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# Simultaneous application of two or more supported liquid-phase organometallic catalysts: heterogeneous multifunctional reaction systems

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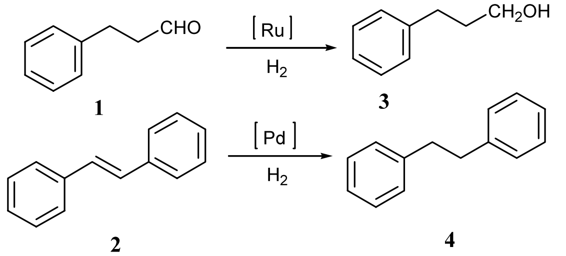
**Abstract**—Using the form of supported liquid-phase catalysts, two or more homogeneous catalysts can simultaneously be used with retaining their own activities and taking the advantage of catalyst–product separation and catalyst recycling. © 2003 Elsevier Science Ltd. All rights reserved.

For the synthesis of desired chemical compounds, it is often necessary for substrates to pass through several reaction and separation steps. It is desirable to use a multifunctional catalyst system for eliminating some of these steps and producing economical benefit. However, this would not be an easy problem to solve with homogeneous organometallic catalysts, since coordination chemistry is normally quite different between the metals to be used.[1] Usually, when two or more homogeneous organometallic catalysts are mixed together, they would lower their respective performance by some negative interactions. There are only a few reports in which a mixture of two homogeneous catalysts is successful.[2] The idea of supported liquid-phase catalyst (SLPC) was proposed by Davis and co-workers to overcome the drawback of homogeneous metal complex catalysts in the separation and recycle of them.[3] In SLPC, a thin hydrophilic liquid film containing organometallic complexes is supported on the surface of a high-surface-area solid. The SLPC is used in a hydrophobic solvent that does not dissolve the film liquid and thus it can be easily separated by simple filtration and recyclable. Recently, it has been reported that SLPC is successfully used for several organic reactions.[4] Besides the advantage in the catalyst separation, the SLPC technique may contribute to the design of multifunctional catalytic systems. Because, when a mixture of two or more different SLPC samples are used in a single reaction system, they may remain being separated by the solvent and hence the interaction between the metal complexes may be avoided. However, this advantage of SLPC has been overlooked for several years. Hence, it is worth investigating such multifunctional catalyst systems using SLPC. In the present paper, the usefulness of this concept has been demonstrated using two model reaction systems such as simultaneous hydrogenation reactions and sequential reactions involving Heck reaction followed by hydroformylation.

As the first example, simultaneous hydrogenation of a mixture of 3-phenylpropionaldehyde **1** and 1,2-diphenylethylene **2** to 3-phenylpropyl alcohol **3** and to bibenzyl **4**, respectively (Scheme 1), was carried out with ruthenium–phosphine complexes and palladium–phosphine complexes. Reaction results obtained are



**Scheme 1.** Simultaneous hydrogenation of 3-phenylpropionaldehyde and 1,2-diphenylethylene.

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**Table 1.** Simultaneous hydrogenation of a mixture of 3-phenylpropionaldehyde and 1,2-diphenylethylene[a]

| Entry | Catalyst | Yield (%) | |
|---|---|---|---|
| | | **3** | **4** |
| Homogeneous | | | |
| 1 | Ru–TPP | 94.1 | 1.0 |
| 2 | Pd–TPP | 0.3 | 98.9 |
| 3 | Ru–TPP+Pd–TPP | 90.1 | 7.8 |
| SLPC | | | |
| 4 | Ru–SLPC[b] | 89.8 | 2.2 |
| 5 | Pd–SLPC[b] | 1.7 | 88.0 |
| 6 | (Ru+Pd)–SLPC[c] | 92.5 | 2.8 |
| 7 | Ru–SLPC+Pd–SLPC | 87.2 | 64.0 |
| 8 | Ru–SLPC+Pd–SLPC[d] | 84.4 | 76.6 |

[a] Solvent (DMF for the homogeneous catalysts and toluene for SLPC), 10 mL; $H_2$, 4 MPa; phenylpropioaldehyde, 7.6 mmol; stilbene, 2.5 mmol; temperature 70°C; time 3 h for the homogeneous catalysts and 4 h for SLPC.

[b] Besides the SLPC sample, 0.5 g of silica containing 0.3 mL of water was added before the reaction.

[c] The catalyst was prepared from an aqueous solution containing both Ru–TPPTS and Pd–TPPTS. Water, 0.6 mL; silica, 1 g.

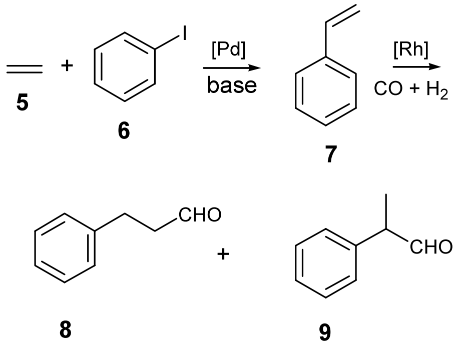
[d] The catalysts for entry 7 was recycled.

given in Table 1[†] and those in homogeneous reactions are described first: with ruthenium–triphenylphosphine (Ru–TPP) catalyst, the hydrogenation of **1** proceeds selectively but the hydrogenation of **2** is not substantial (entry 1). In a reverse manner, palladium–triphenylphosphine (Pd–TPP) catalyst is selectively active for the hydrogenation of **2** (entry 2). When a mixture of Ru–TPP and Pd–TPP is used (entry 3), the yield of **3** is comparable to that obtained with Ru–TPP alone, while the yield of **4** is very low as compared with Pd–TPP alone (entry 2). This means that Pd–TPP becomes much less active by the presence of Ru–TPP, although Ru–TPP is little affected by the presence of Pd–TPP. These observations indicate a limitation of using a mixture of homogeneous metal complex catalysts due to negative interactions between them. Preliminary NMR measurements for Pd species have indicated some differences in $^{31}P$ and $^{1}H$ spectra in the absence (corresponding to entry 2) and presence (entry 3) of Ru species but not for Ru species. The structure of only Pd species may change by the presence of Ru species, resulting in the disappearance of the activity as observed (entry 3).

Instead of homogeneous Ru–TPP and Pd–TPP, SLPC samples including ruthenium–triphenylphosphine trisulfonnate trisodium salt (Ru–TPPTS) and/or palladium–TPPTS in water film on a silica gel were used. Hereafter, these SLPC samples are designated as M–SLPC (M=Ru, Pd, etc.). Ru–SLPC and Pd–SLPC selectively hydrogenate the substrates **1** and **2**, respectively (entries 4 and 5). When Ru–TPPTS and Pd–TPPTS are included in the same supported water film (entry 6), the yield of **4** is low, similar to the homogeneous reaction using both Ru–TPP and Pd–TPP (entry 3). When a physical mixture of Ru–SLPC and Pd–SLPC is used (entry 7), both the yields of **3** and **4** are still high.

The results obtained show that a bifunctional catalytic system can be achieved by using the SLPC technique. After the reaction with SLPC, no metal leaching was observed to occur and the catalysts were easily separated by simple filtration. They were then recycled for another run and retained their initial activity (entry 8). There are differences in the yields between homogeneous and SLPC reactions. This is due to complicated kinetics features of multiphase SLPC reactions. The overall rate of SLPC reaction depends on several factors such as thickness of supporting liquid film, concentration of active species in the film, solid (SLPC) to solvent ratio, and so on, which are not needed to consider in homogeneous reactions.[5] The optimization of those factors is necessary for practical applications.

As the second example, sequential reactions involving Heck reaction and hydroformylation (Scheme 2) have been carried out with Pd–SLPC and Rh–SLPC. In the



**Scheme 2.** Sequential reactions of Heck coupling followed by hydroformylation.

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[†] **Experimental**:

*Preparation of the catalysts*: Ruthenium chloride, palladium acetate (for the hydrogenation), palladium chloride (for the Heck reaction) and $Rh(CO)_2(acac)$, (acac=acetylacetone) were used for the metal precursors. The precursor (0.062 mmol) and TPPTS (0.25 mmol) were dissolved in 0.3 mL of water (for the hydrogenation reactions) or ethylene glycol (for Heck and hydroformylation reactions). The solution was pre-treated at 70°C for 1 h under 2 MPa of $H_2$ (Ru–TPPTS), ambient atmosphere (Pd–TPPTS), or 0.1 MPa of $CO/H_2$ (Rh–TPPTS). Then 0.5 g of a porous silica gel (Aldrich Davisil grade 646) was added into the solution and mixed well to obtain dry powder. For the SLPC samples containing two metal complexes, the metal–TPPTS solutions were pre-treated separately and then mixed before adding silica. Ru–TPP and Pd–TPP were pre-treated in 2 mL of DMF under the same conditions for their analogous TPPTS complexes. The reaction experiments were performed using a 50 mL mechanically agitated autoclave. The catalyst prepared, 20 mL of the solvent, and the liquid substrates were charged into the reactor. After purging with $H_2$, ethylene or $CO/H_2$ several times, the reactor was heated to desired reaction temperatures and the gaseous substrate was further introduced up to desired pressures. For the sequential reactions of Heck and hydroformylation, the reactor was once cooled to room temperature after the former reaction and ethylene remained in the reactor was purged with $CO/H_2$ before the latter reaction. After the reactions, the substrates and the products in the liquid phases were analyzed by a gas chromatograph with FID and mass spectrometer.

**Table 2.** Sequential reactions of Heck reaction of ethylene and idobenzene and hydroformylation of styrene produced[a]

| Catalyst | Heck reaction | Hydroformylation[b] | | |
|---|---|---|---|---|
| | Yield of **7** (%) | Yield of **8** (%) | Yield of **9** (%) | **8**:**9** |
| Pd–SLPC + Rh–SLPC | 50.5 | 29.6 | 60.3 | 0.49 |
| (Pd + Rh)–SLPC[c] | 68.6 | 6.4 | 17.8 | 0.36 |

[a] Ethylene grycol, 0.3 mL; silica 0.5 g; toluene 20 mL; ethylene, 4 MPa; iodobenzene 5 mmol; triethyl amine, 5 mmol; CO, 3 MPa; $H_2$, 3 MPa; temperature, 100°C; time, 45 h (Heck) and 6 h (hydroformylation).

[b] Yields are based on the amount of **7** formed in the Heck reaction.

[c] The catalyst was prepared from an ethylene glycol solution containing both Pd–TPPTS and Rh–TPPTS.

first step, styrene **7** is formed via Heck reaction of ethylene **5** and iodobenzene **6**. Then styrene produced is converted to 3-phenylpropionaldehyde **8** or 2-phenylpropionaldehyde **9**. After the Heck reaction was run under certain conditions, syngas ($CO/H_2$) was introduced and the hydroformylation was run under different conditions. Pd–SLPC and Rh–SLPC are known to catalyze the first and second steps, respectively. This synthetic method is important, since the derivative of **9** can be a potential precursor to produce α-arylpropionic acid derivatives such as ibuprofen and naproxen, which are important anti-inflammatory agents.[6] Reaction results obtained are shown in Table 2.[†] It is seen that the yields of **8** and **9** significantly decrease by using (Pd+Rh)–SLPC instead of the mixture of Pd–SLPC and Rh–SLPC, whereas the yield for the first Heck reaction is not affected by the catalyst system. Thus, the hydroformylation activity of Rh–TPPTS is significantly lowered by the presence of Pd–TPPTS in the same liquid (ethylene glycol) film. Table 2 also shows that the *n*:*iso* ratio of the aldehydes formed also changes by the catalyst system used.

The results obtained in this study clearly demonstrate that effective application of two homogeneous catalysts retaining their individual activities is possible by using the SLPC technique. The concept of multi-functional catalyst system using different SLPC has broad ranging applications, since it allows using two or more metal complexes in the SLPC form in any combination of them. Additionally, SLPC is flexible in adjusting individual metal to ligand ratio and/or one metal to other metal combination ratio. Such cocktails of several metal complexes in the form of SLPC may also give new chemical transformations and contribute to the reduction of reaction steps (reactors).

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