MODELING AND DESIGN OF AN ENVIRONMENTALLY BENIGN REACTION PROCESS

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Abstract

High-pressure carbon dioxide is attractive as an environmentally-benign replacement for organic solvents, such as benzene, in the synthesis of compounds of high chiral purity. Of particular interest here is the allylic epoxidation of *trans*-2-hexen-1-ol to (2R,3R)-(+)-3-propyloxiranemethanol. In the modeling and design of this reaction system, difficulties were encountered when standard tools were used to model the phase behavior of the compounds present. These difficulties are demonstrated by modeling the high-pressure phase behavior of carbon dioxide with *trans*-2-hexen-1-ol and with *tert*-butyl alcohol. Several examples are used to illustrate the problems encountered. The major problems occurred near the three-phase boundary and in the region with retrograde behavior. By using a technique based on interval mathematics, these difficulties were eliminated and correct results obtained. Final results of the phase behavior modeling lead to an improved design that employs a much lower pressure than originally proposed.

Keywords

Phase equilibrium, Environmentally benign processing, Solvent substitution, Supercritical fluids, Interval analysis, Reaction engineering.

Introduction

High-pressure gases and supercritical fluids are attractive substitutes for organic solvents in important chemical reactions. Carbon dioxide is particularly attractive as an environmentally benign solvent. Numerous reactions have been done successfully in liquid and supercritical CO_2, sometimes with rates and selectivities as good as or better than can be achieved in conventional liquids. The solvent properties of CO_2 can be tuned by selecting appropriate operating conditions. Carbon dioxide is also non-flammable, non-toxic and relatively inexpensive. In addition, there is a wealth of literature detailing its physical and chemical properties, and there are numerous studies of binary and ternary mixtures containing carbon dioxide.

Because the solubility of many compounds is rather low in CO_2, high pressures may be needed to achieve reasonable concentrations. Also, because CO_2 may not equally solubilize products and reactants, high pressures are used routinely to guarantee a homogeneous, single-phase reaction process. However, the use of lower pressures may be possible and is desirable to reduce costs and improve safety.

In order to select lower pressure conditions for the reaction, knowledge of the phase behavior of the reaction mixture in carbon dioxide is needed. In the absence of extensive experimental data, a modeling tool should be used to make educated predictions of the most promising conditions. These can then be explored further with a reduced number of experiments. Thus, there is a need for reliable modeling tools that can provide adequate predictions of high-pressure phase behavior.

The reaction process studied here is the allylic epoxidation of *trans*-2-hexen-1-ol to (2R,3R)-(+)-3-propyloxiranemethanol. This was chosen because it is one of a class of industrially important syntheses for producing compounds with high chiral purity. Normally, this reaction has been performed in organic solvents (e.g., benzene), and results in two stereochemical centers formed with very high enantiomeric selectivity. Recently, however, Tumas (1996) has shown that it can also be done in liquid CO_2 at 30°C and 346 bar, also with very high enantiomeric selectivity. Thus, the subject of our study was to determine the phase behavior of the reaction mixture for this process (Fig. 1) in high-pressure CO_2. Titanium (IV) isopropoxide is present as a catalyst; diisopropyl L-tartrate is a ligand used to control chirality; *tert*-butyl hydroperoxide acts as an oxygen donor and renders *tert*-butyl alcohol as a byproduct. The reaction is not equilibrium limited and goes essentially to completion.

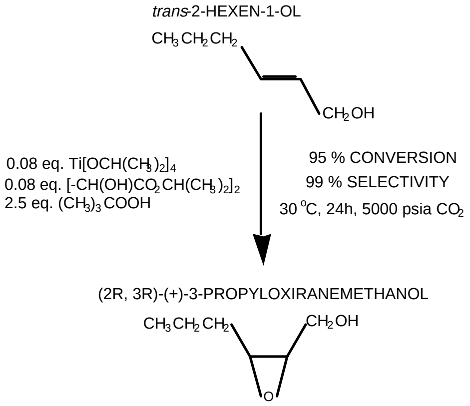

Figure 1. Allylic Epoxidation (Tumas, 1996)

The phase behavior of this system is controlled by multiple interactions on the molecular level. These can be captured, at least partially, by using a cubic equation of state (EOS) model, and by then determining the binary interaction coefficients of each component with CO_2. The intrinsic assumption is that the interactions with the solvent are dominant in determining phase behavior. Since the CO_2 solvent is the major component of the mixture, this represents a reasonable initial assumption. Thus, first the binaries with CO_2 are modeled, and the resulting binary interaction coefficients are then used in modeling the complete multicomponent system.

The modeling of high-pressure phase behavior can be a very challenging computational problem. We present several examples below that illustrate the difficulties that arise in computing the phase equilibrium using standard tools, namely Aspen Plus (Aspen Technology, Inc.) and IVC-SEP (Hytoft and Gani, 1996). In addition, we introduce a new computational tool (INTFLASH), based on interval mathematics, that can handle these difficulties, and correctly determine the phase equilibrium in all cases. We concentrate on the high-pressure phase behavior of carbon dioxide with *trans*-2-hexen-1-ol and with *tert*-butyl alcohol. However, similar computational challenges were found with the other compounds.

Methodology

The Peng-Robinson EOS was used to model both the liquid and gas phases. Standard van der Waals mixing rules were used with a single temperature-independent binary interaction parameter (k_{ij}) for each binary with CO_2. The standard modeling tools were, from Aspen Plus, the FLASH3 module, which can be used for vapor/liquid and vapor/liquid/liquid equilibrium calculations, and the RGIBBS module, which can be used for phase equilibrium or combined phase and reaction equilibrium calculations, and, from IVC-SEP, the two-phase flash routine LNGFLASH, which employs Michelsen's well-known approach. In addition, a new multicomponent, multiphase phase equilibrium routine (INTFLASH), based on interval mathematics, is used.

INTFLASH combines local methods for doing phase split calculations with a global method for verifying phase stability. The key is the use of a technique based on interval analysis in performing the phase stability analysis. This involves the *global* optimization of a tangent plane distance function to verify that the global minimum is nonnegative (otherwise the phase being analyzed will split). By using an interval Newton/generalized bisection technique, the global optimum can be determined *with mathematical and computational certainty*. As applied to EOS models, this approach was first described by Hua *et al*. (1996), with later generalizations and improvements given by Hua *et al*. (1998). By incorporating this technique for global phase stability, INTFLASH provides a guarantee that correct phase equilibrium results are obtained. Complete details of INTFLASH will be provided elsewhere.

Results and Discussion

As noted above, we concentrate here only on the high-pressure phase behavior of CO_2 with *trans*-2-hexen-1-ol and with *tert*-butyl alcohol.. The critical temperature T_c, critical pressure P_c, acentric factor ω, and binary interaction parameter k_{1j} with CO_2 (component 1) of these two compounds are given in Table 1.

Table 1. Properties of Compounds.

Compound	T_C (K)	P_C (bar)	ω	k_{1j}
trans-2-Hexen-1-ol	601.76	36.73	0.724	0.084
tert-Butyl alcohol	506.21	39.73	0.611	0.108

The binary interaction parameters were determined by parameter estimation using experimental VLE data. Details of the physical property determinations are provided in Stradi *et al*. (1998). Phase equilibrium calculations were then done with these model parameters in order to compare the model predictions to experimental measurements. In Table 2, we present the results of some of these computations, focusing on examples of cases in which difficulties were encountered using standard tools.

Referring to Table 2, the first five cases are for CO_2 and *trans*-2-hexen-1-ol at 303.15 K. In discussing these problems it is useful to refer to the P-x-y diagram shown in Fig. 2, which shows both the model prediction and our experimental data. At 303.15 K, the model predicts a three-phase line at 68.8 bar; above this pressure there are two two-phase envelopes, a very small vapor/liquid envelope (shown in the inset) near the pure CO_2 axis, and a larger high-pressure envelope in which the CO_2-rich phase has a liquid-like density. Below the three-phase line, there is a single large vapor/liquid envelope. The model curves were verified by direct examination of the Gibbs energy surface and application of tangent plane analysis. The experimental points follow the low-pressure envelope. This is expected since we used a static measurement apparatus. The high-pressure envelope may be accessible using a variable volume high-pressure cell.

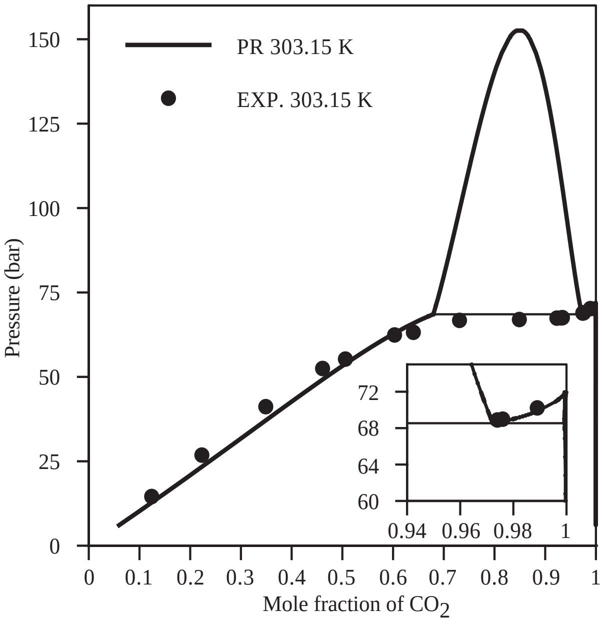

Figure 2. P-x-y plot for trans-2-hexen-1-ol/CO_2.

The first case is at a pressure well below the three-phase line, and all four tools for computing the phase split generate the correct answer. In case 2, at a pressure just below the three-phase line, FLASH3, RGIBBS and INTFLASH converge normally to the correct answer. LNGFLASH indicates correctly that the mixture will split, but it fails to converge to a result for the phase compositions in 1000 iterations. This is unusual, as this code generally converges in well under 10 iterations.

In the third case, the pressure is just above the three-phase line, and the conventional tools LNGFLASH, FLASH3 and RGIBBS all generate the same, but incorrect result. These tools essentially do not "see" the very small vapor/liquid envelope just above the three-phase line. Case 4 is at a pressure just slightly (0.00101 bar) higher than the previous case. FLASH3 and RGIBBS continue to give the wrong result; however, now LNGFLASH does give the correct answer. In general, the unpredictability with which reliable results can be generated was an issue in using all three conventional tools near the three-phase line. Only INTFLASH was consistently reliable.

In the fifth case, the pressure is lower than in the previous two cases, but still above the three-phase line. Here all three conventional tools predict incorrectly that there is no phase split, while INTFLASH gives the correct results. The difficulties encountered by the conventional tools here, and in the previous two cases, appear to be related to the presence of multiple real volume roots from the cubic equation of state near the correct composition of the CO_2-rich phase. In INTFLASH, the existence of multiple real volume roots, and selection of the right ones, is never an issue, since the method automatically uses the right volume roots.

The next three cases also involve *trans*-2-hexen-1-ol, now at a temperature of 323.15 K. At this temperature, we are just above the temperature range in which a three-phase-line is possible. The system has a single two-phase envelope. Looking at these three cases (cases 6, 7 and 8), each of the conventional tools fails once. RGIBBS fails to predict the phase split in case 7, and FLASH3 fails to predict the phase split in case 8. In case 6, LNGFLASH predicts that the mixture will split, but encounters a numerical computation error and does not converge to a result for the phase compositions. This is again indicative of the unpredictability with which reliable results can be obtained using the conventional tools. Again, only INTFLASH solves all the problems correctly.

The final case involves the mixture of CO_2 with *tert*-butyl alcohol at 305.95 K and 74.66 bar. This is in a region of retrograde condensation. Here both FLASH3 and INTFLASH give the correct result. LNGFLASH indicates correctly that the mixture will split, but it fails to converge after 1000 iterations to a result for the phase compositions. RGIBBS fails to predict the phase split.

Multicomponent Phase Behavior

After determining the binary interaction parameters of all reactants and products with CO_2 (Stradi *et al*., 1998), these were used to make predictions of the multicomponent phase behavior, assuming that all other binary interaction parameters were zero. Results indicated that the desired single phase reaction mixture could be maintained at operating pressures considerably lower than the 346 bar originally used by Tumas (1996), in fact as low as about 125 bar. Based on this prediction, Tumas's group at Los Alamos repeated their experiments at a pressure of only 136 bar. Their results confirmed single phase behavior, and also indicated that very high enantiomeric selectivity was maintained. Thus, by using modeling tools to interactively guide experimental work, an improved design was achieved that uses a much lower pressure than originally proposed.

Concluding Remarks

Especially near three-phase regions and regions of retrograde condensation, conventional tools for modeling phase behavior may become unreliable. The unreliability may be manifested in several ways, including convergence failures, computing the wrong number of phases, and computing incorrect phase compositions. From point to point within these difficult regions the reliability of the conventional tools is very hard to predict. Only the new INTFLASH tool was completely reliable, always computing the correct number of phases and phase compositions.

INTFLASH is reliable since it uses interval methods, which eliminate the need for initial guesses and provide mathematical and computational guarantees of reliability, though these guarantees come at the expense of additional computation time (Hua *et al.*, 1998). INTFLASH can also be applied to multicomponent and multiphase (more than two phases) problems. A complementary tool for reliably computing all critical points of mixtures would also be useful in this context. This would establish the limits of stability of mixtures without computation of the entire phase diagram.

The approach to modeling and design used here is simple and readily applicable to other reaction systems involving environmentally benign replacement solvents. Only binary interaction coefficients are needed, many of which can be found in or computed from published data. The results are insightful and allow targeting experimentation time to those conditions most likely to produce good designs.

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Table 2. Examples Showing Computational Difficulties.[1]

	Binary Mixture			LNGFLASH		FLASH3		RGIBBS		INTFLASH	
Case	Feed (z_{CO2})	Temp. (K)	Pressure (bar)	x_{CO2}	y_{CO2}	x_{CO2}	y_{CO2}	x_{CO2}	y_{CO2}	x_{CO2}	y_{CO2}
	trans-2-Hexen-1-ol/CO_2										
1	0.985	303.15	63.819	0.6133	0.9995	0.6134	0.9995	0.6134	0.9995	0.6131	0.9995
2			67.871	**NC1**		0.6686	0.9993	0.6686	0.9993	0.6683	0.9993
3	0.800	303.15	71.00725	**0.7315**	**0.9986**	**0.7310**	**0.9987**	**0.7309**	**0.9987**	0.6846	0.9690
4			71.00826	0.6842	0.9690	**0.7310**	**0.9987**	**0.7309**	**0.9987**	0.6846	0.9690
5	0.700	303.15	70.09	**NPS**		**NPS**		**NPS**		0.6828	0.9702
6	0.970	323.15	97.75	**NC2**		0.6267	0.9948	0.6267	0.9949	0.6281	0.9947
7	0.742	323.15	130	0.7234	0.9554	0.7232	0.9560	**NPS**		0.7240	0.9554
8[2]			135	0.7345	0.9490	**NPS**		0.7347	0.9515	0.7352	0.9489
	tert-Butyl Alcohol/CO_2										
9	0.995	305.95	74.66	**NC1**		0.9935	0.9962	**NPS**		0.9937	0.9963

[1] The mole fractions x_{CO2} and y_{CO2} in each phase are given. Entries in bold indicate incorrect results. The notation NPS indicates that no phase split was predicted. NC1 and NC2 indicate that the program predicted a phase split, but that the phase split calculation did not converge. With NC1 there was no convergence after 1000 iterations, and with NC2 numerical computation error occurred, the program generating the result NaN (not a number).

[2] RGIBBS gives an answer but with an error message.