Hydroformylation of 1-Hexene in Supercritical Carbon Dioxide Using a Heterogeneous Rhodium Catalyst. 2. Evaluation of Reaction Kinetics

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Environmental needs associated with green chemistry require a reduction in the use of reaction solvents and separation materials. Heterogenization of homogeneous catalysts can be used to simplify the recovery steps in a reaction process. The use of a supercritical fluid for reaction and separation can further reduce the need for organic solvents throughout the process. The current paper describes the development of a tethered homogeneous catalyst for the hydroformylation of 1-hexene in supercritical carbon dioxide that is shown to be active, stable, and selective for the reaction. A reaction rate model that shows similarities to both the homogeneous and heterogeneous models is developed based on the assumption of a tethered catalyst and provides rate constants that are consistent with previous estimates.

Introduction

Also referred to as the "oxo reaction", hydroformylation was first carried out using cobalt catalysts at high temperatures and high syngas pressures.[1,2] The reaction adds 1 equiv each of carbon monoxide and hydrogen to an alkene, forming an aldehyde product. The hydroformylation of ethene produces propanal exclusively, but for C_3 and higher alkenes, mixtures of isomers are observed. Over 600 000 t/year of C_3 and C_4 aldehydes are produced through commercial processes that are based on homogeneous catalysts, mostly using rhodium. The use of phosphine-modified rhodium catalysts permits operation at lower pressure and provides higher activities and regioselectivities than does the use of cobalt catalysts, albeit at a higher catalyst cost. Phosphine-based ligands are known to increase the selectivity to the linear isomers.

For low-molecular-weight substrates, the Ruhrchemie/Rhone-Poulenc (RCH/RP) process, based on a water-soluble catalyst, is used commercially, but for substrates of C_6 and greater, the alkene is not sufficiently soluble in the aqueous phase to obtain sufficient activity to be commercially feasible.[1] In these cases, a solvent such as N-methyl pyrrolidone is added to bring the reactants into a single phase. All homogeneously catalyzed systems require catalyst separation and recovery steps. Alternate solvents, such as supercritical CO_2 ($scCO_2$), could potentially be employed to minimize the use of organic solvents and simplify the catalyst separation and recovery steps.

Because the product selectivity is a critical parameter in determining the economics of the process, a significant amount of research has been devoted to the synthesis and characterization of new ligands for homogeneous catalysts. Water-soluble chelating ligands of the BINAP and BISBI types are used at a ligand-to-Rh ratio of 7/1 to achieve a yield of 75% for hydroform-

ylation of 1-octene.[3] Selectivity (S = linear-to-branched ratio) generally decreases as the conversion of alkene increases. For example, hydroformylation yields of 97% were obtained using phosphonite ether ligands, but the regioselectivity was only 1.2 or less.[4] Conversions greater than 99% with 77−92% chemoselectivity to aldehydes were achieved for the hydroformylation of 1-hexene using bulky phosphites,[5] but significant hydrogenation was observed, and the selectivity (S = n/iso) was no higher than 1.4. A kinetic study undertaken by Purwanto and Delmas[6] evaluated the hydroformylation of 1-octene in a biphasic system using $RhCl(TPPTS)_n$ as the homogeneous catalyst and provided overall kinetics that could be modeled according to the complex rate expression

$$r = \frac{k[\text{octene}][\text{H}_2][\text{CO}]}{(1 + K_{\text{H}}[\text{H}_2])(1 + K_{\text{CO}}[\text{CO}])^2} \quad (1)$$

The development of a successful heterogeneous catalyst would allow a much simpler commercial process to be implemented. The use of a heterogeneous catalyst would eliminate the need for catalyst recovery and allow for the use of a fixed-bed type of reactor. Attempts have been made to produce a selective heterogeneous catalyst by attempting to anchor a homogeneous catalyst, or its analogue, to a solid support. For example, catalysts have been prepared by incipient wetness absorption of HRh(CO)(PPh_3)$_3$ on carbon nanotubes, rhodium supported on polysiloxane polymers with grafted alkyl phosphine chains,[7] rhodium supported on Ti−hexagonal mesoporous silica (Ti−HMS),[8] rhodium supported on clay,[9] and rhodium supported on activated carbon.[10] In general, high selectivity could only be achieved at low conversion, and hydrogenation and loss of rhodium from the support to the reaction mixture presented recurring problems.

The use of $scCO_2$ offers unique advantages as an environmentally benign solvent with tunable properties. By using the adjustable solvent power of a supercritical fluid (SCF) solvent, postreaction separation processes can be greatly simplified. Meehan et al.[11] demonstrated

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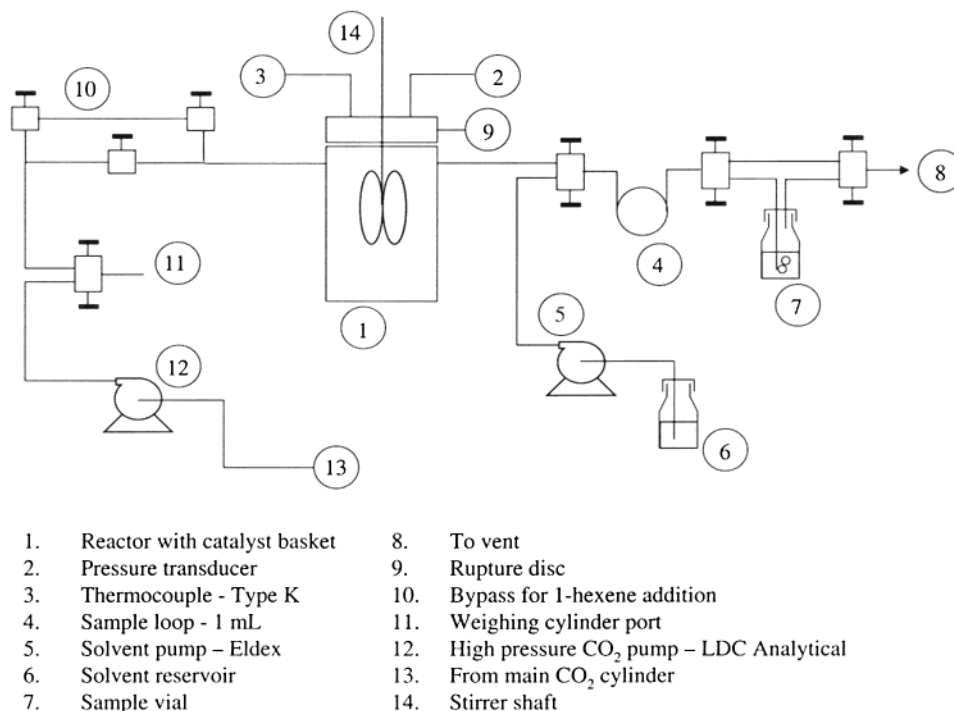‡ Department of Chemistry.

1.	Reactor with catalyst basket	8.	To vent
2.	Pressure transducer	9.	Rupture disc
3.	Thermocouple - Type K	10.	Bypass for 1-hexene addition
4.	Sample loop - 1 mL	11.	Weighing cylinder port
5.	Solvent pump – Eldex	12.	High pressure CO_2 pump – LDC Analytical
6.	Solvent reservoir	13.	From main CO_2 cylinder
7.	Sample vial	14.	Stirrer shaft

Figure 1. Schematic diagram of the experimental apparatus.

90% recovery of unreacted substrate in a $scCO_2$ flow reactor using two-stage depressurization. The combination of a heterogeneous catalyst and a SCF solvent offers a more economical and efficient process as an alternative to those presently used in industry.

Rathke et al.[12] first reported on the hydroformylation of propene using $scCO_2$ as a reaction solvent. The reaction was catalyzed by homogeneous cobalt complexes and was investigated using high-pressure NMR spectroscopy. No hydrogenation of propene to propane or of the aldehydes to alcohols was found, and 88% yield to butanals was achieved. The rates of reaction were comparable to those obtained in the liquid-phase hydroformylation of 1-octene.

Major efforts have centered on the development of a catalyst complex that is active for hydroformylation, soluble in $scCO_2$, and phase-separable through a pressure change. Rhodium complexes incorporating fluorinated phosphines as ligands[13–15] have been repeatedly shown to give high aldehyde yields with selectivities between 2 and 5 through the reaction of 1-hexene and 1-octene in supercritical CO_2. Interestingly, even insoluble ligands such as $P(OC_6H_4\text{-}4\text{-}C_9H_{19})_3$ and $Ph_2\text{-}PCH_2CH(CO_2\text{--}C_{16}H_{33})CH_2CO_2C_{16}H_{33}$ were active for hydroformylation of 1-hexene, and greater selectivity was achieved as the ligand concentration increased;[16] however, the activities of these systems were lower than those obtained for comparable systems in which the ligand was soluble in the supercritical fluid.[17]

In an attempt to overcome the limitations of solubility and recovery for homogeneous catalysts during hydroformylation in $scCO_2$, investigations of heterogeneous Rh catalysts have recently been reported. A catalyst prepared by grafting N-(3-trimethoxysilyl-n-propyl)-4,5-bis(diphenylphosphino)phenoxazine onto a silica surface was reacted with $Rh(acac)(CO)_2$ to bind Rh to the phosphine[11] and used to achieve octene conversions of up to 14% at $S = 33$. Rhodium supported on activated carbon was prepared through incipient wetness and used in propene hydroformylation in $scCO_2$.[18] Aldehyde

yields were low because of irreversible adsorption onto the support; however, $S = 1.5$ was obtained. In follow-up experiments in which rhodium was absorbed onto nonporous silica supports,[19] aldehyde yields of 20% could be achieved with $1.1 \leq S \leq 2.5$; however, the rhodium was rapidly leached from the catalyst surface.

In the current paper, we continue our investigation of the heterogeneously catalyzed hydroformylation of 1-hexene in supercritical carbon dioxide. In this case, the kinetics of the reaction is evaluated to determine whether a heterogeneous catalyst can be developed that takes advantage of the transport properties of supercritical CO_2 to achieve the selectivity and activity of a homogeneous system with a stable heterogeneous catalyst.

Experimental Section

Catalysts were evaluated by reaction with 1-hexene, carbon monoxide, and hydrogen in supercritical CO_2 using a batch reactor system. A reactor system was constructed around an Autoclave Engineers stirred-batch reactor, as shown in Figure 1 and described in more detail previously.[19]

The catalysts used in this research had an average particle size of less than 100 μm in diameter. A nylon mesh material with an opening of 5 μm was obtained from Spectrum Labs. This material was used to make envelopes in which the catalyst was placed. Welding the seams shut using a variable-wattage soldering iron sealed the catalyst envelopes. In practice, the nylon envelopes demonstrated near 100% containment of the catalyst. The catalyst envelopes were clamped between two heavy-gauge screens, which were mounted on disks fixed to the reactor stirrer shaft.

n-Heptane was used as the internal standard and was added to the reactor by syringe injection through an open fitting prior to final sealing of the reactor. After the internal standard was added, the reactor was sealed, and the gaseous reactants were added.

Before the experimental run, a measured amount of 1-hexene was loaded into a bypass section of tubing. Carbon monoxide and hydrogen were added to the reactor by first filling sample cylinders (Whitey) to 75 bar, weighing the total mass, and then connecting the cylinder to the reactor to transfer the gas. The amount of gas added was taken as the change in mass following the addition. Carbon dioxide was also added to the reactor through the use of sample cylinders. A high-pressure liquid pump (LDC Analytical) was used to fill a 150-mL sample cylinder (Whitey) with liquid CO_2. The filled sample cylinder was connected to the feed side of the liquid pump. CO_2 was then added to the reactor from the sample cylinder using the liquid pump.

After addition of H_2, CO, and CO_2, stirring, and reactor heating were started, and the reactor was brought to 75 °C and a stable pressure approximately 35 bar below the desired reaction pressure. The stirrer was set to 300 rpm for all experiments. After the temperature achieved a stable value, the CO_2 pump was used to pump CO_2 from the second CO_2 cylinder through the bypass tubing, forcing the 1-hexene into the reactor and bringing the reactor to the desired pressure. The time required to add the 1-hexene was less than 5 min in all cases. As the final pressure was reached, the bypass line was sealed, and the CO_2 pump was shut down. This was taken as time zero for the reaction.

Samples were taken during the reactor runs by use of a tubing sample loop. The loop was opened to the reactor and then isolated and vented. The loop was opened to the reactor a second time and then isolated, and then, the contents were expanded through 1 mL of 2-propanol. Duplicate samples were normally collected and showed a high degree of reproducibility. A total of 8−10 samples were taken during each 6−7-h experiment. Each sample resulted in a pressure drop of approximately 1 atm; thus, the total pressure loss in the reactor was normally in the range of approximately 8−10 atm over the course of the experiment, a change of less than 10% of the total pressure in the worst case.

Following a reaction, the heating was stopped, and the reactor was allowed to cool to room temperature, at which point the pressure was drained through the laboratory hood. Once the reactor had reached atmospheric pressure, the reactor cap was removed from the body. The catalyst envelope was removed from the stirrer shaft and weighed. The liquid products at the bottom of the reactor were removed by pipet, placed in a sample vial, and reserved for later GC analysis.

Quantitative analysis was performed using a HP-5890 gas chromatograph, equipped with a 30-m Alltech EC-1 capillary column and a FID detector using He as the carrier gas. Initial temperature was 50 °C for 5 min, followed by a temperature ramp at 10 °C/min to 150 °C, which was held for 5 min. Quantitative measurement of the organic reactants and products was accomplished through preparation of known mixtures of the compounds of interest and *n*-heptane, the internal standard. Calibration was performed from the reactor, using the experimental sampling method to obtain samples of reactants and products dissolved in isopropane and then injected into the GC, to account for any systematic errors in the sampling process.

Catalyst Preparation and Characterization. Tetraethoxysilane (9.00 g, 0.0432 mol, Aldrich Chemical) and $Ph_2PCH_2CH_2Si(OEt)_3$ (1.807 g, 0.0048 mol, United Chemical Technology) were added to 40 mL of 95:5
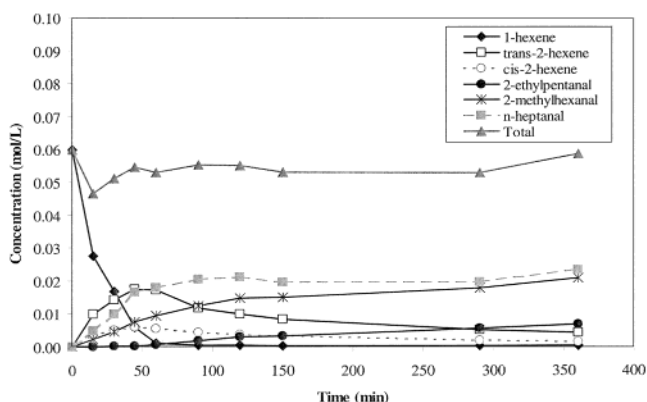

Figure 2. Time course of the reaction species for an experiment conducted at 75 °C and 184 atm, with initial concentrations of [CO] = 1.2 M, [H_2] = 1.17 M, and [1-hexene] = 0.06 M.

ethanol/water under an atmosphere of nitrogen. Acetic acid was slowly added to adjust the pH of the solution to 5.5, and the resulting solution was stirred at room temperature for 2 days. The solution was then heated at 60 °C for about 8 h to evaporate the ethanol. The phosphinated silica thus obtained was dried overnight at 120 °C.

Rhodium incorporation was achieved by stirring a mixture of $Rh_2Cl_2(COD)_2$[20] (COD = 1,5-cyclooctadiene) (0.579 g, 1.16×10^{-3} mol) and the phosphinated support (4.00 g, 4.65×10^{-3} mol of P) in 150 mL of 95:5 ethanol/water under an atmosphere of nitrogen for 6 h. Volatiles were removed in vacuo to yield a yellow solid that was subsequently stored and manipulated under argon or nitrogen.

The presence of intact $Ph_2PCH_2CH_2Si$ moieties on the silica support was verified by CP MAS NMR spectra obtained on a Chemagnetics M200-S spectrometer operating at 50.168 (^{13}C) and 80.756 (^{31}P) MHz. The spinning rate for the samples was 6 kHz. ^{13}C CPMAS NMR spectra confirmed the methylene and phenyl substituents of the $Ph_2PCH_2CH_2Si$ unit. ^{31}P CP MAS NMR spectra exhibited a singlet at −7.8 ppm for the free phosphine. The presence of phosphine oxide in some samples was indicated by a singlet resonance at 43.5 ppm, similar to that reported for $Ph_2P(O)CH_2CH_2Si$ groups bound to silica as prepared by Bemi and co-workers.[21] Rhodium incorporation was evidenced by a shift in the free phosphine ^{31}P NMR resonance from −7.8 to 40.0 ppm upon treatment of the phosphinated support with $Rh_2Cl_2(COD)_2$. Elemental analyses, performed by Schwarzkopf Microanalytical Laboratories, Woodside, NY, confirmed a 2:1 ratio of phosphorus to rhodium in the catalyst samples.

Results and Discussion

All reactions were carried out in a batch reactor, so all data are unsteady state in nature. Figure 2 shows the concentrations of various species for a typical reaction, performed at 184 atm and 75 °C with initial concentrations of [CO] = 1.2 M, [H_2] = 1.17 M, and [1-hexene] = 0.06 M. The 1-hexene is rapidly depleted, reaching negligible concentration after only about 75 min. *cis*- and *trans*-2-hexene are produced rapidly, but then are depleted at longer reaction times, with the *trans*-2-hexene produced in greater yield. The normal and branched aldehyde products, *n*-heptanal and 2-methylhexanal, are also produced in significant yield, and 2-ethylpentanal, a hydroformylation product from 2-hex-
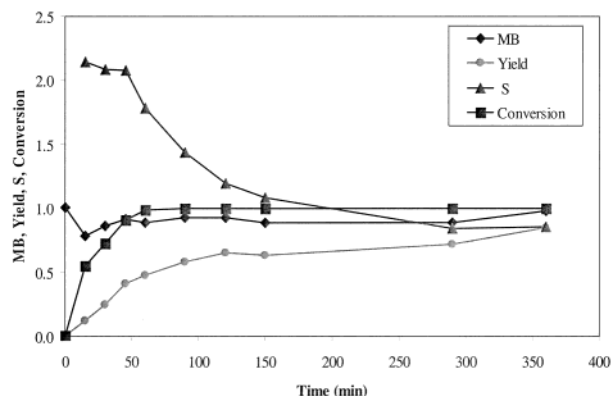
Figure 3. Time course of the reaction showing the change in process variables (alkene conversion, aldehyde yield, selectivity, and total mole balance) from the experiment of Figure 2.

Figure 4. Change in aldehyde yield resulting from repeated experimental runs using the same catalyst sample at constant reaction conditions.

ene, is produced in minor quantities at longer reaction times. The total concentration represents the total concentration of organic species in the reactor at any time and remains near the initial concentration of 1-hexene for the entire duration of the run.

Important performance metrics are conversion, yield, and selectivity, each of which changed with time, as shown in Figure 3 for the same conditions as reported in Figure 2. A mole balance was also calculated for the hydrocarbon components. The conversion of 1-hexene is the amount of 1-hexene that is consumed by the reaction. It is calculated as

$$X_{1-\text{hexene}} = \frac{[1\text{-hexene}]_0 - [1\text{-hexene}]}{[1\text{-hexene}]_0} \qquad (2)$$

Conversion increased monotonically to approximately 1 after about 75 min of reaction time.

The yield is defined as the total aldehyde yield

$$Y = \frac{[\text{heptanal}] + [2\text{-methylhexanal}] + [2\text{-ethylpentanal}]}{[1\text{-hexene}]_0} \qquad (3)$$

The aldehyde yield increased to approximately 0.7 in 150 min and then increased more slowly for the remaining 250 min of reaction. This is consistent with previously reported reaction pathways,[22] which indicated rapid hydroformylation of the terminal alkene to produce normal and branched aldehydes, followed by slower hydroformylation of the internal alkene to produce branched aldehydes only.

The regioselectivity is a measure of the quantity of the desired products relative to the quantity of undesired products formed during the reaction. For the case of 1-hexene hydroformylation, the desired product is the linear aldehyde, n-heptanal. Both 2-methylhexanal and 2-ethylpentanal, the branched products, are also observed. The regioselectivity is defined as

$$S = \frac{[\text{heptanal}]}{[2\text{-methylhexanal}] + [2\text{-ethylpentanal}]} \qquad (4)$$

As shown in Figure 3, the selectivity was initially above 2, in the range expected for rhodium-catalyzed hydroformylation using comparable catalysts.[2] Note that, after 75 min, the selectivity decreased because of hydroformylation of the internal alkene, which cannot yield the desired n-heptanal.
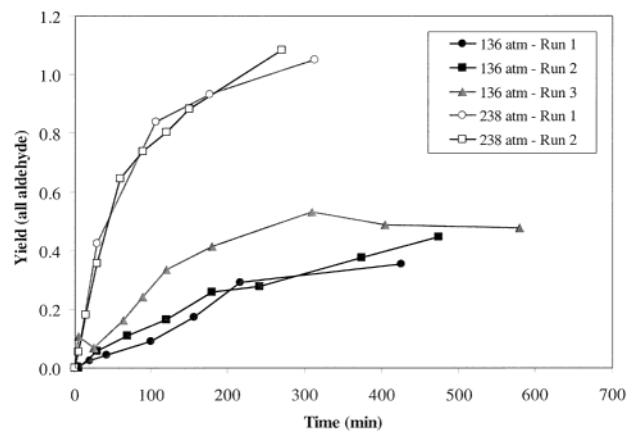
To ensure that the measured concentrations of different species in the reactor were accurate, a mole balance was calculated. Hydrogen and carbon monoxide concentrations were not measured during the reaction, so they could not be included in any balances. Because both the hydroformylation reaction and the isomerization reaction produce only one mole of product for one mole of reactant (excluding H_2 and CO), the quantities of 1-hexene and products at any point can be compared to the initial amount of 1-hexene added to the reactor. Thus, the mole balance was calculated as

$$MB = \frac{[1\text{-hexene}] + [2\text{-hexenes}] + [\text{aldehydes}]}{[1\text{-hexene}]_0} \qquad (5)$$

The mole balance remains near 1 over the course of the reaction, indicating that we observed all of the significant products within the reaction sequence. The small deficit in mole balance observed at 10 min was seen consistently in all experiments and is attributed to heat transfer and phase behavior creating a brief nonuniformity in the system; thus it is not included in our analysis of the results. 1-Heptanol was observed in some experiments but in very low concentrations. In experiments where 1-heptanol was observed, it was not included in calculations of the reaction yield.

One important feature of a heterogeneous catalyst is its stability under reaction conditions. Previous work with rhodium hydroformylation catalysts prepared through wet impregnation showed poor catalyst stability during reaction in $scCO_2$.[19] Nearly complete leaching of rhodium into solution was reported, resulting in poor catalyst performance because of deactivation. However, a stable catalyst has been reported through covalent bonding of the rhodium onto the support.[11] The catalysts used in this investigation were prepared by methods through which the rhodium was covalently bonded to the support through a tethered phosphine group.

To test the efficacy of this method for reducing deactivation by leaching, portions of catalyst were run through repeated reactions. Figure 4 shows the total aldehyde yield for two sets of repeated runs. The first consists of three reactions run using the same portion of catalyst, all at 136 atm and 75 °C. Not only is there no loss of activity (defined as aldehyde yield) over these three runs, representing a total of more than 24 h of reaction time, but the activity actually appears to increase with repeated catalyst use. The second set

Table 1. Summary of Rate Constants Calculated Using Polynomial Regression

| reaction number	concentration (mol/L)			reaction rate (mol of aldehyde)/[(mol of Rh) h]	
	CO	H_2	hexene	n-heptanal	2-methylhexanal
16	0.29	0.30	0.058	24.9	8.7
17	1.22	0.28	0.061	88.5	39.5
18	0.30	1.28	0.059	19.4	7.9
19	1.23	1.17	0.060	122.5	62.5
22	0.31	0.32	0.098	15.6	5.5
21	1.22	0.27	0.097	115.3	42.9
20	0.31	1.19	0.010	145.4	52.4
25	1.18	1.19	0.096	345.5	136.3
27	1.19	1.17	0.080	366.9	146.3
28	0.31	0.96	0.057	82.7	31.2
23	0.75	0.30	0.057	127.0	51.4
29	0.75	0.74	0.079	173.2	67.8
26	0.77	0.74	0.080	238.5	97.5

includes two runs at 238 atm and 75 °C using a separate portion of catalyst, and again, no loss of activity (based on aldehyde yield) was observed during these experiments. Evaluation of the selectivity (not shown) shows comparable results in that the selectivity did not change significantly with subsequent reaction experiments.

We also evaluated the phosphorus and rhodium contents of fresh and used catalyst. The initial phosphorus content was supposed to be 3.6 wt % but was measured at 2.9 wt %. With repeated use, the phosphorus loading decreased to 2.7 and 2.3 wt %, representing a phosphorus loss of approximately 20%. Rhodium analysis also showed a loss of metal from the catalyst with use. For a target Rh loading of 5.4 wt %, an initial loading of 4.2 wt % was measured. The rhodium loading decreased to 3.4 and 2.8 wt % with repeated use, representing a total rhodium loss of approximately 33%. Analysis of other catalyst samples not described in the current work showed little loss of phosphorus but a consistent loss of rhodium, particularly when the rhodium content was high.

In terms of reactivity, the catalyst was stable for repeated use. However, metal loss was also clearly observed. Although we have no direct evidence, we propose that active rhodium was chemically bound to the catalyst support through the phosphorus linkage, whereas inactive rhodium physically adsorbed onto the surface could be leached from the support. Thus, the loss of rhodium did not negatively affect catalyst performance.

Hydroformylation. To compare rates of reaction across different reaction conditions, initial rates of formation for each product were determined. A third-order polynomial was fit to the reaction product concentration data over the course of the reaction. The polynomial was differentiated with respect to time to obtain dc/dt and the derivative was evaluated at $t = 0$ min to give the initial rates of formation of the products. The resulting initial rates are provided in Table 1, in terms of the turnover frequency (h^{-1}) for the formation of n-hexanal and the formation of 2-methylhexanal. The initial rates obtained in supercritical CO_2 are approximately an order of magnitude lower than those expected for hydroformylation in liquid systems using homogeneous catalysts,[2] but they are approximately an order of magnitude greater than reported for vapor-phase heterogeneous catalysis of ethene.[23]

The system kinetics was evaluated by varying the reactant concentrations according to a designed experiment. A 2^3 factorial design was chosen, with the
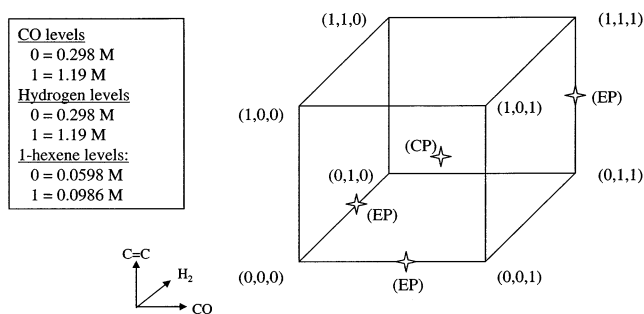
Figure 5. Schematic diagram describing the reactant concentrations used within the N^3 factorial design experiment.
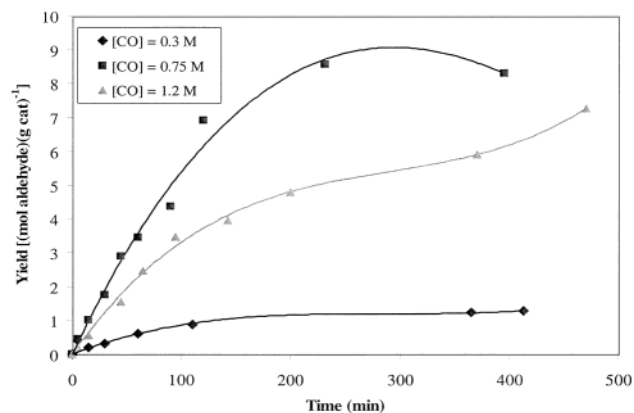
Figure 6. Effect of CO concentration on the yield of aldehyde during the hydroformylation of 1-hexene in supercritical CO_2 at 75 °C and 184 atm; $[H_2]$ = 0.3 M, [1-hexene] = 0.058 M. The curves represent a third-order polynomial approximation of the experimental data.

concentrations of H_2, CO, and 1-hexene as factors. Two levels were chosen for each concentration. This creates a cube in a three-dimensional space where each axis is a species concentration. The experiments to be run are the vertexes of this cube. In addition to the vertexes, the center point, and three edge points of the cube were run. The experiment design and location of the edge points are shown in Figure 5. These experiments were run at 184 atm and 75 °C, using a fresh portion of the Rh/P = 1:2 phosphinated-only catalyst for each test.

The effects of increasing CO concentration can be seen in Figure 6, which shows the temporal variation of aldehyde yield as the CO concentration is increased (184 atm, 75 °C, $[H_2]$ = 0.3 M, [1-hexene] = 0.058 M). The curves in the figure represent the third-order polynomial used to convert the data from concentration to reaction rate, and the upturn in yield at long reaction times is an artifact of the polynomial approximation. Notice that the highest aldehyde yield was obtained at the intermediate CO concentration. Such behavior is typically observed in catalytic systems in which reactants are required to be present and the more strongly bound species competes favorably for binding sites, limiting access of the other species to the catalyst.

The maximum in hydroformylation rates with respect to CO is not surprising. Several rate expressions proposed in the literature are negative-order in CO.[6,23,24] At low CO concentrations, increases in CO concentration are generally reported to increase the rate of hydroformylation. At higher CO concentrations, the catalytic complexes can coordinate excess CO, preventing the
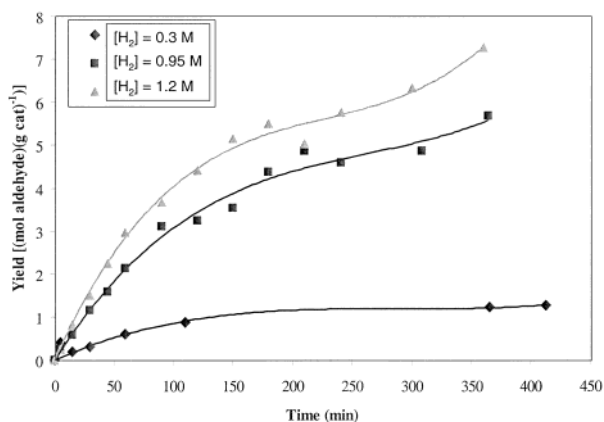
Figure 7. Effect of H_2 concentration on the yield of aldehyde during the hydroformylation of 1-hexene in supercritical CO_2 at 75 °C and 184 atm; [CO] = 0.31 M, [1-hexene] = 0.058 M. The curves represent a third-order polynomial approximation of the experimental data.
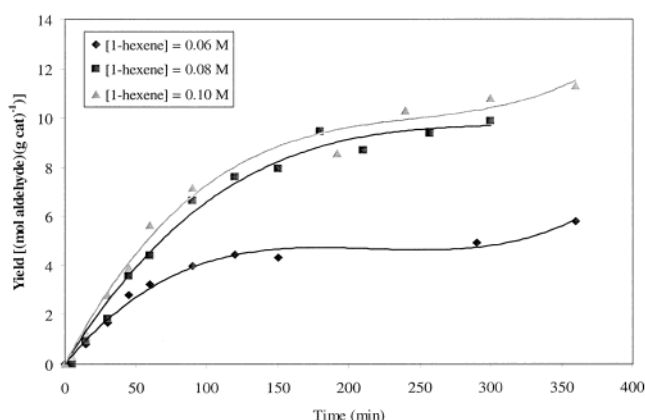

Figure 8. Effect of 1-hexene concentration on the yield of aldehyde during its hydroformylation in supercritical CO_2 at 75 °C and 184 atm; [CO] = 1.18 M, [H_2] = 1.18 M. The curves represent a third-order polynomial approximation of the experimental data.

addition of hydrogen to form the five-coordinate intermediate and the subsequent release of the aldehyde product.

The effect of increasing H_2 pressure on aldehyde yield can be seen in Figure 7 (184 atm total pressure, 75 °C, [CO] = 0.3 M, [1-hexene] = 0.058 M), where once again the curves represent the third-order polynomial approximation of the aldehyde yield. Increasing H_2 concentration increased the yield of total aldehyde, most dramatically between the low and medium levels. Again, it is not surprising to find a positive effect associated with increasing H_2 concentration. The same literature models that use a negative order for CO use a positive order for H_2. It has been proposed in the literature that the addition of H_2 to the acyl rhodium complex is the rate-determining step for aldehyde formation.[2] However, there are other indications that the reaction rate is more complex and that, at elevated pressures, as in the commercial process, the hydroformylation rate should be zero-order in H_2 and first-order in alkene, whereas, at low pressures, it should be first-order in H_2 and zero-order in alkene.[2]

Figure 8 shows the effect of increasing 1-hexene concentration on the aldehyde yield, at 184 atm, 75 °C, [CO] = 1.18 M, and [H_2] = 1.18 M. An increase in 1-hexene concentration increased the aldehyde yield significantly at low concentration and then less so at

higher 1-hexene concentration. This suggests the possibility of a saturation phenomenon in which 1-hexene competes for access to the catalyst, inhibiting the ability of other kinetically significant species to bind to the catalyst complex.

Statistical Analysis. The purpose of running a factorial-designed experiment is to apply statistical techniques to interpret the experimental observations, thus providing information that can be used in the development of an appropriate kinetic model. The interpretation is performed through an analysis of variance (ANOVA), which assigns the variation in the observations to the different factors of the model equation. For an N^3 factorial experiment, the model is shown in eq 6

$$Y_{ijk} = \mu + \sum A_i C_i + \sum B_{ij} C_i C_j + D_{ijk} C_i C_j C_k + \epsilon_{ijk} \quad (6)$$

where Y_{ijk} is the observation, μ is the grand mean for all of the data, A_i is the multiplier for the concentration of species i, B_{ij} is the two-way interaction of C_i and C_j, and ϵ is the error term. Computations were carried out using MINITAB v13.31. MINITAB constructs the ANOVA table for the experimental data and calculates a sum of squared deviations from the mean (SS). A mean square (MS) can be calculated by dividing the SS by the number of degrees of freedom (df). An F test is constructed by dividing each factor or interaction MS by the error MS and comparing to the statistical table. MINITAB reports the P value, or probability that the effect or interaction is *not* significant. For a value to be significant at the 95% confidence level, the P value calculated by MINITAB should be less than or equal to 0.05. The model used above is linear in each factor and interaction. To check for curvature, an experiment at the center point of the design is performed, and a significance test for curvature is computed.

The effect of species concentration on the rate of hydroformylation was evaluated first and revealed that the rate is dependent on the concentrations of H_2 ($P = 0.019$) and CO ($P = 0.024$), but independent of the concentration of 1-hexene ($P = 0.905$) and all interaction terms. A similar analysis was performed to determine the effect of concentration on selectivity, using the rate of formation of n-aldehyde relative to the total rate of aldehyde formation as an indication of the initial selectivity. The selectivity was found to depend on the concentration of 1-hexene ($P = 0.021$) and H_2 ($P = 0.048$), with no dependence on the concentration of CO ($P = 0.208$) or any of the interaction terms.

Following standard procedures,[25] interactions or terms that are not significant can be used as error terms for subsequent analysis. This converts model eq 6 into an alternate linear model

$$Y_{ijk} = \mu + \sum A_i C_i + \sum \epsilon_{ij} + \epsilon'_{ijk} + \epsilon_{ijk} \quad (7)$$

wherein the interaction terms are now included as additional error terms. This grouping of interactions into the error terms increases the degrees of freedom available to calculate the error and increases the ability of the new test to identify the effect of concentration on the initial reaction rate.

The modified analysis was performed by assuming all two-way interactions could be classified in the error term, as described above. Under this assumption, the statistical analysis for the rate of hydroformylation
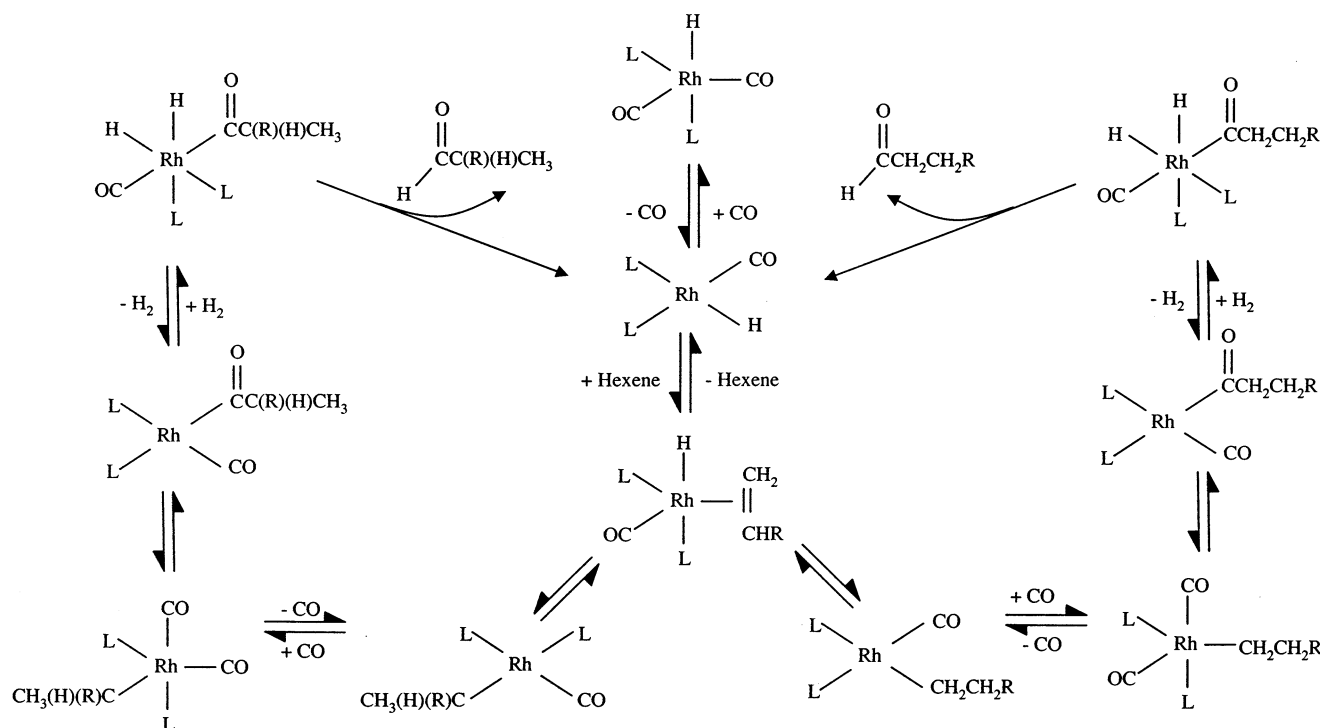
Figure 9. Plausible mechanism for the hydroformylation of 1-hexene, based on the commonly accepted mechanism for homogeneous hydroformylation using rhodium catalysts.[2] Pathways to both linear and branched aldehydes are illustrated. L = phosphine, R = *n*-Bu.

provides results similar to those obtained with the full model, indicating a dependence of the rate on the concentrations of H_2 ($P = 0.010$) and CO ($P = 0.016$) but no dependence on the concentration of 1-hexene ($P = 0.942$). However, the revised assumption suggests that the initial selectivity is independent of all concentration terms ($P_{H_2} = 0.192$, $P_{CO} = 0.572$, $P_{1-hexene} = 0.069$). At no time was any significance associated with the center point term, and the assumption of linearity used in the model was not rejected.

Statistical analysis of the designed experiment suggests that the rate of hydroformylation is dependent on the concentrations of both H_2 and CO but not dependent on the concentration of 1-hexene. However, analysis of the data provided in Figures 6–8 suggests that the yield of aldehyde was dependent on the concentrations of all three reactants and that increasing the concentration of H_2 or 1-hexene increased the aldehyde yield. Thus, the analyses are consistent in their prediction of reaction rate dependence on the concentrations of CO and H_2, although it is not clear whether any dependence on the concentration of 1-hexene can be ascribed.

Kinetics. The Langmuir–Hinshelwood–Hougen–Watson approach to developing kinetics combines the concepts of adsorption on surfaces and surface concentrations of species to develop a set of elementary steps that can describe how a chemical reaction actually proceeds.[26] For the case of the catalysts studied here, surface adsorption is not an appropriate model; however, the same method can be used, substituting a reactant binding to the complex for a species adsorbing to a surface.

Once the set of elementary steps has been produced, a rate expression for each species is written using the individual steps. Many of the species are intermediates or species adsorbed on surfaces that cannot be measured directly. These unknown quantities must be expressed as groups of constants and expressions containing

measurable quantities so that the kinetic model can be compared to experimental data. Different assumptions of a rate-determining step (RDS) can be applied, and so, different rate expressions developed. These expressions can be tested against the experimental data to determine whether a certain mechanism is suggested.

For a complex reaction system, the process of reducing the ultimate rate expression to one in which only measurable quantities appear can be challenging or even impossible. The 1-hexene hydroformylation system investigated here is a complex system, including isomerization of the reactant through the formation of numerous intermediate species. To reduce the complexity, the concentration data were used to model initial rates only. This permits a significant reduction in the complexity of the elementary set by eliminating the reversibility of the substrate isomerization, as well as eliminating the internal alkene hydroformylation. Figure 9 shows a diagram of the limited reaction system based on the generally accepted mechanism for homogeneous hydroformylation.[2]

A rate expression was written for each of the intermediates. The rate-determining step was assumed to be the addition of H_2, so all preceding kinetic steps were considered to be at pseudo-equilibrium. It was thought that the functional form of the expression would be the same regardless of which product was considered and that a good first approximation of the rate of reaction would be obtained by considering only one-half of the mechanism. The final rate expression derived in this manner is

$$(r_{HF})_0 = \frac{K_A[\text{1-hexene}]_0[H_2]_0[CO]_0}{1 + K_C[\text{1-hexene}]_0 + (1 + K_B[CO]_0)^2} \quad (8)$$

This model has a positive dependency on the concentration of H_2 and complex dependency on the concentration

Table 2. Model Coefficients, Confidence Intervals, and Errors

model	K_A [(mol/L)$^{-2}$ h^{-1}]	K_B [(mol/L)$^{-1}$]	K_C [(mol/L)$^{-1}$]	K_D [(mol/L)$^{-1}$]	mean error
proposed	1.37×10^9	0.224	56.2	–	0.3319
±95%	3.21×10^8	0.0524	13.1		
Purwanto[6]	2.65×10^8	0	0.344	–	0.3460
±95%	6.46×10^7	–	0.0926		
Chuang[23]	9.17×10^8	0.0170	0.267	12.56	0.2624
±95%	1.81×10^8	0.00336	0.0528	2.487	
Erkey[24]	8.27×10^6	0.0785	–	–	0.3561
±95%	1.96×10^6	0.0186	–	–	

of CO, as suggested by the statistical analysis of the designed experiment described in the previous section.

The proposed model also is functionally consistent with previous hydroformylation models reported in the literature. For example, a semiempirical rate expression for homogeneous hydroformylation of 1-octene using a Rh/TPPTS system,[7] previously provided as eq 1, has a positive dependence on all reactants at low concentrations but inhibition by CO at high concentration of CO. A LHHW model developed for heterogeneous hydroformylation of ethylene over Rh/SiO$_2$[22]

$$(r_{HF})_0 = \frac{K_A[\text{ethene}][\text{CO}][\text{H}_2]}{(1 + K_B[\text{CO}] + \sqrt{K_C[\text{H}_2]} + K_D[\text{ethene}])^2} \quad (9)$$

also shows positive-order dependence on all species at low concentration but inhibition by all species at elevated concentration. More recently, an empirical rate expression was proposed to model the homogeneous hydroformylation of 1-octene in scCO$_2$ using a fluorinated rhodium catalyst[23]

$$(r_{HF})_0 = \frac{K_A[\text{1-octene}]^{0.5}[\text{cat}]^{0.84}[\text{H}_2]^{0.48}}{1 + K_B[\text{CO}]^{2.2}} \quad (10)$$

which again shows positive-order dependence on all reactants at low concentration, and CO inhibition at higher concentration. All of these kinetic models show positive order dependence at low concentration and inhibition by CO at elevated concentration of CO, as expected from the statistical analysis of our reaction data described in the previous section.

Best-fit rate parameters were estimated for each of the kinetic expressions given by eqs 1 and 8–10, using the experimental data reported in Table 1. The rate constants were evaluated using Microsoft Excel Solver, which uses the generalized reduced gradient (GRG2) nonlinear optimization code to perform multiple nonlinear regressions. Estimates of the rate constants were calculated as the values that minimized the relative sum-of-squares error between the model predictions and the experimental rates. The model constants, the mean error, and the 95% confidence intervals are collected in Table 2. Although it is difficult to ascribe significance to the variation in the specific values of the constants within the models, the quality of fit described by the mean error demonstrates the ability of the specific model to predict the experimental data given in Table 1. The proposed model fits the data as well as the Purwanto[6] model for homogeneous hydroformylation; however, both models are slightly less effective than the model of Chuang[23] for the heterogeneous system.

Figure 10 provides a parity plot of the predicted rates vs the experimental rates using the three models that
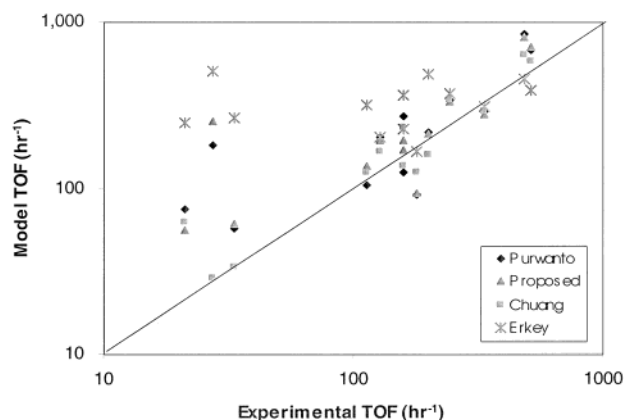

Figure 10. Comparison of proposed model predictions for hydroformylation rate with models previously proposed for heterogeneous vapor-phase hydroformylation of ethylene,[22] liquid-phase hydroformylation of 1-octene,[6] and hydroformylation of 1-octene in supercritical CO$_2$.[24]

adequately describe the data. Here, it is clear that the heterogeneous model of Chuang[23] provides the best approximation to the experimental data, particularly at low values of reaction rate, whereas all four models perform comparably at higher rates. Because the model of Chuang was developed from data obtained at low reaction rate, this model can be expected to provide a better representation of the experimental data in this region. The model developed in this work is roughly equivalent to the model previously used for homogeneous hydroformylation, matching the data equally well over the entire range of reaction rates obtained. Interestingly, the empirical model developed for hydroformylation in supercritical CO$_2$ fails to adequately match the experimental data.

These three reaction rate models, obtained under extremely different reaction conditions and for the hydroformylation of different alkenes, provide roughly equivalent approximations of the experimental data. The aim of using a phosphinated silica support was to produce a heterogeneous catalyst that performed comparably to the conventional homogeneous material. The good fit of both the homogeneous and heterogeneous models is far from conclusive, but it might indicate that the catalyst system studied was truly a tethered homogeneous system.

Conclusions

Tethered homogeneous catalysts were prepared and shown to be active for the hydroformylation of 1-hexene in scCO$_2$. These catalysts exhibited reaction rates that were intermediate between those expected for homogeneous hydroformylation in liquid solution and heterogeneous vapor-phase hydroformylation. The initial selectivities toward the desired product were comparable to literature values for heterogeneous catalysts. In all experiments, significant substrate isomerization was observed. Hydroformylation of the internal alkene led to a decrease in the selectivity at extended reaction time. The catalysts were stable through repeated experimental runs, as evidenced by constant aldehyde yields with repeated use.

A 2^3 factorial-designed experiment was conducted to evaluate the effect of concentration on the initial rate of hydroformylation. The rate of aldehyde formation increased with increases in either the hydrogen or

alkene concentration, but a maximum was observed at an intermediate CO concentration. Analysis of the concentration dependence led to the development of a reaction rate model that was similar in structure to previously reported models for both homogeneous and heterogeneous hydroformylation. Evaluation of the rate constants for these models provided fits of essentially equivalent quality, suggesting similarities in the reaction mechanisms in both the homogeneous and heterogeneous cases.

Acknowledgment

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