Transesterification between Ethyl Acetate and *n*-Butanol in Compressed CO_2 in the Critical Region of the Reaction System

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The critical parameters, phase behavior, and density of the reaction system for the transesterification between ethyl acetate and *n*-butanol in compressed CO_2 was determined. The isothermal compressibility K_T of the reaction system was calculated using the density data. On the basis of the phase behavior, the equilibrium constant K_x of the reaction at different conditions was measured, and the effect of pressure and composition on the K_x was studied in the critical region and outside the critical region of the reaction system. The Peng−Robinson equation of state was used to predict the K_x at different conditions. It was demonstrated that the K_x was very sensitive to pressure as the reaction mixture approaches the critical point (CP), bubble point (BP), and dew point (DP) in the critical region, whereas the effect of pressure on K_x was not significant outside the critical region. The sensitivity of K_x to pressure is closely related with the K_T of the reaction mixture. It is interesting that the K_x increases significantly as the pressure approaches the DP and CP, whereas it decreases as the pressure approaches the BP; i.e., pressure has the opposite effect on the K_x in the subcritical region and in the supercritical region. The Peng−Robinson equation of state can predict the K_x far from the critical region satisfactorily. However, the difference of the predicted results and the experimental data becomes larger as the reaction system approaches the CP, BP, and DP in the critical region. All the phenomena may be related with the special intermolecular interaction in the critical region, which affects the fugacity coefficients of the reactants and products. The results of this work also illustrate that the reaction can be carried out in the critical region with a suitable amount of CO_2, whereas this is impossible without the solvent. Therefore, the clean solvent can also be used as a green solvent to adjust the critical point and phase behaviors of the reaction system, so that the reaction can take place in the critical region, and the reaction can be tuned effectively by pressure. Reaction in the critical region of the reaction mixtures is an interesting field where lots of new concepts and new experimental findings are to be investigated.

1. Introduction

In recent years, increasing numbers of chemists have begun to study reaction chemistry in supercritical fluids (SCFs).[1] Some have been attracted by the possibility of using environmentally benign SCFs to replace organic solvents, whereas others have been driven by inherent scientific interest. There are some unique advantages to conduct chemical reactions in SCFs, especially in the critical region.[2] For example, reaction rates, yields, and selectivity can be adjusted by varying the pressure; SCFs (such as CO_2, H_2O) can be used to replace toxic solvents; mass transfer is improved for heterogeneous reactions; and simultaneous reaction and separation may be accomplished for some reactions. It is not surprised that in recent years the use of SCFs, especially supercritical CO_2 and H_2O, as solvents for chemical reaction media has received much attention; this topic has been reviewed,[3] and there are some books.[4]

The features of the reactions in SCFs are closely related with the special intermolecular interactions. Up to now many techniques have been used to study the intermolecular interactions and microstructures of SCFs and dilute SC solutions, such as spectroscopy,[5] small-angle X-ray scattering (SAXS),[6] partial molar volume (PMV) measurement,[7] calorimetry,[8] and theoretical and computer simulation.[9] Many results indicated that the local densities of the SC solvent and the cosolvent around the solute molecules differ from those in the bulk, which is often referred to as local density enhancement and/or local composition enhancement, or clustering. Many researchers have discussed the effect of inhomogeneities or “clustering” on the thermodynamic[10] and kinetic[11] properties of reactions in dilute SC solutions. This is a very interesting question that needs further investigation, even the concentration of the reactants is very low. Collins et al.[12] investigated the disproportionation of toluene at conditions near the critical point of toluene. They found that the selectivity for the commercially desirable product, *p*-xylene reaches a maximum near the critical region, which could be attributed to clustering near the critical point. Hou et al.[13] carried out the esterification reaction of acetic acid with ethanol in compressed CO_2 at 333.2 K, and they reported that the apparent equilibrium constant varied considerably as the reaction mixture changed from a one-phase region to a two-phase region.

Researchers often use the phase diagram of a pure substance to discuss what is SCF. This is reasonable because “supercritical” has clear meaning for a pure substance. A pure SCF has some unique features, especially near its critical point.[2,14] The solvent properties (e.g., density, dielectric constant, solubility parameter, diffusivity) are sensitive to pressure. Therefore, pressure is an effective variable factor to optimize the operating conditions in the applications. However, a SCF loses most of these features as it is far from the critical point. One can approximately assume that a reaction takes place in a SCF when the reaction temperature and pressure are higher than the critical temperature and critical pressure of the solvent when the concentrations of the reactants or the products are low. In

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practice, however, the concentrations of the reactants and the products are not low during the reaction processes for most reaction systems. In this case, the critical parameters and phase behavior of a reaction system may differ from those of the solvent significantly because the critical parameters and phase behavior of a mixture depends on the properties of components and its composition.[15]

Scientists know pure SCFs or dilute SC solutions much better than the complex mixtures in the critical region. Recently, the phase behaviors of some reaction mixtures have been studied.[16] To explore the advantages of the reactions under supercritical condition or in the critical region, the critical parameters and phase behavior of the reaction mixtures should be considered, and reaction properties and the phase behavior of the reaction systems should be combined in the study. In this work, we show the first example of how pressure and composition of a complex reaction system affect the equilibrium constant above the CP, BP, and DP of the reaction mixture, and the transesterification between ethyl acetate and *n*-butanol in compressed CO_2 is studied, which can be expressed as

$$CH_3COOC_2H_5 + n\text{-}C_4H_9OH \xleftrightarrow{\text{compressed } CO_2} CH_3COOC_4H_9 + C_2H_5OH \quad (1)$$

There are three reasons for selecting the transesterification reaction: (1) The reaction is reversible and the side reaction is negligible. Therefore, we can study how the phase behavior affects the equilibrium constant. (2) The total number of molecules does not change with conversion in a batch reactor, which simplifies the expression of the phase diagram of the reaction system. (3) It can be expected that the phase behavior of the reaction system may not change considerably with conversion because the reactants and the products have similar physical and chemical properties. This allowed us to study how the equilibrium constant changes as the pressure approaches the CP, BP, and DP of the reaction system.

This work also shows an example that the reaction can be carried out in the critical region with a suitable amount of CO_2, whereas this is impossible without the solvent. In other words, the clean solvent can also be used as a green solvent to tune the critical point and phase behaviors of the reaction system, so that the reaction can take place in the critical region, and the reaction can be tuned effectively by pressure.

2. Experimental Section

Materials. CO_2 was supplied by Beijing Analytical Instrument Factory with a purity of 99.995%. *n*-Butanol, ethanol, ethyl acetate, and butyl acetate were A. R. grade produced by Beijing Chemical Plant. Nafion film was purchased from Aldrich. All were used without further purification.

Nafion film was a perfluoropolymer and its properties were reported by other authors.[17] We used Nafion film as catalyst because it was not soluble in the reaction mixture. Therefore, it did not influence the phase behavior of the reaction mixture.

Apparatus and Procedures. The schematic diagram of the apparatus is shown in Figure 1. It was similar to that used previously for determining the phase behavior, critical points, and density of mixtures.[18] The main difference was that a sampling unit was added in this work. It could be used to determine the bubble point, dew point, and critical point of the reaction system and could sample the reaction mixture. Briefly, it consisted mainly of a high-pressure view cell, a constant temperature water bath, a CO_2 bomb of 35 mL, a sample-collecting bomb of 11 mL, a pressure gauge, and a magnetic stirrer. The high-pressure view cell was composed of a stainless steel body, a stainless steel piston, and two borosilicate glass windows. The volume of the cell could be changed in the range from 20 to 50 mL by moving the piston. The cell was immersed in a constant temperature water bath controlled by a Haake-D3 temperature controller, and the temperature was measured by an accurate mercury thermometer with the accuracy of better than ±0.05 K. The pressure gauge was composed of a pressure transducer (FOXBORO/ICT Model 93) and an indicator. Its accuracy was ±0.025 MPa in the pressure range 0−20 MPa.

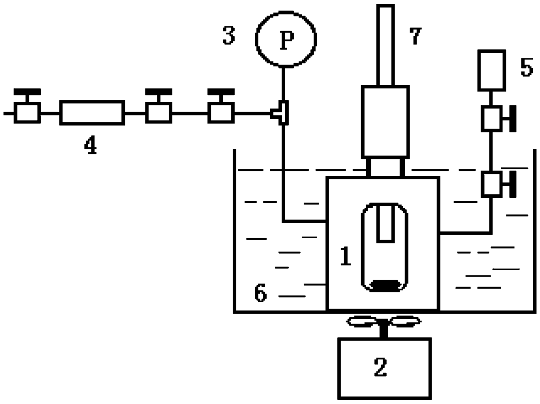

Figure 1. Schematic diagram of the experimental apparatus: (1) high-pressure view cell; (2) magnetic stirrer; (3) pressure gauge; (4) CO_2 bomb; (5) sample collecting bomb; (6) constant temperature water bath; (7) piston.

Only the experimental procedures to study the reaction are described because the procedures to determine the phase behavior and density were simpler and were the same as that described previously.[18] In a typical experiment, Nafion strips were placed into the view cell. The air in the system was removed by vacuum pump. The desired amount of ethyl acetate and *n*-butanol were charged. A suitable amount of CO_2 was then introduced into the cell with the CO_2 bomb. The amount of CO_2 charged was known from the masses of the bomb before and after charging the CO_2. The mole fraction of CO_2 in the reaction mixture was calculated on the basis of the quantities of the chemicals charged. The temperature of the water bath was controlled at 329.9 K. The system was compressed by moving the piston until the desired pressure was reached. The sample was collected after the system had been equilibrated for a suitable time. During the sampling process, the pressure of the system remained constant by moving the piston. The reaction system was equilibrated at another pressure and the sample was collected. The reaction equilibrium could be reached after a reaction time of 24 h, which was known from the fact that the composition of the reaction system remained unchanged with time after 24 h at a fixed pressure. It should be mentioned that we paid much attention to safety because the experiments were carried out at high pressure.

All the samples were analyzed by GC (Angilent 4890D) with a FID detector and a capillary column (Innowax, 30 m × 0.25 mm × 0.25 μm).

3. Results and Discussion

General Idea and Principle. The critical parameters of a mixture change with composition and are usually different from those of the components. This can be explained simply by a typical pressure versus composition ($P-X$) phase diagram of a binary system, as shown in Figure 2. X_1 is the mole fraction of the light component; C_1 is the critical point at $T = T_1$. ABC_1 is bubble point curve at this temperature, and C_1DA is the dew

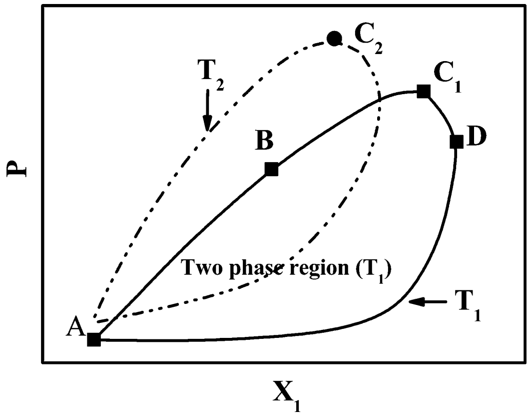

Figure 2. *P*−*X* phase diagram of binary mixture ($T_2 > T_1$).

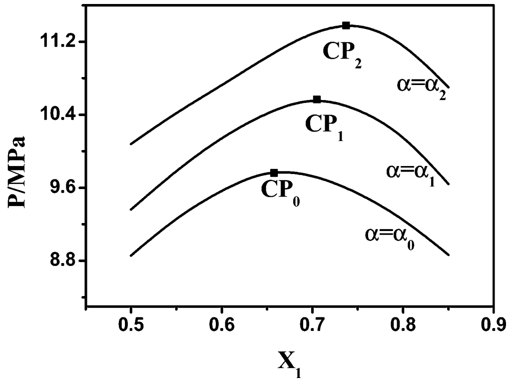

Figure 3. Effect of conversion α on the phase behavior of reaction system at constant temperature. α_0, α_1, and α_2 stand for different conversions.

point curve. Generally, a mixture above the bubble point curve can be regarded as a homogeneous subcritical fluid, and a homogeneous mixture with $X_1 > Xc_1$ is considered as a vapor or a supercritical mixture. The mixture where both composition and pressure are close to the critical point can be regarded as being in the near critical region.

The critical pressure and critical composition at T_2 (the dotted line) are different from those at T_1, as qualitatively shown in Figure 2 ($T_2 > T_1$). Many books and papers have discussed similar phase diagrams of mixtures in details.[19] We only emphasize that critical parameters and phase behavior of a mixture depend on the properties of the components and the composition of the mixture, and the phase diagram will be more complex with increasing number of components.

The phase behavior of a reaction mixture is different from those commonly studied in that its composition changes with reaction time or conversion. Therefore, the phase behavior of the system changes with conversion at fixed temperature. Figure 3 illustrates the principle about the effect of conversion on the phase behavior of a reaction system in which the total number of molecules in the system is not changed during the reaction like transesterification reactions. X_1 is the mole fraction of the solvent. The curves in the figure are isoconversion curves; i.e., the conversion on each curve is the same. For example, the curve at $\alpha = \alpha_0$ indicates how the phase separation pressure changes with the concentration of the solvent as conversion is zero, and CP_0 is the critical point. Similarly, the curve at $\alpha = \alpha_1$ shows the phase separation pressure as a function of solvent concentration at $\alpha = \alpha_1$. Obviously, the phase behavior and the CP of a reaction change with conversion at fixed temperature. We can study how the composition and pressure affect the thermodynamic and kinetic properties of the reaction in the critical region of the reaction system if the CP, BP, and DP are not sensitive to conversion.

TABLE 1: Critical Parameters of the Reaction System at Different Conversions[a]

conversion (%)	T_c (K)	P_c (MPa)	D_c (g/mL)
0	329.7	9.92	0.561
30	329.7	9.93	0.556
50	329.9	9.91	0.557
70	329.9	9.90	0.558
100	330. 0	9.95	0.557

[a] The initial molar fraction of CO_2:$CH_3COOC_2H_5$:C_4H_9OH = 0.94:0.03:0.03.

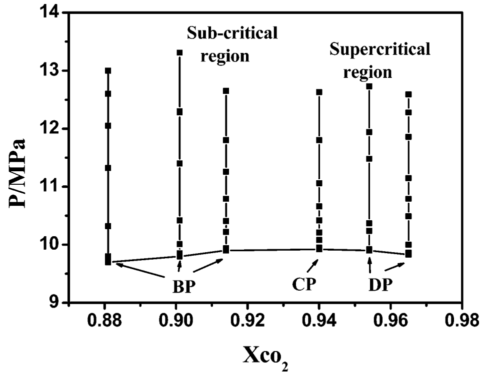

Figure 4. Effect of conversion (α) on the phase behavior of the reaction system at 329.9 K. The curves at α = 0, 0.2, 0.4, 0.6, 0.8, and 1.0 overlap; the vertical lines are experimental conditions for reaction experiments.

Phase Behavior of the Reaction System. The reaction is expressed by eq 1. We determined the critical parameters and phase behavoir of the reaction system by simulating the compositions of the reaction system at different conversions. There are three components in the reaction system before reaction, CO_2, $CH_3COOC_2H_5$, and C_4H_9OH, and there are five during the reaction process, CO_2, $CH_3COOC_2H_5$, C_4H_9OH, $CH_3COOC_4H_9$, and C_2H_5OH. The composition of the reaction system is a function of the original molar ratio (before reaction) of CO_2:$CH_3COOC_2H_5$:C_4H_9OH and the conversion of the reaction. Therefore, the composition of the reaction system at different conversions can be calculated because the original molar ratio of CO_2:$CH_3COOC_2H_5$:C_4H_9OH is fixed. In this work, we determined the critical parameters, DP, and BP of the reaction system by preparing the mixtures using the pure chemicals.

The critical parameters of the reaction system with an original molar ratio of CO_2:$CH_3COOC_2H_5$:C_4H_9OH = 0.94:0.03:0.03 are listed in Table 1. The critical parameters are nearly independent of conversion, as can be seen from the data in the table. For example, the critical temperature varies in the range 329.7−330.0 K in the entire conversion range, which is nearly within the experimental error of this work.

We also studied the effect of conversion on the BP and DP of the reaction system at 329.9 K in the conversion range from 0 to 1, and the total original mole fraction of the two reactants ($CH_3COOC_2H_5$ and C_4H_9OH) changed from 0.03 to 0.12; i.e., the mole fraction of CO_2 changed from 0.97 to 0.88. The molar ratio of the two reactants, $CH_3COOC_2H_5$ and C_4H_9OH, was 1:1 for all the experiments in this work. The constant-temperature phase diagram of the reaction system at various conversions is illustrated in Figure 4. The curve in the figure is the phase boundary. Above the curves is the one-phase region, and below the curves is the two-phase region. As discussed above, the critical region implies that both the composition and pressure

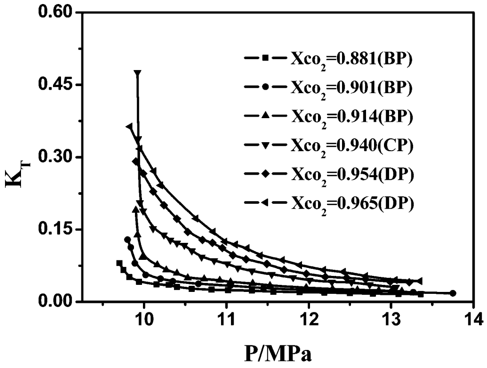

Figure 5. Isothermal compressibility of the reaction system at 329.9 K.

are close to the critical point. Figure 4 demonstrates that the curves at different conversions nearly overlap. In other words, the CP, DP, and BP do not change noticeably with conversion. This is ideal for us to investigate how the composition and pressure influence the reaction in the critical region of the reaction mixture.

Isothermal Compressibility. The isothermal compressibility K_T of a fluid is an important characteristic parameter related to the intermolecular interaction. In this work, we also determined the density of the reaction system at the equilibrium condition. The K_T values of the reaction mixture were calculated using the density data and the following well-known equation.

$$K_T = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_T \qquad (2)$$

where ρ is the density of the fluid. The dependence of K_T on pressure is shown in Figure 5. The lowest pressure in each curve corresponds to the phase separation point (CP, or BP or DP) of the reaction mixture. K_T is very sensitive to pressure near the phase separation points in the critical region, as can be seen from the figure.

Transesterification Reaction. In this work, we focus on how pressure and composition affects the reaction equilibrium constant in the critical region of the reaction system. On the basis of the phase behavior of the reaction system discussed above, we selected some typical conditions to conduct the reaction, which are shown by the vertical lines in Figure 4. These conditions can represent the homogeneous mixtures above the CP, BP, and DP in the critical region and far from the critical region. In Figure 4 a homogeneous mixture is a vapor or supercritical on the right side of the critical point, and on the left side of the critical point, a homogeneous mixture is compressed liquid or homogeneous subcritical fluid when the pressure is higher than the bubble point pressure. All the experiments for the reaction study were carried out in one-phase region.

Figure 6 shows the dependence of the equilibrium constant (K_x), which is defined by eq 3, on pressure at different original molar ratios of CO_2 and the reactants

$$K_x = \frac{X_c X_d}{X_a X_b} \qquad (3)$$

where X_a, X_b, X_c, and X_d are the mole fractions of $CH_3COOC_2H_5$, C_4H_9OH, $CH_3COOC_4H_9$, and C_2H_5OH, respectively.

For each curve in Figure 6, the lowest pressure corresponds to the phase separation pressure, which is similar to the case in Figure 5. In other words, the mixture will separate into two phases (vapor phase and liquid phase) if the pressure is reduced further.

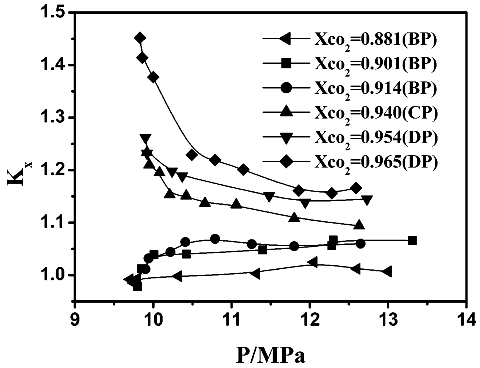

Figure 6. Dependence of equilibrium constant (K_x) on pressure at 329.9 K.

It is interesting that the K_x is very sensitive to pressure as the reaction mixture approaches the CP, BP, and DP in the critical region, where the mole fractions of CO_2 ($X_{CO_2} = 0.965$, 0.954, 0.940, 0.914, 0.901) are equal or close to the critical composition and the pressures are close to critical pressure. In the high-pressure region where the reaction mixture is far from the CP of the reaction system, the effect of pressure on K_x is not significant. It means that the K_x cannot be tuned effectively by changing the pressure outside the critical region.

Extensive experimental and theoretical studies of pure SCFs and dilute SC solutions have shown that there exists local density and/or local composition enhancement in the highly compressible region,[5-9] which is often referred to as "clustering" or "aggregation" between molecules. Compared to the dilute SC solutions, little work has been conducted for studying the intermolecular interactions of the mixtures near their critical region. We believe that the interesting phenomena discussed above must be related to the local density and/or local composition enhancement in the critical region of the reaction system.

It can be known from Figures 5 and 6 that the sensitivity of K_x to pressure is closely related with the K_T of the reaction mixture. The K_T increases sharply as the pressure approaches the CP, DP, and BP in the critical region, and the K_x is very sensitive to pressure. The degree of clustering may become larger as the pressure approaches the phase boundary in the critical region because the K_T becomes larger. The data in Figures 5 and 6 hint that as the clustering in the reaction mixtures nears the CP affects the K_x of the reaction. This will be discussed qualitatively below.

The thermodynamic equilibrium constant can be expressed as

$$K_f = \frac{f_c f_d}{f_a f_b} \qquad (4)$$

where f_i stands for the fugacity of component i. K_f is a function of temperature. K_f can also be expressed as below.

$$K_f = K_x K_\gamma \qquad (5)$$

K_x and K_γ are defined by eq 3 and the following equation, respectively.

$$K_\gamma = \gamma_c \gamma_d / \gamma_a \gamma_b \qquad (6)$$

where γ_a, γ_b, γ_c, and γ_d are fugacity coefficients of $CH_3COOC_4H_9$, C_2H_5OH, $CH_3COOC_2H_5$, and C_4H_9OH, respectively.

K_f is a constant at a fixed temperature, and obviously, K_x will change as K_γ is varied because K_f is a constant. The clustering influences the fugacity coefficients of the reactants and the products, or K_γ. In the critical region, the degree of clustering is large and sensitive to pressure, and thus pressure has a more pronounced effect on the fugacity coefficients of the components. Hence, K_γ or K_x is sensitive to pressure in the critical region.

Figure 6 shows another very interesting phenomenon. The K_x increases significantly as the pressure approaches the DP and CP, whereas it decreases as the pressure approaches the BP. In other words, pressure has the opposite effect on the K_x in the subcritical region and in the supercritical region. Thus, to tune the conversion of the reaction by pressure, it is necessary to conduct the reaction in the supercritical region. The reason is that K_γ changes in the opposite way as the pressure is changed.

At $X_{CO_2} = 0.881$, which is far from the critical composition, the K_x is nearly independent of pressure even as the reaction system approaches the BP, as can be known from Figure 6, indicating that the K_x is sensitive to pressure only when the composition is close to critical composition. A reaction usually has a suitable reaction temperature range. Meanwhile, the critical parameters of a reaction mixture can be adjusted by the concentration of CO_2. Therefore, clean solvents, such as CO_2 and H_2O, can also be used as green reagents to tune the critical points and phase behaviors of reaction systems, so that the reactions take place in the critical region, and the reaction may be optimized effectively by pressure.

It should be emphasized that the effect of pressure on the K_x of the transesterification reaction is not large even in the critical region of the reaction system. The main reason is that the physical and chemical properties of the reactants are similar to those of the products. Therefore, fugacity coefficients of the reactants and the products change in similar ways as the pressure is changed, and thus, the K_γ does not change significantly with pressure, which is not favorable to tuning the conversion or K_x effectively by pressure. On the other hand, the phase behavior of the reaction system is relatively simple compared with many other complex reactions, and therefore we can study the effect of pressure and composition on the K_x in detail. For many other reactions the properties of the reactants and products are quite different. It can be expected that pressure may be a more powerful tool to tune the thermodynamic and kinetic properties in the critical regions of the reaction systems. However, the variation of phase behavior with conversion and pressure will be more complex for these reactions.

Prediction of the Equilibrium Constant. K_f is related to the standard Gibbs free energy change of the reaction by the following equation

$$\Delta G^\circ = -RT \ln K_f \tag{7}$$

K_f depends only on temperature for a reaction. In this work we calculated the ΔG° at the reaction temperature of this work (329.9 K) from the standard Gibbs free energy of formation and standard enthalpy of formation of the reactants and products at 298.15 K[20] and the two well-known equations below.

$$\frac{\mathrm{d}\left(\dfrac{\Delta G_\mathrm{m}^\circ}{T}\right)}{\mathrm{d}T} = -\frac{\Delta H_\mathrm{m}^\circ}{T^2} \tag{8}$$

$$\Delta_\mathrm{r} H_\mathrm{m}^\circ(T) = \Delta_r H_0 + \int_{298.15}^{T} \Delta C_p \, \mathrm{d}T \tag{9}$$

TABLE 2: Standard Enthalpy of Formation (ΔH_f°), Standard Gibbs Free Energy of Formation (ΔG_f°) at 298.15 K, and Dependence of Constant Pressure Capacity (C_p) on Temperature

	ΔH_f° (kcal/mol)	ΔG_f° (kcal/mol)	A^b	B^b	C^b	D^b
ethanol	−56.12	−40.22	2.153	5.113	−2.004	0.328
ethyl acetate	−105.86	−78.25	1.728	9.725	−4.996	6.818
butanol	−65.65	−36.04	0.78	9.984	−5.354	11.19
butyl acetate	−116.26	−74.23[a]	3.253	13.15	−5.442	−0.189

[a] Calculated.[23] [b] $C_p = A + B \times 10^{-2}T + C \times 10^{-5}T^2 + D \times 10^{-9}T^3$, T in K and C_p in cal/(mol·K^{-1}).

The thermodynamic parameters required are listed in Table 2. The calculated value of K_f from eqs 7−9 and the data in Table 2 was 1.146 at 329.9 K. At equilibrium, eq 6 should be satisfied. We used the trial-and-error method to predicate the K_x because both composition and fugacity coefficients are not known in the predication process. Briefly, we first supposed a composition and then K_x and K_γ were calculated. This procedure was continued until eq 5 was satisfied, and the predicated K_x was obtained.

In this work the Peng−Robinson equation[21] was used to calculate the fugacity coefficients, which can be expressed as

$$P = \frac{RT}{V - b} - \frac{a}{V(V + b) + b(V - b)} \tag{10}$$

$$a = 0.457235 \frac{R^2 T_\mathrm{c}^{\,2}}{P_\mathrm{c}} \alpha \tag{11}$$

$$b = 0.077796 \frac{RT_\mathrm{c}}{P_\mathrm{c}} \tag{12}$$

$$\alpha = [1 + m(1 - \sqrt{T/T_\mathrm{c}})]^2 \tag{13}$$

$$m = 0.37464 + 1.54226\omega - 0.26992\omega^2 \tag{14}$$

For a mixture, the van der Waals mixing rules are applied:

$$a = \sum_i \sum_j x_i x_j a_{ij} \tag{15}$$

$$b = \sum_i x_i b_i \tag{16}$$

$$a_{ij} = (1 - k_{ij})\sqrt{a_{ii} a_{jj}} \tag{17}$$

where T_c, P_c, and ω stand for the critical temperature, critical pressure, and acentric factor, respectively. k_{ij} is the binary interaction coefficient. In this work, k_{ij} of $CO_2-CH_3COOC_2H_5$, $CO_2-C_4H_9OH$, $CO_2-CH_3COOC_4H_9$, and $CO_2-C_2H_5OH$ pairs were obtained by correlating the bubble points of the binary mixtures determined in this work using the apparatus and procedures reported previously.[19] For the binary mixtures without CO_2, the k_{ij} values are set to zero because CO_2 is a main component, which is an effective way for complex mixtures, as reported by Poliakoff and co-workers.[16a]

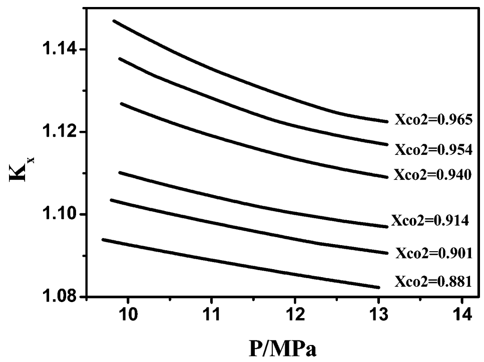

Figure 7. Equilibrium constant (K_x) predicated by the PR equation of state at 329.9 K.

On the basis of the equation of state and mixing rules, the fugacity coefficient of each component can be calculated by the following equation.[22]

$$RT\ln\gamma_i = RT\ln\frac{V}{V-b_{mix}} + \frac{\sum_j x_j a_{ij}}{\sqrt{2}b_{\mathrm{mix}}}\ln\frac{V+(1-\sqrt{2})b_{\mathrm{mix}}}{V+(1+\sqrt{2})b_{\mathrm{mix}}} + \frac{a_{\mathrm{mix}}b_{\mathrm{mix}}b_i}{(\sqrt{2}b_{\mathrm{mix}})^3}\ln\frac{V+(1+\sqrt{2})b_{\mathrm{mix}}}{V+(1-\sqrt{2})b_{\mathrm{mix}}} - RT\ln\frac{PV}{RT} + \frac{b_iPV}{b_{\mathrm{mix}}} - \frac{b_iRT}{b_{\mathrm{mix}}} \qquad (18)$$

The values of K_x predicted are illustrated in Figure 7. Comparing the experimental data in Figure 6 and the predicted results in Figure 7, we can conclude that the predicted results agree well with the experimental data as the reaction mixtures are far from the critical point. However, the difference of the predicted results and the experimental data becomes larger as the reaction system approaches CP, BP, and DP in the critical region. We think the clustering of the molecules in the critical region may be one of the main reasons. The bulk composition is used in the prediction process. This is reasonable as the reaction mixture is far from the critical region because the inhomogeneity in the mixture is not significant. In the critical region, the local density and/or local composition are more pronounced, and the local composition around the reaction species may differ from that of the bulk significantly, and we cannot consider this in the calculation process. Therefore, the difference between the experimental and calculated results is larger.

All the interesting phenomena are related with special intermolecular interactions in the critical region of the mixtures. Reaction in the critical region of the reaction mixtures is an interesting field where lots of new concepts and new experimental findings are to be investigated. Conducting reactions under SC conditions have potential advantages to optimize many reactions effectively and will solve more challenging problems after our fundamental understanding of SCFs improves.

4. Conclusion

The phase behavior, K_T, and the K_x of the reaction system for the transesterification between ethyl acetate and *n*-butanol in compressed CO_2 were studied systematically.

The K_x was very sensitive to pressure as the reaction mixture approaches the CP, BP, and DP in the critical region where both composition and pressure are close to the CP of the reaction mixture. However, the effect of pressure on the K_x is not significant outside the critical region. The sensitivity of K_x to pressure is closely related with the K_T of the reaction mixture. The K_T increases sharply as the pressure approaches the CP, BP, and DP in the critical region, and the K_x is very sensitive to pressure. The K_x increases significantly as pressure approaches the DP and CP, whereas it decreases as pressure approaches the BP; i.e., pressure has the opposite effect on the K_x in the subcritical region and in the supercritical region. To tune the conversion of the reaction by pressure effectively, it is necessary to conduct the reaction in supercritical region. Peng−Robinson equation of state can predict the K_x far from the critical region very well. However, the difference of the predicted results and the experimental data becomes larger as the reaction system approaches CP, BP, and DP in the critical region.

To tune the reaction effectively by pressure, the reaction system should be carried out in the critical region; i.e., the critical parameters of the reaction mixture should be considered. CO_2 not only can be used as a clean medium for chemical reactions but also can be used as green solvent to tune the critical points and phase behaviors of reaction systems, and the reaction may be optimized by pressure effectively. Reaction in the critical region of the reaction mixtures is an interesting field where lots of new concepts and new experimental findings are to be investigated.

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