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Hydroformylation in perfluorinated solvents; improved selectivity, catalyst retention and product separation

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Abstract—The hydroformylation of linear terminal alkenes using rhodium based catalysts under fluorous biphasic conditions in the presence and absence of toluene is reported. Using fluorinated ponytails to modify triarylphosphites and triarylphosphines, good selectivities and reactivities can be obtained, along with good retention of the catalyst and ligand within the fluorous phase. Using $P(O{-}4{-}C_6H_4C_6F_{13})_3$ (P/Rh=3:1) as the ligand in toluene/perfluoro-1,3-dimethylcyclohexane, good results are obtained at 60°C, but decomposition of the catalyst and/or ligand occurs on increasing the temperature. More impressive results are obtained by omitting the toluene, with higher rates, better l/b ratios, and better retention of the catalyst and the phosphite within the perfluorocarbon solvent. Competing isomerisation restricts linear aldehyde selectivities to $<76\%$. When $P(4{-}C_6H_4C_6F_{13})_3$ is used as the ligand in the absence of toluene, even more impressive results can be obtained, with linear aldehyde selectivities up to 80.9%, high rates, and the retention of up to 99.95% of the rhodium and up to 96.7% of the phosphine within the fluorous phase. These results are compared with those of commercial systems for propene hydroformylation and with those previously reported in the literature for hydroformylation under fluorous biphasic conditions. Phase behaviour studies show that 1-octene is completely miscible with the fluorous solvent under the conditions used for the hydroformylation experiments, but that the product nonanal, phase separates. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Hydroformylation is an important industrial process used in the production of some 6 M tonnes per year of aldehydes for use in the manufacture of soaps, detergents and plasticisers.[1,2] One of the big challenges left in this area is to develop rhodium based processes for the hydroformylation of long chain alkenes (C_8–C_{24}) to aldehydes, which are important intermediates for plasticisers and detergents. Current technology, which produces >1 M tonnes of product per year is based on cobalt catalysts, often modified with tertiary phosphines.[1,3] However, the products of these cobalt catalysed reactions are usually alcohols rather than aldehydes. These catalysts suffer from the disadvantages that they require very forcing conditions (close to 200°C and 100 bar) and that catalyst recycling is difficult. Often the percentage of the linear product produced in these processes is low, although Shell have introduced a phosphine formally derived from addition of $C_{20}H_{42}PH_2$ across cycloocta-1,5-diene, which can give linear/branched (l/b) ratios as high as 10.[4]

There is considerable interest in replacing the cobalt based catalysts with ones based on rhodium, since they are much more active, work under much milder conditions and give good l/b ratios. Such catalysts, modified with PPh_3, are used commercially for the hydroformylation of short chain alkenes (C_2–C_5), but cannot be used for higher alkenes because they decompose below the boiling point of the product aldehyde and so the separation of the reaction product from the catalyst is very difficult. One approach to the resolution of this problem has been to render the catalyst water soluble by sulphonating the ligand and to carry out the reaction in a two phase aqueous–organic system.[5] This process has been commercialised for propene and works well for chain lengths up to C_7, but the very low solubility of longer chain alkenes in the aqueous phase, where the reaction takes place, means that the rates of reaction are too low for a commercially viable process for detergent aldehydes to be developed based on this approach. To date, no rhodium based system has been commercialised for the hydroformylation of long chain alkenes, although the installation of a process involving Rh/PPh_3 and low pressure distillation of the products is currently in progress.[6]

Various new approaches to the development of rhodium based catalysts for the hydroformylation of long chain

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alkenes are being explored, but amongst the most promising is the use of a biphasic system based on fluorous and organic solvents, originally introduced by Horváth.[7,8] These perfluorocarbon solvents ostensibly do not mix with organic solvents. So, if a catalyst is designed to be selectively soluble in the fluorous phase, any product that will be in the organic phase can be separated by simple decantation. The great beauty of the system that Horváth explored, which gives it advantages over the aqueous biphasic approach, is that one phase is formed under the hydroformylation conditions, and phase separation occurs rapidly and cleanly on cooling. In his work, Horváth used rhodium complexes of the fluorous-derivatised trialkylphosphine, $P(CH_2CH_2C_6F_{13})_3$, and demonstrated that they could give good activity for the hydroformylation of 1-decene with good retention in the fluorous phase, such that the catalyst could be recycled 9 times with only 4.2% loss of rhodium. Leaching of the phosphine into the organic phase, although not measured, was believed to be more extensive on the basis of changes in the kinetics and selectivity of the reaction with catalyst reuse. The one problem with Horváth's results is that the selectivity to the desired linear product (l/b ratio) was modest unless high concentrations of the expensive fluorous modified ligand were employed (ligand concentrations of 152 and 304 mmol dm^{-3} at 1ligand/Rh ratios of 103 and 102, respectively, gave the best l/b ratios at 6.3 and 7.8, respectively). In addition, alkene isomerisation was a competing reaction, consuming 8–9% of the terminal alkene in many cases.

Xiao has described an alternative system in which the phosphine ligand is incorporated into a polymer by copolymerising styryldiphenylphosphine with 1*H*,1*H*,2*H*,2*H*-perfluorodecylacrylate.[9] This proved to be active as a ligand for hydroformylation under fluorous biphasic conditions (hexane/toluene/perfluoromethylcyclohexane (40:20:40% v/v), with selectivities for 1-decene hydroformylation to the linear aldehyde of up to 85%, but the rates are relatively low (turnover frequencies at 100°C$<$150 mol product mol Rh^{-1} h^{-1}). Experiments on catalyst leaching suggested 1 ppm Rh loss per hour, but complete loss of the perfluoromethylcyclohexane into the organic phase by the end of the third run. 70,000 catalyst turnovers were obtained with the one batch of catalyst.

It is well known that triarylphosphine ligands can give much better linear selectivity in rhodium based hydroformylation reactions than trialkylphosphines,[1,2,10] so we reasoned that triarylphosphines bearing fluorous ponytails might be good ligands for rhodium catalysed fluorous biphasic hydroformylation. We, therefore, tested them and also investigated fluorous derivatised triarylphosphites. Horváth has suggested that these phosphines may be less suitable because their higher polarity might make them more soluble in the organic phase than the trialkylphosphines.[8] This may, however, not be a serious problem provided that the rhodium is retained in the fluorous phase, since the ligands are expected to be thermally more stable than their rhodium complexes and could be separated from the aldehyde products by conventional distillation and recycled to the reactor. We now report the results of these studies together with results obtained in systems where the organic solvent is omitted. Using just a perfluorinated solvent proved superior in many ways, giving better activity, linear aldehyde selectivity, and retention of both the ligand and the rhodium complex in the fluorous phase. A preliminary communication of some of these results has been submitted[11] and two patents have been filed.[12]

2. Experimental

Gas chromatographic analyses of the product mixtures were carried out on a Hewlett–Packard 5890 series gas chromatograph equipped with both a flame ionisation detector (GCFID) (quantitative analyses) and a Hewlett–Packard 5890 series mass selective detector (GCMS) for qualitative analyses. The gas chromatograph was interfaced with a Hewlett–Packard Chemstation for the determination of peak areas by electronic integration. The GCMS method employed a Supelco™ Meridian MDN-35 low polarity, bonded crosslinked phase comprising of (35% phenyl)-methylpolysiloxane fused silica capillary column (30 m×0.25 mm×0.25 μm film thickness). The GCFID method employed the more polar column: Supelcowax 10, bonded carbowax 20 M poly(ethylene glycol) fused silica capillary column (60 m×0.32 mm×1.0 μm film thickness).

ICPMS analyses for Rh and P content in the organic phases were carried out at the Chemical Analysis Group of Agilent Technologies UK Ltd on an Agilent 7500a instrument. The instrument was modified for precise addition of oxygen into the carrier gas to ensure complete organic sample decomposition and a special plasma torch with narrow internal diameter injector was used to reduce the effects of the solvent vapour on the plasma. Platinum tipped cones were employed together with a self-aspirating nebuliser and solvent resistant seals. All measurements were carried out in triplicate and compared with calibration curves obtained using toluene solutions of known concentrations of Rh and P, in the form of $[Rh(2,4\text{-pentanedionato})(CO)_2]$ ($[Rh(acac)(CO)_2]$) and PPh_3, respectively.

The perfluorocarbon solvents, perfluoromethylcyclohexane and perfluoro-1,3-dimethylcyclohexane (Apollo) were thoroughly dried (by distillation from CaH_2) and degassed (N_2 purge) before use. Toluene (Ultrafine) and the various alkenes (Aldrich) were dried and degassed by distillation from Na under a N_2 atmosphere. The complex $[Rh(acac)(CO)_2]$ (Strem) was used as received whilst the fluorous ligands were prepared by standard literature procedures.[13]

2.1. Phase behaviour

A high pressure NMR tube consisting of a 10 mm sapphire tube and titanium head was charged with the liquids under study.[14,15] It was then pressurised with CO/H_2 as required and observed behind a screen. The tube was heated by placing it in a beaker of silicon oil at known temperatures and the phase behaviour observed. The sample was agitated when necessary by gently shaking the tube.

Attempts to use HPIR in a CIR cell[14,15] and to monitor the concentration of toluene in the fluorous phase were unsuccessful.

2.2. Catalytic reactions

2.2.1. Typical run. An autoclave, fitted with a substrate injector containing 1-octene (1 cm^3, 6.37 mmol), a mechanical stirrer, a gas delivery system, an injection port and a thermocouple was flushed with CO/H_2 (1:1) to remove air. Perfluoro-1,3-dimethylcyclohexane (4 cm^3) containing dicarbonyl(2,4-pentanedionato)rhodium(I) ($[Rh(acac)(CO)_2]$, 0.01 mmol) and $P(O-4-C_6H_4C_6F_{13})_3$ (0.03 mmol) was added through the injection port against a stream of CO/H_2 using a syringe. The autoclave was pressurised with CO/H_2 (1:l) to 20 bar and the pressure released. This flushing procedure was repeated twice more. After pressurising to 16 bar the stirrer was started (1000 rpm) and the autoclave was heated to 60°C for 45 mins. The 1-octene was then added to the autoclave by forcing it in through the substrate injector using a CO/H_2 pressure of 20 bar. The temperature, pressure in the autoclave and pressure in a ballast vessel, from which gas was fed into the autoclave through a mass flow controller to keep the pressure within the autoclave constant at 20 bar, were monitored and recorded every 5 s.

After 1 h, the stirrer was stopped and the autoclave was allowed to cool. The gases were vented and the mixture was syringed into a sample vial. The phases were separated using a Pasteur pipette and then analysed. The colourless organic phase was analysed for its organic components by GCFID and GCMS, and for its rhodium and phosphorus content by ICPMS. Samples of the as-obtained organic phases were diluted with 9× the volume of pure xylene prior to the ICPMS analysis. The fluorous phase from selected experiments were analysed for their organic content by GCFID and GCMS. Kinetic data were obtained from an analysis of the pressure drop in the ballast vessel versus time.

For reactions carried out in 50:50 toluene/fluorous solvent mixtures, 2 cm^3 toluene replaced 2 cm^3 of the fluorous solvent so that the total amount of solvent remained constant. Reactions were carried out at a variety of different temperatures and loadings of rhodium precursor and/or ligand. Most reactions were carried out once, but several were carried out in duplicate or triplicate and show excellent reproducibility for the catalytic results and reasonable to good reproducibility for the leaching measurements. Table 2 contains results obtained during pre-screening of a number of different ligands and Tables 3 and 4 contain the results obtained while studying the ligands, $P(O-4-C_6H_4C_6F_{13})_3$, and $P(4-C_6H_4C_6F_{13})_3$, respectively, in more detail.

3. Results and discussion

3.1. Phase behaviour

Horváth has reported that mixtures of alkene, toluene and perfluoromethylcyclohexane (20:40:40% by volume) are monophasic above 100°C under the hydroformylation conditions he used (10 bar CO/H_2 1:l).[8] In order to have more information on the phase behaviour of our mixtures, we examined visually solutions contained in a 10 mm sapphire NMR tube. The results are presented in Table 1 and confirm that the mixtures described by Horváth are monophasic under his conditions. More interestingly, we discovered that 1-octene is fully miscible with perfluoromethylcyclohexane at temperatures ≥ca. 60°C under typical hydroformylation conditions employed in this work (20 bar CO/H_2 1:l), but that nonanal phase separated even at 80°C.

Table 1. Phase behaviour of the perfluoromethylcyclohexane/toluene solvent system under typical hydroformylation conditions used in this work (20 bar CO/H_2 1:1)

Component[a] of mixture (cm^3)				Phase behaviour
T	F	1-O	N	
2.5	2.5	–	–	Partially miscible at 80°C
2	2	1	–	Homogeneous single phase≥ca. 60°C
2	2	–	1	No apparent mixing up to 80°C
2	2	0.5	0.5	Two layers persist
–	4	1	–	Homogeneous single phase≥ca. 60°C
–	4	–	1	No apparent mixing up to 80°C

[a] Toluene (T), perfluoromethylcyclohexane (F), 1-octene (1-O), nonanal (N).

3.2. Preliminary ligand screening

Table 2 lists the results obtained from the preliminary screening of a variety of ligands in the rhodium catalysed hydroformylation of l-hexene under fluorous biphasic conditions using perfluoro-1,3-dimethylcyclohexane and toluene as the solvents together with a comparison with PPh_3 or $P(OPh)_3$ under identical conditions and using PPh_3 in toluene alone. Throughout these preliminary screening experiments, the extent of rhodium leaching was not measured, but visually, the retention into the fluorous phase looked very good (Fig. 1). These results show that the reaction with PPh_3 is almost unaffected by the presence of the fluorous solvent, the kinetics are zero order in both cases, although a reduced extent of alkene isomerisation leads to an increased selectivity to the linear aldehyde. Horváth[8] also reported a higher l/b ratio in the biphasic mixture in the hydroformylation of l-decene, although in his case the extent of isomerisation was very similar for the two solvent systems. Horváth found a slightly higher rate in toluene, but our studies suggest a higher rate in the biphasic system.

Excitingly the phosphites, $P(O-3$ or $-4-C_6H_4C_6F_{13})_3$ showed much better l/b ratios and higher initial rates than PPh_3. These reactions were generally carried out at a [Rh] of 10 mmol dm^{-3} (about l0–100× those used by Horváth),[8] and even at a ligand concentration of only 30 mmol dm^{-3}, the l/b ratios of the aldehyde product were as high as 8.4. It should be noted that l/b ratios depend on the total ligand concentration not on the 1igand/rhodium ratio, and that, because of the cost of the ligand, it is desirable to keep the ligand concentration as low as possible. One experiment was carried out using $P(O-4-C_6H_4C_6F_{13})_3$ with both the ligand and rhodium concentration reduced by a factor of 10 (to a similar rhodium loading to that used by Horváth, but with a much lower ligand loading) but this gave, as expected for the order of magnitude reduction in ligand concentration, a lower l/b ratio (3.1). One disadvantage of

Table 2. Hydroformylation of 1-hexene, using rhodium complexes of various phosphines and phosphites under fluorous biphasic conditions

Ligand	Conv[a] (%)	Isom[b] (%)	Branched[b] (%)	Linear[b] (%)	l/b[c]	Rate const[d] (s^{-1})	TOF(I)[e] (h^{-1})
PPh_3[f]	99.1	6.1	25.1	67.9	2.7 (2.2)	2.5×10^{-3}[g]	900
PPh_3	99.1	1.8	24.0	73.3	3.1 (2.8)	3.2×10^{-3}[g]	1150
$P(4\text{-}C_6H_4C_6F_{13})_3$	98.4	10.6	18.2	69.6	3.8 (2.4)	6.3×10^{-3}	3600
$P(OPh)_3$	99.6	8.0	23.7	67.9	2.9 (2.1)	4.8×10^{-3}[g]	1700
$P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$	99.2	14.6	9.0	75.6	8.4 (3.2)	4.6×10^{-3}	2650
$P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$[h]	98.6	9.3	21.8	67.5	3.1 (2.2)	1.8×10^{-3}	10400
$P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$[i]	99.6	10.7	11.7	77.2	6.6 (3.4)	3.2×10^{-3}	1850
$P(O\text{–}3\text{-}C_6H_4C_6F_{13})_3$	99.9	3.9	15.4	80.6	5.2 (4.2)	2.3×10^{-3}	1300
$P(O\text{–}2\text{-}C_6H_4C_6F_{13})_3$	99.9	0.8	53.6	45.5	0.9 (0.8)	7.3×10^{-3}	4200
$P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$[j]	99.0	14.0	10.8	74.2	6.9 (3.0)	3.1×10^{-3}	1300
$P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$[k]	86.1[l]	24.9	64.5	10.4	0.2 (0.2)	2.1×10^{-3}	880

A solution of $[Rh(acac)(CO)_2]$ (10.0 mmol dm^{-3}), phosphine/phosphite (30.0 mmol dm^{-3}) in a mixture of perfluoro-1,3-dimethylcyclohexane (2.0 cm^3), toluene (2.0 cm^3) and l-hexene (1.0 cm^3, 8.0×10^{-3} mol) at 70°C and 20 bar CO/H_2 (1:1) for 1 h.

[a] Conversion (100%−% residual 1-hexene).

[b] Percent of product by mole fraction. Isom=sum (2- and 3-hexene); branched=sum (2-ethylpentanal+2-methylhexanal); linear=*n*-heptanal.

[c] l/b=ratio of linear to branched aldehyde product. The figure in brackets refers to the ratio of *n*-heptanal to the sum (branched aldehyde+isomerised alkene).

[d] All reactions were found to be first order in [1-hexene] to over 80% of 1-hexene consumption, unless denoted by footnote g.

[e] TOF(I)=initial turn over frequency. Moles 1-hexene converted to aldehyde per mole Rh per hour.

[f] In toluene only (4 cm^3).

[g] Zero order rate constant, mol dm^{-3} s^{-1}. Gas uptake consistent with 'saturation' kinetics typically found when aryl phosphines are present at such low concentrations (zero order becoming first order after some time).

[h] $[Rh(acac)(CO)_2]$ (1.0 mmol dm^{-3}) and phosphite (3.0 mmol dm^{-3}).

[i] 8 bar CO/H_2 (1:1).

[j] 1-Nonene as substrate; Isom=sum (2-, 3- and 4-nonene); branched=sum (2-butylhexanal+2-propylheptanal+2-ethyloctanal+2-methylnonanal); linear=*n*-decanal.

[k] 2-Nonene as substrate, other assignments as footnote j.

[l] Conversion (100%−% residual 2-nonene).

these phosphite ligands was that significantly higher isomerisation was observed than when using PPh_3. Electron withdrawing groups (fluorous tails) attached to the aryl ring of phosphites (or phosphines) afford less basic ligands, resulting in more facile CO dissociation in the catalytic cycle and increased rates of hydroformylation. However, and particularly with phosphites, the concomitant increase in the electophilicity of the metal centre leads to increased amounts of isomerisation which, in part, accounts for the high l/b ratio observed for $P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$.[16,17] Using $P(O\text{–}2\text{-}C_6H_4C_6F_{13})_3$ as the ligand gave poor selectivity, presumably because the *ortho* substituent results in significant steric crowding on coordination.[13b]

The l/b ratio is determined in the catalytic cycle by two effects. The sense of addition of the Rh–H bond across the alkene (Markovnikov, branched cycle, or anti-Markovnikov, linear cycle) determines which cycle will be followed, but the branched alkyl complex can either undergo carbonylation to give the aldehyde or β-hydrogen abstraction to give the isomerised alkene. Lack of anti-Markovnikov selectivity in the first step reduces the l/b ratio, but lack of carbonylation selectivity in the second leads to an increased l/b ratio at the expense of total aldehyde production. A better indication of the success of these hydroformylation reactions is the overall selectivity to linear aldehyde, which is the desired product. On this criterion, the phosphites are not significantly better than PPh_3. The fluorinated phosphine, $P(4\text{-}C_6H_4C_6F_{13})_3$, showed first order kinetics and a high rate, but the selectivity under these conditions was unexceptional.

Figure 1. Retention of catalyst in fluorous phase (orange) after hydroformylation below the colourless organic phase (toluene/aldehyde).

One other experiment conducted in these screening runs used 2-nonene as the substrate. Rhodium catalysts are often not very active for the hydroformylation of internal alkenes, but the catalyst based on $P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$ gave a rate constant that was ca. 2/3 of that obtained for 1-nonene and significant quantities of linear aldehyde (decanal) were obtained.

Following these preliminary results, we were interested to investigate the ligand, $P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$, in more detail and under more realistic conditions. These optimisation reactions were carried out using 1-octene as the substrate.

3.3. $P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$ as ligand with toluene/perfluoro-1,3-dimethylcyclohexane as solvent

The results obtained using $P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$ as the ligand for the hydroformylation of 1-octene under different conditions are shown in Table 3. For comparative purposes,

Table 3. Hydroformylation of 1-octene at 20 bar CO/H_2 (1:1) employing the fluorinated phosphitc ligand, $P(O–4\text{-}C_6H_4C_6F_{13})_3$

Solvent[a]	[Rh][b] (mmol dm^{-3})	[P][b] (mmol dm^{-3})	T (°C)	Time (min)	Conv[c] (%)	Octane[d] (%)	Isom[d] (%)	Branched[d] (%)	n-Nonanal[d] (%)	l/b[e]	Rate constant[f] (s^{-1})	TOF(I)[g] ($h^{-1)}$)	[Rh]/Ald[h] (mg mol^{-1})	[P]/Ald[h] (mg mol^{-1})
T/F	2.0	6.0	60	60	96.9	0.4	13.0	14.3	69.2	4.8 (2.5)	8.7×10^{-4}	2000	15.7 (9.7)	31.8 (21.8)
T/F	2.0	6.0	70	60	96.2	0.4	12.7	16.4	66.7	4.1 (2.3)	1.4×10^{-3}	3200	62.9 (38.9)	69.1 (47.4)
T/F	2.0	6.0	80	60	96.3	0.5	16.3	15.9	63.6	4.0 (2.0)	2.5×10^{-3}	5700	87.7 (54.3)	87.8 (60.1)
T/F	2.0	6.0	90	60	93.0	0.6	26.3	12.1	54.0	4.5 (1.4)	–[i]		88.0 (54.5)	106.2 (72.7)
T/F	2.0	6.0	100	60	69.8	0.7	32.3	6.7	30.1	4.5 (0.8)	–[i]		134.7 (83.4)	129.9 (89.0)
T/F	10.0	30.0	70	30	97.0	0.5	16.9	8.5	71.1	8.4 (2.8)	4.5×10^{-3}	2100	24.0 (3.0)	55.4 (6.9)
F	2.0	6.0	60	60	97.6	0.3	12.4	9.7	75.2	7.8 (3.4)	1.3×10^{-3}	3000	10.3 (6.4)	14.0 (9.6)
F	2.0	6.0	70	30	97.5	0.4	13.8	9.5	73.8	7.8 (3.2)	3.5×10^{-3}	8000	10.2 (6.3)	14.7 (10.1)
F	2.0	6.0	80	30	96.6	0.5	15.6	11.1	69.4	6.3 (2.6)	6.8×10^{-3}	15600	8.2 (5.1)	17.1 (11.7)
F	10.0	30.0	60	45	97.2	0.3	13.7	7.6	75.6	9.9 (3.6)	1.9×10^{-3}	870	20.6 (2.6)	28.6 (3.9)
F	10.0	30.0	70	30	97.3	0.4	13.8	8.1	75.0	9.3 (3.4)	4.9×10^{-3}	2250	26.7 (3.3)	43.7 (6.0)
F	10.0	30.0	80	30	96.5	0.5	13.1	9.8	73.1	7.5 (3.2)	1.1×10^{-2}	5000	53.0 (6.6)	97.0 (13.3)
T	10.0	30.0[j]	60	60	97.8	0.4	3.7	26.7	67.0	2.5 (2.2)	3.2×10^{-3}	1500		
T	2.0	6.0[j]	70	60	98.2	0.4	2.0	31.1	64.7	2.1 (2.0)	2.4×10^{-3}[k]	4400		

[a] Reaction solvent. Either 4 cm^3 of perfluoro-1,3-dimethylcyclohexane (F) or a mixture of 2 cm^3 each of toluene and perfluoro-1,3-dimethylcyclohexane (T/F).

[b] Concentration in mmol dm^{-3} of $[Rh(acac)(CO)_2]$ [Rh] or $P(O–4\text{-}C_6H_4C_6F_{13})_3$ [P] in 5 cm^3 reaction solution (i.e. 4 cm^3 of either F or 50/50 T/F+1 cm^3 1-octene). [1-octene]=1274 mmol dm^{-3} for all reactions.

[c] Conversion (100%−% residual 1-octene).

[d] Percent of product by mole fraction. Isom=sum (2-, 3- and 4-octene), generally >95% 2-octene; branched=sum (2-propylhexanal+2-ethylheptanal+2-methyloctanal), generally >95% 2-methyloctanal.

[e] l/b=ratio of linear to branched aldehyde product. The figure in brackets refers to the ratio of n-nonanal to the sum (branched aldehyde+isomerised alkene).

[f] All reactions were found to be first order in [1-octene] to over 80% of 1-octene consumption, unless denoted by footnote k.

[g] TOF(I)=initial turn over frequency. Moles 1-octene converted to aldehyde per mole Rh per hour.

[h] Rhodium and phosphine loss to the organic product. Given as the concentration of Rh and P by weight (mg) per mole of aldchyde product. Figure in brackets is the % of Rh/P lost from the catalyst phase to the organic product phase.

[i] Kinetics of gas uptake confirm a self catalysing decomposition of catalyst on injection of substrate—hydrolysis or, more likely, reaction of aldehyde with phosphite (see Section 3).

[j] $P(OPh)_3$ reactions (4 cm^3 toluene+1 cm^3 1-octene).

[k] Zero order rate constant (mol dm^{-3} s^{-1}).

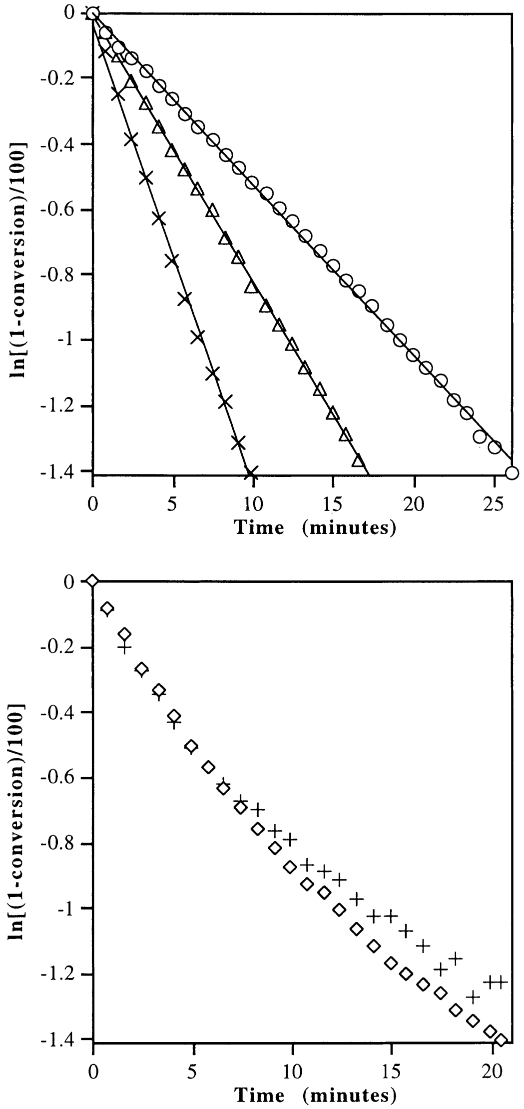

Figure 2. ln[(1−conversion)/100] vs time plot for the hydroformylation of 1-octene with Rh/P(O-4-$C_6H_4C_6F_{13}$)$_3$ in a 1:1 toluene/C_8F_{16} solvent mixture under 20 bar CO/H_2 (1:1) with [Rh]=2.0 mmol dm^{-3}, [P(O-4-$C_6H_4C_6F_{13}$)$_3$]=6.0 mmol dm^{-3} and [1-octene]=1274 mmol dm^{-3} at (○) 60°C, $k=8.7\times10^{-4}$ s^{-1}; (△) 70°C, $k=1.4\times10^{-3}$ s^{-1}; (X) 80°C, $k=2.5\times10^{-3}$ s^{-1}; (◇) 90°C; and (+) 100°C.

examples using toluene as solvent and P(OPh)$_3$ or PPh$_3$ as the ligand are also included in Tables 3 and 4, respectively.

As expected the rate increased as the temperature was increased from 60–80°C, but above 80°C, the kinetics of the gas uptake suggested that the catalyst was decomposing during the course of the reaction (Fig. 2 and Table 3). Incomplete conversion of the 1-octene was also obtained at these higher temperatures. The l/b ratio dropped slightly from 4.8–4.0 as the temperature was increased from 60–80°C, mainly because of lower anti-Markovnikov selectivity in the formation of the alkyl intermediates, as indicated by a lower selectivity to nonanal. At the higher temperatures, isomerisation seems to be a more important pathway and this is most obvious when the catalyst is being destroyed. At 60°C, the organic phase appeared colourless, but ICPMS analysis showed significant leaching of rhodium (9.7%). This rhodium leaching increased up to 83.4% at a reaction temperature of 100°C. ICPMS was also used to analyse the organic phase for phosphorus and this was significant at 60°C (21.8%) again increasing on heating to 89% at 100°C. The increases observed on heating clearly show that the catalyst and/or ligand are decomposing. If they were stable, the amount of leaching would be expected to be independent of temperature, since the separation is carried out at the same temperature for each product solution. Provided that the catalysts and ligand are stable under the reaction conditions and the rhodium and phosphorus loadings are constant, the amount of rhodium and phosphorus in the organic phase should be determined solely by the partition coefficients of the catalyst and the ligand respectively between the two phases.

The high amounts of rhodium and phosphorus leaching in the reactions carried out at 60–80°C (Table 3) initially appears to be inconsistent with the classic first order kinetics observed at these lower temperatures (Fig. 2). However, this kinetic behaviour itself confirms that catalyst decomposition, and concomitant leaching of rhodium and phosphorus, only occurs when the majority of the 1-octene has been converted to aldehyde; it takes only 26, 17 and 10 min for 75% of the 1-octene to hydroformylate at 60, 70 and 80°C, respectively (Fig. 2), whereas the reactions were allowed to proceed for 60 min in order to reach completion. The evidence from the first order kinetics, leaching data, and the detection of HO–4-$C_6H_4C_6F_{13}$ in the GCMS of the aldehyde product from all the reactions suggests that the mode of decomposition of the catalysts involves the decomposition of the phosphite ligand in the presence of the product aldehyde. There are a number of ways in which the aryl phosphite may decompose to afford HO–4-$C_6H_4C_6F_{13}$ under the hydroformylation conditions employed in the present study.[18,19] Simple thermal or metal catalysed decomposition can be ruled out as its effect would become apparent during the catalyst equilibration period, 45–60 min, before injection of the 1-octene. Other modes of decomposition of aryl phosphites in hydroformylation reactions include hydrolysis, nucleophilic attack on aldehydes and oxidative cyclisations with aldehydes.[18,19] Again, the simple first order kinetics suggests that hydrolysis cannot be taking place before the formation of the aldehyde i.e. the presence of residual water in the reactor cannot account for the decomposition. Aldol condensation of the aldehyde product could lead to traces of water but we have found no evidence for any traces of the expected Aldol products from GCMS (under known conditions for detection) of the reaction products, even for those reactions carried out at 90 and 100°C where catalyst decomposition is evident even at the start of aldehyde formation (Fig. 2). When we tried to carry out the hydroformylation reactions with the same [Rh] concentration (2.0 mmol dm^{-3}) but with a 15:1 ratio of phosphite to rhodium at 80°C (minimum temperature to achieve significant reaction), the gas uptake, on injection of the substrate, very quickly began to deviate from first order behaviour and at the end of the reaction the fluorocarbon layer was, in contrast to the normal orange catalyst solution colour, completely colourless and apparently devoid of catalyst. The GCMS of the organic layers in the reactions employing the high phosphite to rhodium ratios not only contained high levels of HO–4-$C_6H_4C_6F_{13}$ but also significant amounts of aldehyde

Table 4. Hydroformylation of 1-octene in perfluoromethylcyclohexane at 20 bar CO/H_2 (1:1) employing the fluorinated phosphine ligand, $P(4\text{-}C_6H_4C_6F_{13})_3$

[Rh][a] (mmol dm^{-3})	[P][a] (mmol dm^{-3})	*T* (°C)	Time (min)	Conv[b] (%)	Octane[c] (%)	Isom[c] (%)	Branched[c] (%)	*n*-Nonanal[c] (%)	l/b[d]	Rate constant[e] (s^{-1})	TOF(I)[f] (h^{-1})	[Rh]/Ald[g] (mg mol^{-1})	[P]/Ald[g] (mg mol^{-1})
2.0	6.0	70	30	97.1	0.3	2.1	20.3	74.4	3.7 (3.3)	1.9×10^{-3}[h]	3400	0.8 (0.5)	9.1 (6.2)
2.0	6.0	80	30	97.2	0.4	4.2	20.7	71.9	3.5 (2.9)	2.9×10^{-3}[h]	5300	2.3 (1.4)	10.7 (7.3)
2.0	6.0	90	30	95.0	0.4	8.4	21.5	64.7	3.0 (2.2)	3.0×10^{-3}[h]	5400	15.8 (9.8)	15.5 (10.6)
1.0	3.0	70	60	98.3	0.3	2.1	21.1	74.8	3.6 (3.2)	9.1×10^{-4}[h]	3300	1.9 (2.3)	6.7 (9.2)
2.0	20.0	70	90	97.8	0.4	3.7	12.8	80.9	6.3 (4.9)	1.9×10^{-3}	4400	0.08 (0.05)	15.9 (3.3)
2.0	20.0	80	30	97.9	0.4	3.1	16.6	77.8	4.7 (3.9)	5.9×10^{-3}	13500	0.38 (0.23)	24.1 (5.0)
2.0	20.0	90	30	97.9	0.5	4.1	17.2	76.1	4.4 (3.6)	1.3×10^{-2}	29800	0.54 (0.33)	18.6 (3.8)
10.0	30.0[i]	60	60	97.1	0.4	0.5	24.0	72.2	3.0 (3.0)	1.1×10^{-3}[h]	400		
10.0	30.0[i]	70	30	97.8	0.3	0.7	24.5	72.3	3.0 (2.9)	3.0×10^{-3}[h]	1100		
10.0	30.0[i]	80	10	97.7	0.3	1.7	24.3	71.4	2.9 (2.8)	7.0×10^{-3}[h]	2500		

[a] Concentration in mmol dm^{-3} of $[Rh(acac)(CO)_2]$ [Rh] or $P(4\text{-}C_6H_4C_6F_{13})_3$ [P] in 5 cm^3 reaction medium (i.e. 4 cm^3 C_7F_{14}+1 cm^3 1-octene). [1-octene]=1274 mmol dm^{-3} for all reactions.

[b] Conversion (100%−% residual 1-octene).

[c] Percent of product by mole fraction. Isom=sum (2, -3- and 4-octene), generally >95% 2-octene; branched=sum (2-propylhexanal+2-ethylheptanal+2-methyloctanal), generally >98% 2methyloctanal.

[d] l/b=ratio of linear to branched aldehyde product. The figure in brackets refers to the ratio of *n*-nonanal to the sum (branched aldehyde+isomerised alkene).

[e] All reactions were found to be first order in [1-octene] to over 80% of 1-octene consumption, unless denoted by footnote h.

[f] TOF(1)=initial turn over frequency. Moles 1-octene converted to aldehyde per mole Rh per hour.

[g] Rhodium and phosphine loss to the organic product. Given as the concentration of Rh and P by weight (mg) per mole of aldehyde product. Figure in brackets is the % of Rh/P lost from the catalyst phase to the organic product phase.

[h] Zero order rate constant, mol dm^{-3} s^{-1} Gas uptake consistent with ‘saturation’ kinetics typically found when aryl phosphines are present at such low concentrations (zero order becoming first order after some time).

[i] PPh_3, reactions (4 cm^3 toluene+1 cm^3 1-octene).

condensation products. Thus, we cannot rule out Aldol condensation as the primary mode leading to phosphite decomposition. However, the most important reaction between a phosphite and an aldehyde is addition to give a phosphonate.[18,19] The reaction is autocatalytic since it is acid catalysed and produces an acidic product. The increased levels of acidic phosphonate together with the extended reaction times (5 h at 80°C) for these higher phosphite to rhodium ratio reactions could also be responsible for the observed Aldol condensation products. We are continuing to investigate the exact mode of catalyst decomposition.

Increasing the concentrations of rhodium and the ligand by a factor of five and carrying out the reaction at 70°C leads to an increase in rate, presumably because the retarding effect of the excess ligand is exceeded by the increase in rate caused by the increased [catalyst]. More dramatically, the l/b ratio is greatly increased (to 8.4), with the rhodium leaching being only 3% (cf. 38.9% under the same conditions at the lower concentration). The phosphorus leaching is also reduced (6.9% cf. 47.4% at the lower loading).

The selectivity to linear aldehyde using $P(O-4-C_6H_4C_6F_{13})_3$ in the mixed solvent system at 60–80°C is similar to that obtained when using $P(OPh)_3$ in toluene (Table 3). However, comparison of the l/b ratios and yields of isomerised alkene, clearly shows an increased tendency for the branched alkyl intermediate to undergo β-hydrogen abstraction when using $P(O-4-C_6H_4C_6F_{13})_3$ as the ligand under biphasic conditions. As stated previously, this type of behaviour is well documented for low pressure hydroformylations when electron withdrawing groups are substituted into the *para*-position of the aromatic ring of phosphites.[16]

3.4. Reactions omitting toluene

Our studies on the phase behaviour of 1-octene and nonanal with perfluoro-1,3-dimethylcyclohexane in the presence and absence of toluene showed that 1-octene is totally miscible with the fluorous solvent at ≥60°C under 20 bar CO/H_2 (1:l), but that nonanal is virtually immiscible. This led us to consider whether there might be advantages in omitting the toluene from the system, the most obvious being that a separate distillation to remove the toluene from the product would be unnecessary. It might also be possible to effect the separation of the product from the fluorous phase at higher temperatures, thus reducing processing costs associated with heating and cooling the various components of the mixture. The higher polarity of the aldehyde relative to that of the toluene/aldehyde mixture and the relatively smaller organic phase might also reduce the extent of the interaction of the phosphite ligand with the aldehyde while also reducing the level of leaching of rhodium into the product. We, therefore, carried out hydroformylation reactions of 1-octene in a system in which the only solvent was the perfluoro-1,3-dimethylcyclohexane (Table 3). There have been three reports of fluorous biphasic reactions being carried out in the absence of an organic solvent.[20–22]

Reactions were carried out under identical conditions, except that the toluene was replaced by the same volume of fluorocarbon solvent. The results are both surprising and remarkable. In particular, the reaction rates are increased significantly and this increase is higher at 80°C (factor of 2.7) than at 60°C (factor of 1.5), and the l/b ratios are dramatically improved, 7.8 at both 60 and 70°C compared with 4.8 and 4.1 at the same temperatures in the presence of toluene. The reason for the higher rate and linear selectivity in the absence of toluene are not clear. The difference in rate may be related to any, or all, of the following: the order of reaction with respect to the two gases, the differential solubility of the gases, since this affects the partial pressure in the gas phase and the solvation of the various complexes in the different solvent systems. Since we have not measured any of these parameters, we feel further speculation is unwarranted. The extent of leaching of the rhodium (6%) and of the phosphorus (9.6 and 10.1% at 60 and 70°C respectively) are greatly reduced and there is much less of a temperature effect suggesting that the catalyst is more stable in this system. This stabilisation is not sufficient, however, to allow the reaction to be successfully carried out at higher temperatures. Using the higher catalyst and ligand loadings, the l/b ratio can be pushed even higher (9.9) and both the rhodium (2.5%) and phosphorus (4%) leaching are reduced in percentage terms, but not in absolute terms.

3.5. $P(4-C_6H_4C_6F_{13})_3$ as ligand

As a consequence of the rhodium and phosphorus leaching and the detection of $HO-4-C_6H_4C_6F_{13}$ in the GCMS of the aldehyde products from the hydroformylation studies with $P(O-4-C_6H_4C_6F_{13})_3$, we decided to investigate further the phosphine, $P(4-C_6H_4C_6F_{13})_3$, which does not react with aldehydes. For these experiments, only fluorous solvent (no toluene) was used and this was perfluoromethylcyclohexane in place of perfluoro-1,3-methylcyclohexane. The change in fluorous solvent was made so as to allow direct comparison of $P(4-C_6H_4C_6F_{13})_3$ with the alkyl phosphine, $P(CH_2CH_2C_6F_{13})_3$, used by Horváth,[8] without the added complication of possible differences in the properties of solvent. The change does, however, complicate direct comparison of $P(4-C_6H_4C_6F_{13})_3$ with $P(O-4-C_6H_4C_6F_{13})_3$. The results for $P(4-C_6H_4C_6F_{13})_3$ are collected in Table 4 together with, for comparative purposes, three examples of toluene reactions using PPh_3 as the ligand.

Under dilute conditions, [Rh] at 2.0 mmol dm^{-3} and a phosphine/Rh ratio of 3:1, these reactions show the zero order (saturation) kinetics expected for low concentrations of phosphine.[8] The l/b ratios are modest at ca. 3.5, but the much lower levels of isomerised products, only slightly higher than those obtained when using PPh_3 in toluene (Table 4), mean that the selectivity to the linear aldehyde is almost as good as for the best reactions using the phosphite. Importantly, there is much less effect on the product distribution from raising the temperature and both the rhodium (0.5–2.5%) and phosphorus (6.2–9.2%) leaching are low and vary little with the reaction temperature. This suggests that the phosphine is stable under these conditions although some increased leaching occurs for the reaction carried out at 90°C. Reducing the rhodium concentration to 1 mmol dm^{-3}, whilst maintaining a phosphine/Rh ratio

Table 5. Comparison of results obtained from the hydroformylation of 1-octene in perfluoromethylcyclohexane using the rhodium catalyst containing $P(4\text{-}C_6H_4C_6F_{13})_3$, a literature precedent and with current industrial processes

	This work[a]	Horváth[b]	UCC[c]	BASF[c]
[Rh] (mmol dm^{-3})	2.0	0.156	2.7	1.8
[P] (mmol dm^{-3})	20	42.7	286	150
[alkene] (mmol dm^{-3})	1274	1012	–[d]	–[d]
Pressure (bar)	2 0	10	15–18	16
Temperature (°C)	70	100	90–95	110
Rate (mol dm^{-3} h^{-1})	8.8	0.16	2–4	1.0
TOF (h^{-1})	4400	1020	740	500
l/b	6.3	4.5	8.8	5.3
Isomerisation (%)	3.7	7.8	–[e]	–[e]
Linear aldehyde (%)	80.9	74.8	89.5	83.0
Rh loss (mg Rh (mol aldehyde)$^{-1}$)	0.08	0.12	–[f]	–[f]
P loss (%)	3.3	Significant	–[f]	–[f]

[a] 1-Octene as substrate, $P(4\text{-}C_6H_4C_6F_{13})_3$ in perfluoromethylcyclohexane.

[b] Ref. 8, 1-decene as substrate, $Rh/P(CH_2CH_2C_6F_{13})_3$ in 50:50 vol% of toluene and perfluoromethylcyclohexane.

[c] Taken from Ref. 1, propene as substrate, Rh/PPh_3 in condensed aldehydes. UCC process as run by Union Carbide, BASF process run by BASF.

[d] Propene introduced in gas phase.

[e] Propene cannot isomerise.

[f] Data unavailable.

of 3:1, does not greatly affect the reaction (both product distribution and initial TOF are virtually identical), although the reaction time is increased. However, increasing the phosphine concentration to 20 mmol dm^{-3} with the [Rh] at 2 mmol dm^{-3} (10:1 ratio) considerably improves the l/b ratio and increases the selectivity to linear aldehyde (80.9%). The reactions in the presence of this excess phosphine become first order, presumably because the phosphine competes with the alkene for the rhodium and some of it is thus trapped as trisphosphine species, but the rate is still very acceptable (see later) and, more importantly, the rhodium leaching is dramatically reduced. In the reaction carried out at 70°C, 99.95% of the rhodium is retained in the fluorous phase, together with 96.7% of the ligand. The absolute amounts of phosphine in the organic phase should be determined by the partition coefficient between the two phases and the total concentration of the phosphine. The fact that this does not increase dramatically when the phosphine concentration is increased by a factor of 3 may suggest that the solubility limit of the phosphine in the aldehyde is being approached.

These results show that the omission of toluene from the system allows the development of a process which is nearing the rigorous retention of rhodium in the system that would be required for commercial application, whilst retaining a high rate and a good selectivity to the linear aldehyde product. Further refinements of the ligand design should allow a truly commercially viable system to be demonstrated.

GCFID and GCMS analysis of the fluorous phases from the later experiments (10 phosphine/1 rhodium) revealed, that ca. 10% of the total organic product remains dissolved in the fluorous phase after phase separation. The relative proportion of each product in the fluorous layer is similar to that of the phase separated organic product and has been ignored in the data collected in the tables. The still dissolved organic product, including unreacted octene, could simply be recirculated in a continuous flow process where it would remain at an equilibrium concentration.

3.6. Comparisons with other systems

It is instructive to compare the performance of the catalysts that we have been developing with those used commercially and reported in the literature. $P(OPh)_3$ and other phosphites have been examined for their utility in rhodium catalysed hydroformylation reactions, and indeed bulky phosphites are amongst the best ligands known, with a bidentate version having recently been commercialised by Union Carbide.[16] Generally, $P(OPh)_3$ modified catalysts give higher rates under comparable conditions than those containing PPh_3, but the l/b selectivities are usually modest (<2:1),[16] unless the reactions are carried out under very low CO/H_2 pressures.[17] Isomerisation is usually more significant with phosphites than with phosphines and we have confirmed that this is indeed the case under the conditions we have been using (Tables 2–4). We have recently shown that high l/b ratios can be obtained when using $P(OPh)_3$ as a ligand for rhodium catalysed hydroformylation in ionic liquids[23] or in $scCO_2$, but in the latter solvent this is probably because the phosphite is insoluble and the catalysis takes place in the solution of the rhodium complex in molten $P(OPh)_3$, where the local [Rh] and [P] are very high.[24] We have subsequently used this reaction to develop continuous flow processes in ionic liquid–supercritical fluid biphasic systems.[23] Our results with $P(O\text{–}4\text{-}C_6H_4C_6F_{13})_3$ show that this ligand, under fluorous biphasic conditions and especially when no additional organic solvent is added, gives an increased selectivity for the linear aldehyde relative to conventional phosphites in organic solvents.

For PPh_3, which is currently used commercially for the hydroformylation of propene and other short chain alkenes, isomerisation is not usually a major problem and l/b ratios can be high leading to aldehyde selectivities in the 80–90% range.[1] Table 5 presents a comparison between the best results we have obtained (in terms of linear selectivity and rhodium retention into the fluorous phase) with those that are obtained using two variants of the commercial process for hydroformylation of propene. These show that, with comparable [Rh] but only 10% of the phosphine loading (important because of the expense of the fluorous ligand) and at a significantly lower temperature, our system is some five to eight times as productive as the commercial system, due to a combination of the use of a fluorous modified ligand of lower basicity combined with the much lower phosphine concentration employed, while giving a linear aldehyde selectivity that is only slightly less at 80.9% compared with 83% for the BASF process; the UCC process is superior in this regard (89.5%). It should be remembered, however, that propene cannot isomerise, so no loss of substrate to isomerised alkenes can occur in the commercial process. The reaction rate is, of course, related to the [alkene] for these first order reactions. The values quoted in Table 5, for both our work and that of Horváth, are those at an alkene loading corresponding to 20% by volume. This would not be an unusual loading at which to operate a continuous flow reactor.

Also included in Table 5 is a comparison of the best results reported in this paper with those obtained by Horváth under the conditions where he was measuring catalyst leaching.[8] His initial [Rh] is much lower than ours, but his [P] is much higher and his [substrate] lower. Our l/b ratios, linear selectivities and reaction rates even expressed as turnover frequencies are much higher, whilst our rhodium leaching is comparable. He did not measure the phosphine loss, although notes that change in rate and l/b on recycling suggests that some ligand leaching is occurring. The dramatic changes observed seem to indicate that this could be of the order of 3% per reaction. This is similar to the level of phosphine leaching that we observe (3.3%).

4. Conclusions

We conclude that by using a system that consists of a fluorous solvent in which long chain alkenes are soluble and a triarylphosphite or triarylphosphine carrying fluorous ponytails on all three aryl groups, hydroformylation can be successfully carried out in such a way that the product aldehyde can be obtained in a substantially pure state as a separate phase at the end of the reaction. Good l/b selectivities and high rates are obtained even at low rhodium loadings and with low P/Rh ratios (3–10). The best results, which compare very well with those obtained using commercial systems are obtained using Rh ($2.0\ \mathrm{mmol\ dm^{-3}}$)/$P(4\text{-}C_6H_4C_6F_{13})_3$ ($20.0\ \mathrm{mmol\ dm^{-3}}$) at 70°C and 20 bar CO/H_2. This gives a linear aldehyde selectivity of 80.9% and an initial productivity of $8.8\ \mathrm{mol\ dm^{-3}\ h^{-1}}$. Rhodium leaching into the aldehyde phase is limited to 0.05% [0.08 mg Rh $(\text{mol aldehyde})^{-1}$] of the rhodium charged and phosphorus leaching to 3.3%.

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References

1. Frohling, C. D.; Kohlpaintner, C. W. *Applied Homogeneous Catalysis with Organometallic Compounds*; Cornils, B., Herrmann, W. A., Eds.; VCH: Weinheim, 1996; Vol. 1, pp. 27–104.
2. *Rhodium Catalysed Hydroformylation*, van Leeuwen, P. W. N. M., Claver, C., Eds.; Kluwer: Dordrecht, 2000.
3. Cornils, B. In *New Synthesis with Carbon Monoxide*; Falbe, J., Ed.; Springer: Berlin, 1980.
4. Shell International Research. Neth. Appl., 6,604,094, 1966.
5. Cornils, B. *Applied Homogenous Catalysis with Organometallic Compounds*; Cornils, B., Herrmann, W. A., Eds.; VCH: Weinheim, 1996; Vol. 1, pp. 577–600.
6. *Chem. Engng. News*, **1999**, (Oct 18) , 20.
7. Horváth, I. T.; Rábai, J. *Science* **1994**, *266*, 72–75.
8. Horváth, I. T.; Kiss, G.; Cook, R. A.; Bond, J. E.; Stevens, P. A.; Rábai, J.; Mozeleski, E. J. *J. Am. Chem. Soc.* **1998**, *120*, 3133–3143.
9. Chen, W.; Xu, L.; Xiao, J. *Chem. Commun.* **2000**, 839–840.
10. MacDougall, J. K.; Simpson, M. C.; Green, M. J.; Cole-Hamilton, D. J. *J. Chem. Soc., Dalton Trans.* **1996**, 1161–1172.
11. Foster, D. F.; Adams, D. J.; Gudmunsen, D.; Stuart, A. M.; Hope, E. G.; Cole-Hamilton, D. J. Chem. Commun. **2002**, 722–723.
12. (a) Cole-Hamilton, D. J.; Foster, D. F.; Gudmunsen, D.; Hope, E. G.; Stuart, A. M. World Patent, WO 00/33956, 2000. (b) Cole-Hamilton, D. J.; Foster, D. F.; Adams, D. J.; Gudmunsen, D.; Hope, E. G.; Stuart, A. M. GB Patent Application, 0126261.7, 2001.
13. (a) Bhattacharyya, P.; Gudmunsen, D.; Hope, E. G.; Kemmitt, R. D. W.; Paige, D. R.; Stuart, A. M. *J. Chem. Soc., Perkin Trans. 1* **1997**, 3609–3612. (b) Adams, D. J.; Gudmunsen, D.; Fawcett, J.; Hope, E. G.; Stuart, A. M. *Tetrahedron*, **2002**, *58*, 3827–3834.
14. Rankin, J.; Benyei, A. C.; Poole, A. D.; Cole-Hamilton, D. J. *J. Chem. Soc., Dalton Trans.* **1999**, 3771–3782.
15. Payne, M. J.; Cole-Hamilton, D. J. *J. Chem. Soc., Dalton Trans.* **1997**, 3167–3175.
16. Kamer, P. J. C.; Reek, J. H. N.; van Leeuwen, P. W. N. M. In *Rhodium Catalyzed Hydroformylation*; van Leeuwen, P. W. N. M., Claver, C., Eds.; Kluwer: Dordrecht, 2000; pp. 35–62.
17. Trzeciak, A. M.; Ziolkowski, J. J. *J. Mol. Catal.* **1986**, *34*, 213–219.
18. van Leeuwen, P. W. N. M. In *Rhodium Catalyzed Hydroformylation*; van Leeuwen, P. W. N. M., Claver, C., Eds.; Kluwer: Dordrecht, 2000; pp. 233–251.
19. Billig, E.; Abatjoglou, A. G.; Bryant, D. R.; Murray, R. E.; Maher, J. M. US Patent, 4,717,775, 1988.
20. de Wolf, E.; Speets, E. A.; Deelman, B. J.; van Koten, G. *Organometallics* **2001**, *20*, 3686–3690.
21. Juliette, J. J. J.; Horváth, I. T.; Gladysz, J. A. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1610–1612.
22. Xiang, J.; Toyoshima, S.; Orita, A.; Otera, J. *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 3670–3672.
23. Sellin, M. F.; Webb, P. B.; Cole-Hamilton, D. J. *Chem. Commun.* **2001**, 781–782.
24. Sellin, M. F.; Cole-Hamilton, D. J. *J. Chem. Soc., Dalton Trans.* **2000**, *11*, 1681–1683.