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Continuous Rhodium-Catalyzed Hydroformylation of 1-Octene with Polyhedral Oligomeric Silsesquioxanes (POSS) Enlarged Triphenylphosphine**

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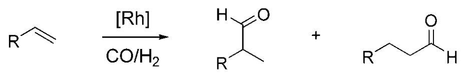
The efficient recovery and recycling of homogeneous catalysts is one of the major drawbacks of this area, especially when the high costs of precious metals are taken into account.[1] Specific solutions have been developed for all larger-scale applications, however, new generic methods, preferably with low energy profiles, are highly desirable for future process intensification and development of more sustainable and "greener" processes. The various approaches that have been studied to date each have their own advantages and disadvantages, and can be divided into two main classes: biphasic catalysis,[2–4] and immobilization on either soluble (molecular weight enlargement, MWE) or insoluble supports (heterogenization).[5–9]

The hydroformylation of alkenes is among the largest-scale industrial applications of homogeneous catalysis (Scheme 1).[10] An elegant example is the Ruhrchemie/Rhône Poulenc (RCH/RP) Process for the biphasic hydroformylation of propene. The water-soluble catalyst (TPPTS/Rh; TPPTS = sulfonated PPh_3, triphenylphosphino trisulfonate) is immobilized in the aqueous phase and the product, *n*-butanal, forms the organic phase, which can easily be removed by phase separation. It is important to note, however, that the applicability of this approach is limited exclusively to lower alkenes with sufficient solubility in the aqueous phase (the process is used commercially only up to butenes). A range of methods that overcome this difficulty have been investigated for the hydroformylation of higher alkenes. Table 1 gives a concise overview of results obtained in the rhodium-catalyzed hydroformylation of alkenes followed by catalyst recycling, either by means of biphasic catalysis (entries 1–6) or by MWE (entry 7). In all cases, a modified version of triphenylphosphine was applied as the ligand.



Scheme 1. The rhodium-catalyzed hydroformylation of *n*-alkenes.

Table 1: Overview of rhodium-catalyzed alkene hydroformylation combined with catalyst recycling.

Entry	Method	Ligand	Substrate	TOF [h^{-1}]	TON	Ref.
1	water/ organic + latex[a]	TPPTS	1-octene	150	n.d.[b]	[4]
2	water/ organic + CD[c]	TPPTS	1-decene	n.d.	2×770	[11]
3	water/ organic + amphiphilic copolymer	covalently bound to polymer	1-octene	760	5800	[12]
4	ionic liquid	TPPTS	1-hexene	2000	10×1600	[13]
5	$scCO_2$[d]	TPPMS[e]	1-octene	180	n.d.	[14]
6	fluorous phase	$P(4C_6H_4\text{-}C_6F_{13})_3$	1-octene	4400	n.d.	[15]
7	MWE	POSS-enlarged	1-octene	1350	120 000	this work

[a] PS-latex used as a phase-transfer agent; [b] n.d. = not determined; [c] CD = cyclodextrin; [d] supercritical CO_2; [e] TPPMS = triphenylphosphino monosulfate.

Nanofiltration is still a relatively unexploited field for the recovery of MWE catalysts. Recently, our research group and others showed the application of nanofiltration for the recycling and reuse of homogeneous catalysts in a diffusion-driven process.[16,17] However, traditional systems for MWE have proven to be rather inefficient in continuous processes, as low conversions were reached because of rapid catalyst deactivation, significant metal leaching, or poor retention of the whole system. Consequently, new concepts have to be developed in order to circumvent these drawbacks. Herein, we report the synthesis of molecular-weight-enlarged triphe-

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nylphosphine, its application as a ligand in the rhodium-catalyzed hydroformylation of 1-octene, and its long-term behavior in a continuous flow nanofiltration reactor setup.

POSS has received relatively little attention for use in MWE.[18–22] These compounds are commercially available at low cost, have a highly defined structure, and are kinetically and thermally stable, thus making them ideal candidates for use in MWE. Moreover, the rigid, cubical shape of the POSS cages is beneficial in nanofiltration, since rigid 3D structures are known to display better retention and less membrane fouling than more flexible macromolecules.[23]

We initially chose to immobilize PPh_3 as it has been the ligand of choice in the industrial rhodium-catalyzed hydroformylation of alkenes. The synthesis of POSS-enlarged PPh_3 turned out to be straightforward (Figure 1). Firstly, 4-bromostyrene (**1**) was hydrosilylated with $HSiCl_3$ in the presence of a Pt catalyst. The product (**2**) was subsequently used in a corner-capping reaction with trisilanol *i*Bu-POSS **3** in the presence of Et_3N to produce 4-bromophenylethyl-POSS **4**. After lithiation of **4** with *n*BuLi and reaction with PCl_3, POSS-enlarged PPh_3 **5** was obtained in 80% yield (Figure 1). The ligand was fully characterized by NMR spectroscopy, elemental analysis, and MALDI-TOF mass spectrometry, and has a molecular mass of 2791 $g\,mol^{-1}$. In order to apply MWE to homogeneous catalysts, several requirements have to be fulfilled: straightforward synthesis, high activity, high total turnover number (TTN), and high retention. Therefore, the activity of POSS-enlarged PPh_3 in the hydroformylation of 1-octene was compared with PPh_3 in an autoclave (batch) experiment. Plots of conversion versus time, based on the uptake of CO/H_2, are shown in Figure 2a. The turnover frequencies (TOF) were determined at 20% conversion, and were found to be high: 1350 h^{-1} and 3150 h^{-1} for POSS-enlarged PPh_3 and unmodified PPh_3, respectively. No degradation of the POSS ligand was observed by ^{31}P NMR spectroscopy after the reaction was finished.

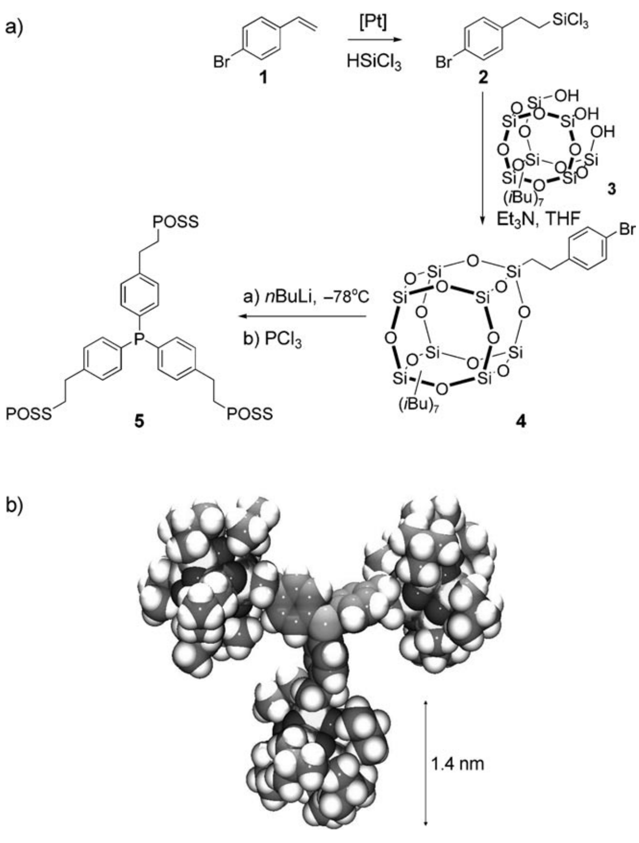

Figure 1. a) Synthesis of POSS-enlarged PPh_3. b) 3D model (MM^+) of POSS-enlarged PPh_3 showing the steric bulk induced by the POSS moieties.

Since our catalytic system based on POSS-enlarged PPh_3/Rh fulfilled all the requirements discussed above, it was applied in a novel, continuous-flow nanofiltration reactor that was designed and developed in-house. This reactor (Figure 3) is filled continuously with substrate solution by an HPLC pump, while a capacitive level sensor controls the liquid level in the reaction vessel by operating the HPLC pump. The product-containing solution is continuously collected at the backside of the membrane module. The reactor consists of two loops: a gas-saturation/reaction loop (A), and a membrane filtration loop (B). Loop A contains the reaction vessel and the gas mixer, in which the reaction mixture is injected into the gas phase for gas saturation. Both loops meet in the crossflow chamber. The reaction mixture subsequently flows along the ceramic nanofiltration membrane in which the product-containing phase is separated from the MWE catalyst and is continuously collected. We chose a ceramic membrane because of its good solvent, pressure, and temperature resistance. The flow in the membrane loop is kept higher than in the reaction loop to guarantee turbulent flow along the membrane (Reynolds number $Re \geq 4400$), thus preventing formation of a polarization layer. The reaction pressure forms the driving force for the nanofiltration in this setup. The flux through the membrane is controlled with a Rheodyne two-position six-port fluid processor (PR700-100-01) equipped with a 500 μL sample loop controlled by a flip-flop relay, and is kept constant during the course of the reaction. The whole reactor, including the membrane unit, is kept at the operation temperature of 80°C. The molecular-weight cut-off (MWCO) of this membrane is 450 Da.[24] Further reactor and reaction specifications are given in the Supporting Information.

From our batch experiments (Figure 2a), we can conclude that under the reaction conditions applied (T, P, [1-octene], [Rh]; see the Supporting Information), the reaction is pseudo-zero-order in 1-octene up to about 90% conversion. For a zero-order reaction we can derive an equation for the conversion X in a CSTR, where $[\mathrm{oct}]_{\mathrm{in}}$ and $[\mathrm{oct}]_{\mathrm{out}}$ are the concentration of 1-octene flowing into and out of the reactor, respectively, τ is the space time, and k is the rate constant [Eq. (1)].

$$X = \frac{[\mathrm{oct}]_{\mathrm{in}} - [\mathrm{oct}]_{\mathrm{out}}}{[\mathrm{oct}]_{\mathrm{in}}} = \frac{\tau k}{[\mathrm{oct}]_{\mathrm{in}}}$$

The results of a variable-flux experiment are shown in Figure 2b, and compared with the expected values according to [Eq. (1)]. In this experiment, the conversion was deter-

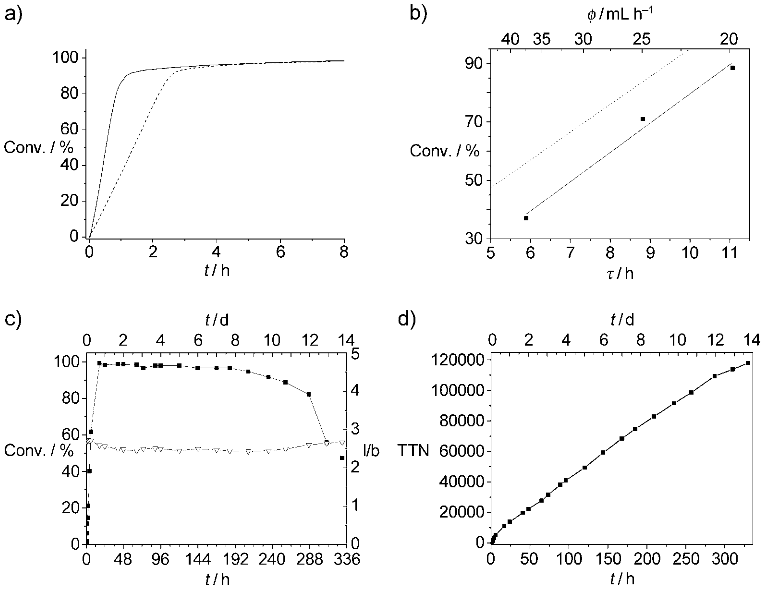

Figure 2. POSS-enlarged PPh_3/Rh catalyzed hydroformylation of 1-octene. a) Comparison of catalytic activity between PPh_3/Rh (5 equiv; ——) and POSS-enlarged PPh_3/Rh (5 equiv; -----) in a batch reactor. b) Comparison between experimentally obtained conversion (■) and conversion predicted by the kinetic model ($X = k_{batch}\tau [oct]_{in}^{-1}$; -----); k_{batch} refers to the value of k calculated from the batch setup; ϕ = flux [$L h^{-1}$]. c) Conversion (■) and regioselectivity (▽) versus time for the continuous hydroformylation of 1-octene in the continuous flow membrane reactor. d) Accumulated turnover number obtained in the continuous-flow membrane reactor.

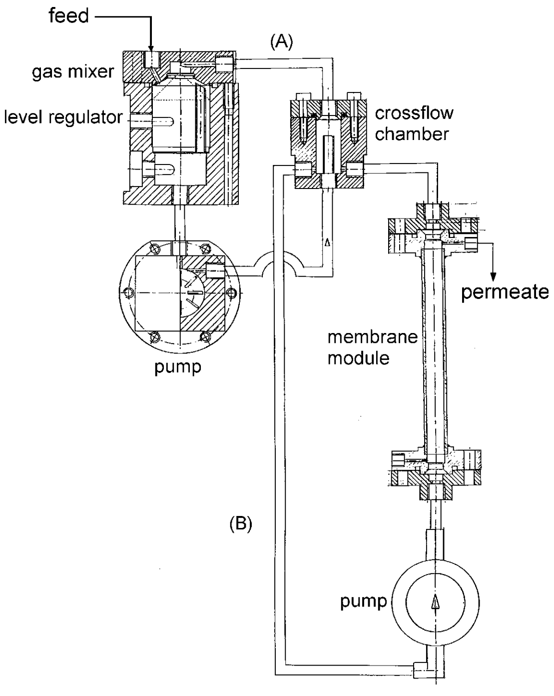

Figure 3. Schematic representation of the continuous-flow nanofiltration reactor developed in-house.

mined at a certain space time τ, after the system had reached steady-state conditions. Figure 2b shows that the conversion that is reached in the CSTR is systematically lower than the expected conversion based on [Eq. (1)]. This behavior can be rationalized by for example, nonideal mixing, premature catalyst decomposition, slight differences in temperature between the batch and continuous setup that result in a different value for k.

Prior to use, the reactor was purged five times with syngas (CO/H_2 1:1; 20 bar). The reactor was then filled with substrate solution by HPLC pump, and again purged five times with syngas (20 bar). The reactor was heated to the reaction temperature (80 °C) and pressurized to the reaction pressure of syngas (20 bar). At time $t = 0$, the catalyst was added to the reaction mixture by means of a dropping funnel connected to the reactor, therefore allowing the catalyst solution to be added to the reactor under the reaction conditions. Samples were taken at regular intervals, and analyzed by GC to monitor the development of conversion and regioselectivity (linear/branched (l/b) ratio) over time (Figure 2c).

After a gradual increase, the highest conversion of 99 % was obtained after 17 hours. The conversion remained greater than 90 % for almost two weeks, which is unprecedented. In this period, the regioselectivity remained constant at an l/b ratio of 2.5, which is identical to the regioselectivity for unsupported PPh_3.

The accumulated turnover number (TTN) versus time is shown in Figure 2d, which shows that the TTN steadily increases to a value of about 120000 Rh^{-1} after 13 days. This result demonstrates the stability and robustness of our POSS-enlarged PPh_3/Rh catalyst.

The significant reduction in activity after 13 days still requires further investigation. The reduction could be caused by ligand decomposition, for example, by cleavage of the P–C bond in the ligand, as has been previously reported.[25,26] However, the ^{31}P NMR spectrum of the reaction mixture at the end of the experiment showed signals of only the free and rhodium-coordinated ligands. Another possibility could be the formation of Rh clusters. The color of the retentate at the end of the reaction was still light yellow, whereas Rh clusters usually cause a brown coloration. Furthermore, very small amounts of impurities present in for example, the solvent or substrate could eventually accumulate in the reactor and lead to catalyst deactivation. Clearly, the observed deactivation is not caused by a substantial loss of Rh, since ICP-OES (induced coupled-plasma–optical emission spectroscopy) analysis of the total product solution revealed a total Rh leaching of only 0.045 % and a total P leaching of 0.74 % of the total amount of Rh and P added, respectively. This result means that 99.96 % of the Rh is effectively retained by the nanofiltration membrane, thus tremendously simplifying the workup as the Rh concentration in the product is extremely low. Moreover, after removal of the retentate, the reactor does not show catalytic conversion of 1-octene (< 1 %), thus indicating that no active Rh species are adsorbed on the membrane or the reactor wall.

In summary, we have introduced POSS as a versatile unit for molecular weight enlargement of homogeneous catalysts, facilitating catalyst recycling, which results in continuous operation. A Rh catalyst based on the bulky, rigid, and robust POSS-modified PPh_3 ligand was applied in the hydroformylation of 1-octene in an in-house engineered continuous flow nanofiltration reactor. Unprecedented results in terms of activity, stability, and retention of the POSS-enlarged catalyst system were achieved as the hydroformylation setup was continuously operated for almost two weeks without any significant deactivation or leaching of the catalyst. These results highlight a major breakthrough in the sustainable conversion of alkenes under homogeneous catalytic conditions without the usual drawback of tedious and often expensive catalyst recovery and recycling. The full scope of the concept of MWE using POSS units is presently under investigation for a range of ligands and metal-catalyzed transformations.

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[1] P. W. N. M. Van Leeuwen, *Homogeneous Catalysis: Understanding the Art*, Kluwer Academic Publishers, Dordrecht, **2004**.
[2] Special issue of *Chem. Rev.* **2002**, *102*, 3215 – 3892, edited by J. A. Gladysz.
[3] *Multiphase Homogeneous Catalysis*, *Vol. 1* (Eds.: B. Cornils, W. A. Herrmann, I. T. Horvath, W. Leitner, S. Mecking, H. Olivier-Bourbigou, D. Vogt), Wiley-VCH, Weinheim, **2005**.
[4] B. Hamers, P. S. Bäuerlein, C. Müller, D. Vogt, *Adv. Synth. Catal.* **2008**, *350*, 332 – 342.
[5] K. Kunna, C. Müller, J. Loos, D. Vogt, *Angew. Chem.* **2006**, *118*, 7447 – 7450; *Angew. Chem. Int. Ed.* **2006**, *45*, 7289 – 7292.
[6] *Catalysis by Metal Complexes*, *Vol. 30* (Eds.: D. Cole-Hamilton and R. Tooze), Springer, Dordrecht, **2006**.
[7] D. J. Cole-Hamilton, *Science* **2003**, *299*, 1702 – 1706.
[8] *Recoverable and Recyclable Catalysts* (Ed.: M. Benaglia), Wiley, Chichester, **2009**.
[9] A. Kirschning, W. Solodenko, K. Mennecke, *Chem. Eur. J.* **2006**, *12*, 5972 – 5990.
[10] C. Müller, M. G. Nijkamp, D. Vogt, *Eur. J. Inorg. Chem.* **2005**, 4011 – 4021.
[11] N. Badi, P. Guegan, F. X. Legrand, L. Leclercq, S. Tilloy, E. Monflier, *J. Mol. Catal. A* **2010**, *318*, 8 – 14.
[12] M. Bortenschlager, N. Schöllhorn, A. Wittmann, R. Weberskirch, *Chem. Eur. J.* **2007**, *13*, 520 – 528.
[13] Q. Lin, W. Jiang, H. Fu, H. Chen, X. Li, *Appl. Catal. A* **2007**, *328*, 83 – 87.
[14] A. C. Frisch, P. B. Webb, G. Zhao, M. J. Muldoon, P. J. Pogorzelec, D. J. Cole-Hamilton, *Dalton Trans.* **2007**, 5531 – 5538.
[15] D. F. Foster, D. Gudmunsen, D. J. Adams, A. M. Stuart, E. G. Hope, D. J. Cole-Hamilton, G. P. Schwarz, P. Pogorzelec, *Tetrahedron* **2002**, *58*, 3901 – 3910.
[16] A. V. Gaikwad, V. Boffa, J. E. ten Elshof, G. Rothenberg, *Angew. Chem.* **2008**, *120*, 5487 – 5490; *Angew. Chem. Int. Ed.* **2008**, *47*, 5407 – 5410.
[17] M. Janssen, C. Müller, D. Vogt, *Adv. Synth. Catal.* **2009**, *351*, 313 – 318.
[18] L. Ropartz, R. E. Morris, D. J. Cole-Hamilton, D. F. Foster, *Chem. Commun.* **2001**, 361 – 362.
[19] L. Ropartz, K. J. Haxton, D. F. Foster, R. E. Morris, A. M. Z. Slawin, D. J. Cole-Hamilton, *J. Chem. Soc. Dalton Trans.* **2002**, 4323 – 4334.
[20] L. Ropartz, R. E. Morris, D. F. Foster, D. J. Cole-Hamilton, *J. Mol. Catal. A* **2002**, *182–183*, 99 – 105.
[21] L. Ropartz, D. F. Foster, R. E. Morris, A. M. Z. Slawin, D. J. Cole-Hamilton, *J. Chem. Soc. Dalton Trans.* **2002**, 1997 – 2008.
[22] N. R. Vautravers, D. J. Cole-Hamilton, *Chem. Commun.* **2009**, 92 – 94.
[23] R. W. Baker, *Membrane Technology and Applications*, Wiley, New York, **2000**.
[24] www.inopor.com.
[25] P. W. N. M. van Leeuwen, *Appl. Catal. A* **2001**, *212*, 61 – 81.
[26] D. R. Bryant in *Catalysis by Metal Complexes*, *Vol. 30* (Eds.: D. Cole-Hamilton and R. Tooze), Springer, Dordrecht, **2006**, pp. 9 – 37.