. 5

Table 3. Amounts of H₂ consumed during H₂-TPR measurements (H₂ uptake), the peaks positions, their binding energies, peak areas, full width at half maximum (FWHM) and O_α/(O_β+O_γ) molar ratio of mixed metal oxides.

Mixed metal oxides	H ₂ uptake ^a [mmol/g]	A ^b /A ^c [a.u.]	Position Co 2p _{3/2} *O 1s ■Mn 2p _{3/2} □Fe 2p _{3/2}	FWHM [eV]	Area [a.u.]	O _α /(O _β +O _γ) ^d
Co ₃ Al ₁ O _x	26.48	0.33	780.35	4.09	11998	0.23
	6.64 ^b		786.26	7.90	4073	
	19.84 ^c		802.84	6.75	2239	
			*527.07	1.72	462	
			*528.77	1.92	2066	
			*530.38	2.08	6369	
			*531.91	2.10	2697	
Mn _{0.1725} Co ₃ Al ₁ O _x	22.84	0.35	781.63	3.79	8333	0.21
	5.90 ^b		785.80	8.90	2826	
	16.94 ^c		804.53	8.64	1134	
			*528.51	1.43	239	
			*530.07	2.09	2126	
			*531.72	2.25	7926	
			*533.41	1.95	2106	
Fe _{0.1725} Co ₃ Al ₁ O _x	23.46	0.29	779.63	3.94	7137	0.32
	5.22 ^b		784.18	8.19	2085	
	18.24 ^c		802.17	8.64	1244	
			*526.58	1.63	324	
			*528.37	2.20	2077	
			*529.81	2.04	4523	
			*531.28	2.06	1933	
	□710.44	5.20	956			

^aCalculated by equation: $Y = 1E-08X + 1E-07$, $R^2 = 0.9996$, and X, Y referred to the area of each reduction peak and the H₂ consumption, respectively. ^bIn the region 50-530 °C. ^cIn the region 530-1000 °C. ^dEstimated from the integrated areas of the respective XPS peaks.

Fig. 6 shows the XANES spectra of Mn(Fe)_{0.1725}Co₃Al₁O_x mixed metal oxides. In comparison to the Co₃O₄ reference spectrum (Co K-edge), the spectrum of Mn_{0.1725}Co₃Al₁O_x at room temperature showed a more intense pre-edge peak which could be rationalized as being caused by a greater proportion of Co ions with a non-centrosymmetric geometry in this sample. Furthermore, an adsorption edge at lower energies – 7717.100 eV at room temperature versus 7716.440 eV after the thermal treatment in He, indicated a lower overall Co oxidation state (Fig 6A). This suggested the presence of a CoAl₂O₄ type spinel where the substitution of Co³⁺ by Al³⁺ in the octahedral position leads to a higher contribution of Co²⁺ Td. Indeed it has previously been shown that

CoAl₂O₄ type spinel phase can form at temperatures as low as 390 °C [35]. The Mn K-edge spectra acquired at room temperature (Fig. 6B) closely resembled that of a Mn₃O₄ spinel reported previously [36]. To date no XAFS data exists concerning mixed Mn and Co spinels although a detailed XRD/vibrational spectroscopic study of Co/Mn substitution suggests that such phases can readily be formed and therefore a mixed Mn_xCo_yO₄ and/or Mn_xCo_yAl_zO₄ could be present in the Mn_{0.1725}Co₃Al₁O_x sample [37]. For Fe_{0.1725}Co₃Al₁O_x mixed metal oxides measured at room temperature, Co K-edge XANES revealed comparable Co speciation to the Mn-containing sample (Fig. 6E). Nevertheless, the Fe XANES spectrum closely resembled that of α-Fe₂O₃ (Fig. 6F), suggesting that unlike Mn, Fe did not incorporate so readily into the Co₃O₄ structure. In agreement, our H₂-TPR results showed separate reduction of iron oxide species in Fe_{0.1725}Co₃Al₁O_x; however, the shift to higher temperatures of Co₃O₄ reduction peak suggests that small amounts of iron must have incorporated into the spinel structure thereby affecting its redox properties.

Changes occurring in Mn_{0.1725}Co₃Al₁O_x mixed metal oxides, in the presence of He and N₂O/He, were followed by studying the Co and Mn K-edge XANES spectra between room temperature and 600 °C. A shift in the Co absorption edge to lower energies as well as a decrease in the pre-edge intensity were observed upon He treatment at 600 °C, which is also consistent with a decrease in the nominal valence of Co in the material (Fig. 6A). The spectra resembled that of the CoO reference constituted by Co²⁺ in an octahedral environment. However, the sample's higher pre-edge intensity when compared to CoO/Co₃O₄ suggested some Co²⁺ was still present in a tetrahedral environment. Considering the H₂-TPR results pertaining to the reducibility of both cobalt oxide species present in the catalyst, it seems that Mn_xCo_yO₄ is reduced to (Mn)CoO while CoAl₂O₄, with Co²⁺ in a tetrahedral environment, remained unchanged. EXAFS *k*-plots for Co and Mn in Mn_{0.1725}Co₃Al₁O_x before and after reduction are shown in Fig. 1S. in the supplementary information. At room temperature the Mn and Co fine structure resembled closely the Co₃O₄ reference while in the reduced sample the fine structure is similar to CoO. This further confirms the presence of the initial spinel environment for both Mn and Co and that in both cases this evolves into the rock salt M²⁺O phase. Similar to Co, Mn also undergoes reduction upon activation in He at 600 °C; the reduced spectra resembling features of MnO [36]. Finally, in the presence of N₂O/He, both Co and Mn oxide species reoxidized to their initial state. Fig 6C and D show the temperature dependence of this reoxidation process; the spectral changes were observed at 300-450 °C

temperature range which coincided with the temperature needed to obtain full N₂O conversion. The MnO appeared easier to reoxidize than CoO since the spectral changes in Mn K-edge XANES commenced at 300 °C while changes in Co K-edge occurred at 350 °C.

Furthermore, the changes in the oxidation state of Co at different reaction stages in Mn_{0.1725}Co₃Al₁O_x were studied by the investigation of the position of the absorption edge (defined as the first maximum of the derivative plot beyond the pre-edge peak). Table 4 presents the Co K-edge absorption positions relative to Co foil ($\Delta E = E_{\text{sample}} - E_{\text{foil}}$) of Mn_{0.1725}Co₃Al₁O_x mixed metal oxides at different stages of the experiment as well as the ΔE of Co₃O₄ and CoO as references. Again, the ΔE of the sample after treatment with He at 600 °C was comparable to CoO. While the reoxidation, under N₂O/He conditions, leads to the recovery of its initial oxidation state. Table 5 lists the results of the curve-fitting analysis for the first coordination shell. First shell quick fit analysis of the EXAFS was carried out to gain insight into the average Co-O distances and coordination numbers. Fitting revealed higher coordination numbers and Co-O bond distances of 0.208 nm for Mn_{0.1725}Co₃Al₁O_x mixed metal oxide pretreated with He at 600 °C, which is consistent with the appearance of CoO type structure. Otherwise, Mn_{0.1725}Co₃Al₁O_x at room temperature or in the presence of N₂O/He at 600 °C showed a shorter Co-O of ~0.191 nm, corresponding to the presence of a majority spinel phase. As expected from XANES, the Co-O shell fitting results Mn_{0.1725}Co₃Al₁O_x and Fe_{0.1725}Co₃Al₁O_x at room temperature gave very similar results.

Fig. 6

Table 4. Co K-edge energy positions relative to Co foil (E_0) for Mn_{0.1725}Co₃Al₁O_x mixed metal oxides at room temperature, after reduction under He and after reoxidation under N₂O/He at 600 °C as well as references at room temperature.

Mixed metal oxides	ΔE [eV]	References	ΔE [eV]
Mn _{0.1725} Co ₃ Al ₁ O _x		room temperature	
room temperature	8.1	CoO	7.4
600 °C He	7.4	Co ₃ O ₄	8.5
600 °C N ₂ O/He	8.1		

Table 5. Coordination numbers (CN), bond distances between adsorbed and backscatter atoms (R), inner potential corrections to account for the difference in the inner potential between the sample and the reference compound (E), Debye-Waller factors ($2\sigma^2$), and residual factors (Rf) of $\text{Mn}_{0.1725}\text{Co}_3\text{Al}_1\text{O}_x$ mixed metal oxides.

Mixed metal oxides	Shell Co-O	CN	R [nm]	ΔE_0 [eV]	$10^{2*\sigma^2}$ [nm]	R _f [%]
$\text{Fe}_{0.1725}\text{Co}_3\text{Al}_1\text{O}_x$ room temperature He		4.0	0.192	4.65	0.017	0.16
$\text{Mn}_{0.1725}\text{Co}_3\text{Al}_1\text{O}_x$ room temperature He		4.0	0.191	4.64	0.021	1.30
after He 600 °C		6	0.208	2.29	0.024	3.2
after N ₂ O 600 °C		2.2	0.191	5.40	0.008	1.9

Fig. 7 presents the results of catalytic tests performed over $\text{Mn}(\text{Fe})_x\text{Co}_3\text{Al}_1$ ($x = 0.0575, 0.0821, 0.1150, 0.1725, 0.2300$, mol.%) mixed metal oxides, while Table 2 lists temperatures necessary to obtain 50% N₂O conversion (T_{50}). The N₂O conversion from the reaction mixture started at about 150-200 °C, while full conversion was reached at about 450-500 °C for all tested materials. Co_3Al_1 reached T_{50} at about 352 °C with the full conversion at 500 °C. Incorporation of Mn or Fe into Co_3Al_1 structure improved the catalytic activity of mixed metal oxides. An exception was $\text{Fe}_{0.2300}\text{Co}_3\text{Al}_1$, which showed catalytic activity similar to Co_3Al_1 . The reproducibility of our results of catalytic tests was confirmed by repeated measurements. The activity differentiated among tested materials however there was no clear trend neither related to the Mn or Fe nor Na (up to 2.3 wt.%) content in the materials. Obalová et al. [32] pointed out that 1.15 wt.% of Na introduced by impregnation already slightly enhanced activity of $\text{Co}_4\text{MnAlO}_x$. While materials with Na loaded by impregnation was reported to facilitate N₂O decomposition this was not the case when Na was present after preparation procedure [33,34]. The optimum of deposited Na content varied also depending on the applied mixed metal oxides: 0.75 wt.% for $\text{Co}_{2.5}\text{Rh}_{0.05}\text{Al}_1\text{O}_x$ [33], 1.5 wt.% for $\text{Co}_3\text{Al}_1\text{O}_x$ [35] or 1.4 wt.% for $\text{Co}_4\text{Mn}_1\text{Al}_1\text{O}_x$ [36]. Farris et al. [37] found out an optimum Na residual content in the range of 3.0-6.0 wt.% in Co-Al-O_x was supposed to promote the decomposition of N₂O facilitating over 80% conversion at 475 °C. Doping with 1.0-2.0 wt.% of Na resulted in comparable results. Further research should be carried out in order to clarify these remarkable observations over investigated mixed metal oxides.

The highest activity among tested materials reached $\text{Mn}_{0.1725}\text{Co}_3\text{Al}_1$. Such catalyst reached with T_{50} at 305 °C with and full conversion at 400 °C. Furthermore, $\text{Mn}_{0.1725}\text{Co}_3\text{Al}_1$ possessed similar activity to the Ag-doped catalysts – (0.7 wt.%) $\text{AgCo}_3(\text{Mg}_1)\text{Al}_1$, and only slightly lower to the (0.7 wt.%) $\text{RhCo}_3\text{Mg}_1\text{Al}_1$, reported as one of the most active and stable hydrotalcite derived mixed metal oxides in the N_2O decomposition with excellent activity and stability performance [7,38]. Catalytic tests were carried out under the same reaction conditions (Fig. 6C). Co_3Al_1 and $\text{Mn}(\text{Fe})_{0.1725}\text{Co}_3\text{Al}_1$ were also tested in the presence of NO and O_2 (350 mg of catalyst, 100 cm^3/min total flow). $\text{Mn}_{0.1725}\text{Co}_3\text{Al}_1$ presented T_{50} of 376 °C, thus temperature of about 70 °C higher than for tests without NO and O_2 . Slightly lower activity above 350 °C was obtained over $\text{Fe}_{0.1725}\text{Co}_3\text{Al}_1$ with T_{50} at 380 °C. Furthermore, for practical applications, Co_3Al_1 and $\text{Mn}(\text{Fe})_{0.1725}\text{Co}_3\text{Al}_1$ were tested in the presence of H_2O (70 mg of catalyst, 75 cm^3/min), as displayed on Fig. 2SA. The highest resistance to water vapour showed $\text{Mn}_{0.1725}\text{Co}_3\text{Al}_1$ with T_{50} of 549 °C. Other materials presented significantly lower resistance to water vapour. Fig. 2SB presents the contribution of NO formation over Co_3Al_1 and $\text{Mn}(\text{Fe})_{0.1725}\text{Co}_3\text{Al}_1$. The highest amount of such by-product in N_2O decomposition appeared over $\text{Fe}_{0.1725}\text{Co}_3\text{Al}_1$. For other materials the formation of NO did not exceed 15 ppm in the studied temperatures of 200-550 °C. Notably, for catalytic tests carried out in the presence of water vapour NO formation decreased. In Fig. 3S, time-on-stream tests were conducted to evaluate the stability of Co_3Al_1 and $\text{Mn}(\text{Fe})_{0.1725}\text{Co}_3\text{Al}_1$ at 450 °C. All materials showed stable conversion during the first 85 min in the $\text{N}_2\text{O}/\text{N}_2$ feed. Subsequently, after introduction of water vapour into the feed, the conversion for all materials significantly dropped, and reached a stable level below 20 %. However, switching from wet to a dry reaction mixture resulted in an increase in catalyst conversion back to the initial dry level. Thus, the introduction of H_2O into the feed did not result in the permanent deactivation of the catalysts.

Obalová et al. [10,16] reported that the high activity of $\text{Co}_4\text{Mn}_1\text{Al}_1$ hydrotalcite derived mixed metal oxides appeared due to an optimum content of components reducible in the temperatures of the maximum conversion of N_2O (between 350-450 °C). Analysis of our reduction peak areas showed similar ratio (0.29 to 0.35) across the samples. Crystal sizes were calculated from (3 1 1) bragg reflection in the XRD patterns using the Scherrer equation; the comparable results of 27, 26 and 30 nm for $\text{Co}_3\text{Al}_1\text{O}_x$, $\text{Mn}_{0.1725}\text{Co}_3\text{Al}_1\text{O}_x$ and $\text{Fe}_{0.1725}\text{Co}_3\text{Al}_1\text{O}_x$ respectively discard size effects in the catalytic performance. Although, the strength of lattice oxygen-metal bonds was reported to determine the catalysts activity in deN_2O [11], we did not observe clear correlation

between $O_{\alpha}/(O_{\beta}+O_{\gamma})$ molar ratio and catalytic activity of mixed metal oxides. Thus it seems that the samples' different reactivity was related mainly to the Mn and Fe speciation observed by XAS. Mn in $Mn_{0.1725}Co_3Al_1O_x$ appeared incorporated within spinel structure; MnO and CoO phases present after activation reoxidize under N_2O/He feed, showing that both take part in redox processes for deN_2O . Indeed it appears that MnO seemed to undergo faster reoxidation suggesting it may act as better electron donor in N_2O activation step considered the rate determining step of the mechanism [39,40]. Indeed this observation of Mn being easier to oxidise back to 3+ than Co, yet harder to reduce to 2+ is completely consistent with the respective redox potentials for the two elements [31]. On that basis Fe in $Fe_{0.1725}Co_3Al_1O_x$ could play a similar role as Mn. Nevertheless, as most of the iron was not incorporated to the spinel but appeared as separate Fe_2O_3 phase, its effect on catalytic activity was less pronounced than for Mn in the $Mn_{0.1725}Co_3Al_1O_x$ sample. Accordingly, decomposition of N_2O over tested mixed metal oxides followed the cationic redox mechanism [11,24], consisting of N_2O activation by electron transfer from metal sites, and diffusive recombination of the surface oxygen intermediates into oxygen, concerted with the back electron transfer that restores the oxidation state of the active sites. The regeneration of the active sites through oxygen desorption is considered as the rate-determining step. In this context, Co oxidizes when N_2O is adsorbed and then Co is again reduced when O_2 is released. Thus, during reaction under N_2O/He conditions, Co is continuously oxidizing and reducing. The doping, in particular Mn, may generate new redox sites at the surface or may enhance the oxygen desorption from cobalt sites. Taking into account the very weak amount of manganese added and the fact that manganese appeared incorporated within structure, the latter assumption seems more likely.

Fig. 7

4. Conclusion

$Mn(Fe)_xCo_3Al_1$ ($x = 0.0575, 0.0821, 0.115, 0.1725$ and 0.2300 , mol.%) hydrotalcite derived mixed metal oxides were synthesized by coprecipitation and subsequent calcination. The catalytic activity of Co_3Al_1 mixed metal oxides was improved in deN_2O by incorporation of appropriate amount of Mn or Fe. $Mn_{0.1725}Co_3Al_1$ mixed metal

oxides reached the highest activity with T_{50} of about 305 and 376 °C under N_2O/N_2 and $N_2O,NO,O_2/N_2$ feed, respectively. The trend for catalytic conversion was $Mn_{0.1725}Co_3Al_1O_x > Fe_{0.1725}Co_3Al_1O_x > Co_3Al_1O_x$. Detailed evaluation of the active species was realized by *in situ* XAFS study. Correlation of the catalytic data with the XAS results suggested that doping Co_3O_4 spinel by Mn (Fe), easier to oxidise, leads to a better facility to desorb oxygen, ~~as the active phase for de- N_2O~~ . The presence of Mn in the spinel structure seemed to provide surface Co active sites easier to release oxygen. The lower activity of the $Fe_{0.1725}Co_3Al_1O_4$ mixed metal oxides was attributed to the fact that Fe did not incorporate so readily into the cobalt spinel structure forming less active iron oxide clusters instead.

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