

Catalytic Production of Dimethylformamide from Supercritical Carbon Dioxide

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Many of the chemical substances produced from toxic carbon monoxide could be prepared more safely from carbon dioxide (CO₂), if only the catalytic efficiency of the reductions of CO₂ were enhanced and the cost of hydrogen were lower. It is our contention that the use of supercritical CO₂ (scCO₂) as both reaction medium and reactant¹⁻³ offers significant advantages for the activation of CO₂. scCO₂ is sufficiently liquid-like to allow the dissolution of many organic compounds⁴ and some transition metal complexes,^{1,5} while it is sufficiently gas-like to retain very high miscibility with other gases including hydrogen.⁶ As a result, homogeneous catalysis in scCO₂ can be extremely efficient and rapid, especially for reactions which have both gaseous and organic components. Particularly appealing are reactions in which scCO₂ itself is one of the reactants. We now report a synthesis of *N,N*-dimethylformamide (DMF) from scCO₂ in which the catalytic efficiency is 2 orders of magnitude higher than any previously reported.

Formation of DMF from CO₂, H₂, and dimethylamine is only barely thermodynamically favorable at standard temperature and pressure, and in the actual synthesis, the equilibrium point is delicately determined by the reaction conditions. However, the reaction has proved to proceed smoothly under our conditions. Thus, in the presence of a catalytic amount of RuCl₂[P(CH₃)₃]₄ as a catalyst precursor, scCO₂ reacts with H₂ and dimethylamine to give DMF with up to 370 000 turnover numbers (TON, moles of product/mole of catalyst). Liquid dimethylammonium dimethylcarbamate is used as a source of dimethylamine for experimental convenience. Free dimethylamine gives the same results. The typical synthetic operation is as follows: a stainless steel reactor loaded with dimethylammonium dimethylcarbamate, RuCl₂[P(CH₃)₃]₄, and a stir bar was prewarmed to 100 °C under 40 atm of H₂. The pressure was increased to 80 atm with H₂ and then to a total of 210 atm with CO₂. After the required reaction time, the reactor was cooled first with cold water and then with an acetone/dry ice mixture. The hydrogen was vented and the reactor thawed, the CO₂ venting as it sublimed. The clean and high-yield synthesis of DMF was confirmed by ¹H NMR spectroscopy of an aliquot of the dried product mixture in CDCl₃.

A number of pioneering efforts were made on amide synthesis by homogeneous hydrogenation of CO₂ in the presence of amine

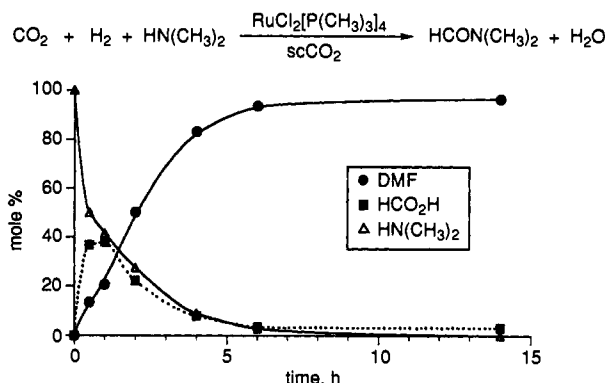
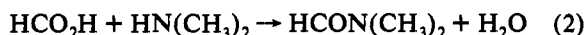
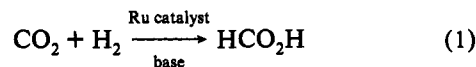


Figure 1. The composition of the product as a function of reaction time for the reaction of dimethylammonium dimethylcarbamate (5.0 mmol), H₂ (80 atm), and scCO₂ (130 atm) at 100 °C catalyzed by RuCl₂[P(CH₃)₃]₄ (2.5 μmol) in a 50-mL vessel.

in liquid solvents,⁷ but the efficiency remained unsatisfactory. We find that the Ru-catalyzed DMF production from scCO₂ has particularly high catalytic efficiency. The conversion of dimethylamine was 99%, and this reaction displayed 99% selectivity for DMF. The product was contaminated with very small amounts of trimethylamine, an over-reduction product,^{7f} and formic acid. An isolated yield of 62 000 TON was attained by running the reaction in a 150-mL vessel using dimethylammonium dimethylcarbamate (88 mmol) and RuCl₂[P(CH₃)₃]₄ (2.5 μmol) at 100 °C for 19 h. At much higher amounts of carbamate, H₂ becomes the limiting reactant; the highest yield obtained under these conditions is 370 000 TON in a 300-mL vessel. This value is far superior to the highest number, 3400 TON (72.5% yield), reported for DMF production from CO₂ in a liquid solvent.^{7c,8} The use of a scCO₂-soluble catalyst is crucially important for this reaction.^{1,2} In fact, the solubility of the Ru catalyst was confirmed qualitatively by passing a scCO₂ solution of the catalyst through a fine filter at 50 °C and 120 atm, and collecting the solid which precipitated at the vent.

The production of DMF from scCO₂ proceeds in two steps. The time-conversion curves in Figure 1 indicate that the fast Ru-catalyzed hydrogenation of CO₂ to formic acid (eq 1)^{1,2} is followed by the slower thermal condensation of formic acid and dimethylamine (eq 2).⁹ Under the reaction conditions, the dimethylammonium dimethylcarbamate is in an equilibrium with dimethylamine and CO₂.¹⁰ Dimethylamine acts as a base to stabilize the formic acid in the first step and serves as a reactant in the second step.



The hydrogenation of scCO₂ to formic acid (eq 1) takes place very efficiently in scCO₂,^{1,2} while the condensation step (eq 2) probably occurs in the liquid phase. The compositions of the liquid and supercritical phases change during the reaction (Figure

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(8) The highest TON recorded in scientific journals was 1460 (% yield not stated) accomplished with Pt₂[(C₆H₅)₂PCH₂CH₂P(C₆H₅)₂]₃.^{7f}

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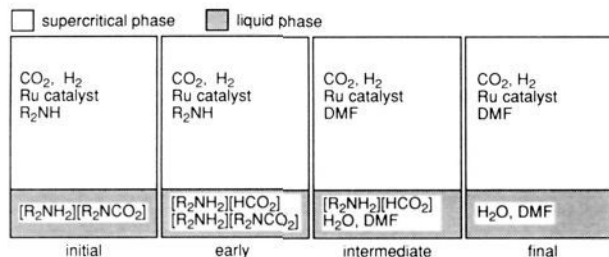


Figure 2. The composition of the phases during the reaction ($R = \text{CH}_3$). The size of the liquid phase is exaggerated; the relative volumes of the supercritical and liquid phases are 84:1 under the conditions of Figure 1 at the start of the reaction.

2). The published^{6b} H₂/CO₂ binary mixture critical pressure and temperature were exceeded in these reactions. Thus the reaction mixture at the start consists of a homogeneous supercritical phase and the insoluble carbamate liquid. The dimethylammonium formate salt and water produced during the reaction are precipitated as a clear liquid. The amounts of liquid carbamate and formate salts decrease as the reactions of eqs 1 and 2 proceed. At the end of the reaction, the water is expected to be mostly in the liquid phase because of its low solubility in scCO₂,⁴ while the DMF product could largely be present in scCO₂ in view of its complete miscibility with liquid CO₂.¹¹

The catalytic efficiency of this synthesis for fixation of scCO₂ exceeds that of the related synthesis of formic acid from scCO₂, H₂, and N(C₂H₅)₃ with the same catalyst.^{1,2} There are two major factors involved. Only small amounts of N(C₂H₅)₃, below the solubility limit in scCO₂, were used in the formic acid synthesis to avoid the possibility of forming a liquid amine phase in which the catalyst would dissolve.^{1,2} For the DMF synthesis, there is

(11) For the solubility of DMF and water in liquid CO₂, see: Francis, A. W. *J. Phys. Chem.* **1954**, *58*, 1099–1114.

no such restriction on the amount of carbamate charged.¹² In addition, the second, condensation, reaction (eq 2) produces water, which prevents the dissolution of the nonpolar Ru catalyst into the liquid phase, thereby keeping its high catalytic activity throughout the reaction.¹² This latter factor increases the efficiency of DMF production to near complete conversion even at high amine:catalyst ratios.

Compared to reported⁷ liquid phase syntheses of DMF from CO₂, the new process is far more efficient. The key issue for the kinetic efficiency is the high rate of eq 1, which is primarily a result of the high H₂ concentration in scCO₂ as well as the lack of unnecessary molecular association around the Ru catalyst.¹ The combination of the two steps, eqs 1 and 2, in a one-pot procedure is also responsible for the high rate of DMF production; such high efficiency cannot be attained by the combination of the two separate synthetic operations, preparation of formic acid and dehydrative condensation of the acid and dimethylamine. Overall, these conditions for DMF synthesis are ideal.

The very high yield and rate of DMF production demonstrate that known homogeneously catalyzed reactions can be greatly increased in efficiency by the use of scCO₂ as the medium for its own fixation. With this improved catalytic efficiency and the lower toxicity of CO₂ compared to CO, the fixation of CO₂¹³ with hydrogen and dimethylamine could become competitive with the carbonylation syntheses of DMF.¹⁴

(12) The Ru catalyst is insoluble in both dimethylammonium dimethylcarbamate and water.

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