Reactions in supercritical fluids. A case study of the thermodynamic solvent effects on a Diels–Alder reaction in supercritical carbon dioxide

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Abstract - The fundamental aspects of chemical reaction kinetics at near-critical conditions are discussed within the framework of transition state theory and the thermodynamics of critical phenomena for multicomponent systems. This discussion emphasizes the geometric analysis of Griffiths and Wheeler which describes the manner in which various thermodynamic properties behave on approaching mixture critical points for multicomponent systems. This analysis is used to explain experimental observations of the reaction kinetics for the Diels-Alder cycloaddition reaction of maleic anhydride with isoprene in supercritical CO_2 at conditions near the critical point of CO_2. The practical aspects of supercritical fluids as solvents for reacting systems are also discussed.

INTRODUCTION

Applications of supercritical-fluid (SCF) solvents in extraction processes and other separation processes has been an active area of research and development in the chemical process industries. Another area with potential applications that has not been explored to an appreciable extent, however, is the use of SCF solvents as reaction media. An important characteristic of supercritical fluids as solvents is the ability to manipulate the physico-chemical properties of the solvent with relatively small changes in pressure and temperature. This can affect solubilities, mass transfer, and the reaction kinetics of reacting mixtures dissolved in SCF solvents, and provides the means for controlling yields, selectivities, and recovery of reaction products. For example, Randolph et al. (Ref. 1) have carried out enzymatic catalysis in supercritical CO_2 to exploit the ease with which products can be recovered from dilute solutions when the solvent is compressed CO_2 rather than water. Tiltscher et al. (Ref. 2) exploit both enhanced mass transfer and solubilities in super-critical fluids to maintain catalyst activity during the neat isomerization of 1-hexene on γ-alumina. Rapid catalyst coking results when hexene is present as either a liquid or a gas, but is not detected when hexene is present as a supercritical fluid. Evidently, supercritical hexene prevents catalyst deactivation by removing oligomers which inevitably form as side products of the isomerization. These compounds would otherwise remain on the catalyst surface and cause complete coking. Liquid hexene would also dissolve and thereby remove these oligomers. However, in contrast to supercritical hexene, the removal of oligomeric compounds from the catalyst surface is mass transfer limited in liquid hexene.

Pressure and temperature can also affect reaction kinetics in SCF solvents. The rate of a reaction in a homogeneous, multicomponent system is typically expressed as

$$\text{RATE} = k \prod_{i=1}^{m} C_i^{\alpha_i} \tag{1}$$

where k is the rate constant, C_i is the concentration of species i, and α_i is the reaction order with respect to species i. In general, the rate constant is a function of temperature, pressure, and mixture composition. Thus, pressure and temperature effects on reaction rate can be obtained through both the rate constant and the concentrations of the reacting species, as determined by the PVT properties of the system. For gases at relatively low densities, the rate constant will be a function of temperature, and pressure will affect reaction rates through concentration changes. For liquids, the rate constant will again be a function of temperature; the pressure effects on both rate constant and the concentrations will be minimal, since liquids are essentially compressible. For supercritical fluids, however, pressure and temperature effects on the rate constant and on the concentrations of reacting species can be substantial, particularly when the fluid is highly compressible (i.e., near the critical point of the SCF solvent).

Pressure and temperature effects on concentrations are important when the SCF solvent is also a reactant. For example, experimental studies (Ref. 3) on the pyrolysis of coal model compounds in supercritical water has shown that enhanced conversion to products and different product spectra relative to neat pyrolysis are obtained with increasing pressure. Since, at high water concentrations, hydrolysis of the coal model compounds competes with pyrolysis, these observed pressure effects can be related to the increase in water concentration at elevated pressures.

For inert SCF solvents, the effect of pressure on rate constant can be significant at conditions near the critical point of the solvent. The objective of this study is to determine the extent to which pressure can be used to control reaction rates in SCF mixtures at elevated pressures. At present, this determination is limited by the small number of experimental studies which have been carried out on well-characterized reacting systems in SCF solvents at elevated pressures, and the inadequacy of current thermodynamic models for describing the high-pressure phase equilibria of such systems, particularly at conditions near the critical point of the solvent. The approach taken in this work is to study reaction kinetics for dilute solutions of reactants at conditions near the critical point of the solvent. Experimental rate data are presented for the Diels-Alder cycloaddition reaction of maleic anhydride with isoprene in supercritical CO_2. Fundamental aspects of kinetic behavior near critical points are also discussed within the framework of transition state theory and the thermodynamics of critical phenomena for multicomponent systems.

DIELS-ALDER REACTION

The Diels-Alder reaction involves the addition of an alkene or alkyne to the 1,4 positions of a diene. The simplest example of this reaction is the addition of butadiene and ethylene to form cyclohexane.
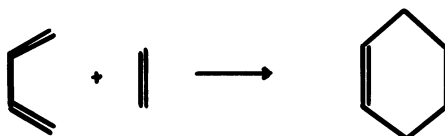
Diels-Alder reactions are of considerable interest in synthetic organic chemistry. Numerous patents cite the use of Diels-Alder chemistry in the synthesis of complex compounds including insecticides (Ref. 4), fragrances (Ref. 5,6), plasticizers (Ref. 7), and dyes (Ref. 8).

Aside from their commercial interest, Diels-Alder reactions are also excellent candidates for fundamental studies of well-characterized reacting systems. These reactions are specifically cited as a class of reactions in which the rates and activation energies are similar in the gas phase and in inert liquid solvents, implying no change in mechanism between these two cases (Ref. 9). Diels-Alder reactions are bimolecular, and have no significant side reactions (Ref. 10). Liquid solvent effects on these reactions have also been characterized extensively (Ref. 11-14), and experimental data on reaction rates at elevated pressures in several liquid solvents are available for the cycloaddition of isoprene and maleic anhydride (Ref. 15). Rate constants for this particular cycloaddition reaction have also been measured at conditions near the upper critical solution temperature of the solvent mixture hexane-nitrobenzene (Ref.16).

EXPERIMENTAL SECTION

The experimental methods used in this study are described in detail elsewhere (Ref. 17). Both kinetic measurements of reaction rates and equilibrium measurements for phase diagrams are presented below.

Phase diagrams were determined for two binary mixtures: CO_2-maleic anhydride and CO_2-methylcyclohexene dicarboxylic anhydride (the adduct for the maleic anhydride-isoprene cycloaddition reaction). These diagrams are presented as PT projections at conditions near the critical point of CO_2, and depict various three-phase (solid-liquid-gas, solid-liquid-liquid, and liquid-liquid-gas) equilibrium curves, four-phase (solid-liquid-liquid-gas) equilibrium points, and upper critical endpoints (gas-liquid critical points in the presence of a third equilibrium phase). Measurements of three- and four-phase equilibrium temperatures and pressures were made while observing the equilibrium phase behavior in a high-pressure view cell. Upper critical endpoint temperatures and pressures were measured the same apparatus by observing critical opalescence.

The resulting PT projections for maleic anhydride-CO_2 and methylcyclohexene dicarboxylic anhydride-CO_2 are shown in Fig. 1 and 2, respectively. These phase diagrams are quite similar. Both maleic anhydride and the adduct have triple point temperatures above the critical temperature of CO_2, and both compounds exhibit an appreciable freezing point depression in the presence of CO_2 at elevated pressures. These freezing point depressions are represented by the three-phase, S_2L_2G (solid-liquid-gas) equilibrium lines which originate at the triple point of either maleic anhydride or the adduct, and terminate at quadruple or
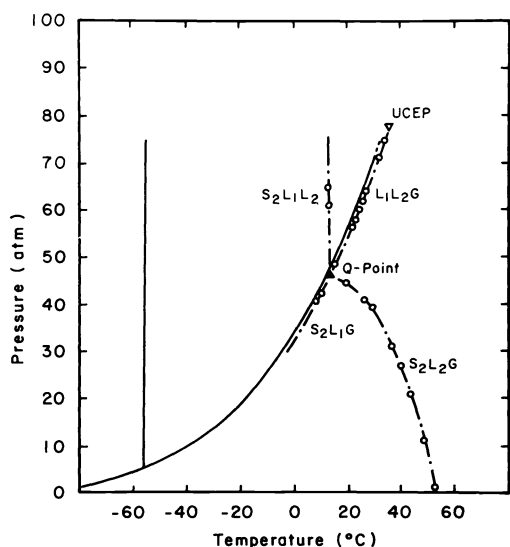
Fig. 1. Pressure – temperature projection for
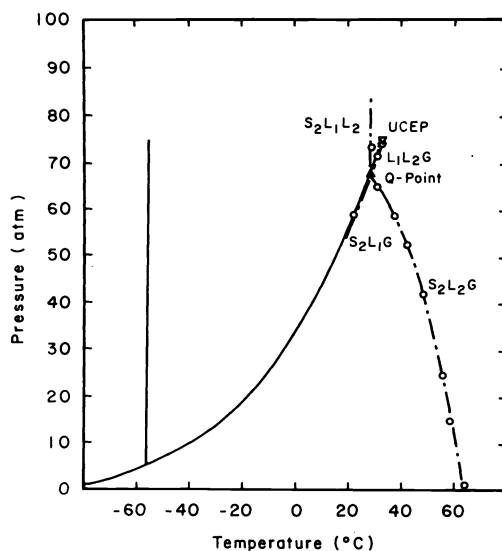maleic anhydride – CO_2 mixtures constructed
from measurements made in this study.

Fig. 2. Pressure – temperature projection for
methylcyclohexene dicarboxylic anhydride-CO_2
mixtures constructed from measurements made
in this study.

Q-point, where four equilibrium phases (solid, 2 liquids, and gas) are present. At higher
pressures, near the critical point of CO_2 (as represented by the terminus of the solid line or
vapor pressure curve for CO_2), three-phase, L_1L_2G (liquid-liquid-gas) equilibrium obtains,
terminating at the upper critical endpoint UCEP (35.8°C and 78.0 atm for maleic anhydride
-CO_2; 33.2°C and 75.2 atm for methylcyclohexene dicarboxylic anhydride-CO_2). The dashed line
connecting the critical point of CO_2 and the mixture upper critical endpoint represents
gas-liquid critical points for the binary mixture in each phase diagram. The conditions at
which the kinetic measurements were made (35°, 45°, and 60°; 80-430 atm) are closed to both
these upper critical endpoints and extend to higher temperatures and pressures. It is
expected that the maleic anhydride and adduct concentrations corresponding to these critical
endpoints are quite low.

The phase diagram for isoprene-CO_2 can be calculated using the Peng-Robinson equation of
state (Ref. 18). The resulting PT projection is shown in Fig. 3, and includes the vapor
pressure curve for both components (solid lines) and the gas-liquid mixture critical curve
(open circles) calculated from the Peng-Robinson equation. The temperatures and pressures at
which the kinetic measurements were made are close to those corresponding to this critical
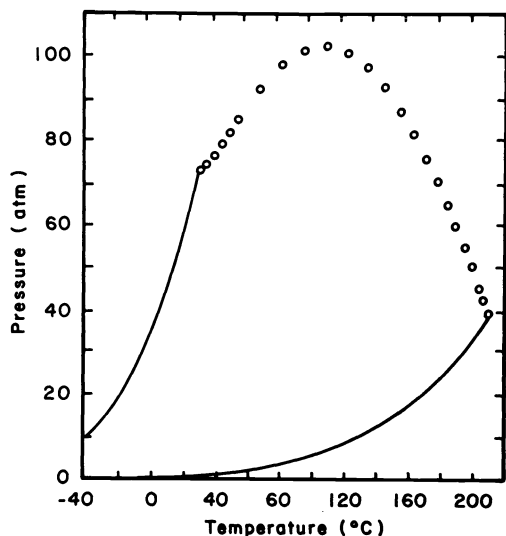curve. Isoprene concentrations increase rapidly as one moves along the mixture critical

Fig. 3. Pressure – temperature projection for
isoprene-CO_2 mixtures calculated using the
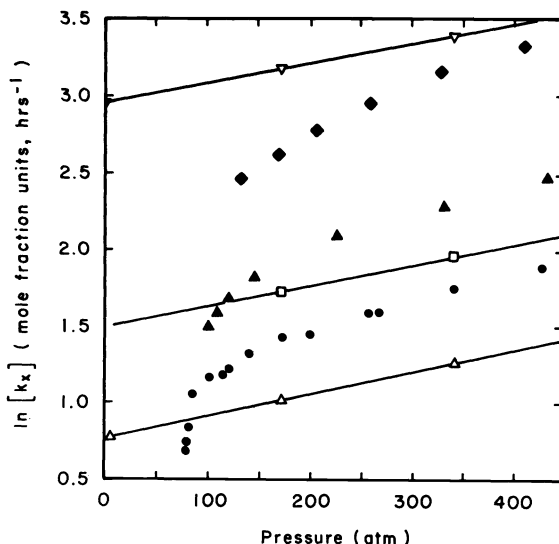Peng-Robinson equation of state.

Fig. 4. Rate constants for the maleic anhydride-
isoprene cycloaddition reaction.

curve, away from the critical point of CO_2, and hence isoprene and CO_2 will form completely miscible mixtures at the low isoprene concentrations of interest in the kinetic studies.

Measurements of reaction rates for the cycloaddition reaction of maleic anhydride and isoprene were made in a high-pressure batch reactor. Reaction rates were determined from measured changes in the ratio of maleic anhydride to methylcyclohexene dicarboxylic anhydride as a function of time. Each measurement was made at constant temperature and pressure, over a range of pressures from 80 to 430 atm and at three temperatures (35°, 45°, and 60°C). The second-order rate constants, obtained from the integrated rate expression, are plotted in Fig. 4 as a function of pressure for all three isotherms. These rate constants are based on concentration units of mole fraction to avoid correcting for the effect on pressure on concentration (Ref. 18). Also plotted in Fig. 4 are rate constants at 35°C for this reaction in three liquid solvents as a function of pressure. These rate constants were determined from the experimental measurements of Grieger and Eckert (Ref. 15).

Comparing rate constants for the four solvents at 35°C, the rate constants obtained for supercritical CO_2 at high pressures (above approximately 200 atm) are similar to those obtained when liquid ethyl acetate is the solvent. Evidently, the relatively large quadrupole moment for CO_2 results in kinetic solvent effects that are comparable to those obtained for moderately polar liquid solvents, such as ethyl acetate. Similar observations have been reported for solubilities in supercritical fluids characterized by molecular thermodynamic models which account for dipole and quadrupole moments (Ref. 19). Furthermore, at high pressures, the effect of pressure on the rate constant is essentially the same for all four solvents. However, at 35°C and pressures approaching the critical pressure of CO_2 (P_c = 72.8 atm; T_c = 31.1°C), the effect of pressure on the rate constant becomes substantial. That is, the volume of activation, $\Delta V\ddagger$, defined by the slope of the ℓnk_x versus pressure curves in Fig. 4.

$$\left(\frac{\partial \ell nk_x}{\partial P}\right)_T = \frac{-\Delta V^{\ddagger}}{T} \qquad (2)$$

takes on large negative values at temperatures and pressures near the critical point of CO_2. The data suggest that pressure can be used to manipulate reaction rates in the SCF solvent at near-critical conditions. This pressure dependence is qualitatively similar to behavior observed for other thermodynamic properties of SCF mixtures. For example, a plot of the logarithm of the solubility of solid naphthalene in supercritical CO_2 at 35°C versus pressure would give a curve comparable to that shown in Fig. 4 for ℓnk_x versus pressure at the same temperature (Ref. 20). The partial molar volume at infinite dilution for naphthalene dissolved in supercritical CO_2 at 35°C also exhibits a similar pressure dependence at near-critical conditions (Ref. 21). The observed divergence of ℓnk_x with pressure on approach to the critical point of CO_2 is not obvious, since the volume of activation in Eq. 2 is the difference in partial molar volumes at infinite dilution for the transition state and the reactants. Hence, some infinite-dilution partial molar volumes may approach large negative values without the activation volume diverging similarly. In the following section, a discussion of the fundamental geometric aspects of near-critical behavior will be presented to explain the experimental observations in Fig. 4 and to identify conditions at which this behavior would be obtained for other reacting systems.

REACTION KINETICS AT NEAR-CRITICAL CONDITIONS

The thermodynamic behavior of dilute solutions at conditions near the critical point of the solvent has received much attention in recent years as a result of new experimental observations related to SCF extraction. Many of these observations have been explained in terms of critical phenomena (Ref. 22 and 23). Wheeler and Petschek (Ref. 24) considered chemical equilibria in dilute solutions at conditions near the critical point of an inert solvent. Their analysis is based on the geometric arguments of Griffiths and Wheeler (Ref. 25) describing the manner in which various thermodynamic derivatives behave on approaching mixture critical points for multicomponent systems. Transition state theory (Ref. 26) provides the framework for applying these same arguments to reaction kinetics at near-critical conditions.

The analysis of Griffiths and Wheeler recognizes that the approach to a critical point is path dependent. This is illustrated in Fig. 5 for the critical point (CP) of a pure fluid. Approaching the critical point along the critical isotherm (T_c in the density-pressure diagram), density changes rapidly with pressure near CP. The isothermal compressibility, which is proportional to the derivative of density with respect to pressure at constant temperature, diverges to infinity at CP. However, approaching the critical point along the critical isochor (V_c on the pressure-temperature projection in Fig. 5) results in different behavior. Neither pressure or temperature changes rapidly on approach to CP, and the

derivative, $(\partial P/\partial T)_{VC}$, is finite at CP. This behavior can be generalized to critical points in multicomponent systems (Ref. 25) by defining field variables or fields (i.e., variables with equal values in equilibrium phases, such as pressure, temperature, fugacity, etc.) and density variables or densities (i.e., variables with different values in equilibrium phases, such as density, composition, molar enthalpy, etc.). A thermodynamic property that can be expressed as the partial derivative of a density variable with respect to a field variable will: (1) diverge strongly on approach to a critical point if only fields are held constant in the derivative, (2) diverge weakly if one density is held constant, and (3) remain finite if two or more densities are held constant. Thus, the isothermal compressibility of a pure fluid,

$$(3) \qquad K_T = \frac{1}{\rho} \left(\frac{\partial \rho}{\partial \rho}\right)_T$$

diverges strongly on approach to the critical point, as was shown in Fig. 5, because it is the derivative of a density with respect to a field with only fields held constant. The constant-volume heat capacity of a pure fluid,

$$C_V = T \left(\frac{\partial S}{\partial T}\right)_V \tag{4}$$

diverges weakly on approach to the critical point (Ref. 27) because it is the derivative of a density with respect to a field with one density held constant.

Following Wheeler and Petschek (Ref. 24), the volume of activation for the initial rate of neat dimerization near the critical point of the monomer is related to

$$\left(\frac{\partial \zeta}{\partial P}\right)_{T,\Delta=0} \tag{5}$$

where ζ is the extent of reaction and Δ is the chemical affinity. This expression is the partial derivative of a density with respect to a field with only fields held constant, and therefore should diverge strongly on approach to the critical point. Fig. 6 shows experimentally determined rate constants for the cyclodimerization of chlorotrifluoroethylene
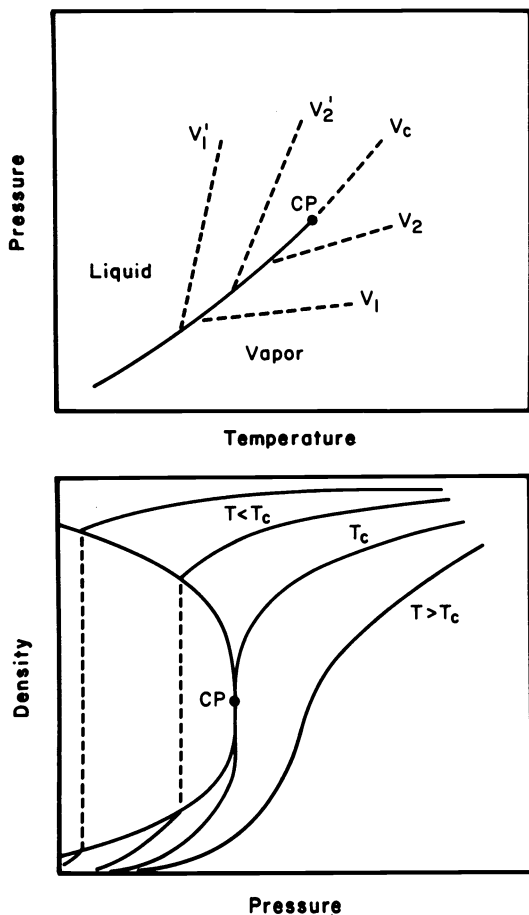

Fig. 6. Rate constants for the dimerization of trifluoroethylene, (Ref. 28).

Fig. 5. Schematic pressure — temperature projection and density — pressure diagram for a pure fluid.
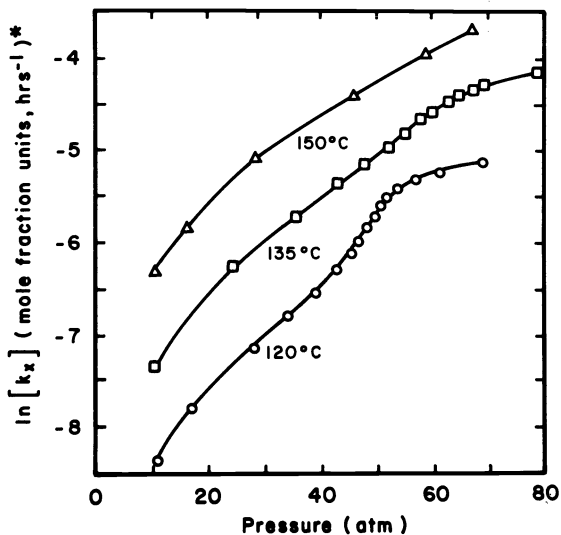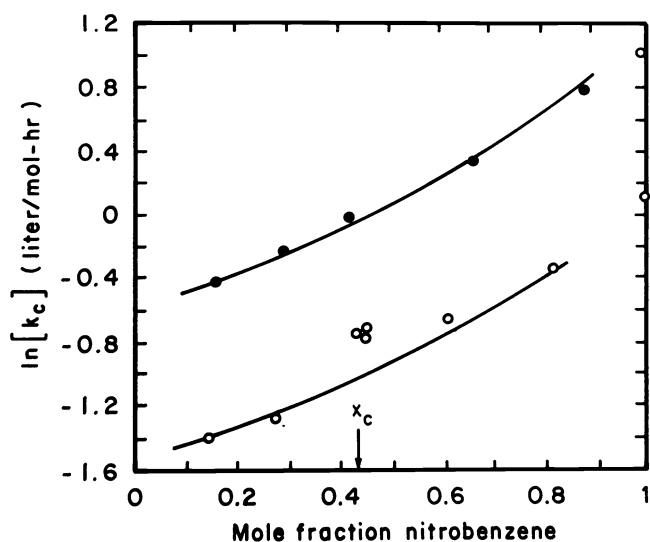
Fig. 7. Rate constants for the maleic anhy-
dride - isoprene cycloaddition reaction in
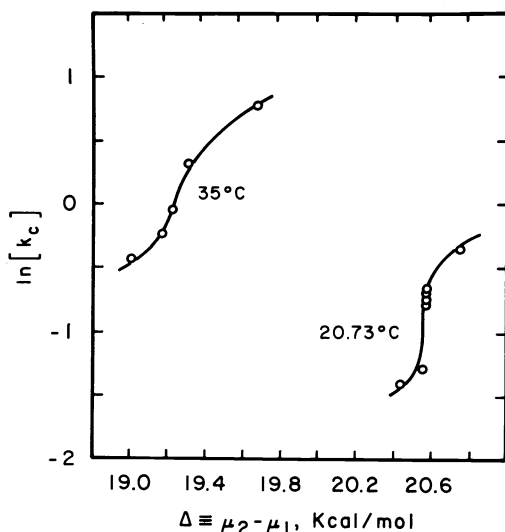dilute solutions of hexane and nitrobenzene,
(Ref. 16).

Fig. 8. Rate constants from Fig. 7 plotted
against the difference in chemical poten-
tials for nitrobenzene (2) and hexane (1).

(T_c = 105.8°C; P_c = 40.1 atm) as a function of pressure (Ref. 28). The rate constants
correspond to initial rates in essentially pure monomer. An inflection point is clearly
present at pressures just above 40 atm for the 120°C isotherm. The inflection is less
pronounced for 135°C isotherm and nonexistent for the 150°C isotherm, suggesting that an
inflection with slope approaching infinity would be observed for the critical isotherm. This
behavior is in agreement with the strong divergence predicted by Eq. 5.

The appropriate thermodynamic derivative for the activation volume of the cycloaddition
reaction of maleic anhydride with isoprene in an inert solvent is

$$\left(\frac{\partial \zeta}{\partial P}\right)_{T,\chi,\Delta} = 0 \tag{6}$$

where χ is the total solute mole fraction in the homogeneous SCF mixture. Since this
expression has one density held constant, it is expected that the activation volume would be
weakly divergent on approach to the critical point of the solvent. However, at low solute
concentrations, the constraint of fixed total solute concentration is equivalent to constrain-
ing all solute fugacities to be constant. This is a consequence of Henry's law behavior in
the limit of infinite dilution. Therefore, activation volumes will diverge strongly on
approach to the critical point of the solvent, if the reacting species are present at low
concentrations in the inert solvent. This is precisely the behavior observed in Fig. 5.

The geometric arguments presented above are general, and hence not limited to gas-liquid
critical points. Fig. 7 shows rate constants for the cycloaddition reaction of maleic
anhydride with isoprene as a function of liquid solvent composition (Ref. 16). The solvent
consists of hexane and nitrobenzene, and has a liquid-liquid critical point at 20.73°C and a
nitrobenzene mole fraction of 0.43. The rate constants at 20.73°C do not exhibit the behavior
observed in Fig. 4 and 6 because the abscissa in Figure 7 is a density variable. Replotting
these data in Fig. 8 as a function of the field variable ($\mu_1-\mu_2$), gives the expected behavior
showing a strong divergence for the 20.73°C isotherm on approach to the liquid-liquid critical
point.

The kinetic behavior observed in Fig. 4 for the Diels-Alder cycloaddition reaction of maleic
anhydride with isoprene in supercritical CO_2 suggests that pressure could be used to
manipulate the rate of this reaction at near critical conditions. Furthermore, the geometric
arguments presented above indicate that this pressure dependence is obtained when the volume
of activation, or the partial derivative in Eq. 6, diverges strongly on approach to the
critical point of CO_2. Strong divergence will be obtained in the dilute solution limit because
the constraint of constant total solute concentration is equivalent to constant solute
fugacities. A similar strong divergence would also be obtained at higher-order critical

points in multicomponent systems, regardless of the concentration. For example, at upper critical endpoints for three-phase solid-liquid-gas equilibrium, the fugacity of the solid component will be constant in all the phases. If the solid component is the solute, then the constraint of constant χ in Eq. 6 can be replaced by constant solute fugacity, and a strong divergence would be expected. A similar situation would occur at an upper critical endpoint for three-phase liquid-liquid-gas equilibrium if the composition of one liquid phase is appreciably different from those for the other two phases and this composition is relatively insensitive to pressure and temperature changes. These liquid-liquid-gas upper critical endpoints are shown in Fig. 1 and 2 for maleic anhydride-CO_2 and methylcyclohexene dicarboxylic anhydride-CO_2 mixtures, respectively. Again, strong divergence in activation volumes would be expected as a consequence of the nature of the upper critical endpoint, and would not be limited to dilute solutions.

CONCLUSIONS

There are several reasons for considering supercritical fluids as solvents for reacthing systems. These include: (1) the control of solubilities with relatively small changes in pressure and temperature, (2) enhanced mass transfer, and (3) the ability to influence reaction kinetics with pressure as well as temperature. The effect of pressure on reaction rate can occur through the pressure dependence of concentrations of reacting species or through the pressure dependence of the rate constant. The latter can be substantial for inert SCF solvents at conditions approaching the critical point of the solvent. This effect of pressure on reacting systems in SCF solvents appears to be unique, and consequently pressure represents an additional parameter with which to manipulate reaction kinetics in supercritical fluids. Fig. 7 illustrates that the solvent composition for a liquid solvent does not affect the rate constant in a similar manner, and the field ($\mu_1-\mu_2$) plotted in Fig. 8 does not represent a practical operating variable.

The circumstances under which a significant pressure effect would be expected are related to the critical phenomena exhibited by the reacting system. Two sets of conditions have been identified in this paper for the Diels-Alder cycloaddition reaction of maleic anhydride with isoprene. The first is when the reacting system is in dilute solution in an inert SCF solvent at conditions near the critical point of the solvent. The second would be for reacting systems near higher-order critical points (e.g., upper critical endpoints) where the presence of additional phases contains solute fugacities to be nearly constant. Although both these circumstances apply, to some extent, for the maleic anhydride-isoprene reaction, further experimental work is needed to assess the relative importance of the upper critical endpoints and the dilute solution limit.

Acknowledgements

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