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One-Pot Synthesis of Fatty Amines: Rh-Catalyzed Hydroaminomethylation of 1-Decene in an Aqueous Microemulsion System—Influence of Reaction Conditions on the Reaction Performance

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Abstract: The hydroaminomethylation of the long-chain olefin 1-decene and diethylamine with a homogeneous Rh(acac)(cod)/SulfoXantphos catalyst complex as a one-pot synthesis was investigated. The influence of reaction conditions such as temperature and synthesis gas pressure was determined, as well as the effects of the initial concentrations of catalyst precursor, ligand, and reactants on the yield of fatty amine. Hydroaminomethylation was successfully carried out in an aqueous microemulsion system using a non-ionic surfactant with a reaction time of 2 h. A maximum yield of 34%, high regioselectivities >97%, and chemoselectivities >85% were achieved.

Keywords: homogeneous catalysis; hydroaminomethylation; hydroformylation; microemulsion; rhodium; reductive amination; tandem reaction

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1. Introduction

Effective reaction control is of great importance for carrying out chemical reactions in industry. Drug synthesis usually consists of several complex steps and the purification and separation of intermediates take more time and incur more costs than the reactions themselves. For example, the industrial approach for the total synthesis of the antiviral drug (−)-oseltamivir by Roche consists of 12 steps [1]. In 2016, Hayashi et al. published a one-pot synthesis of this antiviral drug. They reduced the total synthesis to only five steps, which can be carried out successively without purification in the same reaction vessel, called one-pot synthesis [2].

This smart implementation of multiple reactions can also be applied to homogeneous catalysis. In so-called tandem catalysis, several metal-catalyzed reactions take place in sequence with distinct mechanisms, either with the same (auto-tandem catalysis) or with different catalysts (orthogonal catalysis), also performed as one-pot synthesis [3]. A well-known example is the hydroaminomethylation of alkenes. Meanwhile, numerous hydroaminomethylation reactions have been published with a variety of catalyst and solvent systems. These include classic homogeneous systems with non-modified catalysts [4], or the use of selectivity-guiding ligands [5–7]. Furthermore, non-classic homogeneous systems, known as a biphasic systems, were investigated. These include unmodified biphasic systems [8], modified systems with ionic liquids [9,10], thermomorphic systems [11,12] and surfactant-based systems, creating a microemulsion system [13,14]. These multiphase systems are more attractive than conventional homogeneous solvents because of the comparatively simple possibility of catalyst recycling. In microemulsion systems, the catalyst and products are ideally in different phases after a successful reaction, which can be separated from each other. This offers enormous advantages for continuous operation in the industrial processes concerning the reuse of expensive metal catalysts, such as rhodium.

Our research group has set a focus on homogeneous catalysis in microemulsion systems. Therefore, we investigated the hydroaminomethylation of the long-chain olefin 1-decene with diethylamine, catalyzed by a water-soluble rhodium/phosphine catalyst complex (see Figure 1) and described the impact of reaction conditions on yields, selectivities and the effective reaction rate.

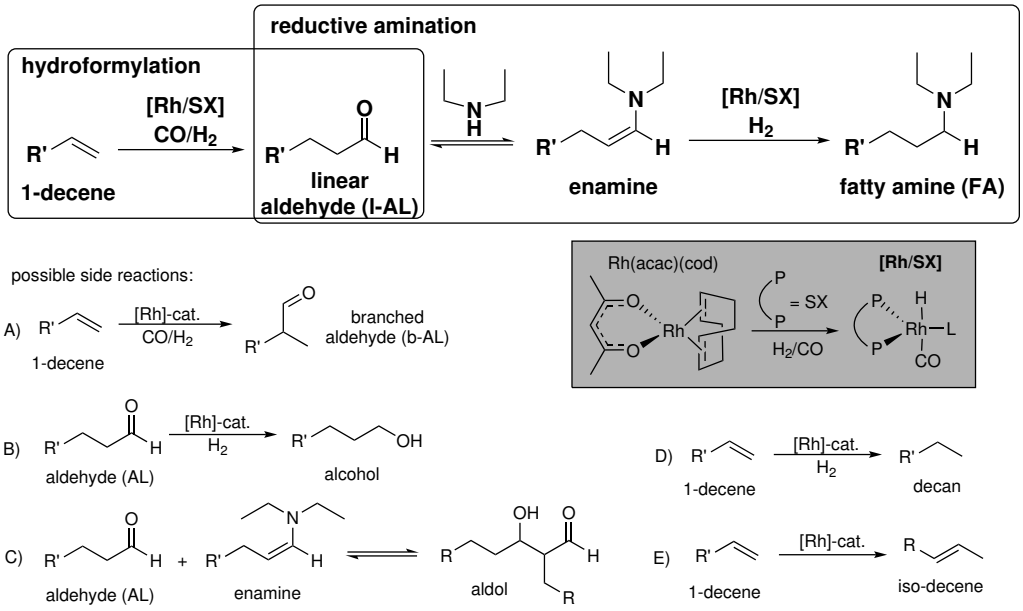

Figure 1. Rh-catalyzed hydroaminomethylation of 1-decene with diethylamine and possible side reactions observed: (**A**) hydroformylation yielding in branched aldehyde, (**B**) hydrogenation of aldehyde, (**C**) aldol reaction, (**D**) hydrogenation of 1-decene, and (**E**) isomerization of the double bond.

Numerous side reactions can occur (reactions A–E) and must be avoided by choosing the optimum reaction conditions and concentrations of reactants. This is the main aim of this work and is discussed in the following sections. We want to clarify to what extent the sequence of two reactions influences the kinetics and how both reactions interact. How do temperature and pressure affect the two reactions, and what is the influence of the initial concentrations of reactants or catalyst complex? E.g., is the hydroformylation influenced by the reactant diethylamine of the reductive amination? Does the catalyst behave similarly in a tandem reaction as in the single reactions? From further results of catalyst recycling in the reductive amination, the strong influence of the fatty amine on the separation dynamics became apparent. In relation to this, it is necessary to identify how the products (aldehyde and fatty amine) affect the separation dynamics of the reaction mixture and to what extent phase separation can be realized. In addition, we will compare our latest results for hydroaminomethylation with observations from further literature. We already studied the hydroformylation of long-chain olefins [15,16] and the reductive amination of long-chain aldehydes [17] in aqueous microemulsion systems individually, both with non-ionic surfactants. Further, these literature results are referred to several times without explicitly naming them.

2. Materials and Methods

2.1. Chemicals

All commercially available chemicals were used without further purification. The reactant 1-decene, the Ir precursor chloro(1,5-cyclooctadiene)iridium(I) dimer (97%), the Rh precursor bis(1,5-cyclooctadiene)rhodium(I) tetrafluoroborate (n.a.) and chloro (1,5-cyclooctadiene)rhodium(I) dimer (98%) were purchased from Sigma-Aldrich (St. Louis, MO, USA). The Rh precursor dicarbonyl(acetylacetonato)rhodium(I) (>99.9%) was donated by Umicore (Brussels, Belgium). Diethylamine (>99.5%), sodium sulfate (>99%, anhy-

drous), and the external GC standard nonane (>99%) were obtained from Carl Roth (Karlsruhe, Germany). The company abcr (Karlsruhe, Germany) delivered the Rh precursors acetylacetonato-1,5-cyclooctadienylrhodium(I) (98%) and the co-solvent dodecane (>99%). The bidentate ligand 2,7-bissulfonate-4,5-bis(diphenylphosphino)-9,9-dimethylxanthene (SulfoXantphos, SX, technical grade) was synthesized by the company Molisa (Magdeburg, Germany). The GC-solvent 2-propanol was purchased from VWR (Radnor, PA, USA). Our water treatment system Synergy UV from Merck (Darmstadt, Germany) provided the used ultrapure water. The synthesis gas (2:1 mixture of hydrogen and carbon monoxide) was obtained from Air Liquide (Paris, France). The non-ionic surfactants of the Marlophen series (specific chain length distribution, technical grade) were provided by Sasol Germany (Hamburg, Germany).

2.2. Preparation of the Catalyst Solution

Unless otherwise stated, 15.5 mg (0.05 mmol, 1 eq.) of precursor acetylacetonato-1,5-cyclooctadienyl-rhodium(I) (Rh(acac)(cod)) and 156.9 mg (0.2 mmol, 4 eq.) of water-soluble ligand SulfoXantphos SX were added, evacuated, and flushed three times with argon in a Schlenk tube. A total of 4 g of water was added through a septum and the catalyst complex was stirred overnight at room temperature, yielding a dark red solution.

2.3. Procedure for the Hydroaminomethylation Experiments

The hydroaminomethylation experiments were carried out in a 100 mL stainless-steel reactor (Halmosi GmbH, Heilbronn, Germany). A detailed experimental setup has already been published and can be found in the literature [17]. The solvents water and dodecane, the surfactant, and the sodium sulfate were added to the reactor, evacuated for 5 min, and flushed with nitrogen. The prepared catalyst solution (Section 2.2) and the diethylamine were injected by a syringe. The reaction mixture was heated up to the reaction temperature under continuous stirring (300 rpm) and pressurized with synthesis gas. The substrate 1-decene was added to the storage vessel and pressurized with synthesis gas. A defined reaction start was set by increasing the stirring speed up to 1200 rpm and by adding the 1-decene. GC samples were taken, dissolved in 2-propanol, and analyzed by a GC Shimadzu GC2010 Plus (30 m × 0.25 mm × 0.25 µm Restek RTX5-MS column, flame ionization detector). For the determination of the pH value, a simulated aqueous phase consisting of the appropriate amounts of water, diethylamine, and catalyst solution, was prepared and measured with the pH meter SevenExcellence S470 of the company Mettler Toledo. The pH value was determined after calibration with known buffer solutions and from the average of a triple determination.

2.4. Catalyst Recycling

The catalyst recycling for the HAM was performed exactly as described in our paper on reductive amination [17]: a typical reaction mixture for the hydroaminomethylation was prepared (21.4 mmol 1-decene, 21.4 mmol DEA, 9 g dodecane, 12 g water, 0.23 mol% Rh(acac)(cod), 0.92 mol% SX, 8 wt% Marlophen NP8, 1 wt% Na_2SO_4). The first run was performed for 2 h (30 bar synthesis gas, 120 °C) and cooled down to 50 °C for reaction gas releasing. After transfer of the reaction mixture into a graduated cylinder (flushed with nitrogen), the mixture was heated up until complete phase separation was observed, without stirring. The aqueous catalyst phase (including the surfactant) was removed by syringe (more detailed information on the temperature can be found in Section 3.4) and transferred to the reactor. After the addition of new reactants (21.4 mmol of 1-decene and DEA) and new co-solvent dodecane (9 g), the reaction was started as usual.

2.5. Used Parameters for Evaluation

For a successful assessment of the reaction performance, different variables are considered. Thus, the initial reaction rates and selectivities are also decisive in addition to yields and conversion. The initial reaction rates r_0 for both sub-steps were determined from

the slopes of the concentration–time diagrams (Equation (1)). It is emphasized here that these are effective reaction rates, which are unsuitable for comparison with other reaction systems from the literature. However, they serve to identify tendencies between the two reactions of hydroaminomethylation, hydroformylation (*HF*) and reductive amination (*RA*). From this, estimations can be made for further kinetic studies.

$$r_{0,HF} = \frac{\Delta c(aldehyde)}{\Delta t} \qquad r_{0,RA} = \frac{\Delta c(fatty\,amine)}{\Delta t} \tag{1}$$

As shown in Figure 1, several side reactions can be observed aside from hydroaminomethylation. The aim is, of course, to suppress these as far as possible. An important parameter, in this case, is chemoselectivity. In our case of hydroaminomethylation, this is calculated using Equation (2). The ratio of the desired products (sum of linear and branched aldehydes *Y(AL)* and fatty amine) and conversion of 1-decene is determined. Our equation for the chemoselectivity includes both steps for the hydroaminomethylation. The higher the chemoselectivity, the fewer side reactions (see Figure 1A–E) occur. Depending on these kinds of side reactions, chemoselectivity is influenced by different parameters. The used catalyst complex has a strong impact on metal-catalyzed side reactions (A, B, D, E), while reactant concentrations affect equilibrium reactions, as in the case of side reaction C.

$$S(chemo) = \frac{Y(AL) + Y(fatty\,amine)}{X(1 - decene)} \tag{2}$$

A further critical parameter for the profitability of a process is the regioselectivity. This type of selectivity is heavily influenced by the catalyst and ligand system. The regioselectivity is determined by the ratio of linear to branched aldehyde, Equation (3).

$$S(regio) = \frac{Y(linear\,aldehyde)}{Y(linear\,aldehyde) + Y(branched\,aldehyde)} \tag{3}$$

In summary, a reasonable reaction performance is defined by high yields of fatty amine and high selectivities (*regio* and *chemo*).

3. Results and Discussion

The concentration profile of the hydroaminomethylation of 1-decene with diethylamine for a typical experiment is shown in Figure 2. The conversion of the olefin starts immediately, and the aldehyde is formed rapidly. However, the formation of the desired fatty amine starts much slower and with a certain delay, despite the aldehyde accumulation.

The previously described side reactions can be observed to a small extent. Only traces (below 1%) of alcohol can be observed. The yield of the other by-products (iso-decenes, decane, and aldol product) is below 5%. The production of the branched fatty amine from the branched aldehyde was not observed. Unless otherwise mentioned, the yield of by-products was determined in this range and was not influenced by the varied parameter, so it will not be discussed further. Experiments with varied stirring speeds (600, 900, 1200, and 1500 rpm) showed no influence on the reaction performance as it was already observed in our hydroformylation and reductive amination experiments.

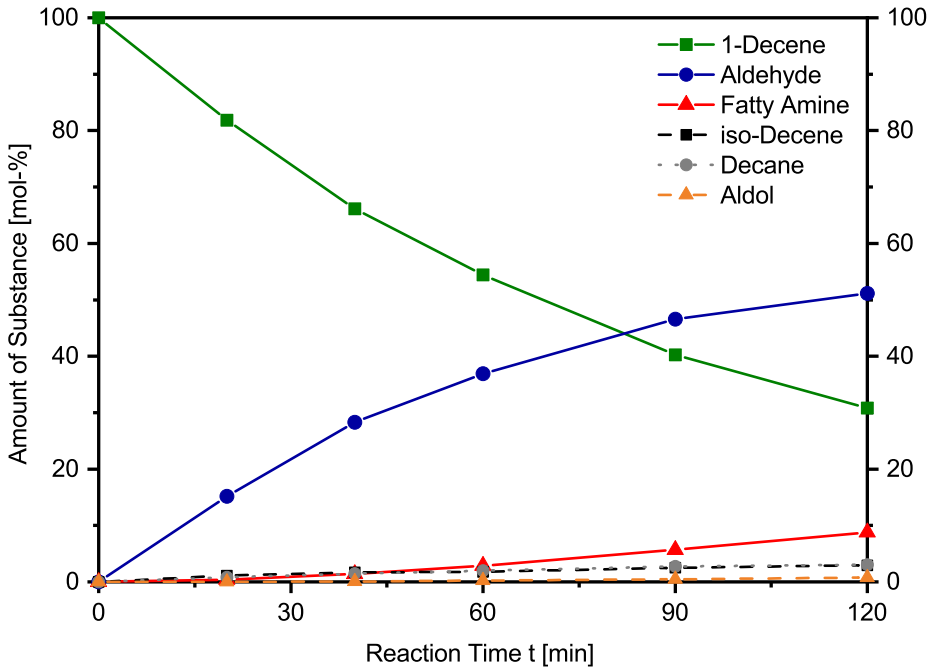

Figure 2. Concentration profile for the hydroaminomethylation of 1-decene with diethylamine in an aqueous microemulsion system. Reaction conditions: p = 30 bar H_2/CO 2:1, 0.23 mol% Rh, 0.92 mol% SX, 21.4 mmol 1-decene, 21.4 mmol DEA, 9 g dodecane (co-solvent), 12 g water, 8 wt% Marlophen NP8, 1 wt% Na_2SO_4, 1200 rpm, t = 4 h.

3.1. Optimal Catalyst Precursor and the Influence of Precursor and Ligand Concentration on the Hydroaminomethylation

The most important aspect of a successful homogeneously metal-catalyzed reaction such as hydroaminomethylation is the choice of catalyst precursor, the ligand, and its concentrations. In Table 1, different catalyst precursors (entries 1–5), varied concentrations of one of them (entries 6–10), and varied concentrations of the bidentate ligand SulfoXantphos (SX, entries 10–14) and their effect on the hydroaminomethylation are summarized.

Table 1. Effect of Rh-precursor (upper section), its concentration (middle section) and ligand concentration (lower section) on the hydroaminomethylation performance [a].

Entry	Precursor	c(Rh/Ir) [mol%]	c(SX) [mol%]	Y(FA) [b] [mol%]	Y(AL) [b] [mol%]	Y(i-Decene) [b] [mol%]	Y(Decane) [b] [mol%]	X(1-Decene) [mol%]	S [%] [c] (l:b AL)	S [%] Chemo
1	$[Ir(cod)Cl]_2$	0.23	0.92	traces	34.9	-	traces	40.3	99.9	87.9
2	$Rh(cod)_2OTf$	0.23	0.92	8.8	52.9	3.5	3.6	72.6	98.2	85.0
3	$[Rh(cod)Cl]_2$	0.23	0.92	4.4	45.8	3.5	3.3	59.9	98.0	83.6
4	$Rh(acac)(CO)_2$	0.23	0.92	8.9	51.2	3.0	3.1	69.6	98.1	86.4
5	Rh(acac)(cod)	0.23	0.92	8.9	51.6	2.9	3.1	69.8	98.1	86.7
6	Rh(acac)(cod)	0.06	0.23	1.7	33.7	2.3	2.3	44.8	98.0	78.9
7	Rh(acac)(cod)	0.11	0.44	3.7	46.0	2.7	2.9	57.5	98.1	86.4
8	Rh(acac)(cod)	0.47	1.87	19.8	52.5	4.1	4.5	84.4	98.1	85.6
9	Rh(acac)(cod)	0.70	2.81	33.7	44.9	4.4	4.8	91.5	98.1	85.9
10	Rh(acac)(cod)	0.23	0.23	3.7	41.5	35.6	2.2	85.0	84.0	53.2
11	Rh(acac)(cod)	0.23	0.46	4.8	42.2	38.0	2.3	89.6	84.4	52.4
12	Rh(acac)(cod)	0.23	1.38	10.4	51.9	4.0	3.9	73.9	98.2	84.3
13	Rh(acac)(cod)	0.23	1.84	11.8	51.9	4.0	4.1	75.2	98.2	84.8
14	Rh(acac)(cod)	0.23	2.34	14.2	47.1	3.8	4.0	71.9	98.3	85.3

[a] Reaction conditions: T = 120 °C, p = 30 bar H_2/CO (2:1), 0.66 mol/L 1-decene and DEA, 12 g organic phase: 3 g 1-decene, 9 g dodecane(co-solvent), 12 g water, 8 wt% Marlophen NP8, 1 wt% Na_2SO_4, 1200 rpm, t = 2 h. [b] Determined via GC. [c] Linear: branched selectivity of aldehyde.

The focus is set on the two main reactions (hydroformylation and reductive amination) of the tandem system. As expected, the stoichiometric reaction (aldol reaction) is not influenced by the catalyst complex and is about 1–2 mol% in all our experiments. For a successful tandem reaction, the choice of the metal is decisive. By using an iridium precursor, only the hydroformylation reaction takes place with a yield of about 35% (entry 1). Due to this, iridium is unsuitable for our reaction and solvent system even if other observations have been made in the literature for a usual homogeneous solvent system [18]. Furthermore, different types of rhodium precursors (neutral and cationic, entries 2–5) are investigated. It is noticeable that the different catalyst complexes showed only minor differences in reaction performance, so the formation of the active catalyst species and its equilibrium are comparable. Two possible mechanisms for reductive amination are discussed in the literature, one with a neutral rhodium species and one with a cationic Rh species [19,20]. An equilibrium between the neutral and cationic active catalyst species is conceivable. This could explain the minor differences in our experiments.

The increasing conversion of 1-decene with an increasing concentration of catalyst (entries 6–9) has also been described in the literature for the hydroformylation and the reductive amination and indicates the kinetic control of the reaction.

The effect of ligand concentration on the different reactions is more complex. We already described the influence of highly selective and bidentate ligands and their concentrations on Rh-catalyzed hydroformylation [21]. In theory, lower ligand concentrations lead to a high catalyst activity but lower stability of the catalyst complex susceptible to decomposition. An increasing ligand concentration yields in high stabilities with lower activity. For our HAM experiments, we can confirm a decreasing alkene conversion with an increasing metal-ligand ratio (which corresponds to increased stability of the inactive catalyst complex) and the increase in regio- and chemoselectivity. Furthermore, an increased yield of aldehyde (up to 52%, entries 12 and 13) and amine (up to 14%, entry 14) was observed. Compared to the single reactions, the catalyst in a tandem reaction, or one-pot synthesis, must undergo two catalytic cycles. It is therefore conceivable that the resulting higher catalyst deactivation is suppressed by higher ligand concentrations. It is also conceivable that a decrease in catalyst activity would be observed with much higher ligand concentrations. However, since this would not bring any advantage, the ligand concentration was only investigated up to an economically justifiable level.

3.2. Influence of Reaction Conditions on the Hydroaminomethylation

3.2.1. Effect of Reaction Temperature

The influence of the reaction temperature is of high importance, not only for the reaction performance and the resulting reaction rates but also for the phase behavior and the separation dynamics of the microemulsion system. Furthermore, higher reaction temperatures can favor side reactions or influence the activity and selectivity of the catalyst system. Therefore, the reaction temperature was varied from 90 to 130 °C; the results are shown in Table 2.

Table 2. Effect of temperature on the reaction performance and selectivity of hydroaminomethylation of 1-decene with diethylamine [a].

Entry	T [°C]	Y(FA) [b] [mol%]	Y(AL) [b] [mol%]	X(1-Decene) [b] [mol%]	S [%] (l:b AL)	S [%] (Chemo)	Y(iso-Decene) [mol%]	Y(Decan) [mol%]	Y(Aldol) [mol%]	Y(Alcohol) [mol%]
1	90	0.2	14.4	16.4	98.5	88.9	0.6	1.0	-	-
2	100	0.6	23.3	28.5	98.4	87.3	1.3	1.5	0.4	-
3	110	2.2	38.2	47.0	98.4	86.1	2.3	2.9	0.8	-
4	115	4.7	47.7	62.2	98.3	84.2	3.2	3.1	1.9	-
5	120	9.4	53.7	74.3	98.0	84.9	3.7	3.6	2.3	0.3
6	130	12.8	51.4	76.7	97.8	83.8	4.7	3.8	2.3	0.4

[a] Reaction conditions: p = 30 bar H_2/CO (2:1), 0.23 mol% Rh, 0.92 mol% SX, 0.66 mol/L 1-decene and DEA, 9 g dodecane (co-solvent), 12 g water, 8 wt% Marlophen NP8, 1 wt% Na_2SO_4, 1200 rpm, t = 2 h. [b] Determined via GC.

With increasing reaction temperature, the yield of products and the conversion of 1-decene increases while the selectivity (chemo and regioselectivity, l:b) decreases. The amount of fatty amine is increased from 0.2% (entry 1) up to around about 13% (entry 6, 64-fold), while the amount of produced aldehyde increases from 14% to 51% (about 4-fold). However, the amount of aldehyde over time must be compared to the separately performed hydroformylation with caution since the aldehyde is consumed and thus passes through a maximum. Nevertheless, it is clear that the reaction temperature strongly impacts the reductive amination of the HAM. At this point, selectivity must also be considered since the temperature cannot be increased arbitrarily. Thus, a drop in chemoselectivity from 89 to 84% and a slight drop in l:b selectivity can be observed when the temperature is increased. Furthermore, the formation of alcohol via the hydrogenation of the aldehyde occurs at temperatures above 120 °C.

From concentration profiles, the initial reaction rates for the hydroformylation and reductive amination were determined, and the activation energies for both steps were calculated from an Arrhenius plot (see Figure 3). The determined activation energy for the reductive amination (89.6 kJ/mol) is higher than the activation energy for the hydroformylation (66.4 kJ/mol). Calculating the activation energies of both reactions of the tandem system increases the uncertainty of the two results. However, these observations are in agreement with the literature, for both hydroformylation (E_A = 59 kJ/mol) and reductive amination (E_A = 76.2 kJ/mol) by Schomäcker et al. and others [22–24].

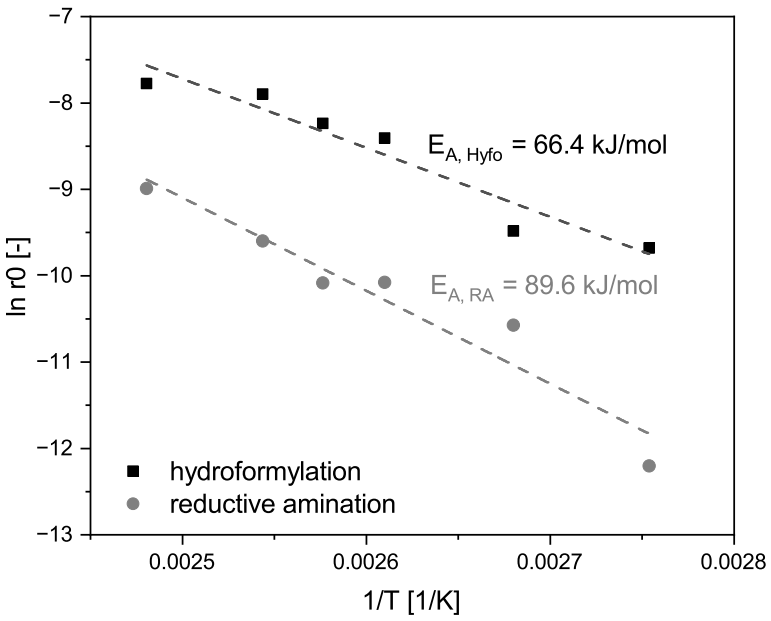

Figure 3. Arrhenius diagram for the substep hydroformylation and reductive amination.

3.2.2. Effect of Synthesis Gas Pressure

From previous hydroformylation experiments, we know that the reaction gas pressure has an enormous effect on forming an active catalyst species. The special feature of the tandem hydroaminomethylation is the requirement of active catalyst species for successive reactions. The pressure of the reaction gas can strongly influence these catalyst equilibria. The impact of the total pressure on the two successive reactions is investigated and shown in Figure 4.

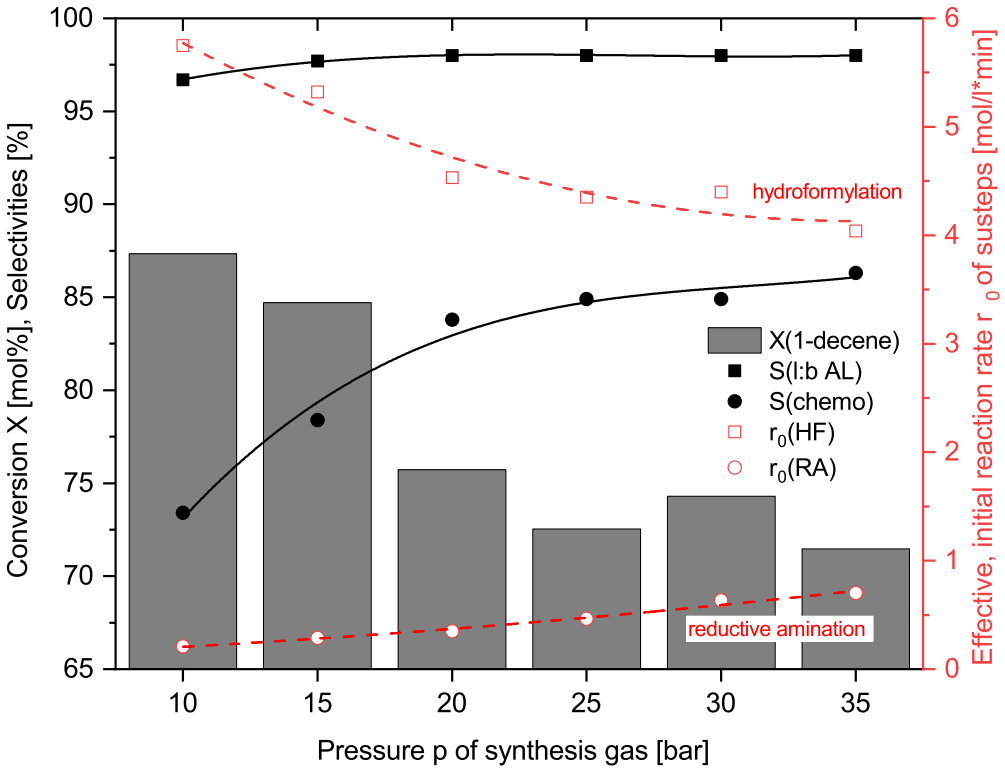

Figure 4. Influence of synthesis gas pressure on the conversion and yield of the hydroaminomethylation of 1-decene and the effect on the effective reaction rates of the partial steps hydroformylation and reductive amination. Reaction conditions: T = 120 °C, p = x bar H_2/CO (2:1), 0.23 mol% Rh, 0.92 mol% SX, 0.66 mol/L 1-decene and DEA, 9 g dodecane (co-solvent), 12 g water, 8 wt% Marlophen NP8, 1 wt% Na_2SO_4, 1200 rpm, t = 2 h.

From the figure, it can be seen that an increasing pressure of synthesis gas affects the improvement of chemo-selectivity by 10% and causes a slight increase in the l:b selectivity of the aldehyde. However, a decrease in substrate conversion from 87% to 72% can be observed. If the consecutive reactions are considered separately, the big difference between hydroformylation and reductive amination is striking. An increasing pressure leads to an increase in the initial reaction rate for the reductive amination (by a factor of 3.4) but a decrease in the initial reaction rate for the hydroformylation (by a factor of 1.4). From this, it is clear that an optimal reaction pressure must be found with these countercurrent effects. Since the RA is much slower than the HF, we decided to perform the HAM at higher pressures (30 bar).

3.3. Influence of Initial Reactant Concentrations

Finally, the variation of reactant concentrations and the effect on the hydroaminomethylation are studied and summarized in Table 3. First, the initial concentration of 1-decene was varied (entries 1–5). With an increasing olefin concentration, its conversion decreases dramatically from 86% to only 6%. According to this, the yield of aldehyde and fatty amine decreases. This entirely agrees with our observations for the reductive amination but not for the hydroformylation. The main difference in the reaction conditions between hydroformylation and hydroaminomethylation is the presence of the second strongly alkaline reactant, diethylamine. Due to the stoichiometry of the HAM (one mole of 1-decene reacts with one mole of DEA), the initial concentration of diethylamine has to be increased too with increasing 1-decene concentration. Therefore, the effect of diethylamine on the hydroaminomethylation was studied at a constant olefin concentration (Table 3, entries 6–9). The same tendencies were seen in terms of conversion and yields: an increas-

ing amount of diethylamine leads to a decrease in reaction performance for both reactions of hydroaminomethylation.

Table 3. Effect of initial amount of reactants on the hydroaminomethylation, upper section: variation of 1-decene concentration; lower section: variation of DEA concentration [a].

Entry	n_0(1-Decene) [mmol]	n_0(DEA) [mmol]	Y(FA) [b] [mol%]	Y(AL) [b] [mol%]	X(1-Decene) [b] [%]	pH [c] [-]
1	7.1	7.1	14.6	60.5	85.5	12.9
2	21.4	21.4	9.4	53.7	74.3	13.2
3	42.8	42.8	2.2	27.5	35.5	13.3
4	64.2	64.2	traces	8.9	11.3	13.4
5	85.6	85.6	traces	4.7	6.0	13.7
6	21.4	0	-	80.8	88.2	7.0
7	21.4	10.7	11.4	58.1	79.6	13.0
8	21.4	42.8	4.1	41.8	55.7	13.2
9	21.4	64.2	traces	18.1	23.3	13.3
10	42.8	21.4	6.8	38.2	56.5	13.2
11	64.2	21.4	4.1	28.2	39.8	13.2
12	85.6	21.4	3.9	20.6	30.9	13.2

[a] Reaction conditions: T = 120 °C, p = 30 bar H_2/CO (2:1), 0.23 mol% Rh, 0.92 mol% SX, 12 g organic phase (1-decene + dodecane), 12 g water, 8 wt% Marlophen NP8, 1 wt% Na_2SO_4, 1200 rpm, t = 2 h. [b] Determined via GC. [c] Determined with pH-meter for a simulated aqueous phase of reaction mixture.

Due to the strong basicity of diethylamine, it can be assumed that the pH value of the aqueous phase is strongly influenced by changing the concentration of DEA. The "hydroaminomethylation" without diethylamine (Table 3, No. 6, resp. "just" a hydroformylation reaction) gives the highest yield of the aldehyde with about 81%, and by addition of only 0.5 eq. DEA (No. 7), the yield of produced aldehyde decreases to 70% (sum of aldehyde and fatty amine, since the fatty amine was produced from the aldehyde). The pH value rises sharply (from 7 to 13). However, even small amounts of the amine cause an enormously increased pH value, which increases only slightly by adding more DEA. Considering only the first step (HF) usually, the concentration of DEA does not matter for this reaction.

Therefore, the experiments of the upper section (entries 3–5) were repeated with a constant DEA concentration (to perform the HAM at a constant pH value). The results are summarized in entries 10–12. Here, the decrease in yield and conversion is also evident, but to a lesser extent than in the previous experiments. E.g., entry 3 yields 28% aldehyde and only 2% fatty amine after 2 h. The same initial amount of 1-decene, same conditions but only 0.5 equivalents of diethylamine (entry 10) gives 38% aldehyde and about 7% fatty amine. In Figure 5 the comparison between the results from Table 3, entries 3–5 and 10–12, are visualized. If the dashed lines are compared with the respective solid ones, it becomes clear again that higher concentrations of diethylamine negatively influence the formation of the aldehyde. However, even with a constant concentration of diethylamine (dashed lines), a decrease in aldehyde yield can be observed with increasing decene concentration. Therefore, at this point, there must be another effect that negatively influences the reaction performance of the hydroformylation if the concentration of decene increases.

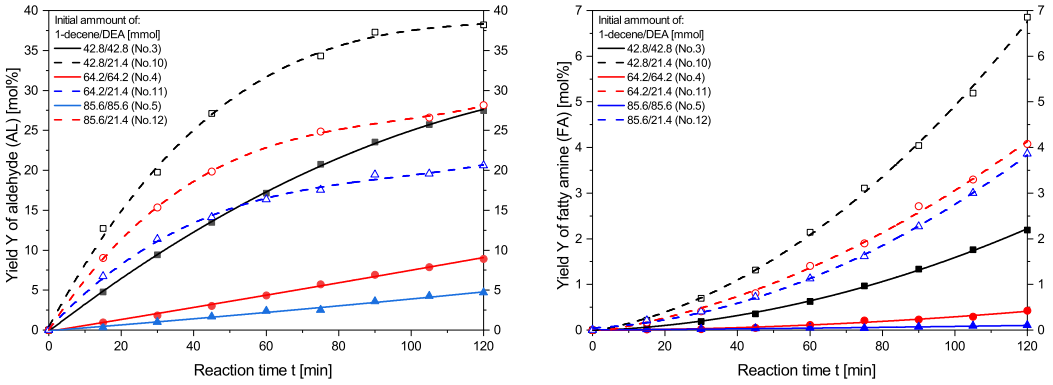

Figure 5. Comparison of aldehyde production (**left**) and fatty amine production (**right**) depending on initial concentrations of 1-decene and diethylamine. Reaction conditions: T = 120 °C, p = 30 bar H_2/CO (2:1), 0.23 mol% Rh, 0.92 mol% SX, 12 g organic phase (1-decene + dodecane), 12 g water, 8 wt% Marlophen NP8, 1 wt% Na_2SO_4, 1200 rpm, t = 2 h.

3.4. Recycling Experiments

Known from previous recycling experiments, the aqueous catalyst phase has been successfully recycled for hydroformylation and reductive amination. After the first run, we observed a complete phase separation into the two phases (upper organic and lower aqueous catalyst phase) at a temperature of 90 °C. After the second run of hydroaminomethylation, no complete phase separation was only reached by increasing the temperature up to 98 °C. Several identical recycling tests confirmed this observation. The increase in separation temperature with each run was also observed for the reductive amination (first run: 80 °C; second run: 90 °C; no separation after third run). Based on these observations, leaching experiments of the catalyst were not performed. From our HF and RA results, we know that Rh leaching from microemulsion systems is very low (below 1 ppm). Due to comparable reaction conditions, the catalyst leaching for the HAM should be similar or in the same order of magnitude.

This implies that the concept of catalyst recycling has failed here. However, it must be mentioned that our batch reaction negatively influences the separation dynamics. Parameters such as temperature and pressure, which vary enormously in our case, have a strong impact on the phase behavior and the resulting separation process. However, in cooperation with Wozny et al., we already demonstrated that a continuous reaction, including catalyst recycling, showed excellent results for the HF with a continuous and stable phase separation over a period of 24 h at a steady-state operation [25]. Therefore, hydroaminomethylation in a continuous miniplant with catalyst recycling is part of current research and our failed results are part of understanding the complexity of the separation dynamic.

4. Conclusions

The described results are in good agreement with our earlier observations for the hydroformylation of long-chain olefins and the reductive amination of the corresponding aldehydes. The results also confirm that the reductive amination is slower than the hydroformylation within the reaction network of the hydroaminomethylation and is thus the rate-determining step in this catalytic process, at least for this type of solvent system. Several aspects were found to be crucial for successfully implementing hydroaminomethylation in a microemulsion system, such as the choice of catalyst and its concentration.

Furthermore, it can be observed that high diethylamine concentrations have a negative effect on the performance for both steps of the reaction by inhibition effects by the reactants. For example, the DEA can bind to the catalyst with its free electron pair and thus block it for further catalytic cycles. Also possible would be an influence of the resulting high pH value on catalyst binding equilibria for the substrates or inhibition by the reactant 1-decene due to the decreasing reaction performance with an increasing initial concentration of 1-decene.

Since several of the mentioned effects can occur simultaneously and reinforce each other, the reaction network for comprehensive kinetic analysis is very complex. In this respect, further mechanistic and kinetic investigations are under investigation.

The first recycling experiments of the catalyst showed complex separation dynamics for the hydroaminomethylation in our batch experiments. The phase behavior and separation kinetics of the tandem reaction during continuous reaction operation in steady-state conditions is currently being investigated. The steady-state composition of the reaction mixture can be established in a region of its phase diagram that facilitates phase separation.

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Abbreviations

The following abbreviations are used in this manuscript:

acac	acetyl acetonate
AL	linear and branched aldehyde
cod	cyclooctadiene
DEA	diethylamine
FA	fatty amine (*N*,*N*-diethylundecylamine)
HAM	hydroaminomethylation
HF	hydroformylation
OTf	triflate group
RA	reductive amination
SX	SulfoXantphos

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