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Continuous Hydroformylation of 1-Decene in an Aqueous Biphasic System enabled by Methylated Cyclodextrins

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Abstract:

For the first time, randomly-methylated-β-cyclodextrin was applied as mass transfer agent in a continuous process. At the example of the Rh-catalyzed hydroformylation of 1-decene a process development was shown in which cyclodextrin was together with the catalyst system continuously recovered and recycled using an aqueous biphasic system. In first experiments the water soluble and commercially available catalyst systems Rh/TPPTS and Rh/sulfoxantphos were scaled up from a 50 ml into a 1000 ml pressure autoclave to show their scalability. Both systems were compared and achieved excellent chemoselectivities (>99%) to the desired linear aldehyde product. Especially high regioselectivity up to 31 was achieved for the Rh/sulfoxantphos system. Investigations on the long-term stability of the mass transfer agent and both catalyst systems were carried out in the continuously operated miniplant process. Showing that the process can be successfully operated at steady state over 200 h with chemoselectivity >97 % to the desired aldehyde product. Simultaneously extremely low Rh leaching with a total of 0.59 % was observed over the entire period of 200 h.

1 Introduction

Hydroformylation is widely used in industry to manufacture high value-added aldehydes and alcohols, and is considered as one of the largest homogenously catalyzed reaction in industry. Still a major issue accompanied with the use of homogenous catalysts is their recovery and separation from the product mixture especially for higher olefins, which is important due to the cost of the employed transition metals. These days, distillation is the most commonly used separation method in the hydroformylation for alkenes >C₅ and therefore the most well-known method.¹ But, distillation conditions required to separate the high-boiling products may lead to catalyst decomposition and parallel loss of metal. Hence, cheaper cobalt catalysts are used, ensuring the processes are still economically viable.² However, cobalt catalysts are less active than rhodium-catalysts, requiring higher reaction temperatures and pressures.³ Therefore, challenge remains to seek ways of converting higher olefins in the hydroformylation, in a manner that will address the separation problem and minimize environmental impact, while not compromising on catalyst selectivity and activity. Some concepts focused in this manner on the intensification of monophasic flow process for the hydroformylation.⁴ Other approaches have been developed in industry and academia to tackle the main issue of catalyst separation from the product using rhodium catalysts. Examples of these are the use of super critical CO₂ (scCO₂)⁵, CO₂ expanded liquid (CXL)^{6,7}, supported ionic liquids (SILP)⁷, nanofiltration (OSN)⁸, thermomorphic multiphase systems (TMS)⁹, microemulsions¹⁰ or biphasic systems¹¹. As some of them work with abounded resources like carbon dioxide and environmentally friendly solvent water, other do not. The use of water as a solvent for process applications is particularly beneficial from an economical and environmental impact viewpoint since water is fairly accessible, nontoxic, nonflammable, odorless, and has a high heat capacity and heat of vaporization.¹² Nevertheless, these benefits have to compete with the intrinsic limitation of low organic substrate solubility in the aqueous catalyst phase, which were also shown in early kinetic studies.^{13,14} Therefore several approaches have been developed to tackle the issue of low space-time yield in biphasic aqueous-organic reaction systems involving poorly water soluble substrates by e.g. make use of surfactants, cosolvents, thermoregulated ligands and cyclodextrins to achieve improved hydroformylation as summarized in the review article by MATSINHA ET AL.¹⁴

In this perspective, this work further focuses on the use of cyclodextrins as mass transfer agent to overcome mass-transfer limitations in the biphasic hydroformylation of 1-decene. Cyclodextrins (CDs) are cyclic oligosaccharides consisting of six (α -CD), seven (β -CD), or eight (γ -CD) α -D-glucopyranose units.¹⁵ They form conical cylinders with an outer hydrophilic surface and inner hydrophobic surface. The inner surface forms a cavity and allows for the formation of an inclusion complex when it binds a hydrophobic substrate (Figure 1).¹⁶ To vary their size and shape, native CDs can be modified by

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substituting their hydroxyl groups with various other functional groups. These are referred to as monoor polysubstituted CDs. Due to their ability to form inclusion complexes with a wide range of compounds, native and modified CDs have applications in various fields.¹⁷ In the field of aqueous biphasic organometallic catalysis, CDs have mainly been employed as mass-transfer agents^{16,18} in order to increase the solubility of hydrophobic substrates in water. For example, in 1995 MONFLIER ET AL.^{16,19–22} described the rhodium-catalyzed hydroformylation in an aqueous/organic two-phase system of 1decene in the presence of randomly methylated β -CD (RAME- β -CD; Figure 1).^{21,23} The phase separation between organic and aqueous phases was described as fast and the rhodium and phosphorus contents in the organic phase were found to be less than 0.5 and 1.2 ppm, respectively. Moreover, TILLOY ET AL. has shown in 1999 the reusability of the Rh/TPPTS/RAME-B-CD catalytic system by performing the rhodium-catalyzed hydroformylation of 1-decene with 5 catalytic recycle runs without loss of activity.²⁴ Later in 2004, LECLERCQ ET AL. investigated the same reaction using the ligand sulfoxantphos which led to increased performances in terms of chemoselectivity and regioselectivity.²⁰ Although, CDs are highly promising as mass transfer agent in an aqueous biphasic system for the selective hydroformylation of higher olefins, they were never applied in a continuously operated process. As our research group has gained an expertise in various continuously operated recycling strategies for homogeneous catalysts for the hydroformylation^{25,26} in previous years we now joined knowledge with the group of MONFLIER to tackle the questions if CDs are applicable for this kind of application. Therefore, we transfer in this work the two catalytic systems (Rh/TPPTS/RAME-B-CD and Rh/sulfoxantphos/RAME-B-CD) into one of our continuously operated miniplants for the aqueous biphasic hydroformylation. As this has never been done before both systems are first scaled-up in different sized batch autoclaves to show their performance in terms of chemo-/regioselectivity and conversion. Also, their reaction profile is determined as benchmark for the residence time in the subsequent continuous process. During continuous operation various parameters like CD concentration and stirrer speed will be investigated to influence the catalytic activity. Eventually the effective recycling of the catalytic systems (supported by leaching data) with optimized parameters is conducted in a long-term experiments showing the potential of cyclodextrins for such applications.



Figure 1: Principle of aqueous biphasic organometallic catalysis mediated by RAME- β -Cyclodextrin

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2 Results & Discussion

Based on the studies by MONFLIER ET AL.^{16,19–22} 1-decene was chosen as the model substrate for the cyclodextrin based hydroformylation. The reaction network is shown in Figure 2. The main product from the hydroformylation is undecanal, which is referred to as l-undecanal (linear undecanal). 1-Decene isomers may occur as by-products and are summarized as iso-decene (isomerized decene). Other by-products are *n*-decane which results from the hydrogenation of 1-decene or iso-decene, respectively, and the branched hydroformylation product (2-methyl decanal) which can arise from the hydroformylation of 1-decene or iso-decene. The 2-methyldecanal is shown as a representative of all branched aldehydes since it was formed as a by-product in the highest amount. The branched aldehydes are summarized as *b*-undecanal (branched undecanal). All undecanal isomers are summarized as undecanal (*I*-undecanal + *b*-undecanal). The remaining by-products are aldol condensates which can result from the condensation reaction of two aldehydes. These are all summarized and the 2-nonyl-tridec-2-enal is given as representative for the aldol condensates.



Figure 2: Reaction network of the 1-decene hydroformylation and typical by-products

Two catalyst systems are investigated in this work as their have shown in previous publications good results towards high product chemo-/regioselectivity. The already published results are gathered in the Table 2.^{18,20,24} Both use water as a solvent, Rh(acac)(CO)₂ as a precursor and RAME-ß-cyclodextrins (Figure 1) as mass transfer agent. They differ only in the choice of the phosphine ligand. On the one hand the monodentate TPPTS and on the other hand the bidentate sulfoxantphos is used.

Table 1: Comparison of aldehydes (chemo-)selectivity and linear to branched aldehyde (I/b) ratio (regioselectivity) for the rhodium-catalyzed hydroformylation of higher olefins by Rh/TPPTS and Rh/sulfoxantphos systems (adapted from HAPIOT ET AL.²¹ and LECLERCQ ET AL.²⁰)

Entry	Olefin	CD	Ligand	Selectivity ^c [%]	l/b
1 ^a	1-decene	RAME-β-CD	TPPTS	98	1.7
2 ^b	1-decene	RAME-β-CD	sulfoxantphos	>99	26

Experimental conditions: Rh(acac)(CO)₂: 0.04 mmol; TPPTS/sulfoxantphos: 0.21 mmol; CD: 0.48 mmol; water: 11.5 ml; olefin: 20.35 mmol; n-undecanal (internal standard):2.03 mmol; p (CO/H₂, 1:1)= 50 bar ^aT= 80 °C, t= 6h; ^bT= 120 °C, t= 24h; ^c Chemoselectivity towards undecanal

2.1 Batch scale-up experiments

Scale-up experiments were first performed since the original reactions were carried out in 50 ml pressure autoclaves. Therefore, two types of pressure autoclaves were used for the experiments (Figure 3). A pressure autoclave with a total volume of 300 ml was used for first reference and scaleup tests. For a comparability of the experiments, the gas volume to liquid volume ratio was maintained to the original experiments by MONFLIER ET AL.¹⁹ and LECLERCQ ET AL.²⁰ resulting in a volume for the reaction solution of 100 ml. This reactor is also referred to as 300 ml pressure autoclave in this work. Another reactor is built into the continuous miniplant process and was used in batch or continuous mode. The reactor has a total volume of 1000 ml and is referred to like this further on. To keep the ratio of gas volume to liquid volume constant the liquid volume is set to 330 ml.



Figure 3: Scale-up reactors used in this work

Scale-up Rh/TPPTS catalyst system 2.1.1

First scale-up experiments are conducted for the Rh/TPPTS catalyst system. Based on the reaction data from the original experiments (Table 1) the precursor $Rh(acac)(CO)_2$ and the ligand TPPTS are used to convert 1-decene to undecanal. The reaction temperature is set to 80°C at a phosphorus to rhodium ratio (n_P/n_{Rh}) of 5 and cyclodextrin to rhodium ratio (n_{CD}/n_{Rh}) of 12. The reaction time was set to 6 hours, as this is the maximum possible residence time in the reactor for the continuous process at

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rhodium to substrate ratio of 496. Before start of reaction 2 hours of preforming were conducted. In the original experiments 50 bar were used for the reactions to ensure sufficient gas solubility and to preclude a limitation of the reaction. Due to apparatus technology, only pressures of 40 bar are used for the 300 ml and 1000 ml autoclave. However, MATHIVET ET AL. mentioned that a reaction pressure of 10 bar is already sufficient and a further increase in pressure has only minor effects.²⁷. The stirrer speed was set to 800 min⁻¹ for the upscaling experiment. The results are shown in Figure 4.



Figure 4: Results of the CD mediated aqueous biphasic hydroformylation of 1-decene using TPPTS in dependence of the reactor size. 50 ml autoclave data adapted from HAPIOT ET AL.²¹

Conditions: 1. 50 ml autoclave²¹: Rh(acac)(CO)₂: 0.041 mmol, TPPTS: 0.21 mmol, cyclodextrins: 0.48 mmol, water: 11.5 ml, 1-decene: 20.35 mmol, T=80 °C, p(CO/H₂)= 50 bar, n= 1500 min⁻¹, no preformation

2. 300 ml & 1000 ml autoclave: Preforming: $p(CO/H_2)=20$ bar, $n_{CO}/n_{H2}=1:1$, T= 80°C, t=2 h; Reaction: $p(CO/H_2)=40$ bar, $n_{CO}/n_{H2}=1:1$, T=80°C, t=6 h, $m_{water}/m_{substrate}=4:1$, $n_{substrate}/n_{Rh}=496$, $n_{CD}/n_{Rh}=12$, $n_P/n_{Rh}=5$, n= 800 min⁻¹.

It is evident that with increasing reactor size catalytic activity is decreasing compared to the original 50 ml experiments. Nearly full conversion is achieved in the 50 ml autoclaves as compared to 300 ml autoclave the conversion decreases to 75 % and eventually to 33 % compared to the 1000 ml autoclave. The chemoselectivity of all three experiments are in the same range with over 95%, which indicates that the Rh/TPPTS catalyst system works as expected for all experiments. The regioselectivity reaches an also expected a *l/b* ratio for all experiments close to 1.8.

As these experiments were conducted to show influence parameters, respectively barriers for a potential transfer into a continuous process the results show that generally a transfer is possible as selectivities stay constant. However, in the continuous process lower conversions have to be expected due to potential mass transfer limitations due to the increase in size of the autoclaves. Since this is a three-phase gas-liquid-liquid system, there may be limitations at the gas-liquid phase interface and/or

at the liquid-liquid phase interface which is supported by investigations of SIEFFERT ET AL. who suggest that the reaction does not take place in the bulk water phase, but in the aqueous phase interface layer.²⁸ Thus, there would be a stronger dependence between the phase interface and the reaction rate and hence the conversion. With scale-up and an increase in volume, the amount of substance scales proportionally, but the phase interface does not. A reaction profile of the reaction for the 300 ml and 1000 ml is shown in the supporting information indicating the potential yield of undecanal for different residence times in the miniplant reactor.

2.1.2 Scale-up Rh/sulfoxantphos catalyst system

Scale-up experiments for the Rh/sulfoxantphos catalyst system are shown in Figure 5. Reaction conditions do not differ a lot to the previous experiments, only reaction temperature was increased from 80°C to 120°C and the time of preforming was extended from 2 hours to 12 hours. Similar to the results from the Rh/TPPTS catalyst system the conversion of 1-decene and the yield to the aldehyde undecanal generally decreases with increasing reactor size. A reaction profile of the reaction for the 300 ml and 1000 ml is shown in the supporting information indicating the potential yield of undecanal for different residence times in the miniplant reactor in continuous operation. However, the decrease of conversion is less compered to TPPTS, due to the surface properties of sulfoxantphos. Lowering herein the conversion from 71 % (50 ml autoclave) to 51 % (1000 ml autoclave). The yield of undecanal decreases in analogy to the conversion from 70 % to 46 % as the chemoselecitivity for all experiments stay over 90 %. Also, the regioselectivity (*I*/*b* ratio) of around 27 for all experiments show high regioselectivity towards the linear product aldehyde.



Figure 5: Results of the CD mediated aqueous biphasic hydroformylation of 1-decene using sulfoxantphos in dependence of the reactor size. 50 ml autoclave data adapted from previous studies.²⁰

Conditions: 1. 50 ml autoclave²⁰: Rh(acac)(CO)₂: 0.04 mmol; sulfoxantphos: 0.21 mmol; CD: 0.48 mmol; water: 11.5 ml; olefin: 20.35 mmol; *n*-undecanal (internal standard): 2.03 mmol; p (CO/H₂)= 50 bar, T= 120°C

2. 300 ml autoclave: preforming: $p(CO/H_2)=20$ bar, $n_{CO}/n_{H2}=1:1$, T= 120°C, t= 12 h; Reaction: $p(CO/H_2)=40$ bar, $n_{CO}/n_{H2}=1:1$, T= 120°C, t= 6 h, $m_w/m_s=4:1$, $n_s/n_{cat}=496$, $n_{CD}/n_{cat}=12$, $n_p/n_{cat}=5$, n= 800 min⁻¹

3. 1000 ml autoclave: Preforming: $p(CO/H_2)=20$ bar, $n_{CO}/n_{H2}=1:1$, T= 120°C, t= 12 h. Reaction: $p(CO/H_2)=40$ bar, $n_{CO}/n_{H2}=1:1$, T= 120°C, $\tau=6$ h, $m_w/m_S=4:1$, $c_{Cat}=0.006$, %, $n_{CD/nCat}=12$, n= 800 min⁻¹

2.2 Continuous miniplant experiments

The proof of concept for a successful scale-up of the Rh/TPPTS and Rh/sulfoxantphos catalyst systems was shown in the previous batch experiments. As regio- and chemoselectivity are nearly constant for these experiments the catalyst systems are transferred for the first time into a continuous process (Figure 10). Herein, especially the long-term stability of the catalytic system in combination with cyclodextrin, but also influence parameter like cyclodextrin concentration and stirrer speed in the reactor were investigated.

2.2.1 Variation of cyclodextrin concentration with TPPTS

In the first continuous experiment the Rh/TPPTS catalyst system was used to show the effect of cyclodextrins as mass transfer agent during reaction at biphasic conditions. The results are shown in Figure 6. The first 8 hours are the starting up time of the plant (marked with the grey bar). Initially no cyclodextrins were added to the system to prove poor reaction activity just in the aqueous biphasic mixture. As expected from hydroformylation experiments in aqueous biphasic systems reported in literature²⁹ the observable yield of undecanal (linear and branched) was low with under 0.5 % after 21 hours at a stirrer speed of 500 min⁻¹. To increase the reaction performance cyclodextrins were added to the system by a molar ratio of 6 compared to the rhodium catalyst. After 29 hours the yield of undecanal increased only to 1 %. Consequently, the stirrer speed was increased from 500 min⁻¹ to 800 min⁻¹ to increase the mixing in the reactor and potentially lowering mass transfer limitations. With these conditions the yield of undecanal reaches a steady value of 11.5 % after 47 hours. After 52 hours more cyclodextrins were added to the reactor. The molar ratio of cyclodextrins to rhodium increased to 12, which was used in the batch experiments before (Figure 4 and Figure 5). The yield increased after some induction time which roughly equals the residence time, so that after 65 hours the yield of undecanal was about 20 %. Compared to the batch experiment in the 1000 ml autoclave (supporting information) for the same conditions the yield of undecanal was determined 10 % less. This was expected to be influenced by the recycling of catalyst. To further increase the conversion more cyclodextrins were added after 76 hours resulting in a molar ratio of cyclodextrins to rhodium by 18. The conversion increased further and reached a steady state value of 32 %.



Figure 6: Yield and selectivity over time in continuous operation with variation of the cyclodextrin concentration and stirrer speed using TPPTS as ligand.

Conditions: Preforming: $p(CO/H_2)=20$ bar, $n_{CO}/n_{H2}=1:1$, T= 80°C, t= 2 h; Reaction: $p(CO/H_2)=40$ bar, $n_{CO}/n_{H2}=1:1$, T= 80°C, $\tau=6$ h, $m_w/m_s=4:1$, c_{Cat} ,=0.0064 mol%, $n_{CD}/n_{Cat}=12$, $n_P/n_{Cat}=5$, $\dot{m}_{1-Decene}=10.2$ g/h, $\dot{m}_{Recycle}=41.1$ g/h.

The regioselectivity (*I/b* ratio) was at the beginning at about 2.8. After the first addition of cyclodextrins the ratio rapidly dropped to 2.0 and then slowly reaching a value of 1.8-1.9 which was the ratio determined for TPPTS in the batch experiments. Further addition of cyclodextrins had no influence on the ratio. The chemoselectivity was over the whole duration of the experiment constant with about 99 % and thus higher than in the batch experiments (Figure 4). In Table 2 catalyst leaching results are presented for this experiment. Samples taken from the product stream showed a total leaching (L) of ligand after 94 hours of 1.2 % and total leaching of rhodium of 0.8 %.

Table 2: Leaching results of catalyst and ligand for the continue	ous experiment using TPPTS as ligand.
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t [h]	P [ppm]	L _{ligand} [%]	L _{ligand} [%∙h⁻¹]	Rh [ppm]	L _{Rh} [%]	L _{Rh} [%∙h⁻¹]
0-39	3	0.64	0.0165	1	0.22	0.0057
39-87	2	0.48	0.0102	2	0.50	0.0106
L(94 h)	-	1.20	0.0128	-	0.80	0.0086

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2.2.2 Stirrer speed variation with sulfoxantphos

As the increase of the cyclodextrin concentration in the reactor showed an increased mass transfer and hence an increased yield to the product for the Rh/TPPTS catalyst system, the same was expected for the Rh/sulfoxantphos system. Therefore, the next continuous experiment does not only investigate the feasibility of the Rh/sulfoxantphos catalyst system in a continuous process, but rather look more into the mixing behaviour of the phase system. For this, the molar ratio of cyclodextrin to rhodium was kept constant to 12 and the stirrer speed at the beginning was set to 800 min⁻¹. The results are shown in Figure 7. The first 8 hours represent the starting up time of the plant (marked with the grey bar). After that the yield of undecanal increased steadily until hour 34 to eventually 32 %, which is a bit lower than the expected yield from the batch reaction profile experiment of 38 % (supporting information). The miniplant operation was considered stable at this point. To investigate if mass transfer-limitation were limiting the conversion the stirrer speed was increased from 800 min⁻¹ to 1200 min⁻¹ to mechanically enhance the mass transfer between both phases and promote a higher conversion. However, the yield of undecanal decreased to 20 %. But, at the same time increased foam formation was observed in the reactor which is considered as a potential reason why the yield even decreased and not increases as a mass transfer between the liquid-liquid phases can be inhibited by foam. After the plant was steady again the stirrer speed was reduced from 1200 min⁻¹ to 500 min⁻¹ at about 66 hours. The yield of undecanal slowly increased after 6 hours (equals the residence time). At the end of the experiment the yield was at 34 %. Furthermore, it should be noted that the foam phase has become considerably smaller at 500 min⁻¹. However, changes in the stirrer speed, hence in the mass transfer have not influenced the chemoselectivity at all by staying >95 % to aldehyde product. The regioselectivity (I/b ratio) started at 27.5 and slowly rose to the stationary value of 30.5 after 20 h which corresponds to the ratios achieved in batch tests. As the differences lie in the range of measurement and continuous operation fluctuations, no direct influence of stirrer speed and I/b ratio can be shown.



Figure 7: Yield and selectivity over time in continuous operation with variation of stirrer speed using sulfoxantphos as ligand.

In Table 3 catalyst leaching results are represented. In the beginning the leaching of rhodium and ligand was slightly higher. This is most likely caused by the start-up procedure and lower average residence time in the decanter. The further loss corresponded approximately to the value determined for the entire operating time. Over the operating time of 93 h with an average leaching of ligand of 0.0122 %/h⁻¹ the total ligand leaching summed up to 1.14 %. The rhodium loss is on average was 0.0059 %/h⁻¹ and thus the total rhodium leaching summed up to 0.55 %.

Table 3: Leaching results of catalyst and ligand for continuous stirrer speed variation experiment using sulfoxantphos as ligand.

t [h]	P [ppm]	L _{ligand} [%]	L _{ligand} [%·h ⁻¹]	Rh [ppm]	L _{Rh} [%]	L _{Rh} [%∙h⁻¹]
0-5	4	0.09	0.0170	2	0.07	0.0128
5-22	4	0.24	0.0147	1	0.09	0.0055
22-45	3	0.30	0.0129	1	0.13	0.0056
45-93	3	0.50	0.0105	1	0.26	0.0055
L(93 h)	-	1.14	0.0122	-	0.55	0.0059

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2.2.3 Long term experiment with sulfoxantphos

In this experiment, the previous results from the miniplant which lead to highest yields and selectivities, were used to show long term effects when the plant is running steady state. Therefore, the experiment was carried out with the sulfoxantphos catalyst system as it has shown generally higher yields and higher regioselectivites compared to the Rh/TPPTS catalyst system. The amount of cyclodextrin is set to n_{CD}/n_{Rh} = 18 regarding to the experiment in Figure 6 and stirrer speed was set to 500 min⁻¹ regarding to the experiment in Figure 7. The results of the experiment are shown in Figure 8. At the beginning of the start-up phase, yield of undecanal was at about 6%. This increased steadily until the stationary value of 39% after 38 hours, which was also expected from the batch reaction profile experiments (supporting information). This value was kept stable in a steady state operation over 200 h with maximum deviations of 1.5% until the end of the test after 241 h. The chemoselectivity of undecanal was initially >99%. Until the stationary point was reached, the chemoselecitivity dropped to 97 %, but kept this value with maximum deviations of 1% over the entire operating time. This behavior of the chemoselectivity was also observed in the previous continuous experiment with sulfoxantphos (Figure 7). The regioselectivity (1/b ratio) was 27 which increased until stationary value of 29.6 after 40 hours of operation. This value was maintained with a minimum of deviation until the end of the experiment.



Figure 8: Yield and selectivity over time in long-term experiment using sulfoxantphos as ligand.

Conditions: Preforming: $p(CO/H_2)=20$ bar, $n_{CO}/n_{H2}=1:1$, T=120 °C, t=12 h; Reaction: $p(CO/H_2)=40$ bar, $n_{CO}/n_{H2}=1:1$, T=120 °C, $\tau=6$ h, $m_w/m_S=4:1$, $c_{Cat}=0.0064$ mol%, $n_{CD}/n_{Cat}=18$, $n_P/n_{Cat}=5$, n=500 min⁻¹, $\dot{m}_{1-decene}=12.7$ g/h, $\dot{m}_{recycle}=51.4$ g/h.

In Table 4 catalyst leaching results are represented for the whole time of operation. In general, no significant deviation in leaching was seen, which supports the evidence that the cyclodextrins work as mass transfer agent very efficiently. Over the operating time of 241 h the average leaching of ligand was 0.0098 %/h⁻¹, so that the total leaching of ligand summed up to 2.17 %. The rhodium loss on average was 0.0027 %/h⁻¹ and thus the total rhodium leaching summed up to 0.59 %. The long-term stability of the system could therefore be demonstrated in this experiment. No makeup stream had to be supplied to maintain the catalytic activity over the whole course of the experiment. During the experiment, a white solid deposit was found in the decanter through a viewing window. This was noticed for the first time after approx. 70 hours of operation and increased over the test period. Thus, the formation of the solid can presumably be attributed to the increase in the cyclodextrin concentration at the beginning in the sulfoxantphos system (n_{CD}/n_{Rh} = 18 here instead of n_{CD} / n_{Cat} = 12 compared to the batch experiments) and not to the long operating time by itself. Solubility problems therefore appear to occur and further increases in the cyclodextrin concentration could become problematic for the continuous operation and should be therefore not considered.

t [h]	P [ppm]	L _{ligand} [%]	L _{ligand} [%·h ⁻¹]	Rh [ppm]	L _{Rh} [%]	L _{Rh} [%∙h⁻¹]
0-8	2	0.07	0.0098	0.3	0.01	0.0022
8-19	2	0.10	0.0098	0.3	0.02	0.0026
19-30	2	0.10	0.0098	0.3	0.03	0.0027
30-43	2	0.12	0.0098	0.4	0.03	0.0031
43-64	2	0.20	0.0098	0.3	0.05	0.0026
64-95	2	0.30	0.0098	0.3	0.07	0.0025
95-122	2	0.26	0.0098	0.3	0.06	0.0023
122-168	2	0.45	0.0098	0.4	0.14	0.0032
168-184	2	0.15	0.0098	0.4	0.05	0.0033
184-221	2	0.36	0.0098	0.3	0.08	0.0023
L(240h)	-	2,17	0,0098	-	0.59	0.0027

Table 4: Leaching results of catalyst and ligand for the 240 h continuous experiment using sulfoxantphos as ligand.

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2.2.4 Distillation & substrate recycle concept

The aqueous biphasic hydroformylation of 1-decene using cyclodextrins as mass transfer agent show high stability, low catalyst leaching and high chemo- and regioselectivity in the presented continuous experiments, but it was also shown that it lacks high turnover rates. To make it a more attractive process for commercial applications process intensification is necessary. In this manner several ways are applicable, e.g. increasing the residence time of 1-decene in the reactor by increasing reactor volume or decreasing feed and recycle flow rates to the reactor to increase conversion. Also, an increased mixing behaviour can achieve a higher turnover by e.g. changing stirrer geometry and stirrer speed, which was already shown in first approaches in Figure 7. Further investigations are right now in execution in this particular field. A third way to improve the efficiency of this process is by recovering and recycling non-converted substrate after the reaction. Figure 8 shows up to 58 % of non-converted substrate is leaving the process after the phase separation. A huge improvement could be made if the substrate could be recovered and recycled. Therefore a potential process concept is proposed in Figure 9 integrating (Step 1: Hydroformylation) a second purification step to the already existing system by using a distillation column to separate the substrate from the product.





To prove that this concept is feasible, a distillation column (Figure 11) was set-up as described in the experimental part. In particular a vacuum distillation was chosen to have temperatures <150 C to suppress isomerization reactions of the substrate but also have an efficient product and substrate separation. Results of the continuous distillation over 8 hours are shown in the Supporting Information. Showing that the distillate stream (top fraction) with a composition of approx. 94.2 wt% 1-decene and 5.8 wt% decane/decene isomers can be established. The regioselectivity (*l/b* ratio) of decene in the feed and in the top of the column remains constant with a value of about 6 wt%. Thus, the isomer

portion of the feed, when completely separated, is decisive for the quality of the distillate stream. Showing therefore in general the feasibility of the process concept.

3 Experimental Section

3.1 Chemicals

In Table 5 all the chemicals used in this work are listed. All solvents and substrates were degassed before reaction but not further purified. The purity of each component was tested via gas chromatography.

Table 5: Chemicals used in the presented work.

Chemicals	Manufacture	Purity [%]
1-decene	Acros organics	99
argon	Messer Industriegase	-
Rh(acac)(CO) ₂	Umicore	-
triphenylphosphine-3,3',3"-trisulfonic acid trisodium salt	Oxea GmbH	-
sulfoxantphos	MOLISA	-
di- <i>n</i> -butylether	Acros organics	99.5
isopropanol	VWR international	98
CO/H ₂	Messer Industriegase	99.9
Bi-distilled water	-	-

3.2 Analytics

A gas chromatograph from Agilent Technologies of type 7890A with an HP-5 column (30 m x 0.32 mm x.025 m) and flame ionization detector (FID) is used for gas chromatographic measurements of offline samples from the batch and continuous experiments. *n*-dodecane is used as standard and isopropanol as solvent. For measuring online samples for the continuous experiments an Agilent Technologies 7890A gas chromatograph is used for gas chromatographic measurements. It is equipped with a flame ionization detector (FID). An HP-5 (30 m x 0.25 mm x 0.25 m) is used as the separation column. The sample volume of 1µl is injected with a split ratio of 1:50 with constant supply of helium as carrier gas.

The content of rhodium and phosphorus in the liquid phases has been quantified via inductively coupled plasma emission spectroscopy (ICP-OES, Thermoelemental Iris Intrepid). The catalyst leaching rate for rhodium and phosphorus can be calculated with the total amount of the related product fraction, the appropriate mass fraction (ppm) contained, and the initial mass of rhodium and phosphorus at miniplant start. E.g. 1%/h leaching represents the loss of 1% of initial catalyst amount via product flow in one hour

3.3 Experimental setup

Batch Experiments

A 300 ml pressure autoclave from the company Parr instruments is used to perform for batch experiments. The autoclave is pressure stable up to 250 bar and has blade stirrer. The reactor was used for creating time curves and performing kinetic experiments to scale-up the reaction. After weighing catalyst, ligand, polar solvent and cyclodextrins in, the autoclave was closed and installed to the reaction equipment. The substrates and solvents were degassed with argon via a frit for 30 min. The substrate 1-decene was then transferred to a dropping funnel via a cannula. The dropping funnel is pressurized with system pressure from the reactor when filled. When the predetermined time for preforming has been reached, the substrate is transferred into the reactor and afterwards continuously fed with syngas. Schlenk technique was used for the preparation of all components and the inert transfer of all substances into the reactor at all times.

A 1000 ml pressure autoclave is used from the company Büchi to perform further scale up experiments. The reactor is stable up to 60 bar including a blade stirrer & baffles. The procedure for carrying out the experiments is the same as for the 300 ml pressure autoclave. The reactor is also used as a CSTR for the continuous miniplant experiments.

Continuous Experiments

The miniplant consists of a 1000 mL continuous stirred-tank reactor (CSTR) which is pressure stable up to 60 bar. Additionally, the reactor is designed with a blade stirrer & baffle. The reactor is connected to a decanter (B2) unit in which the reaction mixture is separated into polar (blue) and non-polar phase (yellow). The catalyst phase (blue) is then fed back by a gear pump to the reactor, while the non-polar product phase is collected on a scale. The miniplant is automated and equipped with an online GC (Figure 10). The initial mixtures containing catalyst, ligand, water and cyclodextrins were prepared for all miniplant apparatuses (reactor, decanter) at once. Therefore, the substances were weighed into several bottles and flushed with argon. The miniplant was tempered, evacuated and the reactor (B1) was filled with the mixture via a pressure-stable dropping funnel. Then synthesis gas was added stepwise in each apparatus and pipe section. At the beginning of the operation the pump for 1-decene was activated. Simultaneously, continuous syngas feeding, and pressure control were started. During miniplant operation samples from the product phase were analyzed periodically with an online gas chromatograph from the decanter. Also, offline samples were taken from product & catalyst phase for ICP analysis but also for validation of the results of the online gas chromatograph.

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8



Figure 10: Flow chart of the continuously operated miniplant

Distillation set-up

Figure 11 shows the general set-up of the distillation column used for the recovery of non-converted substrate from the product stream. The column is operated at a pressure of 15 mbar by a diaphragm vacuum pump. The product solution from the miniplant (Figure 10, B2) is conveyed into the column via a storage tank with a solenoid-driven diaphragm metering pump. Feed solution is heated up in the column by a heating rod and the steam rises and passes through 15 separation stages, which are achieved with Sulzer DX (30 mm) laboratory packs, each 5.5 cm high and with a HETP value of 0.085 m. At the top of the column, the distillate stream passes through a water-cooled condenser in which a split is installed in order to set a reflux. The distillate stream is collected in a container. The bottom of the column is designed as a natural circulation evaporator to ensure internals-free mixing. In addition, there is an overflow in the bottom from which the bottom product reaches another container. To protect the column bottom from drying out due to condensed gas, the overflow is also equipped with a gas trap.

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4 Conclusion

The Rh-catalyzed aqueous biphasic hydroformylation of 1-decene was successfully conducted using only water as environmentally friendly solvent and RAME-β-cyclodextrin as green mass transfer agent. In a first approach two catalyst systems costing of Rh/TPPTS and Rh/sulfoxantphos were scaled-up from a 50 ml autoclave to a 1000 ml pressure autoclave to show the feasibility of these phase systems for a potential continuous process application. Herein, both systems performed well in terms of chemoselectivity towards the product aldehyde with >95 %. However, these experiments have shown that for both catalyst systems the reaction rates slowed down in the larger autoclaves, so that the conversion decreased from 99 % to 30 % (Rh/TPPTS) respectively from 70 % to 50 % (Rh/sulfoxantphos). However, as the chemoselectivity stayed high for both systems, they were tested in two continuous experiments (each over 90 h). These experiments showed that the reaction activity can drastically be influenced by the stirrer speed and the cyclodextrin to rhodium ratio inside the reactor. As the Rh/sulfoxantphos catalyst system performed not only better in terms of yield to the product aldehyde with 45 % compared to 30 % to the Rh/TPPTS system, but also gained higher regioselectivities (I/b ratios) with 27 compared to 1.7 it was chosen for a long-term experiment. With 240 h of total operation in a continuous miniplant and more than 200 h of steady state operation leaching of catalyst was determined to be extremely low, having a loss of ligand of 0.0098 %/h and loss of rhodium of 0.0027 %/h. Compared to an commercialized hydroformylation process (Shell) and other recently proposed processes (SILP/CXL & Aqueous TMS) in literature, the CD based system does not show the highest turnover rates in continuous operation, but one of the highest chemo- und regioselectivities and lowest rhodium leaching rates (Table 6). Also, the CD process operates at very mild conditions with 120 °C and 40 bar compared to the other process.

Parameter	Cyclodextrins (Rh) ⁺	SILP/CXL (Rh) ^{30*}	Aqueous TMS (Rh) ²⁶	Shell (Co) ³¹
T [°C]	120	100	140	200
p [bar]	40	100	21	80
S _{aldehyde} [%]	97	98	93	80
l/b ratio [-]	27	3	19	-
TOF [h ⁻¹]	19	500	1500	20
TOS [h]	240	40	21	-
Rh loss [ppm/h]	0.01	0.005	0.7	-

Table 6: Comparison of different concepts for the continuous hydroformylation of higher olefins.

*Referring to experiment Figure 8; *SILP/CXL= Supported ionic liquid phase + carbon dioxide expanded liquids;

TOS= Time on stream

Green Chemistry

Reaction rate improvements like stirrer speed, stirrer type, phase ratios and cyclodextrin concentrations are still under investigation and will be discussed in an additional publication in more detail. Process optimization on the other side was successfully shown, by continuous distillation of the product mixture (undecanal, 1-decene, iso-decenes) and recovering non-converted substrate 1-decene with 94 % purity. With the possibility of continuous distillation of the non-converted substrate a new process concept was proposed by implementing a second recycle loop into the process. Bringing that all together an aqueous biphasic hydroformylation process using methylated- β -cyclodextrins for higher olefins with extremely low catalyst leaching and high chemo- and regioselectivities towards the corresponding product aldehyde can be achieved.

5 Supporting Information

Reaction profiles for the Rh/TPPTS and Rh/sulfoxanthpos system are shown for both the 300 ml autoclave and the 1000 ml autoclave. Also, the composition of the distillate stream for the continuously operated distillation is shown.

6 Conflict of interest statement

The authors declare no conflict of interest.

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1. References

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Long term application of cyclodextrins in the aqueous biphasic hydroformylation of higher olefins with high selectivites and simultaneously catalyst recycling.