

Continuous flow homogeneous catalysis: hydroformylation of alkenes in supercritical fluid–ionic liquid biphasic mixtures

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Rhodium complexes of [1-propyl-3-methylimidazolium]₂ [PhP(C₆H₄SO₃-3)₂] dissolved in the ionic liquid, 1-butyl-3-methylimidazolium hexafluorophosphate catalyse the hydroformylation of oct-1-ene at a constant rate for > 20 h in a continuous flow process in which the substrate, gases and products are transported in and out of the reactor dissolved in scCO₂; < 1 ppm rhodium is present in the collected product.

Rhodium catalysts show very high activity and good regioselectivity under mild operating conditions for the hydroformylation of long chain hydrocarbons, but have not yet been commercialised for linear alkenes with > 6 C atoms because of problems associated with the separation of the low volatility product aldehydes from the thermally sensitive catalyst.¹ Instead, the less efficient cobalt based catalysts are still in use for the synthesis of soap and detergent range alcohols.² Various new ways are being investigated to overcome this separation problem but the ideal system would provide a continuous flow process in which the advantages of reactions in the homogeneous phase (all catalytic sites equally accessible, high activity and high selectivity) could be combined with transport of the substrate, CO and H₂ into the solution and transport of the product aldehyde from the solution. This would mimic the systems currently in use for hydroformylation of propene and ethene.¹ As part of our on going studies on the use of supercritical fluids in homogeneous catalysis,^{3–5} we have recently reported such a system,⁵ where the catalyst is dissolved in a triaryl phosphite and the reactants are introduced dissolved in scCO₂, which is also used to remove the products from the reaction; both the ligand and the catalyst have low solubility in scCO₂. The initially high activity and selectivity to the desired linear aldehyde are gradually lost because the phosphite slowly dissolves in the scCO₂ and is removed from the system; it is also degraded by water.⁵

For a continuous flow system, an involatile solvent, which is insoluble in scCO₂ and contains a polar (preferably ionic) catalyst would be ideal and these properties are met by ionic liquids.⁶ Previous attempts to carry out hydroformylation in room temperature ionic liquids using rhodium complexes of sulfonated triphenylphosphine ligands, showed rather low conversions,⁷ perhaps because of the low solubility of permanent gases in the ionic liquid. Somewhat improved conversions could be obtained if other solvents (THF, toluene or water) were added. Even so, conversions were only of the order of 30%.⁷ More recently, such reactions have been successfully carried out in ionic liquids using rhodium complexes of cobaltocenium based diphosphine ligands.⁸

A recent report has shown that scCO₂ is highly soluble in certain ionic liquids (up to 0.6 mol fraction), whilst the ionic liquid is insoluble in scCO₂.⁹ Since scCO₂ is fully miscible with permanent gases and is a good solvent for alkenes and aldehydes, we reasoned that scCO₂ might help transport the permanent gases into the ionic liquid and could then also act as the transport medium for a flow system. A very recent paper shows that scCO₂ can extract a wide range of organic compounds from ionic liquids of this type.¹⁰ We now report

results of a study of the hydroformylation of alkenes in supercritical fluid–ionic liquid biphasic mixtures.

Table 1 shows results obtained from the hydroformylation of hex-1-ene in the ionic liquid, 1-butyl-3-methylimidazolium hexafluorophosphate using triphenylphosphite as the rhodium based ligand.† As with other ligands,⁷ the results obtained in the pure ionic liquid are poor with a selectivity to aldehyde of only 15.7%, and the linear : branched (l:b) ratio is low at 2.4 although all of the hex-1-ene is converted. The main products arise from aldol condensation of the product aldehydes. On adding scCO₂, the rate of reaction falls, but the selectivity to aldehyde increases to 82.3% and the l:b ratio to 6:1. Using toluene as solvent, the rate and selectivity to aldehydes are high, but the l:b ratio is low (2.5).

In view of the success of the reaction in the biphasic system, we carried out similar reactions of hex-1-ene or non-1-ene, flushing the products from the reactor with scCO₂ at the reaction temperature and pressure at the end of the reaction and decompressing into a second autoclave held at low temperature.^{4,5} After all the product had been removed by this flushing process, the reactor was cooled, depressurised and recharged with fresh substrate, CO, H₂ and CO₂. Several repetitive uses of the same catalyst show that it retains activity and selectivity for 2–3 runs, but then loses both. Visual inspection shows that the catalyst solution has become black and ³¹P NMR studies show the presence of O₂PF₂[–] and P(OPh)_nF_{3–n} (n = 1–2). These products arise from reaction of the PF₆[–] with water, releasing HF, which then attacks the phosphite.

Because of the water sensitivity of the ligands in this system, we investigated sulfonated triphenylphosphines, for which both the ligands and the rhodium complexes are insoluble in scCO₂. Complexes derived from the sodium salts of mono- and trisulfonated triphenylphosphine show low activity, at least in the case of the trisulfonate because of low solubility in the ionic liquid. We, therefore, synthesised [Ph₂PC₆H₄SO₃]_– [BMIM] and used it together with [Rh₂(OAc)₄] as the catalyst precursor for the hydroformylation of non-1-ene in the scCO₂–[BMIM]PF₆ biphasic system with flushing of the products from the reactor with scCO₂. Fig. 1 shows that the activity of a rhodium catalyst derived from this ligand remains high for 12 runs (turnover number = 160–320 h^{–1}) and the l:b ratio is acceptable. Rhodium leaching is not observed (< 0.003%) for

Table 1 Hydroformylation of hex-1-ene catalysed by [Rh₂(OAc)₄]/P(OPh₃)^a

Solvent	Co-solvent	Conversion (%)	Aldehyde selectivity (%)	l:b
Toluene		> 99	83.9	2.5
[BMIM]PF ₆		> 99	15.7 ^b	2.4
[BMIM]PF ₆	scCO ₂ ^c	40	83.5	6.1

^a [Rh₂(OAc)₄] (10 mg, 4.5 × 10^{–5} mol), P(OPh₃) (0.2 g, 6.7 × 10^{–3} mol), hex-1-ene (2 cm³, 1.8 × 10² mol), 4 cm³ of solvent, 70 bar CO/H₂, 100 °C, 1 h. ^b The majority of the product is condensed aldehydes. ^c Total pressure = 230 bar.

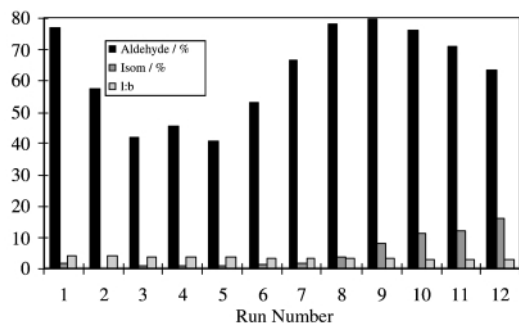


Fig. 1 Repetitive use of a catalyst synthesised *in situ* from $[\text{Rh}_2(\text{OAc})_4]$ (10.3 mg, 4.7×10^{-5} mol Rh) and $[\text{BMIM}][\text{Ph}_2\text{P}(\text{C}_6\text{H}_4\text{SO}_3)]$ (0.33 g, 0.7 mmol) for the hydroformylation of non-1-ene (2 cm^3) in $[\text{BMIM}]\text{PF}_6$ (4 cm^3), CO/H_2 40 bar, total pressure 185 bar, 100°C , 1 h. The products were flushed from the reactor using scCO_2 at the reaction temperature and pressure after each run. The reactor was then depressurised, recharged, repressurised and reheated.

the first 9 runs. Throughout the series of runs, the 1:b ratio falls slowly (from 3.7 to 2.5), isomerisation increases and, after the ninth run, Rh leaching becomes significant. ^{31}P NMR studies of the organic phase show no P resonances confirming that the phosphine is not leaching, but the ^{31}P NMR spectrum of the ionic liquid after the 12th run shows only PF_6^- and $[\text{Ph}_2\text{P}(\text{O})\text{C}_6\text{H}_4\text{SO}_3][\text{BMIM}]$. The rhodium leaching after run 9 can then be attributed to the ligand oxidation so that the active species is $[\text{RhH}(\text{CO})_4]$, which is soluble in scCO_2 and which is known to give more isomerisation and lower 1:b ratios than phosphine coordinated systems.¹ Isomerisation increases and 1:b ratio decreases with increased recycling of the catalyst as a result of the increased ligand oxidation. The observed ligand oxidation may arise from contamination with air during the many openings of the reactor. However, the stability of the ligand framework towards degradation led us to select a similar ligand for continuous flow studies.

The apparatus used for the continuous flow reactions is shown in Fig. 2 and consists of separate feeds for the alkene, the CO and H_2 and the CO_2 . These join above the reactor and pass through the ionic liquid before being removed from the reactor still in the scCO_2 undergoing a two stage decompression to recover the products, which are then analysed by GC. Fig. 3 shows the results of an experiment using $\text{PhP}(\text{C}_6\text{H}_4\text{SO}_3)_2$ - $[\text{PMIM}]_2$ (PMIM = 1-propyl-3-methylimidazolium) and $[\text{Rh}_2(\text{OAc})_4]$ dissolved in $[\text{BMIM}]\text{PF}_6$, with the oct-1-ene substrate being transported into and the products being transported out of the reactor using scCO_2 as the transport vector. The experiment was carried out for 33 h and the linearity of the graph over 8–30 h shows that the catalyst is stable at least over this period of time.[‡] The 1:b ratio of the product aldehydes is 3.1 throughout the reaction, showing that ligand oxidation is not occurring. Rh analysis of the recovered products shows < 1

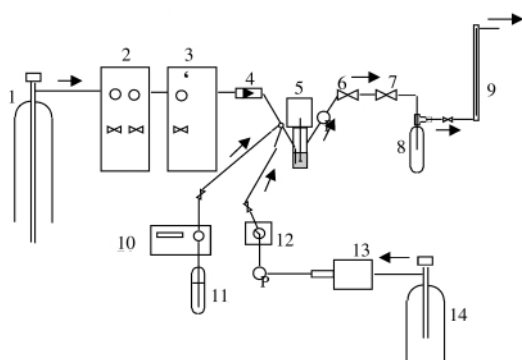


Fig. 2 Reactor for continuous flow hydroformylation. 1 CO_2 supply, 2 Liquid CO_2 pump, 3 Pressure regulator, 4 Non-return valve, 5 Autoclave with magnetically driven paddle stirrer, 6 1st expansion valve, 7 2nd expansion valve, 8 Collection vessel, 9 Flow metre, 10 Liquid substrate pump, 11 Liquid substrate supply, 12 CO/H_2 dosimeter, 13 Gas booster, 14 CO/H_2 supply.

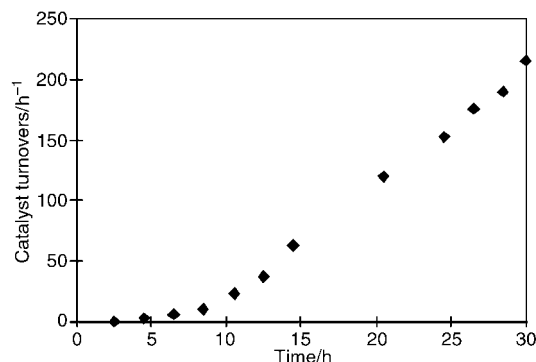


Fig. 3 Catalyst turnovers during the continuous flow hydroformylation of oct-1-ene ($0.03 \text{ cm}^3 \text{ min}^{-1}$, $1.91 \times 10^{-4} \text{ mol min}^{-1}$) catalysed by $[\text{Rh}_2(\text{OAc})_4]$ (10 mg, 4.5×10^{-5} mol Rh)/ $[\text{PMIM}][\text{PhP}(\text{C}_6\text{H}_4\text{SO}_3)_2]$ (0.47 g, 7.1×10^{-4} mol) dissolved in the ionic liquid, $[\text{BMIM}]\text{PF}_6$ (6 cm^3). CO/H_2 ($0.45 \text{ dm}^3 \text{ min}^{-1}$), 200 bar total pressure, 100°C .

ppm of Rh in any of the samples (< 0.06% of the Rh loaded). GCMS and NMR analyses of the recovered liquid products show the presence only of the two aldehyde products and unreacted substrate, indicating that the continuous flow supercritical fluid–ionic liquid biphasic system provides a method for continuous flow homogeneous catalysis, with built in separation of the products from both the catalyst and the reaction solvent, and that this is possible even for relatively low volatility products. The only related system to have been reported uses a catalyst supported on a sol–gel silica operating as a heterogeneous catalyst again with the transporting agent being scCO_2 .¹¹ Since submission of this paper, two other relevant papers have appeared. Asymmetric hydrogenation has been carried out in an ionic liquid, with the product being removed by flushing with scCO_2 ¹² and hydrogenation of alkenes or of CO_2 , the latter in the presence of triethylamine, has been carried out in an ionic liquid– scCO_2 biphasic system with flushing of the products from the reactor with scCO_2 and reuse of the catalyst up to four times.¹³

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Notes and references

† We have shown that triphenylphosphite complexes of rhodium are active and selective for hydroformylation in scCO_2 whilst also being insoluble.⁵
‡ In more recent studies we have shown that aldehydes can be produced at a constant rate and selectivity (1:b = 3.8) for 72 h.

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