Continuous heterogeneous catalytic oxidation of primary and secondary alcohols in $scCO_2$

Adrian O. Chapman, Geoffrey R. Akien, Nicholas J. Arrowsmith, Peter Licence and Martyn Poliakoff*

Received 7th July 2009, Accepted 17th November 2009
First published as an Advance Article on the web 7th January 2010
DOI: 10.1039/b913434d

A miniature catalytic reactor has been developed for the oxidation of alcohols with O_2 in supercritical CO_2. Particular attention has been given to ensuring good mixing of O_2 and CO_2 prior to contact with the substrate. The reactor was optimised using the oxidation of 2-octanol over 5% Pt + 1% Bi on Al_2O_3 and the mass balance was measured. The reactor was then evaluated for the oxidation of a series of secondary alcohols, and also the primary alcohol, 1-octanol.

Introduction

Devising cleaner and more efficient oxidation reactions is still a major challenge for green chemistry. Supercritical CO_2 ($scCO_2$) is an appealing solvent in this context because it is already fully oxidised and cannot react with O_2. $scCO_2$ has an excellent heat capacity, and is also completely miscible with O_2. The use of O_2 as an oxidant in $scCO_2$ has been reported by numerous authors, for example Wang *et al.*,[1] He *et al.*,[2] and Kimmerle *et al.*,[3] and a comprehensive review of these reactions has been recently published by Seki and Baiker.[4] In addition, we have demonstrated[5] that O_2 can be combined with a CO_2-soluble photosensitiser to perform reactions of singlet O_2 in $scCO_2$ as efficiently as in CCl_4.

Most relevant to this paper has been the elegant work by Baiker on the continuous oxidation of 2-octanol.[6] He and his co-workers were able to achieve good selectivities for the formation of 2-octanone combined with a long catalyst lifetime. However, this was with relatively low conversions because of difficulties in dissipating the heat produced by the reaction. They also oxidised 1-octanol, but with lower selectivity than with 2-octanol.

The aim of the work reported here was to build on Baiker's experiments by increasing both the yield and the selectivity to 2-octanone, while also achieving a high mass balance. As we show later, a significant amount of organic material can be lost through total oxidation. We have examined the reactions of other secondary alcohols, and the oxidation of 1-octanol, a more challenging substrate, because the intermediate aldehyde can be oxidised further to form the corresponding carboxylic acid.

The apparatus and its development

Safety warning: High pressure experiments are potentially dangerous and high pressure oxidations have the additional possibility of runaway reactions leading to explosive failure of the equipment. It is the responsibility of researchers to ensure the suitability of their own equipment.

The apparatus which we have developed for continuous flow oxidations in $scCO_2$ differs from previous continuous flow equipment in a number of ways, all aimed at enabling O_2 to be used safely at high pressures. The apparatus also differs from that of Baiker in that it is much smaller, because miniaturisation reduces the risks even further. Our initial objective was to demonstrate that the apparatus could be used safely, reliably and predictably before any further studies could take place.

The final apparatus design, shown in Fig. 1, is a substantially modified version of that previously used in our group for continuous hydrogenations in $scCO_2$.[7] As with the hydrogenations, a Rheodyne 7000L switching valve was used to dose O_2 (rather than H_2) into the CO_2 stream. The higher the rate of valve switching, the higher the concentration of O_2 in the $scCO_2$.

An initial series of experiments was conducted to ensure that the concentration of O_2 was both accurately controllable and reproducible using this particular gas dosing method. For increased safety, these first tests were carried out using N_2 rather than O_2 because, under these conditions, the physical properties of N_2 and O_2 are very similar. Thus, N_2 in CO_2 was tested with gas dosing frequencies calculated to deliver concentrations of 5 or 10 mol% N_2, comparable to those of O_2 used elsewhere.[6,8] The mixture of N_2 and CO_2 was passed through a heated, sand-filled reactor and the concentration of N_2 was monitored at the BPR outlet by a microGC fitted with a Thermal Conductivity Detector (TCD).

The traces in Fig. 2(a) clearly demonstrate that the concentration of N_2 fluctuated substantially over time, despite maintaining a mean concentration close to the calculated value. Therefore, both the gas dosing volume and the gas over-pressure were reduced so that the gas dosage frequency could be increased, while still delivering the same amount of gas at the reactor outlet. Fig. 2(b) shows the effectiveness of these modifications, now using O_2 for the same target concentrations as previously. It is clear that the large fluctuations in gas concentration have been smoothed out, resulting in a more uniform concentration. A model liquid substrate was also introduced in a further set of experiments (not shown here) to demonstrate that the control over the gas concentration was maintained under near-reaction

---

School of Chemistry, University of Nottingham, University Park, Nottingham, UK NG7 2RD.
E-mail: martyn.poliakoff@nottingham.ac.uk; Fax: +44 (0)115 951 3058; Tel: +44 (0)115 951 3520

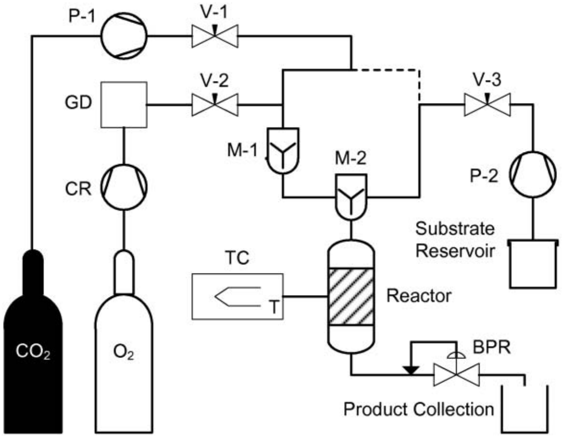


Fig. 1 Schematic of the $scCO_2$ oxidation reaction system. The CO_2 is pressurised and delivered by a Peltier-cooled piston pump P-1 (Jasco PU-1580-CO_2) in constant flow mode. O_2 is dosed in at a known pressure (set by a cylinder regulator CR) into the system by a 6-port HPLC switching valve GD (Rheodyne 7000L) fitted with small gas reservoirs (50-200 μL), the supply being isolable using the needle valve (V-2). Organic substrates are delivered at a constant flow rate *via* an HPLC pump, P-1 (Jasco PU-980). The CO_2 stream is divided into two, and then each stream mixed separately with O_2 and substrate. The O_2 is mixed with CO_2 in a static mixer M-1 (a sand-filled reactor) heated to 60 °C, before being combined with the CO_2 + substrate stream in another static mixer M-2 (a Y-piece). The mixed stream is then passed through a packed catalyst bed with an internal thermocouple. Products are collected after depressurisation of the fluid mixture with an electronically-controlled backpressure regulator, BPR (Jasco BP-1580-81). Since the commissioning of the equipment, it was realised that safer operation could be realised by eliminating the pipework shown with a dashed line, as, if there is a blockage, it is possible for the flow to be reversed. However, most of the experiments in this work were conducted with this pipe in place.

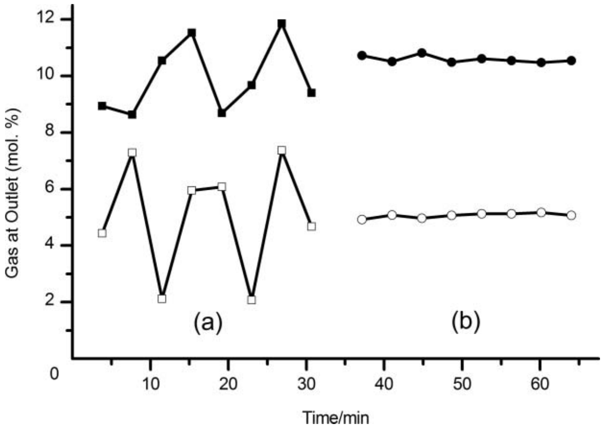


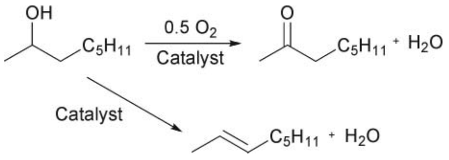
Fig. 2 Traces showing the results of the gas dosing experiments with a nominal 5 and 10 mol% of gas. (a) shows the large variation in N_2 concentration in the original apparatus and (b) shows the results for the equivalent experiments for O_2 after alteration of the apparatus, showing the improvement in homogeneity. Conditions: pressure: 100 bar; temperature: 50 °C; CO_2 flow rate: 1 mL min^{-1}, with (a) gas reservoir volume: 500 μL, N_2 over-pressure: 50 bar; and (b) gas reservoir size: 100 μL, O_2 over-pressure: 50 bar.

conditions. However, our test oxidation reaction showed that further modification of the apparatus was required.

Oxidation of 2-octanol

Test reaction

The oxidation of 2-octanol was chosen as the test reaction as both the starting material and products are liquids and the reaction is relatively simple, with octenes being the only significant by-product, as in Scheme 1.



Scheme 1 Oxidation of 2-octanol with O_2 and a catalyst, including the possible dehydration side-reaction.

Previous investigations by Baiker *et al.*[6,8] had shown that this reaction works well in $scCO_2$. However, we found supported Pt catalysts to be more active than Pd catalysts similar to those used by Baiker. In particular, a supported platinum and bismuth catalyst was chosen as further studies by ourselves and others have shown this to be less susceptible to deactivation than Pt alone.[9-11]

A 0.5 mm diameter thermocouple was carefully pushed upwards through the centre of the reactor, so that the tip was situated half-way up the catalyst bed. This thermocouple was connected to a data logger to provide continuous recording of the internal temperature of the catalyst bed. The small size of this thermocouple and its direct contact with the catalyst meant it was able to respond rapidly to any temperature changes occurring in the reactor. The oxidation of 2-octanol was then performed under conditions similar to those used by Baiker *et al.* The temperature data produced from this experiment are shown in Fig. 3(a), where it can be seen that large, regular exotherms occurred within the catalyst bed, with temperature spikes of >300 °C. This can easily be explained by the fact that an inhomogeneous O_2 concentration will lead to higher

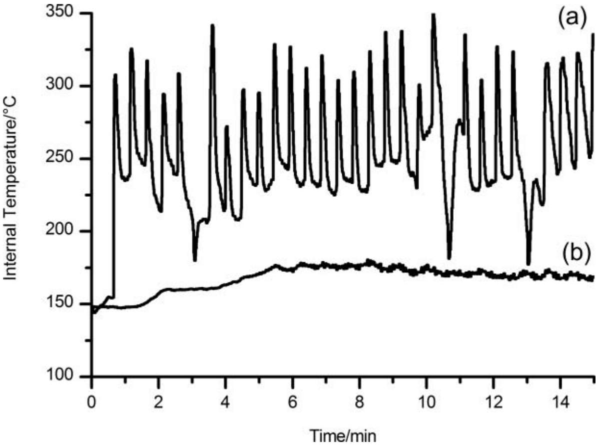


Fig. 3 Traces of the temperature at the centre of the catalyst bed during the oxidation of 2-octanol (a) before and (b) after further reducing the gas reservoir volume from 100 μL to 20 μL, and adding an additional heated mixer to the CO_2 + O_2 stream. Conditions: pressure: 100 bar, temperature: 150 °C, CO_2 flow rate: 0.5 mL min^{-1}, 2-octanol: 2.50 mol%, O_2:2-octanol ratio: 1.5.

local O_2 concentrations. This will increase the rate of reaction in these regions, which, since the reaction is exothermic, would increase the temperature, causing a further increase in the rate *etc.*, leading to a "hot-spot".

The frequency of these exotherms was identical to the O_2 dosing rate, indicating that the O_2 concentration was still inhomogeneous within the reactor, with variations large enough to cause substantial over-oxidation, probably to CO_2 and H_2O, because no other species were detected by offline GC. The temperatures reached were also high enough to rapidly deactivate the catalyst, presumably by sintering of the metal component. When the experiment was continued further, the measured temperature inside the reactor returned to 150 °C, indicating that the reaction had ceased in the region around the thermocouple. Approximately 30 minutes later, no more 2-octanone was detected at the BPR outlet, demonstrating that the whole catalyst bed was now inactive. Fig. 3(b) shows that the exotherm problem could be completely removed when the mixing of O_2 and CO_2 upstream of the reactor was improved even further by 1) reducing the gas reservoir volume again from 100 µL down to 20 µL, and 2), adding an additional static mixer heated to 60 °C in the CO_2 + O_2 flow path (labelled M-1 in Fig. 1).

Once the apparatus had been completely modified, the reaction gave a steady yield of 2-octanone of 75% for 5 hours with no evidence for catalyst deactivation or the formation of octenes.

Mass balance

The real test of this reaction is to establish an accurate mass balance. This is complicated in oxidation reactions by the fact that over-oxidation can lead to the formation of CO_2, which would be masked by the large excess of CO_2 used here as the solvent. Nevertheless, a series of experiments were conducted to determine the mass balance of the reaction.

Two different reactor designs were tested, as shown in Fig. 4; one was the original tubular reactor, and the second was a catalyst-filled tee-piece. Experiments were conducted using each reactor with varying O_2:2-octanol ratios. The quantities of 2-octanol and 2-octanone recovered at the outlet were accurately measured and compared to the quantity of 2-octanol pumped into the apparatus.

Although some material was lost in both reactor designs (there is enough O_2 remaining to totally oxidise the unaccounted-for material), the tee-piece reactor performed better, with >90% mass balance at a 75% yield of 2-octanone. In both cases, the "missing" mass may well be due to total oxidation of some of the substrate leading to the formation of CO_2 and H_2O. The tee-piece possibly performed better because the concentrations of reactants at the mixing point were lower than in the tubular reactor. However, many other factors are also changing between the two reactor designs, *e.g.* the residence time distribution or the fluid dynamics.

As far as we are aware, this is the first time such an in-depth study of the mass balance of oxidation reactions has been conducted in $scCO_2$. It demonstrates that these reactions can be performed with both high efficiency and acceptable recovery, at least on a small scale.

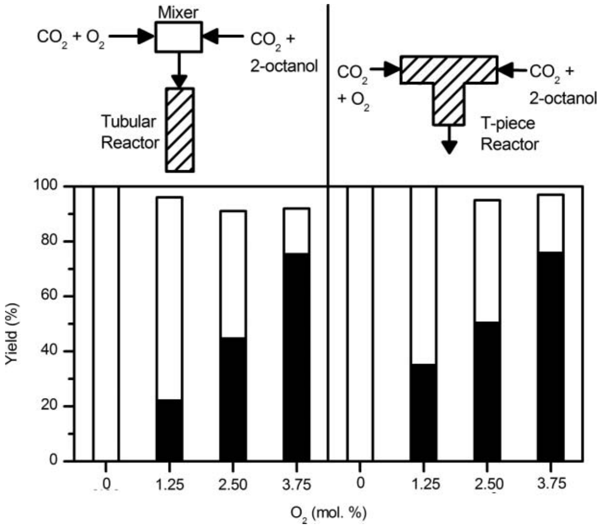


Fig. 4 The results from the mass balance experiments for the two reactor designs, 2-octanol represented by white bars, and 2-octanone with black bars. Each bar shows the fraction of material recovered, calibrated to the result without O_2. No octenes were observed during any of these experiments. Conditions: pressure: 100 bar, temperature: 150 °C, CO_2 flow rate: 0.5 mL min^{-1}, 2-octanol: 2.50 mol%.

Variation of experimental conditions

A range of experiments were then performed to investigate the impact on the reaction of changing the conditions. Due to the small volume of the apparatus, steady state was usually reached in under 5 minutes, allowing rapid study of the reaction. One of the most important parameters turned out to be the temperature, as shown in Fig. 5.

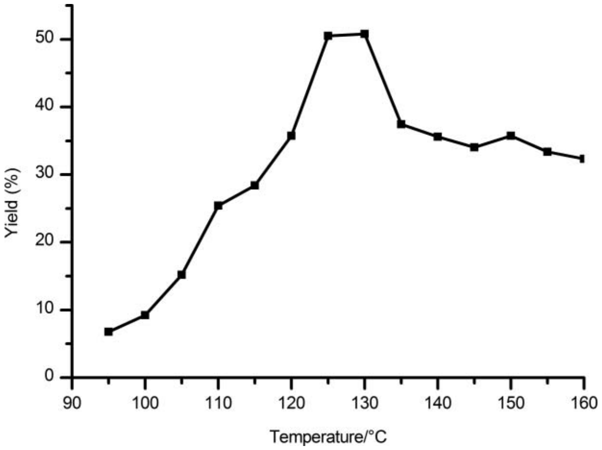


Fig. 5 Variation in the yield of 2-octanone with temperature, using a 5% Pt + 1% Bi/Al_2O_3 catalyst. No octenes are formed with this catalyst, unlike with a similar undoped catalyst. Conditions: pressure: 100 bar, CO_2 flow rate: 0.5 mL min^{-1}, 2-octanol: 2.5 mol%, O_2:2-octanol ratio: 1.5.

As the temperature was increased, the yield increased correspondingly as might be expected. However, above 130 °C, the yield decreased, perhaps because of a change to single phase conditions where the concentrations of reactants could be lower. Although the concentrations are lower than in the work of Baiker,[6] we believe that their phase behaviour measurements at the very least indicate that a phase transition to a single phase would be possible under these conditions. It does not seem plausible that the catalyst was sintering, since this usually takes place at higher temperatures (>300 °C). In general, octenes were produced at higher temperatures (higher than shown here), which other experiments have shown were mainly due to dehydration promoted by the catalyst support.[11] The Bi-doped catalyst also required higher temperatures than the undoped Pt catalyst to catalyse the formation of octenes.[11]

Another key parameter was the O_2:substrate ratio, as shown in Fig. 6. The 2-octanone yield increased with increasing O_2 concentration as expected, and correlated well with previous literature data,[6] although Baiker *et al.* have also reported a decrease in the yield with more than 2 equivalents of O_2. The effect of increasing the O_2 concentration is less marked at higher ratios, presumably because mass transfer limitations are overcome.

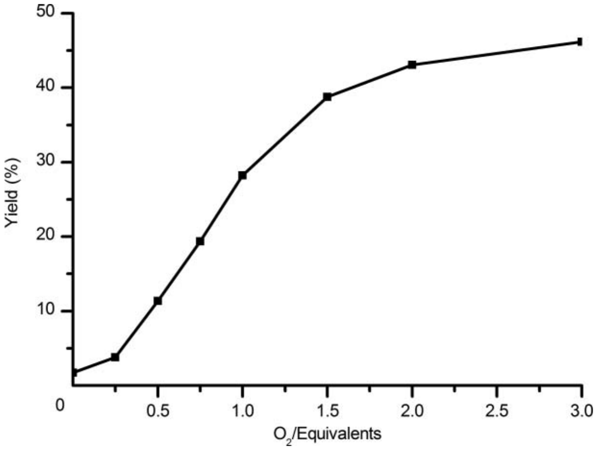


Fig. 6 Variation in the yield of 2-octanone with O_2 concentration. The 2-octanone yield increases with increasing O_2 concentration. Conditions: pressure: 100 bar, temperature: 125 °C; 2-octanol: 1.94 mol%.

Oxidation of other secondary alcohols

To investigate how widely the same approach could be applied, a range of other secondary alcohols was oxidised, as shown in Table 1. Standard conditions were chosen only to give a partial conversion of 2-octanol so that one could easily establish whether any particular alcohol behaved better or worse than 2-octanol.

In general, most of the secondary alcohols gave 33–46% yield, with the exception of 2-pentanol, which was much higher. Phenyl-substituted alcohols gave much lower yields, perhaps due to increased steric demands, but despite the expectation of increased product stability from delocalisation of the C=O bond of the product into the aromatic ring.

We encountered issues with reproducibility when using 3-pentanol; it sometimes deactivated to zero activity within an hour of start-up. However, subsequent re-injection of 2-octanol showed that the catalyst was still functioning normally when compared to routine use with 2-octanol alone, and a satisfactory reason for the lack of reproducibility could not be found, despite several experiments with mixed alcohol feeds to investigate this further. This decay in activity was also observed for 3-heptanol, although the deactivation occurred over twice as long a timescale. Both the 3-pentanol and the 3-heptanol were pure by GC, apart from traces of the corresponding ketone.

Table 1 Oxidation of different secondary alcohols

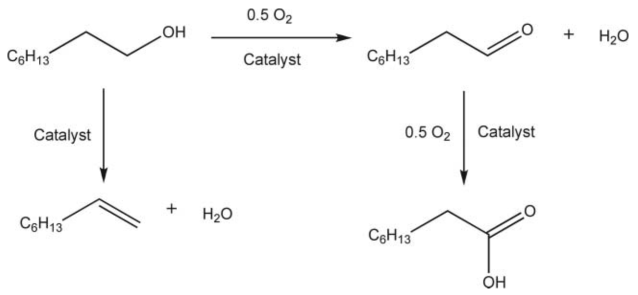
Entry	Alcohol	Yield (%)
1	2-propanol	37.7
2	2-butanol	43.6
3	2-pentanol	70.0
4	2-heptanol	45.8
5	2-octanol	33.7
6	2-decanol	43.2
7	3-pentanol	deactivates[b]
8	2-heptanol	45.8
9	3-heptanol	deactivates[b]
10	4-heptanol	21.0
11	1-phenylethanol	10[c]
12	1-phenyl-1-propanol	10

[a] Conditions: pressure: 100 bar, temperature, 130 °C, alcohol: 1.93 mol%, O_2:alcohol ratio 0.5. [b] See text for more details. [c] Selectivity was also poor, with five unidentified by-products being observed by GC with an approximate total yield of 5% by peak area.

We thought that the reaction transferred well to other substrates, so the logical continuation was on to the oxidation of primary alcohols.

Primary alcohols—1-octanol

The reaction of 1-octanol to form octanal is a more challenging prospect than the oxidation of 2-octanol, because the aldehyde could easily react further to form the acid, as shown in Scheme 2.



Scheme 2 Oxidation of 1-octanol with O_2 and a catalyst, including the possible dehydration side-reaction. Note that H_2O also catalyses the transformation of the aldehyde into the acid.[6]

As with 2-octanol, the reactor temperature was varied for the oxidation of 1-octanol. As can be seen in Fig. 7, the conversion did not change much with increasing temperature, perhaps because all of the O_2 was being consumed at all of the temperatures tested. Interestingly, above 100 °C, the yield of octanoic acid decreases with increasing temperature. As was noted by Baiker *et al.*,[6] biphasic conditions occurred over the majority of the conditions they tested in the oxidation of 2-octanol (5 mol% 2-octanol in $scCO_2$). 1-Octanol is known to have substantially higher miscibility pressures and temperatures than the other isomers of octanol,[12] suggesting that the reaction mixture may well be biphasic here too, despite the lower substrate concentrations (2 mol% *versus* 5 mol%). For the acid to form at an appreciable rate, the aldehyde must be hydrated before it can be dehydrogenated. Increasing the temperature

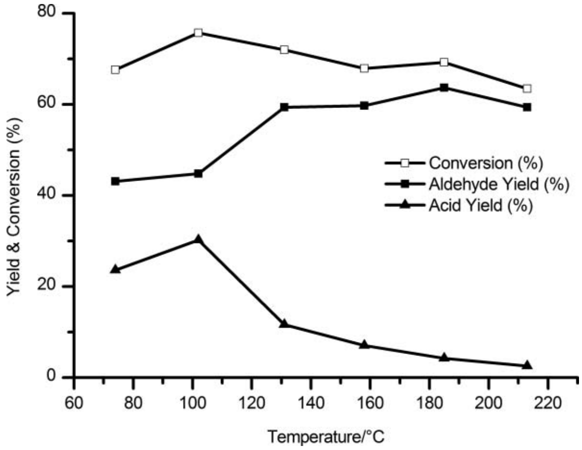


Fig. 7 Variation in yields in the oxidation of 1-octanol with varying temperature, using a 5% Pt + 1.5% Bi/Al_2O_3 catalyst. Trace quantities of the ester octyl octanoate were observed, but no octenes were detected by GC. Conditions: pressure: 100 bar, CO_2 flow rate: 1 mL min^{-1}, 1-octanol: 1.96 mol%, O_2:1-octanol ratio: 0.5.

could possibly increase the partitioning of the aldehyde and/or water into the vapour phase, thereby decreasing the likelihood of the aldehyde being hydrated by a water-rich liquid phase covering the catalyst surface. Although challenging because of the high temperatures, investigations into the phase behaviour of this system would prove interesting.

The behaviour of 1-octanol with increasing O_2 concentration largely echoes that of 2-octanol, although the maximum conversion is shifted to significantly lower O_2 concentrations, as shown in Fig. 8.

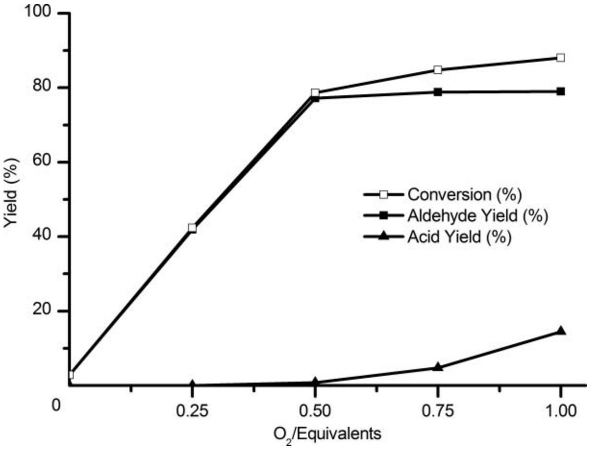


Fig. 8 Variation in the yield of octanal; with O_2 concentration. Conditions: pressure: 100 bar, temperature: 135 °C, CO_2 flow rate: 1 mL min^{-1}, 1-octanol: 1.96 mol%.

Conclusions

In this paper we have described a miniature reactor which can be successfully used for the continuous oxidation of primary and secondary alcohols with O_2 in $scCO_2$. In the case of 2-octanol, we have shown that a 75% yield of 2-octanone can be achieved with a >90% mass balance. The oxidation of a series of other secondary alcohols was also investigated. High selectivity to octanal was obtained during the oxidation of 1-octanol. We are now investigating this methodology for the oxidation of more complex substrates.

Experimental

The following materials were used without purification: CO_2 (SFC grade, >99.99%, BOC Gases), O_2 (BOC), He (CP Grade, 99.999%, BOC Gases), H_2 (99.995%, BOC Gases), air (BOC Gases), Ar (BOC Gases), 2-octanol (97%, Alfa Aesar), 1-octanol (>99%, Aldrich), 2-propanol (reagent grade, Fisher), acetone (reagent grade, Fisher), ±-2-pentanol (99%, Alfa Aesar), 3-pentanol (98+%, Alfa Aesar), 2-butanol (99%, Alfa Aesar), 2-decanol (98%, Aldrich), ±-1-phenylethanol (96%, Fluka), 1-phenyl-1-propanol, 3-heptanol, 2-heptanol, 5 wt% Pt + 1 wt% Bi on Al_2O_3 (batches M01620C/D, Johnson Matthey), 5 wt% Pt + 1.5 wt% Bi on Al_2O_3 (batch M04432, Johnson Matthey), sodium borohydride (Fisher), ethanol (reagent grade, Fisher), 40–60 petroleum ether (reagent grade, Fisher), sodium sulfate (Fisher). Water was obtained from an in-house deionisation and purification system (Elga PureLab Option S). 4-Heptanol was not readily available commercially so was synthesised according to a modified literature preparation, and its identity confirmed by ^1H and ^{13}C NMR (Jeol EX-270).

The 2-octanol experiments used the 5% Pt + 1% Bi/Al_2O_3 catalyst, and the 1-octanol experiments the 1.5% Bi analogue. In a typical reaction, the tubular reactor (78 mm long, 3.05 mm I.D., volume 0.57 mL) was filled with catalyst (typically ~300 mg), and then pressurised and heated with CO_2 at the desired flow rate. The substrate and O_2 were then introduced, and this was defined to be the beginning of the experiment.

Gas analysis was performed with a Varian CP 4900 Micro-Gas Chromatograph (microGC), fitted with 20 m M5A molecular sieve and 0.4 m HSA porous polymer columns for analysing low molecular weight gases and heavier components, respectively. The carrier gas was Ar and detection was with a Thermal Conductivity Detector (TCD).

Reactions were analysed by Gas Chromatography (GC) using a Shimadzu GC-2010 fitted with RTX-5 (Restek, 10 m × 0.1 mm I.D. × 0.20 μm film thickness) or BETADEX 110 (Supelco, 30 m × 0.25 mm I.D. × 0.25 μm film thickness) columns. He was used as the carrier gas, and appropriate temperature programming was used to separate the components before detection with a Flame Ionisation Detector (FID). Samples were prepared by dilution of the BPR effluent in acetone or methanol, and compared with external standards to determine concentrations. Analysis was quantitative for the mass balance experiments, but qualitative for others.

Acknowledgements

We are grateful to the EPSRC and DICE for support (grant no. EP/FO15275/1), and Johnson Matthey for the kind donation of catalysts. We thank Xue Han for her assistance and M. Guyler, P. Fields and R. Wilson for technical support.

Notes and references

1 X. G. Wang, H. Kawanami, S. E. Dapurkar, N. S. Venkataramanan, M. Chatterjee, T. Yokoyama and Y. Ikushima, *Appl. Catal., A*, 2008, **349**, 86–90.

2 J. L. He, T. B. Wu, T. Jiang, X. S. Zhou, B. J. Hu and B. X. Han, *Catal. Commun.*, 2008, **9**, 2239–2243.
3 B. Kimmerle, J.-D. Grunwaldt and A. Baiker, *Top. Catal.*, 2007, **44**, 285–292.
4 T. Seki and A. Baiker, *Chem. Rev.*, 2009, **109**, 2409–2454.
5 R. A. Bourne, X. Han, A. O. Chapman, N. J. Arrowsmith, H. Kawanami, M. Poliakoff and M. W. George, *Chem. Commun.*, 2008, 4457–4459.
6 G. Jenzer, M. S. Schneider, R. Wandeler, T. Mallat and A. Baiker, *J. Catal.*, 2001, **199**, 141–148.
7 P. Stephenson, P. Licence, S. K. Ross and M. Poliakoff, *Green Chem.*, 2004, **6**, 521–523.
8 G. Jenzer, D. Sueur, T. Mallat and A. Baiker, *Chem. Commun.*, 2000, 2247–2248.
9 R. Anderson, K. Griffin, P. Johnston and P. L. Alsters, *Adv. Synth. Catal.*, 2003, **345**, 517–523.
10 M. Besson and P. Gallezot, *Catal. Today*, 2000, **57**, 127–141.
11 A. O. Chapman, Ph.D., University of Nottingham, 2007.
12 F. Fourie, C. E. Schwarz and J. H. Knoetze, *J. Supercrit. Fluids*, 2008, **47**, 161–167.