Catalytic combustion of isopropanol over Co–ZSM-5 zeolite membrane catalysts in structured fixed-bed reactor

Xiaotong Zhang and Ying Yan

School of Chemistry and Chemical Engineering, Guangdong Provincial Key Lab of Green Chemical Product Technology, South China University of Technology, Guangzhou 510640, People’s Republic of China

Catalytic combustion of isopropanol in the structured fixed-bed reactor was investigated over Co–ZSM-5 zeolite membrane catalysts. Firstly, ZSM-5 zeolite membrane catalysts with different Si/Al ratios were coated onto the surface of stainless steel fibres via secondary growth method and wet lay-up paper-making method. Then, cobalt oxides were loaded onto the zeolite membranes by impregnation method. The performance of catalytic combustion of isopropanol was conducted over the prepared zeolite membrane catalysts, and the experimental results showed that the catalyst with infinite Si/Al ratio has the highest catalytic activity for the combustion with the lowest $T_{90}$ of isopropanol ($285^\circ$C). Finally, the effects of bed structure, feed concentration, gas hourly space velocity and reaction temperature on the catalytic performance were investigated to analyse the kinetics of isopropanol over the catalyst with infinite Si/Al ratio in the structured fixed-bed reactor. The results showed that the longer residence time could cause higher reaction contact efficiency of isopropanol combustion. $T_{90}$ of isopropanol can be dramatically decreased by 105°C in the fixed-bed reactor packed with Co–ZSM-5 zeolite membrane catalysts, compared to the fixed-bed reactor packed with granular catalyst.

1. Introduction

Catalytic combustion as the most effective method for the removal of volatile organic compounds (VOCs) from the exhaust gases is widely used in the industrial area. However, from the chemical engineering standpoint, the main problem of VOC removal is the
very high dilution of reactants in large gas streams, which implies that the overall process rate is controlled by diffusion [1]. Fixed-bed reactors are widely used in VOC combustion due to their low cost and convenience in operation. Conventional fixed-bed reactors always pack with granular catalysts, which may lead to a higher diffusion resistance according to the particle size of catalysts and voidage of the bed. Therefore, a series of structured catalysts such as honeycomb catalysts (ceramic or metallic) where the active phase is deposited and foam catalysts can overcome these disadvantages. As Fan et al. reported, open-cell SiC foams clearly are promising materials for continuous-flow chemical applications such as heterogeneous catalysis and distillation [2,3], the X-ray micro-computed tomography characterization results showed that the spatial voxel size of cellular β-SiC foams was 13.6 μm³, and diffusion coefficient of laminar flow within foams was dramatically increased. Xu et al. [4] prepared the hydroxyapatite foam as a catalyst for formaldehyde combustion at room temperature based on hydroxyl groups bonded to Ca²⁺ inside channels of HAp which may play an important role in adsorption/activation of HCHO. Ribeiro et al. [5] investigated the effects of preparation methods of Pt zeolite coated on cordierite foams on the catalytic performance for toluene combustion. The results showed that the enhanced performances of the structured catalysts for toluene catalytic combustion were due not only to open structure of foams and homogeneous thin zeolite layers deposited on their wall cells but also the fact that the size and location of Pt particles present in zeolite are changed during the dipping steps. In addition, Sebastian et al. [6] designed a microreactor with Pt/zeolite catalytic films for the selective oxidation of CO, and the best result can be obtained with total CO combustion temperatures as low as 125°C. However, honeycomb materials that are made of parallel channels have some limitations concerning the laminar flow occurring inside the channels, the mass transfer from the gas phase to the catalytic layer on the walls and difficulties to control temperature for many exothermic or endothermic reactions [7]. Meanwhile, although foam catalysts with open porosity (85–90%) allow increasing the turbulence and the radial mixing [8], the accurate shapes of these foam catalysts should be prepared for the fixed-bed reactor loading due to the mechanical strength. In our previous reports [9–11], a novel gradient paper-like microfibrous zeolite membrane catalyst was prepared for VOC combustion. The results showed that higher contact efficiency with the lower internal and external diffusion resistance was obtained from the prepared catalysts.

The activity of the catalysts should also be adjusted to the enhanced transport properties of the prospective structural reactors in order not to limit the process yield. Noble metals [12–14] and transition metal oxides [15–17] were extensively investigated in the catalytic combustion of VOCs. It is reported that cobalt oxides as the transition metal oxides showed good catalytic activities in VOC combustion [18,19] and have been widely used for the total oxidation of VOCs. A comparison between the catalytic performance of bulk and alumina-supported nanocrystalline cobalt oxide catalysts has been analysed to investigate the influence of crystallite size, nature of the support (α, γ and mesoporous alumina) and cobalt loading on the catalytic performance of propane combustion in Solsona’s work [20]. Bahlawane prepared monolithic cordierites with low specific surface area, which were uniformly coated with cobalt oxide thin films by chemical vapour deposition method to completely convert methane to CO₂ below 550°C [21]. Ataloglou et al. [22] investigated the effects of the preparation method on the structure–activity of cobalt oxide catalysts supported on alumina for complete benzene oxidation.

Isopropanol as a typical organic pollutant is widely used for solvent and reactant and is released to atmosphere in large concentration. As our extension work, the catalytic performance of isopropanol combustion over cobalt oxides modified zeolite membrane catalysts with different Si/Al ratios will be investigated, and the kinetics of isopropanol in the structured fixed-bed is to be explored by analysing the influence of residence time and reaction temperature on the isopropanol conversion.

2. Experimental procedure

2.1. Materials

Stainless steel fibres with an average diameter of 6.5 μm and length of 3 mm were purchased from Huitong Advanced Materials Co., Ltd (Hunan, China). Tetrapropylammonium hydroxide (TPAOH, 25% aqueous) was purchased from Quansheng Fine Chemical Co., Ltd (Xi’an, China). Tetraethoxysilane (TEOS, greater than 99%) was purchased from Fuchen Chemical Reagent Factory (Tianjin, China). Ethanol (C₂H₅OH, greater than 99.8%), ammonia water (NH₃, 25–28% aqueous) and sodium aluminate (NaAlO₂, anhydrous) were all purchased from Sinopharm Chemical Reagent Co.,
Cobalt nitrate (Co(NO$_3$)$_2$·6H$_2$O) was purchased from Guangzhou Chemical Reagent Factory (Guangzhou, China).

2.2. Preparation of Co–ZSM-5 zeolite membrane different Si/Al ratio

First, the paper-like stainless steel fibres were prepared by using wet lay-up paper-making process and modern sintering method according to previous reports of our group [7]. Next, the silicalite-1 seeds were prepared from a mixture solution with the ratio: 9 TPAOH : 25 TEOS : 500 H$_2$O : 100 C$_2$H$_5$OH [23].

Then, ZSM-5 zeolite membranes coating on the surface of stainless steel fibres with different Si/Al ratios (Si/Al = $\infty$, 180 and 60) were prepared by secondary growth method from a mixture with the mole ratio 100 H$_2$O : 0.112 TPAOH : a NaAl$_2$O$_3$ : 1 TEOS ($a = 0$, 0.008, 0.016). TPAOH solution was mixed with NaAlO$_2$ under vigorously stirring for 10 min. Then TEOS was added dropwise into the mixed solution and stirred for 24 h in the magnetic stirrer. The seeded stainless steel fibres were immersed vertically in a Teflon-lined autoclave with the secondary synthesis solution and treated hydrothermally in an oven at 150°C for 48 h. Then, the sample was washed by the deionized water, air-dried (at 100°C for 12 h) and calcined (in air at 550°C for 6 h at a heating rate of 1°C min$^{-1}$) to remove the organic template (TPAOH).

Finally, cobalt oxides modified ZSM-5 zeolite membrane were prepared by impregnation with 30 ml aqueous solution containing known amounts of Co(NO$_3$)$_2$·6H$_2$O of 0.5 M, and the excess of water was removed in an oven at 100°C until dryness for 12 h and subsequently calcined in air for 4 h at the calcination temperature of 500°C.

2.3. Characterization

X-ray diffraction (XRD) was performed on a D8 ADVANCE (Bruker, Germany) diffractometer with Cu Kα radiation (40 kV, 40 mA) with 2θ range of 1–10° and 5–60° to determine the crystalline phases present in the catalysts. The textural and morphological information of the samples were observed by scanning electron microscopy (SEM, S-3700N, Hitachi, Japan). The samples were coated with Au films before the SEM analysis. Meanwhile, the energy dispersive spectroscopy (QuantAX400, Bruker, Germany) for element mapping (EDS mapping) was used to analyse the dispersion of Si, Al, Co and O in the ZSM-5 zeolite membrane. The pore structure of paper-like microfibrous stainless steel was tested by using mercury intrusion porosimetry (MIP), a mercury analyser (AutoPore IV 9500 V1.09, Micromeritics, USA) was used with contact angle of 130.0°, Hg surface tension of 485.0 dyn cm$^{-1}$ and Hg density of 13.6 g ml$^{-1}$. The N$_2$ adsorption and desorption isotherms were measured on a 3H-2000PS1 instrument in static measurement mode. All of the samples were outgassed at 200°C for 2 h before measurements. The specific surface area was calculated using the Brunauer–Emmett–Teller (BET) mode, the total pore volume was calculated by the analysis of N$_2$ adsorption–desorption isotherms, the micropore volume (Vmicropore) and the mesopore volume (Vmesopore) were calculated by HK (Horvath–Kawazoe) method and BJH (Barrett–Joyner–Halenda) method, respectively.

2.4. Kinetics of isopropanol combustion

The catalytic combustion of isopropanol over Co–ZSM-5 zeolite membrane catalysts was carried out in a structured fixed-bed reactor with a stainless steel tube (10 mm i.d., 450 mm length) at atmospheric pressure. The experimental set-up for isopropanol combustion is shown in figure 1 and the schematic diagram of structured fixed-bed reactor is shown in figure 2. The prepared zeolite membrane catalysts were cut into discs with the thickness of 2 mm and placed coaxially in the reactor with a bed height of 1 cm. The temperature in the structured fixed-bed reactor was controlled automatically by E-type thermocouples located in the middle of the bed outside the reactor under temperature-programmed condition. The effect of different bed structure on the catalytic performance was analysed by adjusting the packing ratios of granular Co–ZSM-5 catalyst ($g$) and Co–ZSM-5 zeolite membrane catalysts ($m$).

Four types of bed structure were composed of only granular Co–ZSM-5 catalyst, $g : m = 3 : 2$, $g : m = 1 : 4$, and only Co–ZSM-5 zeolite membrane catalysts, respectively. The isopropanol gas was generated by bubbling air through the saturators, and the accurate flow rate was adjusted by mass flow controllers. The reaction temperature was adjusted from 140 to 320°C (catalytic combustion temperature) with a heating rate of 5°C min$^{-1}$, the reaction temperature was measured every 20°C which kept for 30 min at the desired temperature. The reactants and the products of the reaction were analysed offline by using GC (Agilent 7890A, Palo Alto, CA, USA) equipped with an FID detector.
3. Results and discussion

3.1. X-ray diffraction

The XRD patterns of Co–ZSM-5 zeolite membrane catalysts coated on microfibrous stainless steel with different Si/Al ratios (60, 180, ∞) are shown in figure 3. As can be seen from figure 3, two diffraction peaks appearing at 2θ = 7–9° and 23–25° in all the samples suggest the standard phase of ZSM-5 zeolite [24]. Meanwhile, the diffraction peaks appearing at 2θ = 43–55° in all the samples can be attributed to the characteristic peak of micro stainless steel fibre, as in our previous report [7]. For cobalt oxides dispersion, all the samples give the same diffraction peaks in the ranges of 2θ = 36.5°, 45°, 52.6° and 65.7°, which matches well with the diffraction patterns of crystalline cubic Co₃O₄ (JSPDS: 42–1467). XRD patterns of Co–ZSM-5 zeolite membranes with different Si/Al ratios are very similar and no specific orientation or orientation differences between the samples could be derived from these patterns, which has been confirmed in other literature as well [25,26].

3.2. Scanning electron microscopy

Morphology and structure of the synthesized Co–ZSM-5 zeolite membrane catalysts coated on microfibrous stainless steel with different Si/Al ratios (60, 180, ∞) were analysed by SEM, and the
results are shown in figure 4. The prepared Co–ZSM-5 zeolite membrane catalysts coated on microfibrous stainless steel indicates a three-dimensional network structure as shown in figure 4a, and the typical coffin-shaped crystals of ZSM-5 were obtained on the surface of micro stainless steel fibres in figure 4b. ZSM-5
zeolite membrane grows well on the surface of the PSSF supports, with a continuous dispersion and random orientation. As the Si/Al ratio increased, the thickness of the zeolite membrane was increased from 4.9 μm in figure 4d to 5.9 μm in figure 4c. According to Hensen’s report [25], at high Al content, the presence of ZSM-5 zeolite membrane crystals is coffin-shaped, and these coffin shapes are better intergrown with increasing Si/Al ratio, which lead to a continuous thicker membranes.

According to the EDS results in figures 5 and 6, the content of Al was decreased as the Si/Al ratio increased. The Co element in yellow colour covered the most part of the Co–ZSM-5 zeolite membrane catalyst with Si/Al = ∞ and its distribution is particularly intensive and uniform. However, as the content of Al increased, cobalt oxides did not disperse uniformly over ZSM-5 zeolite membrane; obviously, agglomeration of the cobalt oxides may be found in the EDS mapping results.

3.3. $N_2$ adsorption/desorption isotherms analysis

The pore structure of paper-like microfibrous stainless steel was tested by using MIP [27], and the results are shown in table 1. It is clear to see that the prepared paper-like microfibrous stainless steel without ZSM-5 zeolite membrane coating was mainly composed of macropores with the average pore diameter of 45.6 nm, and a higher porosity structure was obtained with the porosity of 98.7%, which is much higher than that of the foam materials (85–90%) [8]. Therefore, the higher porosity structure can effectively reduce the external diffusion resistance of the fluid, and the internal diffusion resistance can be dramatically decreased based on the micropore structures in micron thickness of ZSM-5 zeolite membrane coated on the microfibrous stainless steel. The results of the specific surface areas and porosity properties based on the $N_2$ adsorption/desorption isotherms are shown in figure 7 and table 2. The $N_2$ adsorption/desorption isotherms of all the samples fitted for a typical microporous feature of such material (type I adsorption isotherm) [28]. From the BET results, the specific surface areas increase with increasing the Si/Al molar ratios of the samples. This result matches well with the result of EDS mapping; agglomeration of the cobalt oxides may block the pores and significantly reduce the specific surface area of the catalyst. Similar results also can be obtained in Shirazi’s work [29].

3.4. Kinetics of isopropanol combustion

3.4.1. Effect of Si/Al ratio

Catalytic performance of isopropanol combustion over Co–ZSM-5 zeolite membrane catalysts coated on microfibrous stainless steel with different Si/Al ratios (60, 180, ∞) under feed concentration of 4.5 mg l$^{-1}$ and a constant gas flow rate (gas hourly space velocity (GHSV) of 15 286 h$^{-1}$) is shown in figure 8. The 50% and 90% conversion temperatures (denoted as $T_{50}$ and $T_{90}$) for isopropanol combustion can be obtained from the curves. As can be seen, Co–ZSM-5 zeolite membrane catalysts with Si/Al = ∞ show the best catalytic performance with $T_{50}$ of 256°C and $T_{90}$ of 285°C, and the activity order of prepared catalysts is as follows: Co–ZSM-5 (Si/Al = ∞) > Co–ZSM-5 (Si/Al = 60) > Co–ZSM-5 (Si/Al = 180).

3.4.2. Effect of bed structure

Catalytic performances of isopropanol combustion in structured fixed-bed reactors packed with different ratios of Co–ZSM-5 zeolite membrane catalysts with Si/Al = ∞ and granular Co–ZSM-5 zeolite catalyst under feed concentration of 4.5 mg l$^{-1}$ and a constant gas flow rate (GHSV of 15 286 h$^{-1}$) is shown in figure 9. As the zeolite membrane catalysts packing ratio in the structured fixed-bed reactor increased, $T_{50}$ and $T_{90}$ of isopropanol conversion decreased. Compared to the fixed-bed reactor packed with only granular catalyst, $T_{50}$ of isopropanol conversion can be decreased by 95°C and $T_{90}$ can be decreased by 105°C in the fixed-bed reactor packed with only Co–ZSM-5 zeolite membrane catalysts. The cobalt oxides dispersed well onto the ZSM-5 zeolite membrane due to the higher porosity of the microfibrous support and open structure of zeolite membrane. As mentioned, the mass transfer enhancement can be attributed to the reduction in external and internal diffusion based on the prepared zeolite membrane catalyst, which can effectively improve the contact efficiency, and the reaction temperature can be dramatically decreased.
3.4.3. Effect of feed concentration and gas hourly space velocity

Firstly, the behaviours of catalytic oxidation of isopropanol were investigated by recording the conversion profiles at different feed concentrations. The experiment was carried out by using different feed concentrations (2.3–6.7 mg l\(^{-1}\)) with a constant gas flow rate (GHSV of 15286 h\(^{-1}\)), the results are shown in figure 10. The values of \(T_{50}\) and \(T_{90}\) of isopropanol conversion increased slightly as the
When the feed concentration increased, isopropanol molecules that adsorbed on the active sites are in competition with oxygen, at a high feed concentration. More isopropanol molecules are adsorbed and the surface oxygen is smaller and becomes the controlling factor, and consequently, the conversion of isopropanol is lower [30].

Meanwhile, GHSV plays a very important role in the catalytic combustion because the resistance time is relevant to GHSV. The catalytic performance for isopropanol combustion in the fixed-bed reactor was investigated by using different GHSV (15 286–30 572 h⁻¹) with a constant inlet concentration of isopropanol in the feed stream (4.5 mg l⁻¹). The experimental results in figure 11 showed that the values of $T_{50}$ of isopropanol conversion increased slightly from 256 to 272°C and $T_{90}$ increased from 285 to 308°C, as the space velocity increased from 15 286 to 30 572 h⁻¹. As the gas flow rate increased, the residence time of isopropanol molecules decreased in the fixed-bed reactor, which indicated the contact time of isopropanol molecules passing through the fixed-bed reactor over catalysts was also decreased, according to Choudhary’s report [31].

**Figure 7.** Nitrogen adsorption/desorption isotherms of Co–ZSM-5 zeolite membrane catalyst at 77 K.

**Table 1.** The pore structures of the paper-like microfibrous stainless steel.

| property | microfibrous |
|----------|--------------|
| total intrusion volume (ml g⁻¹) | 3.7 |
| total pore area (m² g⁻¹) | 0.3 |
| median pore diameter (volume) (nm) | 66519.3 |
| median pore diameter (area) (nm) | 52589.2 |
| average pore diameter (V/A) (nm) | 45570.3 |
| bulk density at 0.51 psia (g ml⁻¹) | 0.3 |
| apparent (skeletal) density (g ml⁻¹) | 20.3 |
| porosity (%) | 98.7 |

**Table 2.** Pore structure characteristics of samples.

| sample   | micropore volume (cm³ g⁻¹) | mesopore volume (cm³ g⁻¹) | total volume (cm³ g⁻¹) | BET surface area $S_{BET}$ (m² g⁻¹) |
|----------|-----------------------------|---------------------------|------------------------|-------------------------------------|
| Co–ZSM-5 (Si/Al = 60) | 0.04 | 0.02 | 0.07 | 115 |
| Co–ZSM-5 (Si/Al = 180) | 0.05 | 0.03 | 0.09 | 160 |
| Co–ZSM-5 (Si/Al = ∞) | 0.05 | 0.04 | 0.10 | 192 |
3.4.4. Effect of reaction temperature

The effect of reaction temperature (240, 260 and 280°C) on the catalytic performance of isopropanol combustion in the fixed-bed reactor was conducted under the feed concentration of 4.5 mg l^{-1} with different GHSV. As can be seen in figure 12, as the reaction temperature increased, the isopropanol conversion increased as well. The conversion increased from 0% at 140°C to 100% at 380°C. The table below shows the isopropanol conversion (%) at different temperatures and GHSV:

| Temperature (°C) | Si/Al = 180 | Si/Al = 60 | Si/Al = ∞ |
|-----------------|-------------|-------------|-----------|
| 140             | 0           | 0           | 1.34      |
| 160             | 0           | 0           | 2.2       |
| 180             | 0           | 1.1         | 5.44      |
| 200             | 0           | 2.32        | 9.77      |
| 220             | 0           | 5.61        | 11.923    |
| 240             | 0           | 9.74        | 23.979    |
| 260             | 10.91       | 17.50       | 56.572    |
| 280             | 40.595      | 57.408      | 85.461    |
| 300             | 78.513      | 93.512      | 96.928    |
| 320             | 96.908      |             |           |

Figure 8. Catalytic performances for isopropanol combustion over Co–ZSM-5 zeolite membrane catalysts with different Si/Al ratio (4.5 mg l^{-1} of isopropanol in the feed gas and GHSV of 15 286 h^{-1}).

| Si/Al = 180 | Si/Al = 60 | Si/Al = ∞ |
|-------------|-------------|-----------|
| 140 1.34 | 1.34 0 | 1.34 0 |
| 160 2.2  | 2.2 0   | 2.2 0    |
| 180 5.44 | 5.44 0 | 5.44 0 |
| 200 9.77 | 9.77 1.21 | 9.77 1.21 |
| 220 11.923 | 11.923 | 11.923 |
| 240 23.979 | 23.979 | 23.979 |
| 260 56.572 | 56.572 | 56.572 |
| 280 85.461 | 85.461 | 85.461 |
| 300 96.928 | 96.928 | 96.928 |
| 320 — | — | — |

Figure 9. Catalytic performances of isopropanol combustion in different bed structure (4.5 mg l^{-1} of isopropanol in the feed gas and GHSV of 15 286 h^{-1}).

| Temperature (°C) | g : m = 3 : 2 | g : m = 1 : 4 | membrane catalyst |
|-----------------|---------------|---------------|-----------------|
| 140             | 1.34          | 1.34          | 1.34            |
| 160             | 2.2           | 2.2           | 2.2             |
| 180             | 5.44          | 5.44          | 5.44            |
| 200             | 9.77          | 9.77          | 9.77            |
| 220             | 11.923        | 11.923        | 11.923          |
| 240             | 23.979        | 23.979        | 23.979          |
| 260             | 56.572        | 56.572        | 56.572          |
| 280             | 85.461        | 85.461        | 85.461          |
| 300             | 96.928        | 96.928        | 96.928          |
| 320 — | — | — |

Figure 10. Catalytic performances for isopropanol combustion over Co–ZSM-5 (Si/Al = ∞) with different feed concentration (GHSV of 15 286 h^{-1}).
conversion increased dramatically. However, the isopropanol conversion curve at the reaction
temperature of 240°C is much sharper than that at the reaction temperature of 280°C. In other words,
the influence of residence time on isopropanol conversion can be reduced under higher reaction
temperature. The possible reason may be that the reaction rate of isopropanol combustion at higher
temperature is much faster. As the GHSV increased, the decrease in the contact time of isopropanol
molecules had little influence on the catalytic performance of isopropanol combustion.

4. Conclusion

Co–ZSM-5 zeolite membrane catalysts with different Si/Al ratios were prepared for isopropanol
combustion in the structured fixed-bed reactor. The catalyst with infinite Si/Al ratio has the best
catalytic activity due to the better specific surface area and better dispersion of cobalt oxides. $T_{90}$ of
isopropanol in the structured fixed-bed reactor packed only with membrane catalyst showed the best
catalytic performance, the $T_{90}$ of isopropanol combustion can be decreased by nearly 100°C compared
to the structured fixed-bed reactor packed only with granular catalyst. According to the kinetics of
isopropanol over Co–ZSM-5 zeolite membrane catalysts (Si/Al = ∞), $T_{90}$ and $T_{50}$ of isopropanol
combustion decreased dramatically as the feed concentration and GHSV decreased. In addition, the
influence of residence time on the catalytic performance can be reduced when the reaction
temperature increased.

Data accessibility. This article does not contain any additional data.

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drafted the first draft of the manuscript, then Y.Y. corrected the manuscript and co-supervised X.Z. directing the
References

1. Lojewska J, Kolodziej A, Lojewski T, Kapica R, Tyczkowski J. 2009 Structured cobalt oxide catalyst for VOC combustion. Part I: catalytic and engineering correlations. Appl. Catal. A-Gen. 366, 206 – 211. (doi:10.1016/j.apcata.2009.07.006)

2. Ou XX et al. 2017 X-ray micro computed tomography characterization of cellular SiC foams for their applications in chemical engineering. Mater. Charact. 123, 20 – 28. (doi:10.1016/j.matchar.2016.11.013)

3. Fan X, Ou X, Xing F, Turley GA, Denissenko P, Williams MA, Batali N, Pham C, Lapkin AA. 2016 Microtomography-based numerical simulations of heat transfer and fluid flow through SiC open-cell foams for catalysis. Catal. Today. 278, 350 – 360. (doi:10.1016/j.cattod.2015.12.012)

4. Xu J, White T, Li P, He CH, Han YF. 2010 Hydroxyapatite foam as a catalyst for formaldehyde combustion at room temperature. J. Am. Chem. Soc. 132, 172 – 173. (doi:10.1021/ja090629f)

5. Ribiero F, Silva JM, Silva E, Vaz MF, Oliveira FAC. 2011 Catalytic combustion oftoluene on Pt zeolite coated cordelite foams. Catal. Today. 176, 93 – 96. (doi:10.1016/j.cattod.2011.02.007)

6. Sebastian V, Husta S, Mallida R, Santanamaria J. 2009 Microreactors with Pt/zeolite catalytic films for the selective oxidation of CO in simulated reformer streams. Catal. Today. 147, 510 – 516. (doi:10.1016/j.cattod.2009.07.061)

7. Sanz O, Erchave Fi, Sanchez M, Monzon A, Montes M. 2008 Aluminium foams as structured supports for volatile organic compounds (VOCs) oxidation. Appl. Catal. A-Gen. 340, 125 – 132. (doi:10.1016/j.apcata.2008.02.007)

8. Bucicman FC, Kraushaar-Czametzki B. 2001 Preparation and characterization of ceramic foam supported nanocrystalline zeolite catalysts. Catal. Today. 69, 337 – 342. (doi:10.1016/S0920-5861(01)00387-x)

9. Chen H, Zhang H, Yan Y. 2012 Preparation and characterization of a novel gradient porous ZSM-5 zeolite membrane/PSf composite and its application for toluene adsorption. Chem. Eng. J. 209, 372 – 376. (doi:10.1016/j.cej.2012.08.020)

10. Zhang D, Zhang HP, Yan Y. 2015 Synthesis of SiA zeolite coating/PSf composites and the application for adsorption of methane from air. RSC Adv. 5, 54913 – 54919. (doi:10.1039/c5ra07380d)

11. Wang T, Zhang HP, Yan Y. 2015 Preparation and characterization of novel porous zeolite beta coating/PSf composite in fluoride media. RSC Adv. 5, 86620 – 86624. (doi:10.1039/c5ra13918b)

12. Hosseini M, Basakat Y, Cusin R, Aboukais A, Su BL, De Weereld G, Siffert S. 2012 Catalytic performance of core-shell and alloy Pd-Au nanoparticles for total oxidation of VOC: the effect of metal deposition. Appl. Catal. B-Environ. 111, 218 – 224. (doi:10.1016/j.apcata.2011.01.002)

13. Liotta LF. 2010 Catalytic oxidation of volatile organic compounds on supported noble metals. Appl. Catal. B-Environ. 100, 403 – 412. (doi:10.1016/j.apcata.2010.08.023)

14. Kim HS, Kim TW, Koh HL, Lee SH, Min BR. 2005 Complete benzene oxidation over Pt-Pd bimetal catalyst supported on γ-alumina: influence of Pt–Pd ratio on the catalytic activity. Appl. Catal. A-Gen. 280, 125 – 131. (doi:10.1016/j.apcata.2004.02.027)

15. Piumetti M, Fino D, Russo N. 2015 Mesoporous manganese oxides prepared by solution combustion synthesis as catalysts for the total oxidation of VOCs. Appl. Catal. B-Environ. 163, 277 – 287. (doi:10.1016/j.apcata.2014.08.012)

16. Blanch-Raga N, Palomares AE, Martinez-Triguero J, Valencia S. 2016 Cu and Co modified beta zeolite catalysts for the trichloroethylene oxidation. Appl. Catal. B-Environ. 187, 90 – 97. (doi:10.1016/j.apcata.2016.01.029)

17. Liang XJ et al. 2016 Performance of Ti-pillared montmorillonite supported Fe catalysts for toluene oxidation: the effect of Fe on catalytic activity. Appl. Clay Sci. 122, 94 – 104. (doi:10.1016/j.clay.2015.05.022)

18. Xia YS, Dai HX, Jiang HY, Zhang L. 2010 Three-dimensional ordered mesoporous cobalt oxides: highly active catalysts for the oxidation of toluene and methanol. Catal. Commun. 11, 1171 – 1175. (doi:10.1016/j.catcom.2010.07.005)

19. de Rivas B, Lopez-Forcada R, Jimenez-Gonzalez C, Gutierrez-Ortiz JI. 2011 Synthesis, characterization and catalytic performance of nanocrystalline Co3O4 for gas-phase chlorinated VOC abatement. J. Catal. 281, 88 – 97. (doi:10.1016/j.jcat.2011.04.005)

20. Solosna B, Davies TE, Garcia T, Vazquez I, Deizos A, Taylor SH. 2008 Total oxidation of propane using nanocrystalline cobalt oxide and supported cobalt oxide catalysts. Appl. Catal. B-Environ. 84, 176 – 184. (doi:10.1016/j.apcata.2008.03.021)

21. Bahalawane N. 2006 Kinetics of methane combustion over CVD-made cobalt oxide catalysts. Appl. Catal. B-Environ. 67, 168 – 176. (doi:10.1016/j.apcata.2006.03.024)

22. Atalougou T, Yako J, Bourak X, Fountoulou Z, Kordulis C, Lycourghiotis A. 2005 Influence of the preparation method on the structure—activity of cobalt oxide catalysts supported on alumina for complete benzene oxidation. Appl. Catal. B-Environ. 57, 299 – 312. (doi:10.1016/j.apcata.2004.11.110)

23. Hedlund J, Schoeman BJ, Sterte J. 1997 Synthesis of ultra thin films of molecular sieves by the seed film method. In Progress in zeolite and microporous materials, Eds H Chon, SK Ihm, YS Uh, pp. 2203 – 2210. Amsterdam, The Netherlands: Elsevier Science BV.

24. Tirny MJ, Higgins JB, von Ballmoos R. 1999 Collection of simulated XRD powder patterns for zeolites. Zeolites 16, 327. (doi:10.1016/S0145-9592(99)00011-9)

25. Kosinov N, Auffret C, Borchgrevink S, Sripadthi VG, Hansen E.M. 2015 Influence of the Si/Al ratio on the separation properties of SSZ-13 zeolite membranes. J. Membr. Sci. 484, 140 – 145. (doi:10.1016/j.memsci.2015.02.044)

26. Nask M, Kolesch P, Dittmar A, Stahr M, Georgi G, Elek F, Ron J. 2006 Effect of crystal intergrowth supporting substances (OSS) on the permeation properties of MFI membranes with enhanced Al-content. Microporous Mesoporous Mater. 97, 88 – 96. (doi:10.1016/j.micromeso.2006.07.031)

27. Diamond S. 2000 Mircroporosity—an inappropriate method for the measurement of pore size distributions in cement-based materials. Cem. Conc. Res. 30, 1517 – 1525. (doi:10.1016/S0008-8846(00)00370-7)

28. John GS, Sing K. 1982 Adsorption, surface area, and porosity, 2nd eds. London, UK: Academic Press.

29. Shirazi L, Jamshidi E, Qasemmi MR. 2008 The effect of Si/Al ratio of ZSM-5 zeolite on its morphology, acidity and crystal size. Cryst. Res. Technol. 43, 1300 – 1306. (doi:10.1002/crat.200800149)

30. Ordóñez S, Bello L, Sastre H, Rosal R, Diez FV. 2002 Kinetics of the deep oxidation of benzene, toluene, n-hexane and their binary mixtures over a platinum on γ-alumina catalyst. Appl. Catal. B-Environ. 38, 139 – 149. (doi:10.1016/S0926-3337(02)00036-X)

31. Choudhary VR, Devadas P. 1997 Influence of space velocity on product selectivity and distribution of aromatics and xlyenes in propane aromatization over H-GaMFI zeolite. J. Catal. 172, 475 – 478. (doi:10.1016/j.jcat.1997.1846)