Homogenous and Biphasic Catalysis in Dense Phase Carbon Dioxide

Author(s): William Tumas

Submitted to: International Symposium on Supercritical Fluids
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Homogeneous and Biphasic Catalysis in Dense Phase Carbon Dioxide

William Tumas
Los Alamos Catalysis Initiative
Chemical Science and Technology Division
Los Alamos National Laboratory
Los Alamos, NM 87545 USA
email: tumas@lanl.gov, FAX: 505-667-9905

We and others have found that dense phase fluids, particularly carbon dioxide, are effective solvents for a wide range of homogeneous catalytic transformations. A major focus of our recent research program at Los Alamos has been to benchmark the reactivity and selectivity of catalytic reactions in liquid and supercritical carbon dioxide relative to conventional organic solvents, as well as to develop new concepts for catalytic chemistry. We will summarize product distributions, selectivity, kinetics, temperature/pressure effects and mechanistic studies for three important classes of catalytic reactions in dense phase carbon dioxide: selective oxidation; reduction including hydroboration and asymmetric hydrogenation; and carbon-carbon bond forming reactions. We will also report on new systems that incorporate “CO₂-philic” ligands for catalysis as well as newly developed systems which involve either CO₂-soluble polymer-supported ligands or biphasic catalysis in carbon dioxide/water emulsions for enhancing reactivity and separation.

We have been investigating the “pigtail” phosphine ligands, \( R_2PCH_2CH_2R' \) and phosphinites, \( R_2POCH_2CH_2R' \) (where \( R' = \text{perfluoroalkyl} \)) in supercritical \( \text{CO}_2 \). Several examples involving homogeneous catalyzed hydrogenations and hydroboration will be presented to illustrate the versatility of these ligands for controlled variation of the steric and electronic properties of the phosphine, a key element for controlling reactivity and selectivity.

The recent development of surfactants capable of forming emulsions and microemulsions of \( \text{H}_2\text{O} \) in \( \text{CO}_2 \) has led to micellar systems which are good solvents for both hydrophilic and hydrophobic species. We have been examining catalytic reactions using water-soluble catalysts and lipophilic substrates in two-phase systems where the catalyst and product are obtained in separate phases after completing the reaction and decreasing the pressure. For example, we have found that the rates and conversions of the hydrogenation of long chain alkenes using water soluble rhodium-phosphine complexes are significantly higher in \( \text{CO}_2/\text{water} \) emulsions than in two-phase \( \text{CO}_2/\text{water} \) or toluene/\( \text{water} \) mixtures.

In collaboration with Prof. J. DeSimone, we have found that random copolymerization of functionalized monomers with fluorinated acrylate monomers leads to functionalized polymers that are soluble in liquid and supercritical carbon dioxide. We have been able to incorporate a wide range of ligands either in the monomer or through chemical attachment at reactive sites after polymerization. Spectroscopic and reactivity studies of these polymeric systems, which are capable of extracting metal ions into carbon dioxide and supporting catalytic metal sites, will be presented.

INTRODUCTION

We will report on results from an exploratory program at Los Alamos National Laboratory aimed at investigating the use of dense phase fluids, particularly carbon dioxide, as reaction media for homogeneous, heterogeneous and phase-separable catalytic reactions in an effort to develop new, environmentally-friendly methods for chemical synthesis and processing. This approach offers the possibility of opening up substantially different chemical pathways,
increasing selectivity at higher reaction rates, facilitating downstream separations and mitigating the need for hazardous solvents.

Developing and understanding chemical transformations in carbon dioxide could lead to greener chemistry at three levels:

1. Solvent replacement
2. Better chemistry (e.g. higher reactivity, selectivity, less energy consumption)
3. New chemistry (e.g. novel separations, use of CO₂ as a C-1 source).

HOMOGENEOUS CATALYSIS

The last decade has seen enormous growth in the scientific literature on chemical reactions and catalytic processes in supercritical carbon dioxide and other fluids. A recent Chemical Review issue has been dedicated to the field and provides an excellent review of catalytic reactions (1). It is becoming clear that there are a number of avenues to capitalize on the properties of carbon dioxide for new or improved chemistry. An excellent opportunity for identifying potential areas could include one or more of the following:

1. reactions with gaseous reagents such as oxygen or hydrogen (i.e. gas miscibility)
2. reactions involving oxidation, i.e. oxidation stability of the solvent
3. reactions that require hazardous solvents, e.g. some high-value pharmaceuticals
4. reactions that exhibit significant solvent effects, e.g. “pressure tunability”
5. reactions that are highly exothermic, i.e. heat transfer medium
6. reactions that could benefit from enhanced downstream separations

We and others have found that dense phase fluids, particularly carbon dioxide, are effective solvents for a wide range of homogeneous catalytic transformations. A major focus of our research program at Los Alamos over last few years has been to benchmark the reactivity and selectivity of catalytic reactions in liquid and supercritical carbon dioxide by comparing rates and yields of known homogeneous catalytic transformations with those obtained in conventional organic solvents. We will discuss product distributions, selectivity, kinetics, temperature/pressure effects and mechanistic studies of three important classes of catalytic reactions, catalytic oxidations, asymmetric hydrogenations/reductions and carbon-carbon bond
forming reactions. Experimental details and reactor concepts have been described elsewhere (2,3). Reactions investigated to date include:

- dihydroxylation or cleavage of olefins by Ru and Os phase transfer catalysts (2)
- vanadium and titanium-catalyzed epoxidation of allylic and homoallylic alcohols (4)
- iron-porphyrin catalyzed oxidation of cyclohexene (5)
- cobalt-catalyzed ring-opening of cyclohexane to adipic acid (3)
- rhodium and ruthenium catalyzed asymmetric hydrogenation/reduction of olefins (6)
- Lewis acid catalyzed acylations and alkylations (3)
- palladium-catalyzed Stille and Heck coupling reactions (7)
- use of CO₂ as a solvent and reagent for isocyanate synthesis (3) and epoxide ring-opening polymerization (2).

In an effort to capitalize on the oxidative stability of carbon dioxide and its miscibility with molecular oxygen, we have examined a number of catalytic oxidation reactions. We have found that range of catalytic oxidations of alkenes can be carried out in liquid or supercritical carbon dioxide using a range of transition metal complexes and oxidants such as alkylhydroperoxides or oxygen. The rate law for the well-studied vanadium (V) catalyzed epoxidation of allylic and homoallylic alcohols using t-butyl hydroperoxide was found to be the same in CO₂ and several organic solvents. Rates are several times faster in carbon dioxide than hexane and comparable to those measured in toluene (4). In an attempt to use molecular oxygen as the primary oxidant, we have examined the catalytic activity of highly fluorinated iron porphyrins and cobalt acetate, both known autoxidation catalysts in conventional organic solvents. Highly fluorinated metalloporphyrins are soluble in supercritical CO₂ and can catalyze the oxidation of alkenes with molecular oxygen (5). Catalytic amounts of 5,10,15,20-tetrakis(pentafluorophenyl)porphyrinato-iron(III)chloride and 2,3,7,8,12,13,1718-octabromo-5,10,15,20-tetrakis-(pentafluorophenyl)porphyrinato iron(III) chloride react with cyclohexene at 80°C in CO₂ to form products derived from allylic oxidation and epoxidation. Selectivities in carbon dioxide were found to be somewhat higher than those observed in benzene, dichloromethane and acetonitrile. Our results suggest that the selectivity enhancements are likely due to the oxidative stability of carbon dioxide and the lack of unselective chain-carrying radicals derived from the organic solvents.
The design of stereoselective reactions that provide only one of two possible product enantiomers remains a primary goal of modern organic and organometallic chemistry. Asymmetric catalysis, which involves the use of chiral transition metal or main group complexes, has emerged as one of the most powerful, cost-effective methods for the generation of a wide variety of enantiomerically enriched compounds. There has been considerable interest in investigating homogeneous and heterogeneous catalytic hydrogenation reactions in supercritical fluids (1). We (6) and others (8) have found that asymmetric catalytic hydrogenations of prochiral olefins proceed cleanly with high enantioselectivities in supercritical carbon dioxide. Our work has focused on rhodium and ruthenium catalysts containing chiral bidentate phosphine ligands, 1,2-bis(trans-2,5-diethylphospholano)benzene (DuPHOS) or 2,2'-bis(diphenyl-phosphino)-1,1'-binaphthyl (BINAP).

The cationic rhodium catalysts can be made soluble in supercritical CO$_2$ by using the highly lipophilic anion (tetrakis(3,5-bis(trifluoromethyl)-phenyl)borate (B(ArF)$_4$) as the counterion. The ability to solubilize cationic catalysts has broad implications for catalysis in supercritical fluids. A wide range of prochiral unsaturated substrates, including enamides, α-enamide esters and N-acyl hydrazones have been found to under hydrogenation with high enantioselectivity. Of particular note, we have observed (6) enhanced enantiomeric excesses for the β,β-disubstituted α-enamides (Table 1) in carbon dioxide relative to methanol and hexane.
We have also investigated several palladium-catalyzed coupling reactions in supercritical CO₂. Palladium catalyzed carbon-carbon bond forming reactions have found widespread applications in organic synthesis. We have examined ligand effects on the Stille coupling reaction of trimethylvinyltin and iodobenzene (to produce styrene) catalyzed by palladium (0) precursors and added phosphine ligands. While ligands such as triphenylphosphine were found to give low conversions due to catalyst insolubility, fluorinated phosphines, such as tri-(3,5-bis(trifluoromethyl)phenyl)phosphine led to homogeneous solutions and high conversions. Rates in CO₂ were found to be within a factor of two of those measured in toluene. Higher conversions for Heck (4) and Suzuki (9) coupling reactions were also observed for fluorinated phosphine ligands.

The nonpolar nature of dense phase CO₂ can limit the scope of homogeneous catalytic reactions that can be effectively run in this medium to only those which involve nonpolar substrates. Recently, there have been extensive efforts to enhance the solubility and reactivity of homogeneous catalysts in supercritical carbon dioxide by incorporating CO₂-philic moieties into phosphine ligands. Leitner (10) and others (1) have focused on incorporating “ponytails” containing fluoro, fluoroether or siloxane groups into phosphines for catalytic reactions CO₂. The fluorinated ligands were initially advanced by Horvath (11) for reactions in fluorocarbons. We have been investigating the “pigtail” phosphine ligands, R₂PCH₂CH₂Rf and phosphinates,
R_2POCH_2CH_2RF, (where RF = perfluoroalkyl) in supercritical CO_2. Several examples involving homogeneous catalyzed hydrogenations and hydroboration (12) will be presented to illustrate the versatility of these ligands, which are relatively easy to prepare, (13) for controlled variation of the steric and electronic properties of the phosphine, a key element for controlling reactivity and selectivity. For example, we have found enhanced selectivity for rhodium catalyzed hydroborations of styrene derivatives using these ligands. In some cases, the selectivity was found to be higher in sc CO_2 than in fluorocarbon or even tetrahydrofuran as a solvent.

![Chemical structure](image)

Table 2. Selectivities of catalytic hydroboration of vinylanisole in sc CO_2, perfluoro-methylcyclohexane and tetrahydrofuran (40°C, see ref. 12).

<table>
<thead>
<tr>
<th>L (4 mol%)</th>
<th>Conv. (%)</th>
<th>Selectivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>PPh_3</td>
<td>89</td>
<td>14</td>
</tr>
<tr>
<td>P[3,5-(CF_3)_2-C_6H_3]_3</td>
<td>92</td>
<td>71</td>
</tr>
<tr>
<td>P(CH_3C_6H_5F)_3</td>
<td>94</td>
<td>75</td>
</tr>
<tr>
<td>Ph_2POCH_2CH_2C_6F_13</td>
<td>91</td>
<td>82</td>
</tr>
<tr>
<td>Cy_2P_2CH_2C_6F_13</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>Ph_2P_2CH_2C_6F_13</td>
<td>89</td>
<td>90</td>
</tr>
<tr>
<td>Cy_2P_2CH_2C_6F_13</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

'Small amounts of polymeric material are observed.

In addition to developing tunable “CO_2-philic” ligand systems, we have been exploring compressed dense phase dimethyl ether as an alternative solvent as well as phase-separable approaches to increase the range of reactions and substrates which can be carried out in dense phase gases. Dimethyl ether is significantly more polar than CO_2 (14). We have found that liquid dimethyl ether is well suited to reactions that are typically carried out in more polar organic solvents such as diethyl ether or tetrahydrofuran. Conversions and selectivities, as well as measured rates in some instances, will be used to compare the reactivity of a number of homogeneous palladium-catalyzed cross-coupling reactions, including Heck, Stille and Suzuki
reactions. Rates for palladium catalyzed coupling reactions in dimethyl ether rival those measured for tetrahydrofuran (15). Dimethyl ether may be a viable alternative solvent given that it is not peroxidizable (16) and can easily be separated as a gas through pressure changes.

RECENT ADVANCES IN BIPHASIC CATALYSIS

While homogeneous catalysts provide for high reactivity/selectivity and are used in a number of commercial applications, the difficulty of catalyst separation from the product creates increasing economic and environmental barriers to their broader application. Recent advances in phase-separable catalytic systems where the catalyst is immobilized in a phase (liquid or solid supported) distinct from the reactants and products have sparked renewed excitement in applications of homogeneous catalysis for efficient synthesis of a wide range of chemicals in the pharmaceutical and chemical industries. Many of the salient features and future developmental issues of aqueous and nonaqueous biphasic catalysts have been reviewed extensively, most recently in an entire issue of Catalysis Today (17). We have been focusing on biphasic catalysis approaches that capitalize on the ability to control phase behavior, solubility, and mass transfer using dense phase carbon dioxide. We have focused on two areas:

1. Phase-separable catalysis utilizing tailored catalysts and surfactants in CO₂/water emulsions and microemulsions and water-soluble catalysts.

2. CO₂-soluble or swellable polymers chemically modified with ligand sites.

The recent development of surfactants capable of forming emulsions and microemulsions of H₂O in CO₂ has led to micellar systems (18-20) which are good solvents for both hydrophilic and hydrophobic species. We have been examining (with Prof. K. Johnston, University of Texas) catalytic reactions using water soluble catalysts and lipophilic substrates in two-phase systems where the catalyst and product are obtained in separate phases after completing the reaction and changing the pressure. For example, we have found (21) that the rates and conversions of the hydrogenation and hydroformylation of long chain alkenes using water soluble rhodium-phosphine complexes are significantly higher in CO₂/water emulsions than in two-phase CO₂/water (22) or toluene/water mixtures. We will discuss preliminary results on the
effect of surfactant concentration, pressure, temperature, and catalyst on the conversion and selectivity.

In collaboration with DeSimone at the University of North Carolina, we have been investigating the chemical modification of polymers known to be soluble in carbon dioxide (16) in order to develop new ligand systems for metals. We have found (22) that random copolymerization of functionalized monomers with fluorinated acrylate monomers leads to functionalized polymers that are soluble in liquid and supercritical carbon dioxide. We have been able to incorporate a wide range of ligands either in the monomer or through chemical attachment at reactive sites after polymerization. These polymeric systems are capable of extracting metal ions into carbon dioxide, as determined by spectroscopic and extraction methods.

ACKNOWLEDGMENTS

We gratefully acknowledge the following colleagues from Los Alamos National Laboratory for their contributions to this work: Drs. Gunilla Jacobson, Charles Carter, Fuchen Liu, Mike Abrams, Kim Powell, John Brady, John Watkin, Mark McCleskey, and Tom Baker. We also are grateful for our fruitful collaborations with Prof. Joe DeSimone (University of North Carolina), Prof. Keith Johnston (University of Texas), and Dr. Mark Burk (Chirotech). This work is part of the Los Alamos Catalysis Initiative and was funded predominantly by Department of Energy LDRD funding through Los Alamos National Laboratory. We also acknowledge the US EPA Office of Pollution Prevention and Toxics, the EPA Risk Reduction and Engineering Lab and the Green Chemistry Institute for funding portions of this work.

REFERENCES


(15) L. Bohnenn, SPC 1979, 6, 300.