CHAPTER 3 SUPPORTED CATALYSTS

Immobilisation of Tailor-made Homogeneous Catalysts

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3.1 Introduction

The enormous increase in knowledge of organometalic chemistry acquired over the past decades has had a great impact on catalysis, and numerous homogeneous transition metal catalysts for commercially interesting conversions are nowadays available. One of the factors hampering the commercialisation of the newly discovered catalytic conversions is the introduction of an additional separation step required to remove the homogeneous catalyst from the product, a problem that is not an issue for heterogeneous catalysts. The importance of the separation problem has been acknowledged for more than three decades [1] and, ever since, intensive research has been devoted to trying to solve this problem. Several elegant strategies to overcome this drawback have been explored including two-phase catalysis using various solvent combinations and the use of supercritical fluids. The most natural solution to combine the advantages of homogeneous and heterogeneous catalysis is the immobilisation of homogeneous catalysts to obtain tailor-made catalysts that can be applied in fixed bed or slurry type reactors. Indeed, this approach is probably the most widely studied as is evident from the numerous papers, reviews and books on this topic [2]. Remarkably, there are many patents on immobilised catalysts, but so far there is only one commercial process based an anionic rhodium complex $[RhI_2(CO)_2]^-$ that is bound to an ion exchange resin and is used for the carbonylation of methanol [3, 9a]. This indicates that there is a common belief that the immobilisation of catalyst on a support is a suitable solution for the separation problem, but there are several difficulties which prevent the step to real commercial success: (a) metal leaching from the support, (b) reduced activity and selectivity upon catalyst immobilisation, (c) limited mechanical strength and swelling properties of the support, and (d) non-innocence of the support. Considering the amount of work published in the literature it is impossible to give a complete overview of this area. We will therefore limit this chapter to important contributions that are illustrative of the field and we will attempt to give a clear view of the current state of the art including a view of the remaining challenges. Since hydroformylation is the model reaction used through-out this book, we will strong focus strongly on supported catalysts developed for this reaction, and we will only briefly discuss a few other reactions.

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3.2 Short Historical Overview

A literature search on “supported catalysts” revealed a few early examples (1923) of nickel and palladium catalysts supported on various substances such as $BaSO_4$ and kieselguhr [4]. These are the first examples of supported catalysts in which the metal is directly attached to the support. Much later, after the development of transition metal complexes as catalysts, methodologies have been explored to immobilise ligands on supports in order to obtain supported transition metal complexes. The first publications and patents involve the immobilisation of cationic platinum complexes on sulfonated polystyrene (Merrifield) via ionic interactions [1]. This work was basically inspired by Merrifield, who had just reported the preparation of polymer supported enzymes [5]. The work rapidly expanded into an active area of research, and at the end of the seventies several reviews had already appeared on this topic [2]. The use of structured, insoluble supports in the form of zeolites and supported liquid phase catalysis as a strategy to immobilise catalysts were also reported in the late sixties [6]. In the early seventies the first supported chiral ligands appeared in the literature [7]. The preparation of immobilised catalysts via sol-gel procedures were introduced much later [8]. Several recent reviews on catalyst immobilisation have appeared [9], discussing various important aspects in more detail, including molecular accessibility [10], immobilised chiral catalyst for asymmetric C-C bond formation [11] and interphase catalysis [12].

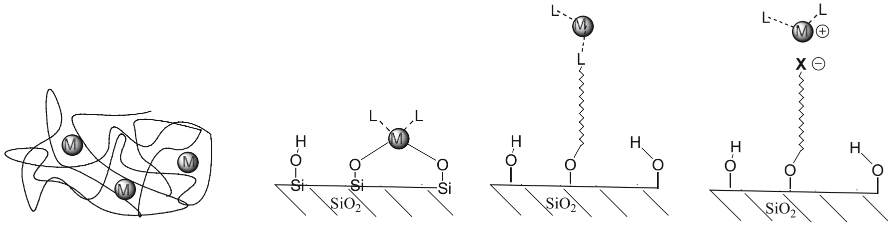
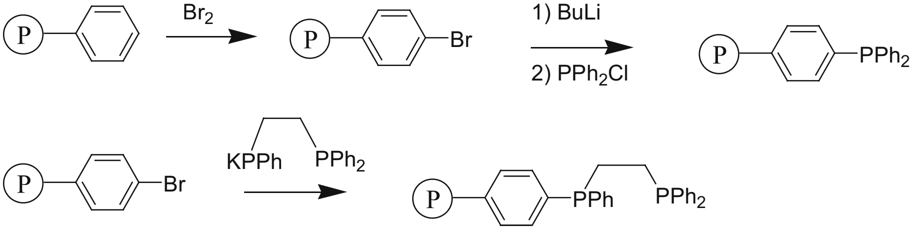


Figure 3.1. Several approaches that lead to supported catalysts: catalyst entrapment, anchoring via an interaction between the metal and the support, anchoring a ligand to a support, and anchoring via ion pairing (or other noncovalent interactions).

There are many ways to make polymer supported catalysts (Figure 3.1). Catalysts can be entrapped, retained by the polymer via ionic interactions or covalently attached to polymeric material. In the latter case the catalyst can be grafted onto a pre-derivatised support or can be co-polymerised. Alternatively, the catalyst can be attached to a support via hydrogen bonds, or it can be dissolved in a thin layer of water adhered to the support (SAPC, supported aqueous phase catalysis). The various ways of immobilisation each have their advantages. One can imagine that entrapped catalysts are easy to prepare since known catalysts can be used without further modification and they likely retain their properties, but catalyst leaching is a severe problem. In contrast, covalently attached ligands can eliminate ligand leaching and metal leaching if the metal-ligand interaction is sufficiently strong, but now a new ligand has to be prepared that enables anchoring to the support. Catalyst anchoring via ionic interactions can work well if ionic catalysts are used, but the properties of the catalyst might change especially if the catalyst performance depends on the counter ion. In addition, catalyst leaching can be expected if salts are produced during the reaction. For hydrogen bonded catalysts one needs to introduce a binding motive, which indeed involves the synthesis of new ligands, and also here competition with substrates, by-products or solvents presents limitations. The type of support ranges from the classical organic supports such as polystyrene (possibly cross-linked with disubstituted reagents or functionalised with polyethylene glycol spacers (TentaGel)) to inorganic supports such as alumina and silica. The choice of support is of crucial importance as all have advantages and disadvantages. For example, the mechanical strength and thermal stability of polystyrene are rather limited, which is a problem that nowadays can be managed through various technical solutions. In addition, these types of organic polymers have swelling properties that depend on the solvent used, and the swelling in turn influences the accessibility of the active sites. So there are many variables in the area of catalyst immobilisation, and there is no general solution that works best for all catalytic conversions. We will discuss various strategies applied to the rhodium catalysed hydroformylation of alkenes and, where required, we will add examples of other reactions. We will focus on catalyst performance, deactivation and metal/catalyst leaching, since these are crucial parameters when it comes to commercial applications.

3.3 Polystyrene Supported Catalysts

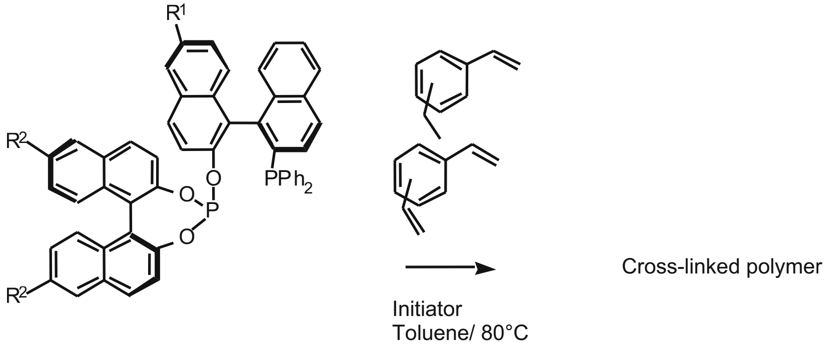
The use of polystyrene as support has the main advantage that it is relatively cheap and commercially available in many variations. For industrial applications polystyrene supported catalysts have some serious disadvantages. For fixed bed reactors the swelling properties of the organic support will lead to blocking of the inter-bead channels reducing the flow through of the reactor bed. The low mechanical strength of the polymer support will result in high resistance in fixed catalyst beds, and to attrition of particles in fluidised beds. These problems become even worse if the (local) temperature is high leading to degradation of the polymer. That polystyrene can be used on a large scale is proven by the fact that ion-exchange materials have found wide application. For laboratory use, polystyrene is an excellent support since most reactions are carried out batch-wise and at relatively small scales. A recent review on the use of polystyrene supported catalysts lists all the reactions that have been explored so far [13], which includes hydroformylation, hydrogenation, hydrosilylation, oligomerisation, Heck arylation, Suzuki coupling, Hartwig-Buchwald amination, allylic substitution, metathesis, cycloaddition, and aldol and Mannich type reactions.



Scheme 3.1. Direct functionalisation of polystyrene with phosphine ligands.

Early work reported by Grubbs showed that polystyrene supported phosphine ligands can be prepared by direct functionalisation of polystyrene via bromination and subsequent lithiation (scheme1) [14]. Rhodium complexes of this material were shown to be active in hydrogenation. The activity strongly depended on the catalyst loading and the degree of cross-linking. Pitman et al. reported an unusually high selectivity (linear branched ratio, l:b, up to 16) in the rhodium catalysed hydroformylation of 1-

pentene upon using polystyrene supported phospine ligands [15]. The explanation is straight-forward; the local concentration of phosphine and rhodium within the resin is much higher then in the homogeneous phase under similar conditions because the resin beads only occupy a small portion of the reaction volume. Indeed if the degree of phosphination of the resin is low, the catalyst properties were close to those of the homogeneous analogue. Hartley et al. studied the rhodium catalysed hydroformylation of 1-hexene using phosphinated polypropylene in detail and they reported similar effects [16]. At relatively low temperature (65 °C) the selectivity for the linear aldehyde is 3.5 times higher (l:b=16) than that of the corresponding homogeneous catalyst. At higher temperatures (85 °C) the selectivity dropped to l:b=6. With respect to catalyst leaching they report that the use of $[Rh(acac)CO_2]$ as precursor is much better then $[RhH(PPh_3)_3CO]$, because of the absence of free triphenylphosphine. Still rhodium leaching is between 5% and less then 1%, which is far too high for bulk processes. Clearly a stronger metal ligand interaction is required. This can be achieved by using bidentate ligands. Pitman et al. prepared one of the first styrene supported bidentate ligands via a simple procedure (Scheme 3.1) [17]. Both the homogeneous and the supported dppe ligands gave rise to low selectivities in hydroformylation of 1-pentene, which we now can attribute to the small bite angle of the bidentate ligand[18]. Interestingly, the supported catalyst could be recycled 20 times with only a little loss in activity. In addition, the leaching of rhodium from the supported catalyst was investigated by extensive extraction of the support with toluene under a relatively low pressure of 1 bar of CO. No change of rhodium content was observed using atomic absorption spectroscopy, suggesting that metal-ligand complexation is indeed strong with this chelating ligand and metal leaching will be at the ppm level or lower. For bulk chemical processes leaching is only acceptable at the ppb (1 part in 10^9) level.



1a R^1=H, R^2=H
1b R^1=vinyl, R^2=H
1c R^1=H, R^2=vinyl
1d R^1=vinyl, R^2=vinyl

Figure 3.2. Chiral phosphine-phosphite ligands on a highly cross-linked polystyrene polymer

For small scale applications asymmetric hydroformylation is more important, and immobilisation of expensive ligands can be worthwhile. An illustrative example of a chiral hydroformylation catalyst immobilised on a highly cross-linked polystyrene support was reported by Nozaki and Takaya [19]. Several BINAPHOS ligands carrying vinyl groups have been prepared and co-polymerised with ethylstyrene and divinylbenzene (Figure 3.2). By using different ligands (**1b-1d**) the degree of freedom of the ligand in the polymer matrix was varied. The influence of the degree of cross-linking and the polymer/catalyst preparation method on the catalyst performance was investigated (Table 3.1). Generally, the selectivity (90 % ee, l:b=0.2) obtained with the polymer-supported catalysts is similar to those obtained using the homogeneous system (run 1, Table 3.1).

TABLE 3.1. Asymmetric hydroformylation of styrene using polystyrene supported rhodium catalysts based on (R,S)-BINAPHOS)[a]

Run	Catalyst	l:b	ee (%)
1	Rh(acac)(**1a**)	0.12	92
2	(PS-**1b**)-Rh(acac)	0.19	89
3[b]	(PS-**1b**)-Rh(acac)	0.25	81
4[c]	(PS-**1b**)-Rh(acac)	0.20	89
5[d]	(PS-**1b**)-Rh(acac)	0.23	84
6	(PS-**1c**)-Rh(acac)	0.12	89
7	(PS-**1d**)-Rh(acac)	0.14	68
8	(PS)-[Rh(acac)(**1b**)]	0.18	90
9	(PS)-[Rh(acac)(**1c**)]	0.11	97
10	(PS)-[Rh(acac)(**1d**)]	0.15	85
11[d]	(PS)-[Rh(acac)(**1b**)]	0.18	90

[a] Conditions: 6.20 mmol styrene in benzene, 0.0031 mmol catalyst, 20 bar CO/H_2 (1:1), 60 °C, 12 hours, conversions to aldehydes >99%. [b] Hexane as solvent. [c] Lower cross-linking degree. [d] Higher cross-linking degree.

Two methods of catalyst-preparation were tested: the co-polymerisation of the ligand and subsequent formation of the rhodium acetylacetonate complex (runs 2-7) and co-polymerisation of the rhodium acac complex of the ligand (runs 8-11). This generally gave the same results, except for ligand **1d** (cf. run 7 and 10). Ligand **1d** is cross-linked with the matrix at three positions, which give rise to constrained conformations. Apparently, this leads to lower enantioselectivity in the hydroformylation reaction. In contrast, the other ligands have more freedom and can therefore form the proper catalyst conformation after the polymerisation. The degree of cross-linking has no significant influence on the selectivity of the reaction (runs 2, 4, 5, and 11). The reaction performed in hexane instead of benzene yielded slightly lower ee. The recycling experiments clearly show the drawback of these types of supports. The polymers were partly crushed by the stirring bar and approximately 50% of the initially charged rhodium was removed after the first run.

In subsequent work the same supported catalysts were used in different reactor set-ups [20] (Figure 3.3). A vapour-phase reactor in which the supported catalyst was mounted on a bed was used for the hydroformylation of volatile alkenes such as *cis*-2-butene and trifluoropropene. The initial activities and selectivity's were similar to those of the homogeneous solutions, i.e. a TOF of 114 and 90% ee in the hydroformylation of trifluoropropene was reported. No rhodium was detected in the product phase, which means less then 0.8% of the loaded rhodium had leached. The results were, however, very sensitive to the conditions applied and, especially at longer reaction times, the catalyst decomposed. In a second approach the polymer supported complex was packed in a stainless steal column and installed in a continuous flow set-up.

Volatile substrates were again reacted in the gas-phase, and selectivities equal to those from the homogeneous phase reactions were obtained. For less volatile substrates supercritical CO_2 was used as mobile phase and the substrates were added via a stepwise injection. For styrene a small drop in selectivity was observed compared to the reaction carried out in benzene (85% vs 92% ee). The most important point is that in these reactors the mechanical breakdown of the support was not observed.

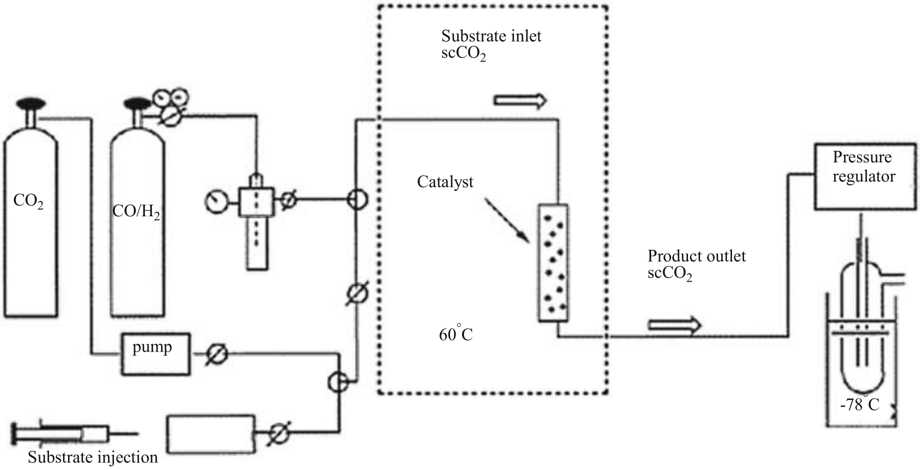


Figure 3.3. Asymmetric hydroformylation of non-volatile substrates using a stepwise injection into continuous flow reactor with $scCO_2$ as mobile phase

3.4 Silica Supported Catalyst

The covalent anchoring of catalysts onto inorganic silica surfaces was already being studied in the late seventies [21]. The most common strategy involves the functionalisation of ligands with alkoxysilane groups, which can subsequently be used to graft the ligand to the surface of silica type materials via a simple condensation step. Nowadays many building blocks required for this synthetic route are commercially available. In the first examples in which hydroformylation catalysts were anchored to an inorganic support a slightly different procedure was followed. Chloromethyl silicone polymers were converted to the iodo-analogues and subsequently reacted to form the diphenylphosphinemethyl polysiloxanes [22]. After treatment with $[RhCl(CO)(PPh_3)_2]$ these materials were used as catalysts in the hydroformylation of 1-hexene (68 bar CO/H_2 (1:1), 100 °C, benzene). Under these conditions metal dissociation from the support was a major problem. The leached metal formed very active rhodium carbonyl species in solution that was responsible for the low selectivity.

An alternative strategy to obtain silica immobilised catalysts, pioneered by Panster [23], is via the polycondensation or co-condensation of ligand functionalised alkoxysilanes. This co-condensation, later also referred to as the sol-gel process [24], appeared to be a very mild technique to immobilise catalysts and is also used for enzyme immobilisation. Several novel functional polymeric materials have been reported that enable transition metal complexation. 3-Chloropropyltrialkoxysilanes were converted into functionalised propyltrialkoxysilanes such as diphenylphosphine propyltrialkoxysilane. These compounds can be used to prepare surface modified inorganic materials. Two different routes towards these functional polymers can be envisioned (Figure 3.4). One can first prepare the metal complex and then proceed with the co-condensation reaction (route I), or one can prepare the metal complex after the polymerisation step (route II). The former route results in far better catalysts due to the higher structural homogeneity. In addition, more stable catalysts are obtained, showing less metal leaching.

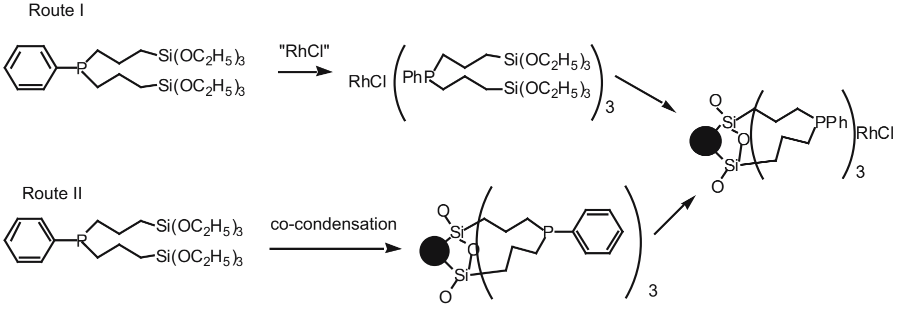
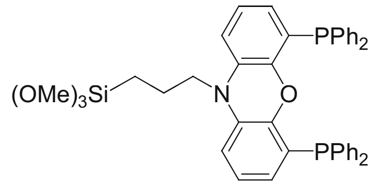


Figure 3.4. Two different routes to prepare sol-gel immobilised transition metal complexes

Panster studied the hydroformylation of 1-octene using a polysiloxane-anchored rhodium phosphine-amine based catalyst in a trickle-bed reactor [25]. The selectivity for the linear product was low (l:b =1.5), but the catalytic performance was retained over a period of 1000 h, and almost no rhodium leaching was detected. Initial leaching of rhodium was in the range of 2-3 ppm, which declined to 0.3 ppm after the start-up phase. Contrary to the homogeneous phase reaction, the presence of an excess of phosphine ligands did not result in a higher selectivity for the linear product, which was attributed to the rigid structure of the polymeric material. Using this type of material the ligands can be considered as site-isolated [26], i.e. they are fixed at such a distance that they are unable to coordinate to the same metal.



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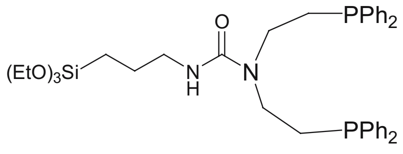

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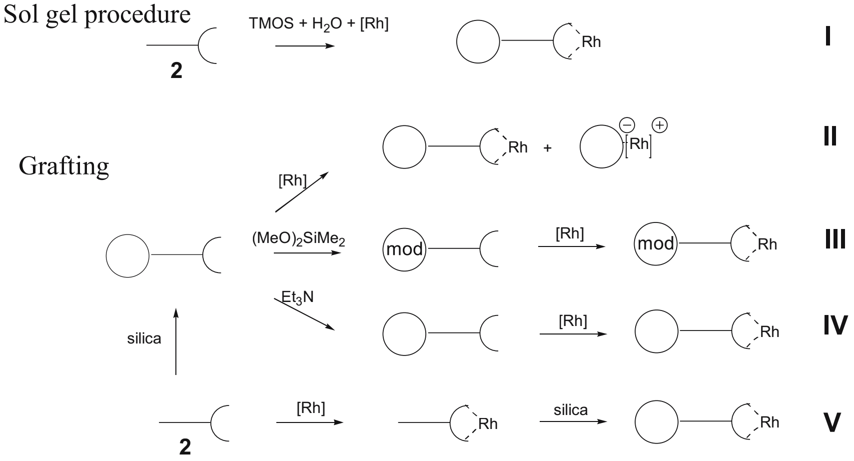
The immobilisation of **2** and **3** on silica has been studied in detail. Both ligands were immobilised using a sol-gel procedure [27] (I, Scheme 3.2) and **2** was also grafted onto commercially available silica in four different ways [28]. In the first three approaches, **2** was covalently tethered to silica to obtain silica(**2**) by refluxing a suspension of **2** and silica in toluene. The subsequent complexation of the rhodium precursor was performed under three different conditions. In the first approach the rhodium precursor [Rh(acac)(CO)$_2$] and silica(**2**) were simply mixed together and stirred in a THF suspension (material II). In the second, silica(**2**) was first reacted with dimethoxydimethylsilane in order to modify the acidic silanols on the silica surface. To this end a suspension of silica(**2**) and dimethoxydimethylsilane was refluxed in toluene and subsequently stirred in a solution of [Rh(acac)(CO)$_2$] in THF at room temperature (material III). In the third approach, [Rh(acac)(CO)$_2$] was added to a pre-stirred mixture of silica(**2**) and triethylamine in THF (IV). The fourth method involved the synthesis of the diphosphine rhodium complex Rh(**2**)(acac)(CO) prior to the immobilisation on predried silica (V). Interestingly, in the examples in which the Rh(acac)(CO)**2** complex was used for the immobilisation, cationic rhodium complexes were formed during the process. These were converted to neutral hydride species under proper hydroformylation conditions.



Scheme 3.2. Schematic representation of different routes to prepare silica immobilised [Rh(**2**) (CO)]$^+$.

The selectivity for the linear aldehyde of sol-gel immobilised **2** was found to be as high as 93%, which is similar to that of the homogeneous catalysed reaction (Table 3.2, entries 1 and 6). Sol-gel immobilised **3** gave a much lower selectivity (70%) for the linear aldehyde, and in the absence of ligand the selectivity to the linear aldehyde is only 26%. This proves that catalysts based on these ligands retain the selectivity upon immobilisation, which means that the selectivity is dominated by the size of the P-Rh-P bite-angle of ligand [18].

TABLE 3.2: Hydroformylation of 1-octene using silica immobilised [Rh(**2**)CO]$^{+\ a}$

Entry	Catalyst	Time (h)	Conv. (%)	TOF^b (h^{-1})	l:b Ratio	l-aldehyde (%)	b-aldehyde (%)	l-alcohol (%)	2-octene, octane (%)
1	sol-gel-**2** **(I)**	2	20	18.3	65	94.6	1.5	3.6	0.2
2	**II**	0.5	97	n.d.	2	40.1	22.0	0	37.9
3	**III**	23	24	8.0	19	85.5	4.5	0	9.9
4	**IV**	22	18	8.7	37	96.2	2.6	1.0	0.2
5	**V**	22	37	13.2	37	90.7	2.6	5.1	1.6
6	hom. **2**	2	19	283	32	93.3	2.9	0	3.7
7	sol-gel-**3**	2	72	119	2	70.0	28.9	0.1	1.0

[a] Ligand to rhodium ratio is 10, catalysis performed in 13 ml of toluene using 1ml of 1-octene as the substrate at 80 °C and 50 bar CO/H_2. Samples were analysed by means of GC and GC-MS.[b] Average turnover frequencies were calculated as (mol product)(mol catalyst)$^{-1}$h^{-1}

The method of catalyst immobilisation appeared to affect its performance in catalysis. Catalyst obtained by method II showed a low selectivity in the hydroformylation of 1-octene (l:b aldehyde ratio was even lower than 2) at a very high rate and high yields of isomerised alkenes (Table 3.2, entry 2), whereas procedure IV resulted in a catalyst that was highly selective for the linear aldehyde (with a l:b ratio of 37) (entry 5). In accordance with examples from literature it is likely that procedure II gave rise to the ionic bonding of ligand-free rhodium cations on the slightly acidic silica surface [29], i.e. a direct connection of the rhodium to the silica material. If the rhodium phosphine complex is prepared prior to anchoring (V) no ligand-free rhodium is attached to the silica. The effect of the acidic silanols on the catalyst preparation can be eliminated via chemical modification of the silica surface (III) or upon addition of a neutralising base (IV). Pre-modification of the silica using dimethoxydimethylsilane largely improved the catalyst selectivity (l:b aldehyde ratio of 19) at the cost of some activity. The addition of triethylamine (IV) also resulted in a very selective hydroformylation catalyst with a l:b aldehyde ratio of 37.

It is interesting to note that using the sol-gel procedure (I) the pre-formation of the rhodium diphosphine complex suppressed the formation of ligand free rhodium-cations on the silica surface. This approach gave rise to a well-defined, very selective hydroformylation catalyst. All immobilised catalysts were 10 to 40 times slower than the homogeneous catalyst under the same conditions, the sol-gel procedure yielding the fastest catalyst of this series.

TABLE 3.3. Hydroformylation of 1-octene using sol-gel and silica immobilised rhodium catalyst **2** in subsequent catalytic runs.[a]

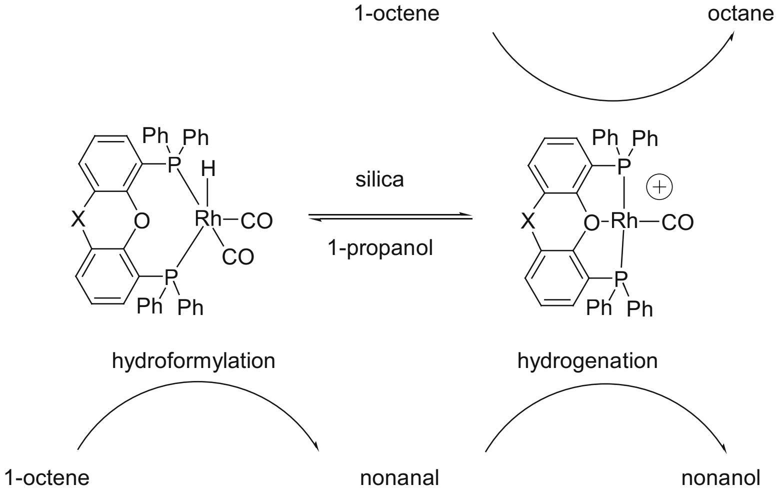
Entry [cycle]	Meth of prep	Time (h)	Conversion (%)	TOF[b] (h^{-1})	l:b Ratio	l-aldehyde (%)	b-aldehyde (%)	l-alcohol (%)	Side-products (%)
1 [1]	I	2	20	18	65	94.6	1.5	3.6	0.2
2 [4]	I	2	12	12	62	89.6	1.6	8.8	0
3 [1]	I	18	38	23	22	61.0	4.1	29.6	5.3
4 [2]	I	18	30	17	25	77.9	3.7	15.1	3.4
5 [1]	V	22	37	13	37	90.7	2.6	5.1	1.6
6 [3]	V	72	61	8	27	79.9	3.5	13.2	3.4
7 [1]	III	23	24	8	19	85.5	4.5	0	9.9
8[4]	III	72	44	5	16	84.8	5.4	0	9.8
9 [1]	I[c]	24	69	35[d]	32	92.8	3.0	2.5	1.7
10 [4]	I[c]	24	67	35[d]	35	94.5	2.7	1.3	2.2
11	I[e]	2.5	7	4	33	92.0	2.8	0	5.2

[a] Ligand to rhodium ratio is 10, catalysis performed in 13 ml of toluene using 1 ml of 1-octene as the substrate at 80 °C and 50 bar CO/H_2. Samples were analysed by means of GC and GC-MS analysis. [b] Average turnover frequencies were calculated as (mol product)(mol catalyst)$^{-1}$h^{-1}. [c] 1 ml of 1-propanol added to the catalyst mixture [d] Initial turnover frequency. [e] 1 ml of triethylamine added to the catalyst mixture.

Sol-gel and silica immobilised Rh(**2**) were tested in successive hydroformylation reactions of 1-octene to investigate the effect of the support on the recyclability of the catalyst (Table 3.3). For both systems the selectivity was found to be similar to that of the homogeneous analogue. Upon recycling, the high regioselectivity for the linear aldehyde was maintained (l:b ratios ranging from 22 to 65) while only a small amount of alkene isomers was formed as side products. A small decrease in hydroformylation activity upon recycling along with an increasing formation of 1-nonanol (4-13 %) was observed, especially at longer reaction times (Table 3.3), a phenomenon not obtained with the analogous homogeneous catalysts. This strongly suggests that the silica support plays a role in this secondary reaction. It is likely that the acidic silica increasingly suppresses the formation of [HRh(**2**)$(CO)_2$] from [Rh(**2**)CO]$^+$. The cationic rhodium complex is responsible for hydrogenation activity converting the aldehyde into the corresponding alcohol, and is not active in hydroformylation [30].

When the silica material with the capped (acidic) silanols was used (III) the influence of the silica on the selectivity after recycling was largely suppressed. No hydrogenation of the aldehyde was observed as a secondary reaction in any of the successive catalytic runs (Table 3.3, entry 7-8). The modification of the surface silanols with alkylsilanes did not yield an optimal catalyst system. The overall selectivity for the linear aldehyde was slightly lower compared with the other catalysts; more isomerisation and branched aldehyde was obtained.

A more subtle method to reduce the influence of the silica comprises the addition of 1-propanol, which leads to an efficient suppression of hydrogenation activity. A high overall selectivity for the linear aldehyde was obtained in subsequent batch-wise runs (Table 3.3, entries 9-10). Interestingly, in other examples alcohols or amines were added to promote the hydrogenation of aldehydes via a transfer hydrogenation reaction [31], showing that this co-solvent can have different functions. In the present example alcohol prevents the formation of the cationic hydrogenation catalyst from the neutral hydroformylation catalyst by deactivating the acidic silanols on the silica surface. The addition of triethylamine as a base also enabled the suppression of the hydrogenation activity (Table 3.3, entry 11).



Scheme 3.3. Schematic representation of the interconversion of the catalyst systems $[Rh(\mathbf{2})(CO)]^+$ and $[HRh(\mathbf{2})(CO)_2]$ and the products generated from each catalyst species.

It is evident that the silica support influences the catalytic performance and it is important to understand the details of the processes involved. For the sol-gel material it was shown by ^{31}P NMR spectroscopy that the immobilised cationic complex completely transforms to the neutral rhodium-hydride species under a CO/H_2 atmosphere (Scheme 3.3). On dried silica, however, this conversion might not be complete since the dried support is more acidic [32]. It is therefore very likely that the neutral and cationic rhodium complexes co-exist on the silica support. ^{31}P NMR measurements on homogeneous rhodium complexes have shown that a simple protonation indeed converts the neutral rhodium hydride species into the cationic complex.

The existence of two different rhodium species co-existing on the silica support can be used as an advantage by controlling their relative amount. Under standard hydroformylation conditions, the cationic species and the neutral hydride complex are both present in significant amounts. Hence hydroformylation and hydrogenation will both proceed under a CO/H_2 atmosphere. Indeed a clean one-pot reaction of 1-octene to 1-nonanol was performed, using the supported catalyst for a hydroformylation-hydrogenation cascade reaction. 98 % of the 1-octene was converted in the hydroformylation reaction and 97 % of the linear nonanal was subsequently hydrogenated to 1-nonanol resulting in an overall selectivity of 90 % for the linear alcohol. Importantly, no heavy-end side-products were observed in this reaction owing to the mild conditions applied. In the first few hours of the cascade process, mainly the hydroformylation of 1-octene to the aldehyde was observed. The hydrogenation towards the corresponding alcohol started at higher aldehyde concentrations. When approximately 90 % of the 1-octene was consumed (after 60 hours) the hydroformylation activity had decreased significantly, which is in line with the first order rate dependency in substrate concentration. In contrast, the hydrogenation of the aldehyde product proceeded after 60 hours. As a result, the aldehyde concentration decreased again after approximately 40 hours, which in turn caused a decrease of the hydrogenation rate.

TABLE 3.4. Results from switching between hydrogenation, hydroformylation and hydroformylation-hydrogenation sequence reactions using sol-gel immobilised $[Rh(\mathbf{2})CO]^+$ [a]

Entry[b]	Time (h)	Conversion Octene (%)	Conversion Aldehyde (%)	l:b	l-aldehyde (%)	b-aldehyde (%)	l-alcohol (%)	Octane[c] (%)
1	172	97	75	23	18.5	3.6	66.7	11.2
2	24	100	100	-	0	0	100	100
3	68	60	16	18	65.2	4.5	13.7	16.6
4	2	98	10	-	0	0	9.7	98
5	96	96	0	18	90.7	5.1	0	4.3

[a] Ligand to rhodium ratio is 10, catalysis performed at 80 °C, in 13 ml of toluene using 1 ml of 1-octene (plus 1 ml of 1-nonanal entries 2 and 4). Samples were analysed by means of GC and GC-MS analysis. [b] Entries 1, 3, and 5; 50 bar syn gas. Entries 2 and 4; 50 bar H_2. [c] Numbers include isomers of 1-octene since these are not separable from octane on GC.

The ratio of the two co-existing catalyst species could be controlled by modification of the conditions and the catalyst was recycled by a simple filtration procedure, enabling the use of the supported catalyst for different subsequent conversions. This was demonstrated by a series of catalyst experiments using 1-octene as the substrate and polysilicate immobilised Rh(**2**). A first reaction under standard conditions, thus with the catalyst as a mixture of the neutral and cationic species, resulted in a product mixture that consisted for 66.7 % of 1-nonanol and 18.5 % of 1-nonanal (Table 3.4, entry 1). After this reaction, the system was recycled and transformed into a hydrogenation catalyst just by washing it with toluene and subsequently adding a mixture of 1-octene and 1-nonanal in toluene to the catalyst mixture. After a reaction time of 24 h under an H_2-atmosphere a complete hydrogenation of both substrates was observed to octane and 1-nonanol, respectively (Table 3.4, entry 2). This modulation is completely reversible; in the third catalyst cycle the system was applied again as a mixed catalyst by changing the atmosphere from H_2 to CO/H_2 and using 1-octene as the substrate. This resulted in a switch of the catalyst from the hydrogenation mode back to the hydroformylation-hydrogenation sequence mode. The regioselectivity for the linear aldehyde and alcohol (overall l:b ratio of 18) was largely restored (Table 3.4, entry 3). This provides evidence that the catalyst is stable during the switching procedure, since even a small amount of decomposed rhodium catalyst would result in a dramatic drop in selectivity. In the fourth cycle, the hydrogenation catalyst 5 was restored (Table 3.4, entry 4). This time, the hydrogenation reaction of a 1:1 mixture of 1-octene and 1-nonanal was stopped after 2 h and a chemoselectivity for the alkene reduction over aldehyde reduction was observed (96 % alkene and 10 % aldehyde was hydrogenated). From these four catalytic runs it can be concluded that the immobilised catalyst system is switched easily and repeatedly between the hydrogenation mode and the hydroformylation-hydrogenation cascade mode. In the fifth run the catalyst was switched to a pure hydroformylation catalyst (Table 3.4, entry 5) by using an atmosphere of CO/H_2 and the addition of 1 ml 1-propanol, along with a fresh batch of 1-octene in toluene. After 96 hours, 1-octene was almost completely converted to the linear aldehyde with a complete suppression of its hydrogenation to the alcohol! These results nicely demonstrate the importance of detailed knowledge of the effect of immobilisation on the catalyst. In this example the immobilised catalyst Rh(**2**) can not only be recycled, but it can also be switched reversibly between two different states leading to different products. In addition, the catalyst is very stable and metal leaching is below the detection limit. An important advantage of the supported catalyst is that solubility issues of the catalyst in the reaction medium do not play a role. As such, a hydroformylation experiment was performed in pure 1-octene and under these conditions the activity was similar as that of the homogeneously catalyzed reaction (TOF = 287 mol/mol/h) [27].

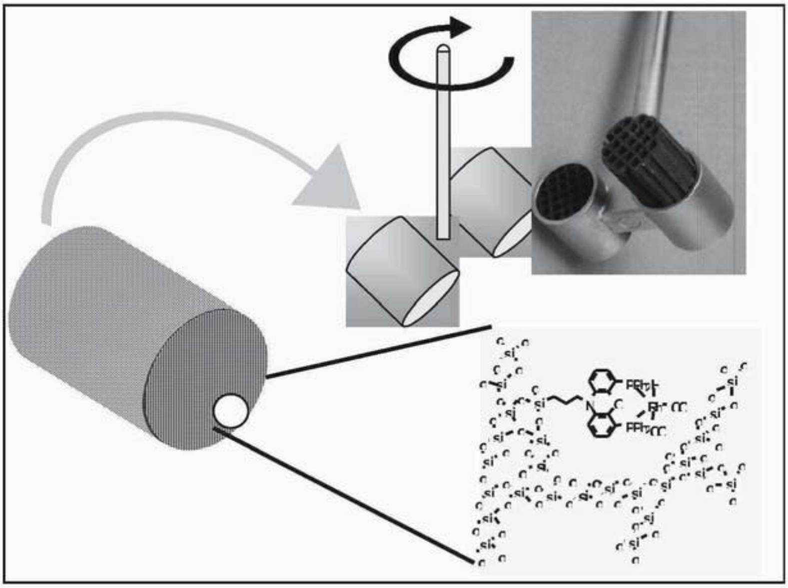


Figure 3.5. Schematic representation of the ROTACAT concept: a homogeneous complex, immobilised on monoliths, and the implementation of these monoliths in the blades of a mechanical stirrer. Inset: a picture of the stirrer with a silicon-carbide monolith

In recent years monolithic reactors have found wide application in gas-solid processes such as automotive emission control [33] and industrial off-gas purification [34]. In addition, these systems are being considered for gas-liquid-solid processes such as hydrogenations and oxidations [35]. Recently, Moulijn et al. reported on a novel reactor configuration in which blocks of monoliths are arranged in a stirrer-like fashion [36]. Using this setup a reasonably large surface area of the immobilised catalyst is retained, but many problems of handling a suspension of finely divided supported catalyst species are eliminated. In an attempt to increase the applicability of immobilised catalyst Rh(**2**) a new concept (ROTACAT: an immobilised homogeneous rotating catalyst) was developed that unites the above-described processes (Figure 3.5) [37]. Rh(**2**) was covalently anchored to monoliths and these monoliths were implemented in two hollow tubes that were constructed as blades of a mechanical stirrer. Two types of monoliths (Si and SiC) were explored that differ in mechanical strength and surface area. The Si monoliths have a higher surface area (120 m^2/g vs 0.5 m^2/g) whereas the SiC monoliths are mechanically far more stable. The SiC monoliths required a special treatment since the surface area of this type of monolith is too low (less than 0.5 m^2/g according to BET surface area measurements). Only very little of ligand **2** could be loaded on a SiC monolith of 3.5 g. To increase the surface area the SiC monoliths were first wash-coated with a porous silica top-layer of approximately 15 weight %. The silicon top layer, causing an increase in surface area to 17 m^2/g (determined by BET surface area measurements), enabled a sufficient ligand loading (0.02-0.04 mmol/g monolith). The Si monoliths could be charged with a sufficient amount of ligand without pre-treatment (~0.05 mmol g^{-1} monolith). The mechanical stirrer of a 200 ml autoclave, consisting of two parallel cylindrical tubes, was charged with two monoliths. A sufficient amount of **2** was immobilised on the monoliths by agitation in a toluene solution of **2** at 80 °C under an inert atmosphere. The immobilised ligand was subsequently functionalised with the rhodium precursor by stirring a toluene solution of $[Rh(acac)(CO)_2]$ at 80 ºC under 50 bar of CO/H_2 (1:1) for 1 hour in an autoclave, equipped with the ligand functionalised rotor.

In the hydroformylation of 1-octene, using Rh(**2**) immobilised on the SiC monoliths, the overall selectivity for 1-nonanal was 89 ± 3 %. As was found previously for the homogeneous system and the silica-immobilised system, the l:b aldehyde ratio was very high (ranging from 20 to 46). Remarkably, the selectivity for the linear product using Rh(**2**) immobilised on the Si monoliths was lower (72 %). The regioselectivity for the linear aldehyde was rather high (l:b ratio of 14) but alkene isomerisation was observed to a large extent (18 %). Furthermore, significant hydrogenation of 1-nonanal to the alcohol was observed (4.8 %). Similar to sol-gel immobilised catalyst the hydrogenation could be completely suppressed by the addition of a small amount of 1-propanol during catalysis, suggesting that the lower catalyst selectivity of the Si- monolith immobilised catalyst is a result of the higher acidity of this material.

The SiC ROTACAT was studied in more detail. The initial rate of hydroformylation under standard conditions was found to be low (between 1 and 2 mol mol^{-1} h^{-1}). Compared to the sol-gel immobilised analogue this is about 15 times lower. In an octene/toluene 1:1 mixture the rate of the reaction increased to 15 mol mol^{-1} h^{-1} as a result of the higher concentration of octene. Under optimised conditions the reaction rate reached 97 mol mol^{-1} h^{-1} when the catalysis was performed in neat 1-octene. The SiC ROTACAT could be reused in ten consecutive catalytic cycles showing no systematic deterioration in hydroformylation performance. To demonstrate the advantage of this multipurpose reactor set-up, the same catalyst was used for hydroformylation reactions in the gas phase (propene), in aqueous phase (propene) and again in toluene. In all cases clear colourless product solutions were drawn from the autoclave that did not contain rhodium or phosphine, as indicated by means of Atomic Emission Spectroscopy. The catalyst showed a remarkable long-term stability. It was found that this catalyst system (2 mg of Rh!) was reusable for over six months without decrease in catalytic performance. This makes ROTACAT among the most stable hydroformylation systems reported in the literature. Importantly, the bond-strength of the chelating diphosphine to the rhodium is sufficiently high and the rhodium-diphosphine complex is solidly anchored on the monolithic rotor. The system enables a straightforward recycling procedure (compared to slurry reactions) in which required washings do not damage the catalyst.

One strategy to reduce the negative effects of catalyst immobilisation on the activity is the use of supercritical fluids such as $scCO_2$. $scCO_2$ has solvation properties comparable to higher alkanes, and at the same time the diffusion is much higher because of the low density [38]. Importantly, dihydrogen and carbon monoxide dissolve very well in $scCO_2$. At Nottingham, a set-up for continuous processes with $scCO_2$ as mobile phase and supported catalyst as stationary phase has been built and successfully applied to hydrogenations, Friedel-Crafts alkylations and etherification reactions [39]. The reactor set-up has also been used to study the properties of immobilised catalyst Rh(**2**) in the hydroformylation of 1-octene [40]. For this purpose the rhodium complex was immobilised on silica with particle size 200-500 μm. Typically 1g of silica with a 0.4% Rh loading was loaded into a 5 ml supercritical flow reactor.

TABLE 3.5. Results from the hydroformylation of 1-octene using silica-immobilised Rh(**2**) using a continuous flow reactor with $scCO_2$ as the mobile phase [a]

Entry	TOF[b]	Linear aldehyde[c] (%)	Branched aldehyde[c] (%)	Alkene isomers[c] (%)	Linear alcohol[c] (%)	l:b ratio	1-Octene conversion (%)
1[d]	39	96.1	2.4	1.5	0	40	3.6
2	87	92.9	3.0	3.8	0.3	32	9.4
3[e]	112	94.4	2.4	2.5	0.7	40	10.1
4[f]	117	92.6	3.8	2.5	1.0	24	10.3
5[g]	44	90.7	4.4	3.7	1.3	21	14.3
6[h]	160	93.5	2.8	2.9	0.8	33	4.1
7[i]	93	96.0	1.9	1.1	0.9	50	14.3
8[j]	96	91.3	4.1	4.3	0.3	23	4.6

[a] Ligand : Rh ratio is 10:1 and the catalysis was performed at 80ºC, 120 bar CO_2 at 0.65 l/min flow rate (at 20ºC, 1 atm), 50 bar overpressure syngas and an 1-octene flow rate of 0.05 ml/min (substrate:syngas = 1:10) unless otherwise stated. Catalyst: see text. Values shown are average numbers over a period of 3-6 hours. [b] Average turnover frequencies were calculated as (mol aldehyde/mol catalyst)$^{-1}$/h^{-1}. [c] Determined by means of GC analysis using decane as an internal standard. [d] Reaction temperature is 70ºC. [e] Syngas overpressure is 25 bar. [f] 0.3 l/min CO_2 flow rate (at 20ºC, 1 atm). [g] 180 bar CO_2. [h] Reaction temperature is 90°C. [i] 1-Octene flow rate of 0.03 ml/min. [j] 1-Octene flow rate of 0.1 ml/min.

The catalyst system converted 1-octene selectively to linear nonanal. The average l:b aldehyde ratio was 40:1. 1-Octene conversions up to 14% per pass were obtained (Table 3.5) and only a few % of octene isomers and a trace amount of alcohol were observed as by-products. At 70 ºC and a 1-octene flow rate of 0.05 ml/min the rate of hydroformylation was moderate (39 mol mol^{-1} h^{-1}, Table 3.5, entry 1). The rate increased to 87 mol mol^{-1} h^{-1} with the catalyst bed at 80 ºC (entry 2) and improved further to 112 mol mol^{-1} h^{-1} on decreasing the syngas pressure from 50 to 25 bar (entry 3). The latter effect is consistent with the negative order in CO pressure that is commonly observed in hydroformylation reactions. A TOF of 117 mol mol^{-1} h^{-1} was observed on increasing the residence time of the substrate in the reactor by decreasing the CO_2 flow rate (entry 4). An increase of the CO_2 pressure resulted in a decrease in TOF to 44 mol mol^{-1} h^{-1} (entry 5). This suggests that a higher pressure, which results in a higher density of CO_2, changes the transport properties in the reactor. The highest TOF (160 mol mol^{-1} h^{-1}) was observed at 90 °C (entry 6). On decreasing the 1-octene flow rate from 0.1 to 0.03 ml/min an increase in the l:b ratio from 23 to 50 (entries 2, 7 and 8) was observed.

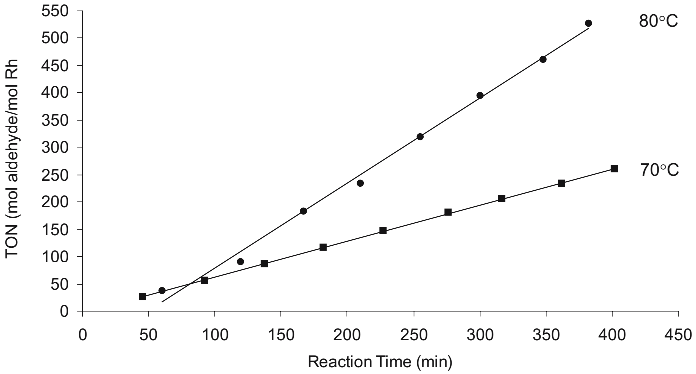


Figure 3.6. Turn over number (TON) displayed as function of time for the hydroformylation of 1-octene using a set-up for continuous processes with $scCO_2$ as mobile phase and supported catalyst **2**

It is remarkable that the hydroformylation rate is at least four times higher than the batch reaction with the use of the same immobilised catalyst in toluene and only half the rate of the homogeneous analogue. The high rate in $scCO_2$ is probably caused by enhanced mass-transport properties and the lower viscosity of the solvent medium. The catalyst appeared to be very robust, as its performance is constant over at least 30 hours. In Figure 3.6, the turnover number (TON), is plotted against reaction time. The TON increased linearly with time at both 70 and 80 ºC. Moreover, the catalyst was used for six non-consecutive days with no observable decrease in either activity or selectivity. Furthermore, no rhodium leaching was found (detection limit of used technique (ICP-AES) is 0.2% of the total amount of rhodium of the catalyst). This again demonstrates that the rhodium-diphosphine bond in this catalyst also remains stable under hydroformylation conditions if $scCO_2$ is used as the solvent.

The process is potentially interesting in the manufacture of chemicals and this approach has several advantages compared to conventional homogeneously catalysed reactions. Firstly, $scCO_2$ is a clean, environmentally benign medium that can be easily separated from the organic phase [38]. Secondly, the application of an immobilised homogeneous catalyst in the flow reactor provides a direct and quantitative separation of the products from the catalyst and avoids any solubility limitations of homogeneous catalysts. Furthermore, the catalyst is very robust and leaching levels are very low. The use of high pressures adds to the cost of the process, but, in addition to the above benefits, it should be mentioned that the space-time yields of the immobilised system are one order of magnitude higher than those of selective homogeneous catalyst systems.

3.5 Catalysis in Interphases

The term "chemistry in interphases" was first introduced in the field of reverse-phase chromatography [41]. In 1995 Lindner et al. transferred the concept to the area of transition metal catalysis [42] and in a recent review the concept is explained in detail [43]. The interphase is defined as a region within a system in which the stationary and a mobile component penetrate on a molecular level without the formation of a homogeneous mixture. In these regions the reactive centre on the stationary phase becomes mobile, thereby simulating the properties of a solution. Therefore, this should lead to a system that is conceptually in between homogeneous and heterogeneous. In practice, this means that the stationary phase consists of an inert rigid matrix functionalised with a flexible spacer with a reactive centre at the end. The mobile phase can be chosen in a more classical way: a solvent or a gas containing the reactants. Of course one can also decide to use $scCO_2$ as the mobile phase.

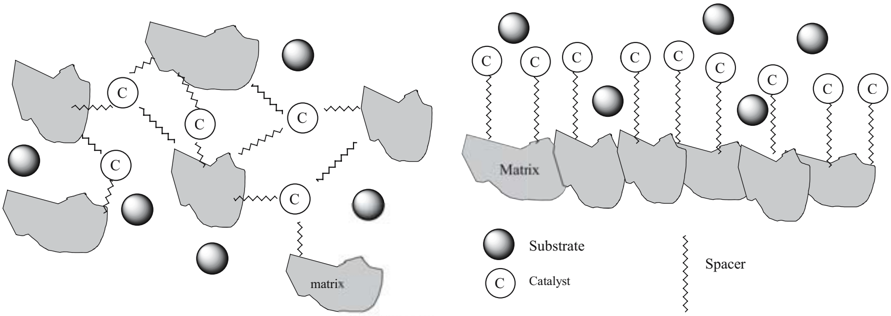


Figure 3.7. The concept of chemistry in interphases; visualisation of two different ways to obtain such a material, sol-gel procedure using different reagents (left) and silica grafted materials with sufficiently long spacers (right). Solvent occupies the space between the spacers

Organic-inorganic hybrid polymers are suitable as matrices (Figure 3.7 left), but also suitable are rigid porous materials with sufficiently long organic spacers between the active centre and the support (Figure 3.7 right). It is noteworthy that these types of materials were already studied before the introduction of the concept of chemistry in interphases. An example is shown in Figure 3.8, where phosphite functionalised polystyrene was grafted on silica [44]. This material was used in a continuous flow reactor and the rhodium catalysed hydroformylation of styrene was carried out for a period of ten days (syngas pressure 30 bar, 100 ºC, benzene). In this period no metal leaching (<0.05%) nor catalyst deactivation was observed. In toluene the catalyst was about 8 times more active, but now a significant amount of metal leaching occurred. The metal leaching was explained by incomplete coordination of the rhodium due to contraction of the polymer in this solvent.

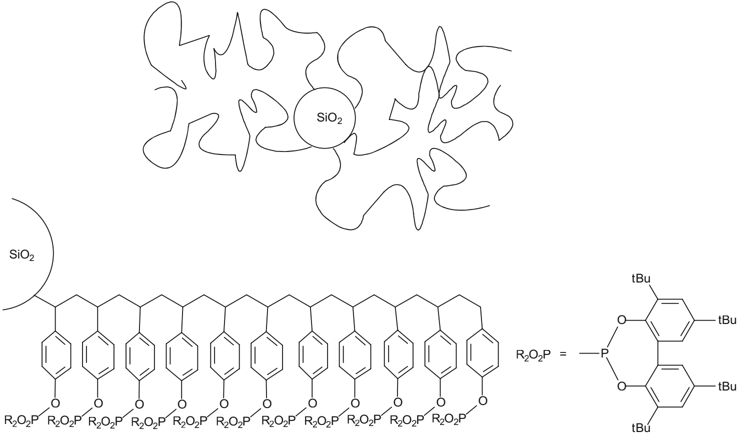
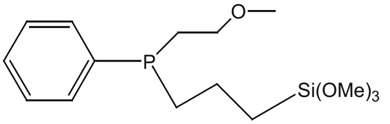


Figure 3.8. An early example of a hybrid support applied in the rhodium catalysed hydroformylation operated in a continuous flow reactor. Polystyrene containing phosphite ligands were grafted on inorganic silica, such that the catalyst will behave as a homogeneous catalyst when using a compatible solvent

Lindner et al. carried out detailed studies on the use of the sol-gel procedure to obtain new materials as suitable matrices [45]. A co-condensation of $Si(OR)_4$, $Si(OR)_3$-spacer-$Si(OR)_3$ and $Si(OR)_3$-spacer-ligand resulted in new hybrid materials, the properties of which strongly depended upon the spacer and the ratio of the different components used. Most of these materials were characterised with IR, EXAFS, and EDX spectroscopy, scanning electron microscopy and solid state NMR spectroscopy. Solid state ^{31}P NMR was used to quantify the mobility of the interphases; the changes in line-widths reflect the flexibility of the material. It is noteworthy that these matrices lost the characteristic properties of silica and showed significant swelling depending on the solvent used. In one of the contributions Linder et al. used hemi-labile ligands such as **4**, and their ruthenium complexes for the sol-gel process and the materials obtained were characterised in detail using solid state NMR spectroscopy [46]. These materials proved to be efficient catalysts for the ruthenium catalysed hydrogenation and some interesting features were observed. The catalytic behaviour was strongly dependent on the solvent used. A significant increase in activity was obtained in polar solvents. There was only a very small effect of the hydrogen pressure and a strong effect of substrate concentration (if bulky phenyl ethyne was used as a substrate). This suggests that the diffusion of these large molecules is involved in the rate limiting step. Importantly, the supported catalyst showed higher activity then the homogeneous analogue. This was attributed to the decrease in formation of inactive rhodium dimer due to the spatially isolation of the metal centres on the stationary phase.



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Lindner et al. also prepared catalysts for the hydroformylation of olefins using a sol-gel-procedure to obtain rhodium complexes **5a-c** (Figure 3.9). The bifunctional co-condensation agent $(MeO)_3Si(CH_2)_6Si(OMe)_3$ and a carbonylhydrido-(trisphosphine)rhodium complex with T-silyl-functionalised diphenylphosphine ligands containing three- or six-membered hydrocarbon spacers were employed as starting materials. The polymer-bound complexes **5a-c** were good catalysts for the hydroformylation of 1-hexene and they have been studied ina wide variety of solvents (toluene, THF, acetone, ethanol, methanol and water). Polar organic solvents such as methanol afforded the highest activities (TOF=340 mol(sub) mol(cat)$^{-1}$ h^{-1}) with low selectivities (l:b=3.3), whereas the selectivity toward the formation of 1-heptanal was optimal in solvents of medium polarity such as ethanol (l:b=5.5) or acetone at the expense of the activity (TOF (ethanol) =234 mol(sub) mol(cat)$^{-1}$ h^{-1}). In water the activity was rather low (TOF=20 mol(sub) mol(cat)$^{-1}$ h^{-1}). The high activity in solvents of medium polarity was explained by the optimal swelling of the polymers in these solvents, and the state of the reactive centres was suggested to be similar to those in solution. In line with this, wide-line separation (WISE) NMR spectroscopic investigations revealed a substantial decrease in line-width for the swollen polymer. In addition to hydroformylation a high isomerisation activity was observed (typical 20-30%).

These materials were also prepared via a sol-gel process in the presence of free phosphine ligands leading to materials with non-coordinated ligands. These supported catalysts gave rise to higher selectivities for the linear aldehyde in the hydroformylation of 1-hexene; a l:b ratio of 14:1 with an average turnover frequency of 164 mol(sub) mol(cat)$^{-1}$ h^{-1} was obtained with these materials. In addition the isomerisation side reaction was suppressed to a large extent (5%). The longer spacers between the catalyst and the solid support in material **5c** were introduced for higher mobility and thus improved performance. However, l:b ratio (6) and turnover frequencies (118) obtained with **5c** were lower than those observed with **5b**. This was attributed to the lower actual concentration of phosphine functions in **5c** (mmoles of phosphine per unit volume of swollen catalyst bead at constant P/Rh) in the swollen polymer. Olefins higher than 1-hexene were also hydroformylated with **5c** giving similar results.

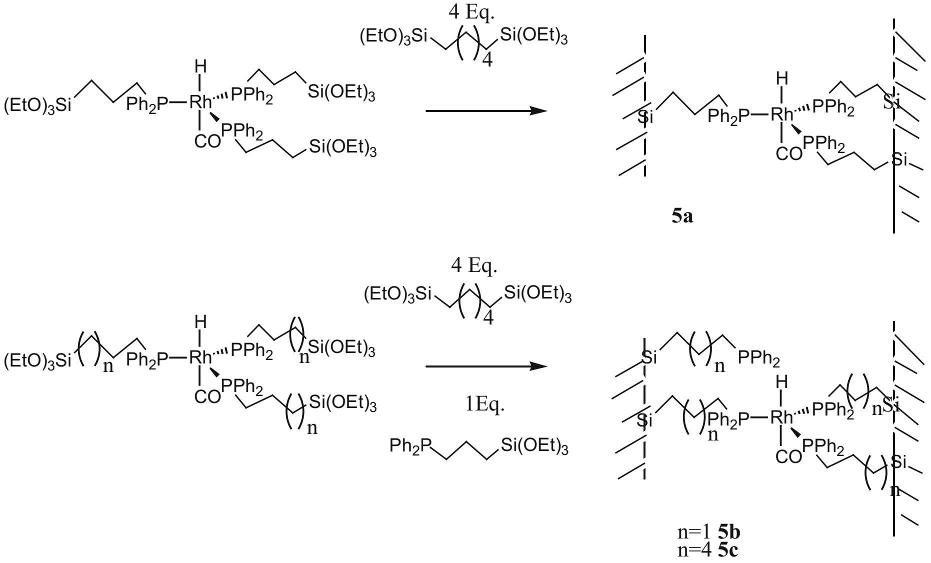


Figure 3.9. Sol-gel processed rhodium complexes using various procedures. These catalysts gave different results in the hydroformylation

In a similar study with modified phosphine ligands several hybrid polymers were prepared [47]. A novel triphenylphosphine analogue was prepared by the introduction of a spacer at the para-position of one of the phenyl rings. Subsequent reaction with a rhodium precursor yielded the catalytically active T-silyl-functionalised rhodium(I) compound $ClRh(CO)[PPh_2C_6H_4NHCONH(CH_2)_3Si(OEt)_3]_2$. The modified complex was co-condensed with $(MeO)_2MeSi(CH_2)_6SiMe(OMe)_2$, $(MeO)_2MeSi(CH_2)_3(1,4\text{-}C_6H_4)(CH_2)_3SiMe(OMe)_2$, $(MeO)_3Si(CH_2)_6Si(OMe)_3$, and $(MeO)_3Si(CH_2)_3(1,4\text{-}C_6H_4)(CH_2)_3Si(OMe)_3$. Structural and mobility investigations of these novel stationary phases were carried out by multinuclear solid-state NMR spectroscopy (^{13}C, ^{29}Si, ^{31}P). Complexes were successfully employed in the hydroformylation of 1-hexene with good turnover numbers. If the reaction was carried out at 60 bar pressure, mobility became less important, and highly cross-linked supports gave better results. This shows that the concept of "chemistry in interphases" works under limited conditions only. No leaching of the transition metal complexes during the reactions was observed by atomic absorption spectroscopy, indicating that the metal-ligand interaction was sufficient for catalyst recycling.

The use of dendrimers as supports to anchor transition metal catalysts has attracted considerable attention over the past decades [48] (see also Chapter 4 of this book). Several groups studied the use of dendrimers immobilised on insoluble supports [49], and this type of material meet the requirements for catalysis in interphases. Alper reported the use of diphosphine functionalised polyamidoamine (PAMAM) dendrimers that were anchored onto a silica support [50] as polydentate ligands in alkene hydroformylation. The dendrimer was actually synthesised on the support, which simplified the synthetic procedures but complicates detailed analysis of the system. The Rh-PPh_2-PAMAM-SiO_2 catalyst was shown to be an active catalyst for the hydroformylation reaction and it was, as expected, more selective towards the branched product. The difference in chain-length (n = 0, 2, 4) (see Figure 3.10) had mainly an impact on the recyclability of the catalyst and it was suggested that this is due to steric congestion of the more compact dendrimers. Indeed, colored product solutions were obtained indicating that slow metal leaching occurred. Additional Soxhlet extraction experiments showed that rhodium leached under catalytic conditions only; both CO and substrate promote metal leaching from the support. Unfortunately, the properties of the supported catalysts have not been compared with the analogous homogeneous compounds.

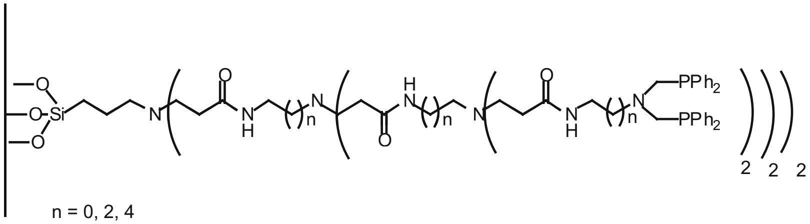
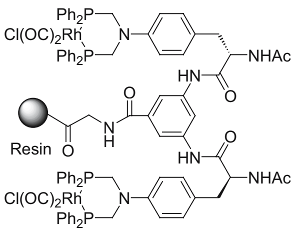


Figure 3.10. Phosphine functionalised PAMAM dendrimers anchored on a silica support

Arya et al. used solid phase synthesis to prepare immobilised dendritic catalysts with the rhodium centre in a shielded environment to mimic nature's approach of protecting active sites in a macromolecular environment (e.g. catalytic sites inside enzymes) [51]. Two generations PS immobilised rhodium-complexed dendrimers, **6** and the more shielded **7**, were synthesised.The PS resin immobilised rhodium-complexed dendrimers were used in the hydroformylation of styrene, p-methoxystyrene, vinyl acetate and vinyl benzoate using a total pressure of 70 bar 1:1 CO/H_2 at 45 °C in CH_2Cl_2.



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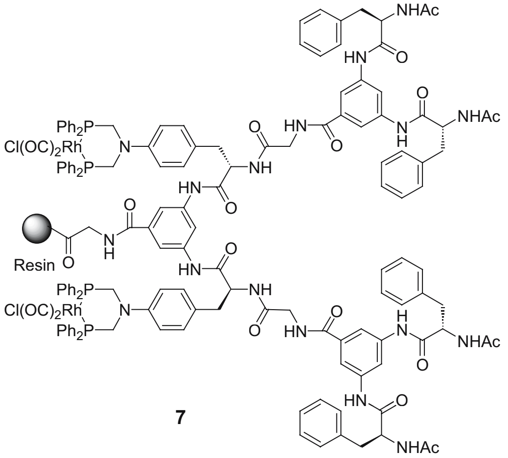

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Using styrene as substrate both **6** and **7** could be recycled four times, apparently without loss in activity or selectivity (>99% conversion after 20 hours; b:l ratio 18 : 1). When p-methoxystyrene was used as a substrate the first three cycles did not suffer from any deactivation (>99% conversion after 20 hours, b:l ratio 17:1). The fourth cycle did not reach full conversion after 20 hours for **6** (56% conversion, b:l ratio = 30:1) nor for **7,** although this more shielded dendritic catalyst did reach a higher conversion (85% conversion, b:l ratio = 30:1). In the hydroformylation of vinyl acetate catalysts **6** and **7** gave similar results. Similar selectivities (b:l 17:1) and slightly declining activities per cycle were observed (99% conversion for the 2nd cycle → 85 % conversion for the 5th cycle). Using vinyl benzoate as substrate the immobilised dendrimers **6** and **7** could be recycled with constant activity and selectivity for three cycles (>99% conversion after 20 hours, b:l 25:1). In the fourth and fifth cycle deactivation of both catalysts was observed. A dramatic drop in activity was found for **6** (4th cycle, conversion 43%; 5th cycle, conversion 20%). A smaller drop in activity was observed for **7**, which was speculated to be due to the larger dendritic environment (4th cycle, conversion 91%; 5th cycle, conversion 83%). Determination of the turn-over numbers of both systems should give a conclusive support for this dendritic effect.

The studies on catalysis in interphases have taught us several lessons. The most important points are that the catalyst must be connected to the insoluble support via a sufficiently long spacer enabling good mixing with the solution that contains the reactants. The spacer should consist of solvophylic material and should not adsorb to the surface. The second point is that the properties of the insoluble support can be fine-tuned by using organic network modifiers. This enables better penetration of the solvents, making the catalyst more accessible to the substrates. These properties can be measured by NMR techniques, but only a limited number of studies have been reported in which these detailed studies have been combined with catalysis. Therefore, it is very hard to judge if examples in the literature meet the requirements for the classification "catalysis in interphase", which makes the border between immobilised catalysts and these systems vague. An important question still to be answered is what the properties of the matrices are with respect to thermal and physical stability. How these materials behave in fixed bed reactors is still a question to be answered.

3.6 Ordered Mesoporous Support

Most examples discussed so far made use of amorphous inorganic supports or sol-gel processed hybrid polymers. Highly disperse materials have recently become accessible via standard processes and, as a result, materials with various controlled particle size, pore diameter are now available. Micelle-templated synthesis of inorganic materials leads to mesoporous materials such as MCM-41, MCM-48, MSU, and these have been extensively used as solid supports for catalysis [52]. Modifications of the polarity of the material can increase the reactivity of the embedded centre, or can decrease its susceptibility to deactivation. In rare cases, enhanced stereo- or even enantioselectivities have resulted from complex immobilisation, via mechanisms related to the "confinement concept" [53]. Accurate control of pore shapes and dimensions is needed to control precisely the environment of the active site, and it is clear that for such aims zeolites and ordered mesoporous molecular sieves offer much better perspectives than relatively disordered, amorphous materials such as silica or alumina. In the case of ordered mesoporous materials, there are several illustrations of the effect of pore diameter on the reactions of embedded complexes [52].

Mesoporous supports have been studied in ligand-free rhodium-catalysed hydroformylation aiming at the stabilisation of specific catalytic species to induce stereochemical control of the regioselectivity. Among the procedures for preparation of Rh-zeolites, dilute aqueous exchange at room temperature with $RhCl_3$ or $[Rh(NH_3)_5Cl]Cl_2$ is most popular [54]. In large-pore zeolites such as Y and mordenite, Rh can be uniformly distributed across the zeolites, while medium pore-size zeolites (ZSM-34 and ZSM-11) show rhodium enrichment at the surface due to hydrolysis. In small pore zeolites (e.g., erionite, zeolite A, ZK-5) surface hydrolysis dominates, and most rhodium is found on the external surface. Depending on the pretreatments of these zeolites, e.g., calcination, autoreduction, reduction at various temperatures, under H_2 or CO, various species can be formed, e.g., lattice-coordinated Rh^{3+}, RhO_2, or Rh_2O_3 particles, metallic Rh^0 clusters, or carbonyl complexes such as $Rh^I(CO)_2$ or $[Rh_6(CO)_{16}]$. These zeolites have been applied for gas and liquid-phase reactions [55]. As an example, gas-phase hydroformylation of 1-hexene was performed with a zeolite CaA synthesised in the presence of Rh. Enhanced selectivity for the linear aldehyde was observed in comparison with an exchanged zeolite, but loss of volatile Rh-carbonyls resulted in a gradually decreasing activity. Liquid phase 1-hexene hydroformylation was investigated with $[Rh(NH_3)_5Cl]^{2+}$ exchanged NaY zeolite after carbonylation treatment. This material contains $[Rh_6(CO)_{16}]$ clusters associated with the zeolite crystals. This catalyst was characterised by a high hydroformylation selectivity and a lack of regioselectivity. This is very similar to the behavior of ligand free rhodium carbonyl complexes, which were indeed present in the reaction mixture. While for Rh^{III}-exchanged NaY and CaA the observed activity is caused by eluted rhodium, experiments with poisons and additives suggested that in materials with NaX zeolites exchanged with $[Rh(NH_3)_5(H_2O)Cl]Cl_2$ the activity was from homogeneous as well as heterogeneous sources. At high reaction temperatures, leaching from the zeolite decreased, possibly because of the formation of larger Rh clusters that are not easily converted into soluble species [56]. Unfortunately, under such conditions, the chemoselectivity is largely in favor of substrate isomerisation, probably catalysed by residual zeolite acidity. We can tentatively conclude that rhodium carbonyls entrapped in zeolites are not an ideal choice for immobilisation since the neutral character of the active species results in severe leaching due to weak binding to the zeolite.

In a recent contribution of Chaudhari et al. several mesoporous and microporous materials were used to encapsulate $[HRh(CO)(PPh_3)_3]$ in the channels of the materials [57]. They functionalised MCM-41and MCM-48 at the inner wall with aminopropyl groups and at the outer wall with diphenylsilane moieties (Figure 3.11). As a reference support MCM-48 with aminopropyl groups at the outside of the material was prepared. The materials obtained were characterised in detail using CP-MAS NMR, FT-IR, TEM, XPS and powder XRD. The catalytic performance was tested in the hydroformylation of styrene, 1-hexene, 1-octene and 1-dodecene. Generally the activity obtained was high, whereas the selectivity was moderate to low. The effect of the location of the catalyst was high: the activity of the MCM-48 material with the catalyst at the outer wall was higher (reported TOF=583 mol(styrene) $mol(cat)^{-1}$ h^{-1}, at full conversion, 100 °C) then that of the encapsulated material (TOF=325 mol(styrene) $mol(cat)^{-1}$ h^{-1}) and the supported catalysts showed similar activity (l:b=0.41). Importantly, the encapsulated catalyst showed significantly less leaching. Typically, the total amount of rhodium leaching after six consecutive cycles was <0.05% for the encapsulated system, whereas the material with the catalyst at the outer wall showed around 6% leaching. In addition, the selectivity and the activity were retained indicating that the encapsulated catalyst was also stable.

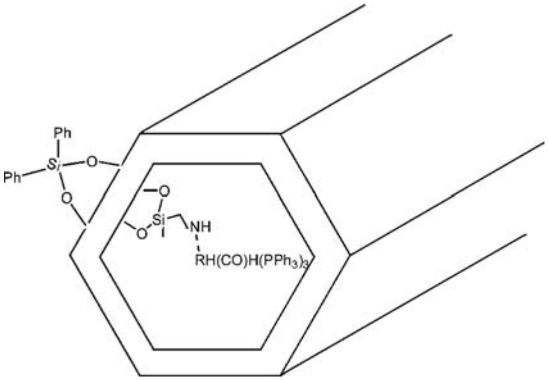


Figure 3.11. Schematic representation of MCM materials functionalised at the outside with diphenylsilane and with the rhodium catalyst encapsulated at the inside of the pores

TABLE 3.6. Comparison of the activity and selectivity in the hydroformylation of linear alkenes using homogeneous [$HRh(CO)(PPh_3)_3$] and [$HRh(CO)(PPh_3)_3$] encapsulated in MCM-48 [a]

Catalyst	Substrate	Substrate concentr. [b]	selectivity aldehyde (%)	Aver. TOF[c]	l:b ratio	1-Octene conv. (%)
[$HRh(CO)(PPh_3)_3$]	1-hexene	3.20	98.8	2467	2.6	98.8
Rh-MCM-48	1-hexene	0.64	99.5	338	2.3	100
[$HRh(CO)(PPh_3)_3$]	1-octene	2.55	98.2	1391	2.4	98.8
Rh-MCM-48	1-octene	0.51	99.4	270	1.7	100
[$HRh(CO)(PPh_3)_3$]	1-decene	2.11	92.2	961	1.4	98.2
Rh-MCM-48	1-decene	0.42	99.2	109	1.5	99
[$HRh(CO)(PPh_3)_3$]	1-dodecene	1.80	89.1	630	0.8	97.4
Rh-MCM-48	1-dodecene	0.36	98.6	88	1.0	99

[a] Reaction conditions: catalysts, 0.96 g/L [$HRh(CO)(PPh_3)_3$] or 8 g/L Rh-MCM-48 (containing 0.69 wt/wt % Rh); P_{CO}, P_{H2} = 2.04 MPa; T=100°C; Toluene. [b] mol/L [c] Average turnover frequencies were calculated as (mol alkene/mol catalyst)$^{-1}$/h^{-1}.

The activity of the encapsulated catalyst was also compared to that of the homogeneous analogue (Table 3.6). Although it is hard to compare the difference in activity because the reactions were performed at different substrate concentrations and the TOF was determined at too high conversions, it seems that the activity of the MCM-48 encapsulated catalyst is lower then the homogeneous analogue. It is noteworthy that the selectivity of the encapsulated catalyst is different from that of its homogeneous counterpart. For 1-hexene the l:b is lower whereas that for 1-dodecene is higher, which was attributed by the authors to the geometric constraints of the substrates accessing the complex inside the support.

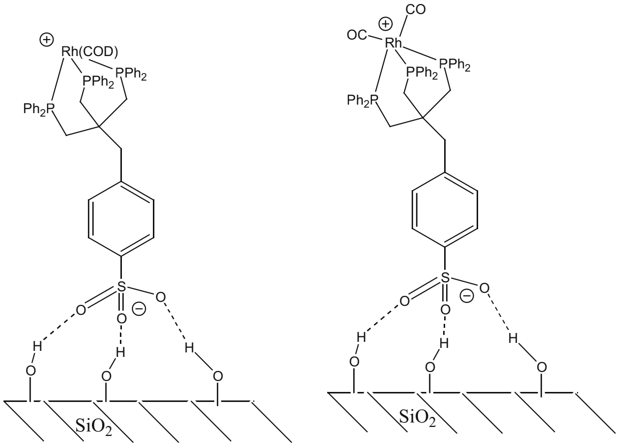
3.7 Non-covalently Supported Catalysts

One of the only examples of a commercial process using immobilised homogeneous catalysts comprises an anionic rhodium complex [$RhI_2(CO)_2$]$^-$ that is bound via ionic interactions to an ion exchange resin [3] and is used for the carbonylation of methanol.

The metal leached from the support is re-adsorbed to a guard bed of ion exchange material. This shows that the concept of noncovalent anchoring is very attractive, especially if the homogeneous catalyst needs no further modification.

Augustine et al. reported a similar approach in which cationic rhodium complexes were immobilised on support via ionic interactions [58]. Heteropoly acids such as phosphotungstic acid (PTA) appeared to be very suitable materials for this purpose, but alumina was also demonstrated to work well. Upon mixing a cationic rhodium complex such as [Rh(dipamp)(COD)]BF_4 with the PTA material, a supported chiral rhodium catalyst was obtained that was active in the asymmetric hydrogenation of methyl 2-acetamidoacrylate. Interestingly, the activity and ee were higher (after the first run) than that of the homogeneous parent complex. The degree to which the nature of the HPA influences the performance of the reaction suggests that a direct interaction between the HPA and the metal is responsible for the increased performance of the catalyst upon immobilisation [59]. The catalyst was recycled 15 times without loss in performance. Analysis of the product mixtures revealed that no rhodium leached from the support (detection limit 1 ppm). The major advantage of this approach is its generality and several pre-formed rhodium catalysts were immobilised in a similar manner. The strategy is limited to ionic catalysts and it can therefore not be used to immobilise neutral hydroformylation catalysts.

Bianchini reported a fascinating strategy, denoted as supported hydrogen-bonded catalysts (SHB-catalysts), in which the immobilisation procedure involved the grafting of tailor-made catalysts equipped with a sulfonate tail on high surface area silica (Figure 3.12) [60]. The interaction between the catalyst and the support is based on hydrogen bonds between the silanols of the surface and the oxygens of the sulfonate group of the ligand. The existence of these interactions was supported by IR, EXAFS and CP MAS ^{31}P NMR studies.



8a **8b**

Figure 3.12 .Silica grafted catalysts for hydroformylation and hydrogenation, the immobilisation is based on hydrogen bonding between the surface and the sulfonate group (supported hydrogen-bonded (SHB) catalysts)

The grafting procedure is straightforward, which is a major advantage of this method. The silica was pretreated to remove water from the support, after which it was added to a dichloromethane solution containing the catalyst. After 6 hours of mixing the supported catalyst was isolated by filtration. The remaining solvent was colourless while the supported had turned yellow. Catalyst **8a** was a good catalyst for the hydrogenation of styrene, 100 % conversion was reached after 3 hours using 1 mol % of catalyst, 120 °C and 30 bar of molecular hydrogen. Catalyst **8a** was also active in the hydroformylation of 1-hexene. Using 1 mol% of catalyst at 120 °C and 30 bar of syngas the substrate was completely converted in three hours. The branched aldehyde was the main product (l:b=0.8, 41 % branched) and also some 2-ethylpentanal (15 %) and hydrogenated product (4 %) were formed. No rhodium was detected in the product phase by atomic absorption analysis, and the recycled catalyst was reused for both hydrogenation and hydroformylation giving identical results as the first runs. The results obtained with the supported catalysts **8** were different from those obtained in the homogeneous phase and in two-phase processes. In THF these catalysts were less chemoselective, hydrogenation being the side reaction, and showed a lower activity. The transformation of the mononuclear rhodium complex into binuclear species was proposed to be responsible for the lower activity in the homogeneous phase, and the better performance of the SHB catalysts was ascribed to the site isolation of the active sites preventing the formation of such dimers. Attempts to use these catalysts in solid-gas hydroformylation reactions failed, whereas solid-gas hydrogenation of ethene was successful. One of the additional advantages of this approach is that the catalyst can be removed from the support by washing with methanol, which enables detailed analysis of the complex after the reaction.

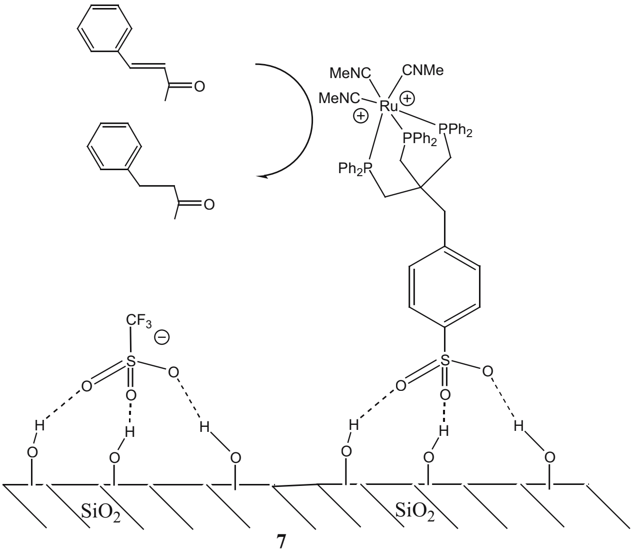


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Figure 3.13. Silica grafted ruthenium catalysts with the counterion also immobilised via hydrogen bonds

In subsequent work the approach was extended to dicationic ruthenium complexes that were active in hydrogenation [61]. The complex is now no longer zwitterionic and the counterion is also bound to the support via hydrogen bonds (Figure 3.13) and therefore the metal complex should be more strongly bound to the support. The hydrogenation of trans-4-phenyl-3-buten-2-one (benzylideneacetone) was more chemoselective with the supported catalyst than the homogeneous parent catalyst, at the expense of activity (factor 14). The supported catalyst yielded mainly benzylacetone as the product, whereas the homogeneous catalyst gave 100 % of the saturated alcohol. The work has been extended to asymmetric hydrogenations, but in at least half of the examples the enantioselectivity was lower than that of the homogeneous analogue [62].

Figure 3.13 already suggests that the use of sulfonated ligands is not required for this approach. Indeed Rege et al. showed that chiral cationic rhodium complexes can be immobilised on silica by using triflate as counterion that forms hydrogen bonds with the support [63]. In fact, this strategy is a hybrid between the two previously described approaches. By stirring a dichloromethane solution containing [(R,R)-Me-(DuPHOS)Rh(COD)]OTf in the presence of MCM-41 the catalyst was immobilised. Powder X-ray diffraction revealed that the MCM-41 structure remained unchanged, whereas elemental analysis showed that the material contained 1 % (wt) rhodium, consistent with the theoretical amount. The BET surface area decreased from 953 m^2g^{-1} to 854 m^2g^{-1}. Interestingly, the mesopore volume decreased indicating that the catalyst was in the pores of the material. The performance of the immobilised catalyst equalled that of the homogeneous analogue and in some examples the selectivity and activity was even better. The catalyst was recycled with retention of catalyst performance. No active catalyst leached from the support, and the catalyst was shown to be stable for 16 h under hydrogen-free conditions.

3.8 Supported Aqueous Phase Catalysis

Davis and Hanson developed a new concept of immobilising homogeneous catalysts, denoted as supported aqueous phase catalysts (SAPC) [64]. They reasoned that in aqueous biphasic catalysis the reaction mainly takes place at the interface. In order to increase this interface they used a high-surface-area hydrophilic support (Figure 3.14). These materials have a thin film of water adhered to the surface, in which the water-soluble catalyst is dissolved. The substrate and the product are in an organic solvent such as toluene, and reaction takes place at the water-organic interface. The supported catalyst has a very large interfacial area, which results in very efficient catalysis for organic substrates. Furthermore, the catalyst stays completely on the support.

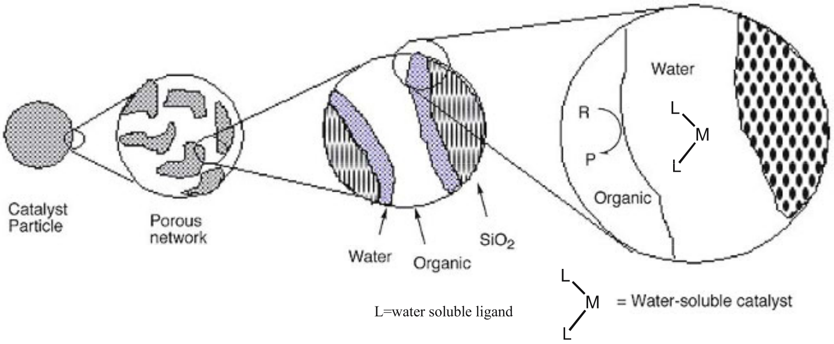


Figure 3.14. Schematic representation of the concept of supported aqueous phase catalysis

The important issues are the generality of the concept, the robustness of the catalyst system and the influence of the thickness of the water layer [65]. This water layer has an enormous impact on the catalytic activity (Figure 3.15). It was observed that if the layer is too thin the activity of the catalyst is much lower due to a decrease of the catalyst mobility. The catalyst is bound to the silica resulting in a heterogeneous system. This was verified by ^{31}P NMR spin relaxation measurements, which show that the spin relaxation declines with increasing water content [66]. It was observed in the hydroformylation of 1-heptene using a [HRh(CO)(TPPTS)$_3$-SAPC] that the TOF increases by a factor as high as 100 when going from 2.9 to 9 wt. % water (Table 3.7). If higher water contents were adhered to the support the water layer became too thick and the substrate had to diffuse into the water layer, or the catalyst had to diffuse to the interface. The result is a decrease in catalyst-product contact time leading to lower activities. This sensitivity towards water is a drawback of this otherwise attractive concept, since it requires an additional parameter to be controlled.

TABLE 3.7. Hydroformylation performance of SAPC compared with homogeneous and biphasic systems

Catalyst system	Substrate	T (°C)	TOF (mol mol^{-1} h^{-1})
SAPC (2.9 wt.% H_2O)[a]	1-heptene	75	0.75
SAPC (9 wt.% H_2O)[a]	1-heptene	75	72
Homogeneous[b]	1-heptene	75	288
SAPC[c]	Mixture[h]	100	432[e]/432[f]/396[g]
Homogeneous[d]	Mixture[h]	100	1656[e]/1800[f]/1800[g]
Biphasic[c]	Mixture[h]	125	17[e]/5[f]/1[g]

[a] [HRhCO(TPPTS)$_3$], P=7 bar (H_2/CO=1:1) [16d]. [b] [HRhCO(PPh$_3$)$_3$] in toluene, P=7 bar (H_2/CO=1:1) [16b]. [c] [HRhCO(TPPTS)$_3$], P=51 bar (H_2/CO=1:1) [18]. [d] [HRhCO(PPh$_3$)$_3$] in hexane, P= 51 bar (H_2/CO=1:1) [18]. [h] The substrate was a 1:1:1 mixture of 1-hexene, 1-octene and 1-decene. [e] Heptanals. [f] Nonanals. [g] Undecanals.

Horváth performed experiments using substrates with different solubilities in water and showed that, under optimal conditions, this solubility did not influence the activity [67]. These experiments clearly support the fact that the reaction takes place at the organic-water interphase. Furthermore, he performed a hydroformylation reaction in a continuous system and even under reaction conditions no leaching of rhodium complex was detected. Water obviously leaches if the SAPC is used in a continuous flow system, which in a practical application should be compensated for by using water-saturated organic solvents.

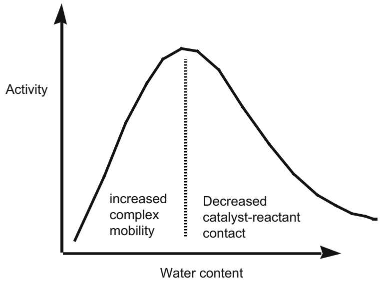
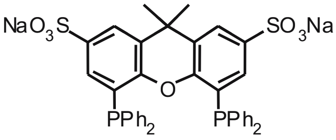


Figure 3.15. The influence of the water contents of the hydrophilic support on the relative catalytic activity

A water-soluble chelating diphosphine ligand (**9**) based on the xanthene backbone was also studied as supported aqueous phase catalysts. It was shown that this ligand performed well as SAPC since it is much more selective than other SAPC systems reported in literature [68]. Recycling experiments showed that these catalysts retained their activity and selectivity for at least ten consecutive runs, whereas under similar conditions the TPPTS based catalyst showed a reduced performance in the fourth run.

This shows that the strong chelating effect of the bidentate ligand efficiently retains the metal attached to the support.



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Mortreux and co-workers compared the activity of the SAPC catalysts with that of the homogeneous analogue in the hydroformylation of methyl acrylate [69]. They observed an activity for the SAPC that was strongly dependent on the amount of water present in the system. More remarkably, the optimised activity of the SAPC was higher than that of the homogeneous systems. This effect was ascribed to the polar interactions between the substrate and the silica support. This effect was not observed for nonpolar substrates such as propene, which supported the hypothesis.

In order to show the versatility of the method Davis extended the concept to other hydrophilic liquids such as ethylene glycol and glycerol [70]. The reactions then take place at the hydrophilic-hydrophobic liquid interface. In this specific example the supported-phase concept was used for asymmetric reduction using a ruthenium catalyst.

3.9 Process Design [71]

A process for the hydroformylation of 1-octene to nonanal was designed for an immobilised homogeneous catalyst. The production capacity was fixed at 100 kton of nonanal. Kinetic data reported for the rhodium catalyst complex of N-(3-trimethoxysilane-n-propyl)-4,5-bis(diphenylphosphino)-phenoxazine immobilised on silica, (**2**) was used as a starting point. Other process specifications are given in Table 3.8.

TABLE 3.8. Process and reactor specifications for hydroformylation of 1-octene

Operating pressure (bar)	50
Operating temperature (ºC)	80
Syngas / 1- octene ratio	10:1
Catalyst: Rh complex with **2** immobilised on silica	0.1 wt%
1-octene conversion per pass	70%
Selectivity toward n-nonanal	93%
by-products: iso-nonanal / 1-nonanol	4% / 3%

A systematic process design procedure going through the levels of black box, conceptual design, and index flow sheet design, resulted finally in the process flow sheet (PFD) shown in Figure 3.16, which was simulated in Aspen Plus. In this process pure 1-octene (#1) is mixed with a recycle stream of 1-octene (#31), pressurized to 50 bar in pump P-101 and heated to 80 ºC in E-102 before it enters reactor R-101. Pure syngas (CO: H_2= 1:1) is mixed with a recycle stream of syngas (#21), pressurised in compressor C-101 to 50 bar, mixed with syngas recycle stream (#14) and heated in E-

101 to 80 ºC before entering the reactor R-101. In reactor R-101 the hydroformylation reaction of 1-octene with syngas to form nonanal takes place (for details see Table 3.8). The reactor consists of a packed bed in which large amounts of syngas is contacted with the liquid 1-octene. It is assumed that the operationing conditions are such that the reaction is kinetically controlled. The proposed first order kinetics in 1-octene favour the plug flow character for the reactor. Since the reaction is also highly exothermic the reactor needs to be effectively cooled to keep the reaction temperature at 80 ºC. Combined this leads to a co-current trickle flow reactor column with in-situ cooling. The reaction product stream (#10) is cooled in E-103 to 40 ºC and is fed to a gas-liquid separator V-103. The gas stream (#12) containing mainly CO, H_2 and a minor amount of 1-octene is recycled after purging 0.01% (#13) and recompressing in C-102. The liquid stream (#15) is expanded to 3 bar, heated in E-104 to 60 ºC before separating the gas from the liquid in V-104. The gas stream (#19) is recycled after purging a small part of the stream. The liquid product stream (#22) is depressurised to 1 bar, heated in E-106 to 100 ºC and separated in distillation columns T-101 and T-102. Column T-101 removes the compounds like 1-octene and minor amounts of CO and H_2 which are lighter than nonanal. These lights (#25) are cooled in E-106 to 25 ºC, the 1-octene condenses and is separated from the gas stream in gas-liquid separator V-105. The gas stream (#27) is purged. The liquid stream (#29) with 98%+ 1-octene is recycled after purging 0.01% and is mixed with fresh 1-octene. Finally, Column T-102 separates the product, the nonanal mixture (#33, 95%+ nonanal, 4% 2-Me octanal) from the rest which is mainly 1-nonanol. At this stage nonanal and 2-Me octanal are not separated but sold as a mixture. The bottom stream of column T-102 contains nonanol, heavies and Rh leached from the reactor. This stream should be treated to recover the lost rhodium. Details of the different process units are shown in Table 3.9.

TABLE 3.9. Specifications of different units in the 1-octene hydroformylation process as shown in Figure 3.16.

Heat exchangers	**E-101**	**E-102**	**E-103**	**E-104**	**E-105**	**E-106**
Duty (kW)	809	458	-1280	215	455	-669
U (W/m^2,C)	165	600	625	600	600	600
A (m^2)	108	12	93	6	21	59
Heat exchangers	**E-107**	**E-108**	**E-109**	**E-110**		
Duty (kW)	-230	1590	-2190	3290		
U (W/m^2,C)	600	600	600	600		
A (m^2)	4	27	36	55		
Flash Drum	**V-103**	**V-104**	**V-105**			
orientation	Vert.	Horz.	Horz.			
Diameter (m)	1.0	0.3	0.25			
Height (m)	4.6	1.2	1.2			
Compressor	**C-101**	**C-102**	**C-103**	**Pump**		**P-101**
P at inlet (bar)	3	45		P at inlet (bar)		1
P at outlet (bar)	50	50		P outlet (bar)		50
Flow (m3/hr at P_{inlet})	1640	1430		Flow (m3/hr)		21
Power (kW)	630	270		Power (kW)		54
Efficiency	72%	72%		Efficiency		52 %
Distillation columns	**T-101**	**T-102**	**Reactor**			**R-101**
Reflux ratio R	0.5	2	Type: Gas Liquid Solid Reactor			
Number of trays	13	46	Pressure (bar)			50
Condensor duty (MW)	-0.23	-2.2	Temperature (C)			80
Reboiler duty (MW)	1.6	3.3	Catalyst volume (m^3)			70*
Diameter (m)	0.83	1.42	Amount of Rh (kg)			70
Height (m)	7.5	24	Duty (MW)			-3.6

* The catalyst volume can be significantly reduced by increasing the Rh concentration on the catalyst. In case of 0.4 wt % Rh the catalyst volume will be 18 m^3.

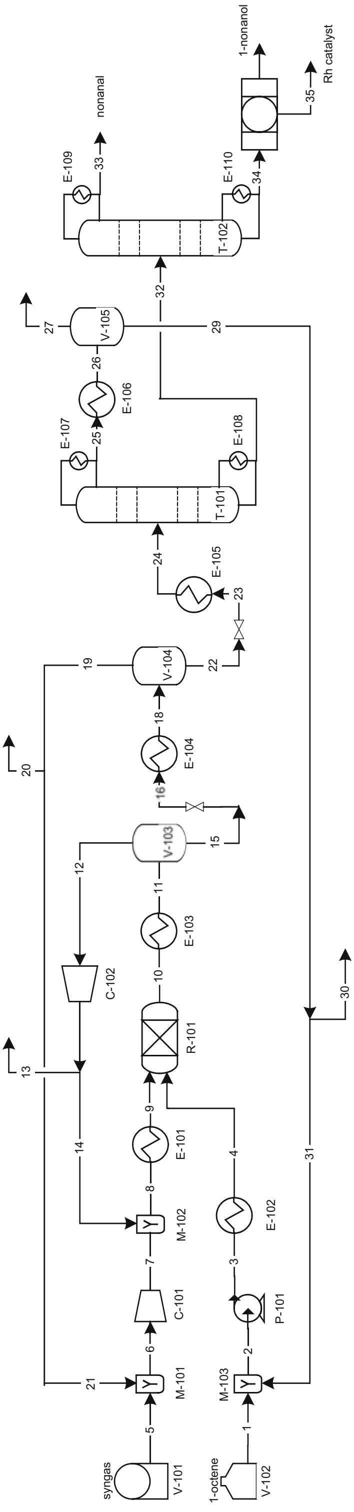

Figure 3.16. Process flow sheet of hydroformylation process of 1-octene to 1-nonanal

For the supported catalyst it is expected that the ligand does not leach since it is chemically bonded to the carrier. In contrast, the rhodium metal bound to the ligand is subject to leaching due to the reversible nature of the complex formation. The amount will depend on the equilibrium between rhodium dissolved in the organic phase and that bound to the ligand. When an equilibrium concentration of 10 ppb Rh is attained, the yearly loss of Rh for a 100 kton production plant will be about 1 kg Rh per year. Compared to the reactor contents of rhodium (see Table 3.9, 70 kg Rh) this would result in a loss of 1.5% of the inventory per year, which would be acceptable.

3.10 Concluding Remarks

The immobilisation of a catalyst on a support is a suitable solution for the separation problem and solutions exist nowadays for most of the problems that prevent the step to commercialisation. Metal leaching from the support has been the major problem for a long time. From the examples given in this chapter it is clear that bidentate ligands are required to retain the metal on the support, and also the use of an excess ligand compared to metal does suppress metal leaching. Most experiments were run as batch reactions, and these are not necessarily representative of continuous processes. Leaching for several cases was below the detection limit, which is roughly 0.1-1 ppm of rhodium in the liquid product. As indicated, for an industrial application for low-value products, this number should perhaps be two orders of magnitude lower and more accurate measurements are required to show that metal leaching is even as low as 1-10 ppb. For high-value products ppm levels of metal losses are economically acceptable, but health, safety and environmental issues should also be taken into consideration. With respect to catalyst anchoring one can conclude that catalysts for hydroformylation cannot be immobilised via ionic interactions between the metal and the support since the active species comprises a neutral species. For cationic (rhodium) catalysts such as those for hydrogenation, this is a proper strategy which is very easy to apply.

With respect to the selectivity of immobilised catalysts one can conclude that the selectivity is generally dominated by the ligand coordination, which remains identical to the homogeneous analogue if chelating bidentate ligands are used. This is clearly demonstrated by the Xantphos type ligands and the BINAPHOS ligands. Upon using monodentate ligands, there is a risk of obtaining monophosphine coordinated species since site-isolation of the ligands can prevent biscoordination. The acidity of the silica can change the chemoselectivity of the reactions as was observed for immobilised Xantphos-rhodium hydroformylation catalyst. Detailed analysis showed that cationic rhodium complexes were responsible for the effect and the formation of these species was suppressed by the addition of alcohol (or triethyl amine) to the liquid phase. Immobilisation of catalysts generally results in a lower activity. This effect can be minimised in several ways.

The lesson learned from the "catalysis in interphase" approach is that the spacer between the insoluble support and the actual catalyst should be sufficiently long and soluble in the solvent of interest to obtain active catalysts. The use of supercritical fluids can also be very beneficial for the activity. Upon using Xantphos immobilised on silica in scCO2 for example, the rates are only half of those of the homogeneous catalyst. Expressed as space-time yields the solid catalysts are almost an order of magnitude faster, admittedly neither of them has been optimised. Thus, there is clearly a benefit in the supercritical system, which has to be weighed against the extra costs of the high pressures involved. The $scCO_2$ runs, however, were continuous runs and the losses over longer periods were below 0.2 %, which was again the detection limit and the actual result may be better than this. Another interesting feature that has so far received little attention is the fast heat transfer in $scCO_2$, in addition to the fast mass transfer. The hydroformylation reaction is highly exothermic and when the rates start approaching those of the homogeneous systems this certainly becomes a limiting factor for heterogeneous hydroformylation catalysts. For lower alkenes the starting alkenes could form the supercritical phase as well, thus reducing the extra costs involved in the high pressures.

For several silica-supported catalysts in condensed phase, including the SAPC system, the rates are disappointing. This can be assigned to slow mass transfer, and perhaps to incomplete rhodium hydride formation as we have discussed and observed. The sol-gel catalyst is relatively fast and is sometimes only a few times slower than the homogeneous one. Since only limited ways of preparation were tested, there is probably more scope for sol-gel catalysts. Space-time yields are promising at the present state of affairs.

The limited mechanical strength and the swelling properties of the support are not necessarily a problem. Silica and alumina have proven their value as supports in various reactor set-ups. The example given by Nozaki clearly shows that polystyrene can also be used in well designed reactors. Considering the recent progress in the field we are confident that the problems related to immobilised catalysts no longer present limitations that prevent commercialisation of processes using these materials.

3.11 References

[1] (a) W.O. Haag, and D. D. Whitehurst, *German Patent* 1969, 1.800.371 and 1.800.379 and 1.800.380. (b) W.O. Haag, and D. D. Whitehurst, *Belgian Patent* 1969, 721.686.

[2] (a) F.R. Hartley, P.N. Vezey, *Adv. Organomet. Chem.,* 1977, **15** 189. (b) F.R. Hartley, 'Supported Metal Complexes. A New Generation of Catalysts,' Reidel, Dordrecht, 1985. (c) Y. Iwasawa, 'Tailored Metal Catalysts (Ed. R. Ugo, B.R. James,)', Reidel, Dordrecht, 1986. (d) W. Keim, B. Driessen-Hölscher, in 'Handbook of heterogeneous catalysis,' vol 1 G. Ertl, H. Knözinger, J. Weitkamp (Ed.), Wiley-VCH, Weinhein, 1997, p. 231. (e) R. H. Grubbs, *CHEMTECH*, 1977, 512. (f) C. C. Leznoff, *Chem. Soc. Rev.* 1974, **3**, 65.

[3] H. Sugiyama, F. Uemura, N. Yoneda, T. Minami, T. Maejima, K. Hamato, *Japan patent*, 235250 1997.

[4] (a) R. Thomas, *J. Soc. of Chem. Ind.,* 1923, 42. (b) Th. Sabalitschka, W. Moses, *Ber.*, 1927, **60B** 786.

[5] R. B. Merrifield, *Science,* 1965, **150**, 178.

[6] (a) N. Takahashi, I. Okura, T. Keij, *J. Am. Chem. Soc.* 1975, **97,** 7489 (b) G.J.K. Acres, G.C. Bond, B.J. Cooper, J.A. Dawson *J. Catal.* 1966, **6**, 139. (c) P.R. Rony *Chem. Eng. Sci.* 1968, **23**, 1021. (d) K.K. Robinson, F.E. Paulik, A, Hershman, J.F. Roth *J. Catal.* 1969, **15**, 245. (d) L.A. Gerritsen, J.M. Herman, J.J.F. Scholten *J. Mol Catal.* 1980, **9**, 241. (e) Th. G. Spek, J.J.F. Scholten *J. Mol. Catal.* 1977, **3**, 81. (f) J. Hjortkjear, M.S. Scurrell, P. Simonsen *J. Mol. Catal.* 1979, **6**, 405.

[7] E. Bayer, M. Mutter, *Nature,* 1972, **237**, 512.

[8] (a) U. Deschler, P. Kleinschmit, P. Panster, *Angew. Chem. Int. Ed. Engl.* 1986, **25**, 236. (b) S. Wieland, P. Panster *Cat. Org. React.* 1994, **62**, 383.

[9] (a) D. J. Cole-Hamilton, *Science,* 2003, **299**, 1702. (b) Thematic issue *Chem. Rev.* 2002, **102**, vol 10 (c) Y.R. de Miguel, E. Brulé, R. G. Margue, J. *Chem. Soc., Perkin Trans. 1,* 2001, 3085. (d) S. V. Ley, I. R. Baxendale, R. N. Bream, P. S. Jackson, A. G. Leach, D. A. Longbottom, M. Nesi, J. S. Scott, R. I. Storer and S. J. Taylor, *J. Chem. Soc., Perkin Trans. 1*, 2000, 3815. (e) R. T. Baker, W. Tumas, *Science,* 1999, **284**, 1477. (f) S. Kobayashi, R. Akiyama, *Chem Commun,* 2003, 449. (g) *J. Mol Catal A*. 2001, **177**, thematic issue.

[10] (a) B. Corain, M. Zecca, Jeřabek, *J. Mol Catal. A.* 2001, **177**, 3. (b) U. Kunz, C. Altwicker, U. Limbeck, U. Hoffmann, *J. Mol Catal. A.* 2001, **177**, 21.

[11] (a) S. Bräse, F. lauterwasser, R. E. Ziegert, *Adv. Synth. Catal.* 2003, **345**, 869. (b) Q-H. Fan, Y.-M. Li, A. S. C. Chan, *Chem. Rev.* 2002, **102**, 3385.

[12] Z.-L. Lu, E. Lindner, H. A. Mayer, *Chem. Rev.* 2002, **102**, 3543.

[13] (a) C. A. Mcnamara, M. J. Dixon, M. Bradley, *Chem. Rev.* 2002, **102**, 3275. (b) N. E. Leadbeater, M. Marco, *Chem. Rev.* 2002, **102**, 3217.

[14] (a) R. H. Grubbs, L. C. Kroll, *J. Am. Chem. Soc.* 1971, **93,** 3062. (b) R. H. Grubbs, S.-C. H. Su, *J. Organom. Chem.* 1976, **122**, 151 (c) R. H. Grubbs, E. W. Sweet, *J. Mol Catal.* 1977, **3**, 259.

[15] C. U. Pittman Jr., R. M. Hanes, *J. Am. Chem. Soc.* 1975, **98,** 5402.

[16] (a) F. R. Hartley, S. G. Murray, P. N. Nicholson, *J. Mol Catal.* 1982, **16**, 363. (b)

[17] C. U. Pittman Jr., A. Hirao, *J. Org. Chem.* 1978, **43,** 640.

[18] P.W.N.M. van Leeuwen, P.C.J. Kamer, J.N.H. Reek, and P. Dierkes, *Chem. Rev.* 2000, **100**, 2741.

[19] (a) K. Nozaki, Y. Itoi, F. Shibahara, E. Shirakawa, T. Ohta, H. Takaya, T. Hiyama, *J. Am. Chem. Soc.* 1998, **120**, 4051. (b) K. Nozaki, F. Shibahara, Y. Itoi, E. Shirakawa, T. Ohta, H. Takaya, T. Hiyama, *Bull. Chem. Soc. Jpn.* 1999, **72**, 1911.

[20] F. Shibahara, K. Nozaki, T. Hiyama, *J. Am. Chem. Soc.* 2003, **125**, 8555.

[21] (a) K. G. Allum, R. D. Hancock, I. V. Howell, S. Mckenzie, R. C. Pitkethly, P. J. Robinson, *J. Organomet. Chem.* 1975, **87**, 203. (b)) K. G. Allum, R. D. Hancock, I. V. Howell, T.E. Lester, S. Mckenzie, R. C. Pitkethly, P. J. Robinson, *J. Catal.* 1976, **43**, 331. (c) J. P. Collman, J. A. Belmont, J. I. Brauman, *J. Am. Chem. Soc.* 1983, **105**, 7288.

[22] M.O. Farrell, C.H. van Dyke, L.J. Boucher, S.J. Metlin, *J. Organomet. Chem.* 1979, **172**, 367.

[23] U. Deschler, P. Kleinschmit, P. Panster, *Angew. Chem. Int. Ed. Engl.* 1986, **25**, 236.

[24] (a) J. Blum, D. Avnir, H. Schumann, H. *CHEMTECH* 1999, **32**. (b) U. Schubert, *New J. Chem*. 1994, **18**, 1049. (c) J. Blum, A. Rosenfeld, N. Polak, O. Israelson, H. Schumann, D. Avnir, *J. Mol. Catal. A,* 1996, **107**, 217. (d) E. Lindner, M. Kemmler, H.A. Mayer, P. Weger, *J. Am. Chem. Soc.* 1994, **116**, 348. (e) C.M. Ingersoll, F.V. Bright *CHEMTECH* 1997, 26.

[25] S. Wieland, P. Panster *Cat. Org. React.* 1994, **62**, 383.

[26] R. H. Grubbs, C. Gibbons, L. C. Kroll, W. D. Bonds, Jr., C. H. Brubaker, Jr., *J. Am. Chem. Soc.* 1973, **95**, 2373.

[27] A.J. Sandee, L.A. van der Veen, J.N.H. Reek, P.C.J. Kamer, M. Lutz, A.L. Spek, P.W.N.M. van Leeuwen, *Angew. Chem. Int. Ed. Engl*. 1999, **38** 3231.

[28] A.J. Sandee, J.N.H. Reek, P.C.J. Kamer, P.W.N.M. van Leeuwen, *J. Am. Chem. Soc.* 2001, **123**, 8468.

[29] L. Bemi, J.A. Davies, C.A. Fyfe, R.E. Wasylishen, *J. Am. Chem. Soc.* 1982, **104**, 438. (b) J.-Z. Yao, Y.-Y. Chen, B.-S. Tian, J. *Organomet. Chem.* 1997, **534**, 51.

[30] P.W.N.M. van Leeuwen, C. Claver (Ed.) Rhodium Catalyzed Hydroformylation, Kluwer Acedemic Publishers, Dordrecht, 2000.

[31] K. Kaneda, T. Imanaka, S. Teranishi, *Chem. Lett.* 1983, 1465. (b) J.-A. Anderson, A.W.S. Currie, *Chem. Commun.* 1996, 1543.

[32] The presence of triethylamine also reduced the reaction rate.

[33] R.J. Farrauto, R.M. Heck, *Kinetics and Catalysis* 1998, **39**, 594.

[34] A. Cybulski, J.A. Moulijn, Structured catalysts and reactors (1998) New York: Marcel Dekker.

[35] H.A. Smits, A. Stankiewicz, W.Ch. Glasz, T.H.A. Fogl, J.A. Moulijn, *Chem. Eng. Sci.* 1996, **51**, 3019.

[36] R.K. Edvinsson, M.J.J. Houterman, T. Vergunst, E. Grolman, J.A. Moulijn, *AlChe Journal* 1998, **44**, 2459.

[37] A.J. Sandee, R.S. Ubale, M. Makkee, J.N.H. Reek, P.C.J. Kamer, J.A. Moulijn, P.W.N.M. van Leeuwen, *Adv. Synth. Catal.* 2001, **343**, 201.

[38] (a) R. Noyori, *Chem. Rev.* 1999, **99**, 475. (b) J.A. Darr and M. Poliakoff, *Chem. Rev.* 1999, **99**, 45. (c) B.M. Bhanage, Y. Ikushima and M. Shirai, *Chem. Commun*. 1999, 1277. (d) A. Baiker, *Chem. Rev.* 1999, **99**, 453.

[39] (a) M. G. Hitzler and M. Poliakoff, *Chem. Commun*. 1997, 1667. (b) M.G. Hitzler, F.R. Smail, S.K. Ross and M. Poliakoff, *Org. Proc. Res. Dev. 2* 1998, 137. (c) M.G. Hitzler, F.R. Smail, S.K. Ross and M. Poliakoff, *Chem. Commun*. 1998, 359. (d) W.K. Gray, F.R. Smail, M.G. Hitzler, S.K. Ross and M. Poliakoff, *J. Am. Chem. Soc.* 1999, **121**, 10711.

[40] N.J. Meehan, A.J. Sandee, N.J.H. Reek, P.C.J. Kamer, P.W.N.M. van Leeuwen, M. Poliakoff, *Chem. Commun.* 2000, 1497.

*[*41] (a) J. A. Marqusee, K. A. Dill, *J. Chem. Phys.* 1986, **85**, 434. (b) J. G. Dorsey, K. A. Dill, *Chem. Rev.* 1989, **89**, 331.]

[42] E. Lindner, M. Kemmler, T. Schneller, H. A. Mayer, *Inorg. Chem.* 1995, **34**, 5489.

[43] E. Lindner, T. Schneller, F. Auer, H. Mayer, *Angew. Chem. Int. Ed.* 1999, **38**, 2154.

[44] (a) T. Jongsma, M. Fossen, G. Challa, P.W.N.M. van Leeuwen*, J. Mol. Catal*. 1993, **83**, 17. (b) T. Jongsma, H. van Aert, M. Fossen, G. Challa, P.W.N.M. van Leeuwen*, J. Mol. Catal*. 1993, **83**, 37.

[45] (a) E. Lindner, A. Bader, H. A. Mayer, *Inorg. Chem.* 1991, **30**, 3783. (b) E. Lindner, A. Jager, T. Schneller, H. A. Mayer, *Chem. Mater.* 1997, **9**, 81. (c) E. Lindner, F. Auer, A. Baumann, P. Wegner, H. A. Mayer, H. Bertagnolli, U. Reinohl, T. S. Ertel, A. Weber, *J. Mol. Catal*. 2000, **157**, 97. (d) E. Lindner, S. Brugger, S. Steinbrecher, E. Plies, M. Seiler, H. Bertagnolli, P. Wegner, H. A. Mayer, *Inorg. Chim Acta.* 2002, **327**, 54.

[46] E. Lindner, M. Kemmler, H. A. Mayer, P. Wegner, *J. Am. Chem. Soc.* 1994, **116**, 348.

[47] E. Lindner, T. Salesch, S. Brugger, F. Hoehn, P. Wegner, H. A. Mayer, *J. Organomet. Chem.* 2002, **157**, 97.

[48 (a) Oosterom, G. E.; Reek, J. N. H.; Kamer, P. C. J.; van Leeuwen, P. W. N. M. *Angew. Chem. Int. Ed.* 2000, **40**, 1828. (b) R. Kreiter, A. W. Kleij, R. J. M. Klein Gebbink, G. van Koten, in "Dendrimers IV: Metal Coordination, Self-Assembly, Catalysis"; F. Vögtle, C. A. Schalley, Ed.; Springer-Verlag, Berlin, 2001, Vol. 217, p. 163. (c) D. Astruc, F. Chardac, *Chem. Rev*. 2001, **101**, 2991. (d) R. M. Crooks, M. Zhao, L. Sun, V. Chechik, L. K. Yueng, *Acc. Chem. Res*. 2001, **34**, 181. (e) L. J. Twyman, A. S. H. King, I. K. Martin, *Chem. Soc. Rev*. 2002, **31**, 69. (f) R. van Heerbeek, P. C. J. Kamer, P. W. N. M. van Leeuwen, J. N. H. Reek, *Chem. Rev*. 2002, **102**, 3717.

[49] A.S.H. King, L.J. Twyman, *J. Chem. Soc., Perkin Trans. 1,* 2002, 2209.

[50] (a) S. C. Bourque, F. Maltais, W. -J. Xiao, O. Tardif, H. Alper, P. Arya, L. E. Manzer, *J .Am. Chem. Soc.* 1999, **121**, 3035. (b) S. C. Bourque, H. Alper, *J. Am. Chem. Soc.* 2000, **122**, 956. (c) P. Arya, N. V. Rao, J. Singkhonrat, H. Alper, S. C. Bourque, L. E. Manzer, *J. Org. Chem.* 2000, **65**, 1881.

[51] (a) P. Arya, G. Panda, N. V. Rao, H. Alper, S. C. Bourque, L. E. Manzer, *J. Am. Chem. Soc.* 2001, **123**, 2889. (b) S.-M. Lu, H. Alper *J. Am. Chem. Soc.* 2003, **125**, 13126.

[52] (a) D.E. De Vos, M. Dams, B. F. Sels, P. A. Jacobs, *Chem. Rev.* 2002, **102**, 3615, and references cited therein. (b) J. M. Thomas, *Angew. Chem. Int ed.*1999, **38**, 3589.

[53] (a) J.M. Thomas, T. Maschmeyer, B. F. G. Johnson, D. S. Shepard, *J. Mol. Catal*. 1999, **141**, 139. (b) B.F.G. Johnson, S.A. Raynor, D.S. Shephard, T. Maschmeyer, J.M. Thomas, G. Sankar, S. Bromley, R. Oldroyd, L. Gladden, M.D. Mantle *Chem. Commun.* 1999, 1167.

[54] J. F. Goellner, B. C. Gates, G. N. Vayssilov, N. Rősch, *J. Am. Chem. Soc.* 2000, **122**, 8056.

[55] (a) W. A. Weber, B. C. Gates, *J. Phys. Chem. B* 1997, **101**, 10423. (b) L. F. Rao, A. Fukuoka, N. Kosugi, H. Kuroda, M. Ichikawa, *J. Phys. Chem.* 1990, **94**, 5317. (c) L. F. Rao, M. Pruski, T. S. King, *J. Phys. Chem. B* 1997, **101**, 5717 (d) E. J. Rode, M. E. Davis, B. E. Hanson, *J. Catal.* 1985, **96**, 563. (e) E. J. Rode, M. E. Davis, B. E. Hanson, *J. Catal.* 1985, **96**, 574. (f) R. J. Davis, J. A. Rossin, M. E. Davis, *J. Catal.* 1986, **98**, 477.

[56] M. E. Davis, ,P. M. Butler, J. A. Rossin, B. E. Hanson, *J. Mol. Catal.* 1985, **31**, 385.

[57] K. Mukhopadhyay, A. B. Mandale, R. V. Ghaudhari, *Chem. Mater.* 2003, **15**, 1766.

[58] (a) S. K. tanielyan, R. L. Augustine, U.S. Patent 1998, 08/994,025, PCT WO-9828074. (b) R. L. Augustine, S. K. Tanielyan, S. Anderson, H. Yang, *Chem. Commun,* 1999, 1257.

[59] R. L. Augustine, S. K. Tanielyan, N. Mahata, Y. Gao, A. Zsigmond, H. Yang, *Appl. Catal. A.* 2003, **256**, 69.

[60] C. Bianchini, D.G. Burnaby, J. Evans, P. Frediani, A. Meli, W. Oberhauser, R. Psaro, L. Sordalli, F. Vizza, *J. Am. Chem. Soc*. 1999, **121**, 5961.

[61] Bianchini, C.; Santo, V. D.; Meli, A.; Oberhauser, W.; Psaro, R.; Vizza, F. *Organometallics* **2000**, *19*, 2433.

[62] C. Bianchini, P. Barbaro, V. Dal Santo, R. Gobetto, A. Meli, W. Oberhauser, R. Psaro, F. Vizza, *Adv. Synth. Catal.* 2001, **343**, 41.

[63] F. M. de Rege, D. K. Morita, K. C. Ott, W. Tumas, R. D. Broene. *Chem. Commun,* 2000, 1797.

[64] J. P. Arhancet, D. E. Davis, J. S. Merola, B. E. Hanson, *Nature*, 1989, **339**, 454.

[65] (a) M. E. Davis, *CHEMTECH*, 1992, August, 498. (b) J. P. Archancet, M. E. Davis, B. E. Hanson, *J. Catal.* 1991, **129**, 110. (c) I. Guo, B. E. Hanson, I. Tóth, M. E. Davis, *J. Organomet. Chem.* 1991, **403**, 221. (d) J. P. Arhancet, M. E. Davis, B. E. Hanson, *J.Catal.* 1991, **129**, 94. (e) Y. Yuan, J. Xu, H. Zhang, K. Tsai, *Catal. Lett.* 1994, **29**, 387. (f) G. Fremy, E. Monfier, J.-F. Carpentier, Y. Castanet, A. Mortreux, *J. Catal.* 1996, **162**, 339.

[66] B. B. Bunn, T. Bartik, B. Bartik, W. R. Bebout, T. E. Glass, B. E. Hanson, *J. Mol. Catal.* 1994, **94**, 157.

[67] I. T. Horváth, *Catal. Lett.* 1990, **6**, 43.

[68] A. J. Sandee, V. F. Slagt, J. N. H. Reek, P. C. J. Kamer, P. W. N. M. van Leeuwen, *Chem. Commun.* 1999, 1633.

[69] G. Fremy, E. Monflier, J.-F. Carpentier, Y. Castanet, A. Mortreux, *Angew. Chem. Int. Ed. Engl.* 1995, **34**, 1474.

[70] (a) K. T. Wan, D. E. Davis, *Nature*, 1994, **370**, 449. (b) K. T. Wan, D. E. Davis, *J. Catal.* 1994, **148**, 1.

[71] R. Melhem and M. Aljarrah. Plant design and feasibility study of a heterogeneous hydroformylation process of 1-octene Report of a Process Plant Design. Project supervised by H. van den Berg and A.G.J. van der Ham, University of Twente, Department of Science and Technology, 2004.