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Fluid phase equilibria in asymmetric model systems.

Part I: CO₂ + diphenylmethane

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Abstract

Asymmetric reservoir fluids with high gas-to-oil ratios and heavy oils could present complex phase behaviors at reservoir or production conditions, as observed in Brazilian Pre-Salt reservoirs. To better understand the phase behaviors of these types of reservoir fluids with high carbon dioxide and methane contents, we initiated a study in our laboratory on the fluid phase equilibria of systems containing supercritical CO₂ and/or methane plus a heavy hydrocarbon. In the initial phase of this program, which forms this article, the choice was made to experimentally determine the phase diagram of the binary system: carbon dioxide + diphenylmethane within the temperature range 293.15 to 378.15 K. In addition, the data were compared with those modeled using a predictive version of the Peng-Robinson equation of state (PPR78).

Keywords: Fluid phase equilibria; carbon dioxide; aromatics.

24 1. Introduction

25 Due to their impacts on energy production, high pressure reservoirs have been the
26 topic of numerous studies [1–3]. These reservoirs are characterized by extreme pressures,
27 often exceeding 50 MPa and temperatures of up to 470 K. Moreover, they can be associated
28 with fluids that are complex in terms of composition [4]. Some of these reservoir fluids are
29 classified as asymmetric, with high methane and carbon dioxide content mixed with heavy
30 hydrocarbons with a significant C₇₊ fraction, with molecules that can contain more than 40
31 carbon atoms [5].

32 The difference in size between the components of asymmetric mixtures can promote
33 complex types of phase behavior, generally associated with significant deviation from
34 ideality at high-pressure conditions [6,7]. Even though reservoir fluids are made up of
35 thousands of different hydrocarbon components, the experiments to study and understand
36 their phase behavior need to be carried out on a simple model. The model systems most
37 commonly used for these studies are binary mixtures of methane or carbon dioxide with *n*-
38 alkanes. Consequently, the phase behavior of these mixtures has been extensively described
39 in the literature [8–16]. Information concerning the type of phase behavior observed
40 (according to the classification proposed by van Konynenburg and Scott [17] and the phase
41 transitions reported as a function of the *n*-alkane carbon number) is summarized in Table 1
42 for both CH₄ + *n*-alkane and CO₂ + *n*-alkane binary systems.

43 Table 1 shows that as the chain length of the alkanes increases, along with system
44 asymmetry, a transition from a simple to a more complex phase behavior is observed. More
45 specifically, the critical behavior of the mixtures shifts from Type I to Type III (according
46 to van Konynenburg and Scott's classification [17]). In type III behavior, a three-phase

47 liquid – liquid – vapor equilibrium (LLVE) region is obtained at low temperature and
48 pressures, reaching a critical endpoint near the critical point of the light compound in the
49 mixture. The phase behavior transitions occur by passing through an intermediate
50 condition, a type V behavior in the case of methane mixed with *n*-hexane and a type IV
51 behavior for a methane + *n*-heptane mixture. A Type IV behavior is also observed in the
52 case of an *n*-tridecane and carbon dioxide system. In the case of heavier alkanes, solid-
53 phase formation hides liquid-liquid-vapor phase separation, which consequently cannot be
54 detected in alkanes with a triple point that is much higher than the critical temperature of
55 the light compound. In these conditions, a solid – liquid – supercritical fluid (SLF) system
56 is observed, with solid and liquid phases in equilibrium with a supercritical phase with a
57 high light-component content. This additional fluid phase behaves like a dense phase at
58 high pressure, and like a dilute phase in low-pressure conditions [10].

59 Among the existing studies concerning the phase behavior of asymmetric light +
60 heavy hydrocarbon systems, there is a lack of experiments on branched-chain alkanes and
61 polyaromatic molecules, as can be confirmed by looking at periodic reports concerning
62 experiments of high-pressure fluid phase equilibria [62–66]. These observations regarding
63 the lack of data on the fluid phase equilibria of model systems led us to undertake an
64 experimental and modeling investigation of binary and multi-component synthetic systems,
65 which could represent complex phase transitions as observed in some reservoir fluids such
66 as those of Brazil’s Pre-Salt fields. In the initial phase of this program, the subject of this
67 first article, the choice was made to experimentally determine the phase behavior of the
68 binary system composed of carbon dioxide and diphenylmethane. Phase transition
69 measurements were carried out using a synthetic method in the temperature range from $T =$

70 (293.15 to 378.15) K. Predictive cubic equations of state were also tested to describe the
71 experimental phase behavior obtained.

72 Some Brazilian Pre-Salt reservoir fluids, characterized by high gas content which can
73 exceed 55.0 mol% [67–69], presented L-L and L-L-V equilibrium domains at high
74 temperatures as described in previous studies [69–72]. The L-L phase immiscibility
75 observed in these fluids under HT-HP conditions (high temperature – high pressure) was
76 characterized by the formation of a dispersed liquid phase in the continuous oil phase,
77 which makes difficult to detect phase changes in these types of black oil systems, but above
78 all, makes it practically impossible to sample and analyze the second liquid phase, thereby
79 limiting understanding of these phase equilibria. Only by combining experimental and
80 modeling techniques it was possible to establish that the L-L immiscibility observed in Pre-
81 Salt oils could be generated by the demixing of heavy hydrocarbon compounds from crude
82 oils [70] rather than by carbon dioxide separation as usually observed at low temperature in
83 CO₂ + *n*-alkane systems. Consequently, modeling plays a crucial role in understanding the
84 complex phase behaviors of these types of reservoir fluids, and their reliability must
85 therefore be verified using a synthetic system. In view of the requirement to perform proper
86 modeling, the experimental data were compared using a predictive PPR78 model based on
87 the Peng Robinson equation of state with the addition of a fully predictive mixing rule,
88 which is therefore particularly well suited to predicting systems with high molecular weight
89 components.

90

91 2. Materials and Methods

92

93 2.1. Chemicals

94 The chemical compounds used to formulate the systems are listed in Table 2, while the
95 molecular weights, melting temperatures, and normal boiling points of the liquid
96 compounds are listed in Table 3. All chemicals were used without any further purification.

97

98 2.2 Experimental technique

99 A full visual PVT cell was used to study phase behavior and prepare the systems, as
100 described in a previous paper [33]. In short, the PVT cell is a high-pressure volumetric
101 piston with a sapphire window at the top that allows total visibility of the cell content.
102 Operating limits were 100 MPa, 30 cm³, and 383.15 K, for pressure, volume, and
103 temperature, respectively. The PVT cell was adapted using a coupled calibrated pressure
104 transducer with an uncertainty $u(p^{gauge})$ of $\pm 0.02\%$ across its entire range. Temperature
105 control was made by circulating a heat-carrier fluid through three flow lines directly
106 managed in the cell body and connected to a thermostatic bath (Ministat 230, Huber with
107 temperature stability of ± 0.02 K). Temperature was measured using a Pt-100 directly in
108 contact with the metal cell body, with an uncertainty $u(T^{gauge})$ of 0.1 K. Additionally, a
109 magnetic bar was put inside the cell to continuously stir the sample studied by means of an
110 external magnetic stirrer system placed beneath the cell.

111 Phase behavior analysis was performed according to the synthetic method at
112 isoplethic conditions. Isopleth composition was therefore precisely controlled during the

113 synthesis of the mixture before the fluid phase behavior analysis. For that purpose, mixtures
114 were prepared directly inside the measurement cell by weighing both the liquid and gas.
115 For this operation, the liquid was first injected into the PVT cell under vacuum, and the
116 amount of liquid transferred to the cell was determined by using an analytical balance with
117 uncertainty in measurement equal to 1 mg. The CO₂ was then added under pressure. To
118 weigh the amount of gas added to the cell, the CO₂ was initially loaded into a large-volume
119 tank (1 l) and placed on a precision balance with uncertainty in measurement equal to 1 mg.
120 In order to avoid errors in mass due to the connection between the cell and the tank, a
121 flexible PEEK tubing with an internal diameter of 1/32" was used to join them. Finally, the
122 CO₂ was stored at Liquid – Vapor phase equilibrium in the tank to maintain constant
123 pressure during the injection. Based on this method, the standard uncertainties for the
124 masses introduced were estimated to be less than 0.005 g for both components, and the
125 combined standard uncertainty for the feed mole fraction z_{CO_2} was estimated using the
126 following relationship:

127

$$128 \quad u_c(z_{CO_2}) = z_{CO_2}(1 - z_{CO_2}) \left(\frac{u^2(m_{CO_2})}{m_{CO_2}^2} + \frac{u^2(m_{arom})}{m_{arom}^2} \right)^{1/2} \quad (1)$$

129

130 After both liquid and gas had been introduced, the prepared mixture was
131 homogenized at high temperature (378.15 K) and high pressure (well above bubble point
132 pressure). When single-phase equilibrium was achieved, the phase transition experiments
133 started by incrementally changing p conditions. Throughout the change process, vigorous
134 stirring was activated. The system was then maintained in equilibrium without stirring to
135 facilitate observation. When a phase appeared, the pressure at which the transition was

136 observed was registered. The standard uncertainty for the phase transition points observed
 137 was $u(p^{obs}) = 0.02$ MPa, related to reproducibility of the visual detection of a new formed
 138 phase. Special care has been taken to visually determine liquid to liquid – liquid phase
 139 transition (L to LL), mainly related to the high phase dispersity formed at high CO₂ content
 140 and high pressure. The observation uncertainty was considered alongside those of
 141 instrument pressure and temperature, $u(p^{gauge})$, and $u(T^{gauge})$, respectively. Finally,
 142 expanded uncertainty to determine the phase transition pressure $U(p^{transition})$ was calculated
 143 based on the error propagations described in the Guide to the expression of Uncertainty
 144 Measurement (GUM) of the National Institute of Standards and Technology [73], as
 145 follows:

146

$$147 \quad U^2(p^{transition}) = u^2(p^{obs}) + u^2(p^{gauge}) + \left[\left(\frac{\partial p^{obs}}{\partial T} \right) u(T^{gauge}) \right]^2 \quad (2)$$

148

149 Partial derivatives with respect to temperature were obtained by numerical differentiation
 150 of the data [50]. For each isopleth, constant mass expansion (CME) tests were performed at
 151 five different temperatures $T = (293.15, 308.15, 323.15, 338.15, 358.15, \text{ and } 378.15)$ K.

152 For detection of solid phase appearance (L → LS), measurements were taken at isobaric
 153 conditions and incrementally changing T up to T^{obs} . This method was adopted because of
 154 the steep slope of the L → LS locus. During this procedure, standard uncertainty was
 155 $u(T^{obs}) = 0.2$ K and expanded uncertainty for LS formation temperature $U(T^{transition})$ was
 156 estimated as follows:

157

$$158 \quad U^2(T^{transition}) = u^2(T^{gauge}) + u^2(T^{obs}) + \left[\left(\frac{\partial T^{obs}}{\partial p} \right) u(p^{gauge}) \right]^2 \quad (3)$$

159

160

161 3. Results and discussion

162 The phase behavior of binary systems composed of carbon dioxide and
163 diphenylmethane was determined based on 11 isoplethic measurements, from 20.13 to
164 95.03 CO₂ mol%. Fluid phase transitions are presented in Table 4, including L → LV and L
165 → LL phase transitions as well as LLV phase equilibria. Additionally, solid-fluid phase
166 transitions L → LS are presented in Table 5. Isoplethic pT diagrams are presented in Figure
167 1 and Figure 2 for low and high CO₂ content mixtures, respectively. From these
168 measurements, it can be concluded that diphenylmethane and CO₂ mixtures present a type
169 III phase behavior in the van Konynenburg and Scott classification scheme [17].
170 Accordingly, the critical line linking the pure compounds' critical points is interrupted and
171 divided into two branches. One of the critical lines goes from the critical point of the
172 diphenylmethane and increases to higher pressures, while the other critical line connects the
173 critical point of the carbon dioxide to a triphasic LLV line through an upper critical
174 endpoint (UCEP).

175 Liquid – liquid immiscibility was first detected in the mixture with 60.18 CO₂ mol %
176 whose results are depicted in Figure 2. This behavior was not reported before because of
177 the small dataset available in the literature for diphenylmethane and CO₂ mixtures [74,75].
178 A comparison between liquid phase compositions obtained by Chung et al. [75] using an
179 analytical method and our measurements is presented in Figure 3 at $T=308.15$ K.
180 Interpolation of our p,T data must be done for this plot as the isopleth measurements were
181 not exactly carried out at $T=308.15$ K. A good graphical agreement is observed between

182 both datasets until 25 MPa but a significant deviation is noted at 30 MPa. At this pressure,
183 Chung's et al data [75] seems to overestimate CO₂ solubility in liquid phase. This leads to a
184 significant underestimation of phase transition pressure in the graph with an observed
185 deviation higher than 10 MPa on the saturation pressure for mixture with 85.0 CO₂ mol %.

186 Additionally, a three-phase LLV equilibria was visually observed at temperatures
187 below the CO₂ critical point, with the formation of a light vapor phase in equilibrium with
188 two liquid phases, as depicted in Figure 4. This LLV locus goes from temperatures below
189 293.15 K until an UCEP corresponding to 306.5 K and 7.70 MPa conditions. For systems
190 with higher carbon dioxide content, the volume fraction of the light liquid phase increases,
191 as one can note in Figure 4(c) for the 75.15 CO₂ mol % mixture.

192 Similar behavior has been reported for 1-methylnaphthalene ($T^m = 242.6$ K) [76], 2-
193 methylnaphthalene ($T^m = 306.6$ K) [77], and alkylaromatics mixtures with CO₂ [51,78,79].
194 The asymmetry and the low melting point of these hydrocarbons lead to the formation of
195 LL insolubility. This liquid-liquid phase separation is not present in CO₂ + aromatic
196 systems when the asymmetry is much less significant as in the case of carbon dioxide with
197 benzene or toluene [80]. The triphasic LLV region is not formed for high condensed
198 polyaromatics because of their elevated LS transition temperatures [57,81–85]. For these
199 heavy compounds, the LS locus occludes the LLV equilibria at low temperatures. Because
200 of the low melting temperature of diphenylmethane (299.0 K) and the decrease in melting
201 temperature caused by CO₂ addition, no LLS equilibria or LLVS (quadruple Q -point) can
202 be detected in the studied temperature and pressure ranges.

203 Isoplethic data were used together with a smoothing function to represent the results
204 in an isothermal (p, z_I) diagram. Polynomial functions were considered to interpolate values
205 at a given temperature, and results are presented in Table 6 and Figure 5. In addition, these

206 isothermal phase behavior were modeled using the Peng-Robinson equation of state [86]
 207 with its classical mixing rules. The critical temperature T_c and pressure P_c of pure
 208 components required to determine a_i and b_i parameters of the cubic equation of state were
 209 obtained from the NIST webbook and are presented in Table 7 [87]. There is only one
 210 value of acentric factor for diphenylmethane reported in the literature [88]. However, in this
 211 publication, the critical parameters are much higher than values reported on NIST database,
 212 e.g., the reported critical pressure is 3.28 MPa while NIST average value for P_c is 2.979
 213 MPa. Considering this divergence in critical properties, the reported value of the acentric
 214 factor for diphenylmethane was not considered. Instead, the acentric factor was calculated
 215 by using the Pitzer's relation, as commonly made for heavy hydrocarbons [89,90]:

216

$$217 \quad \omega = \frac{-\ln(P_c) - 5.92714 + 6.09648 \cdot \theta^{-1} + 1.28862 \cdot \ln(\theta) - 0.169347 \cdot \theta^6}{15.2518 - 15.6875 \cdot \theta^{-1} - 13.4721 \cdot \ln(\theta) + 0.43577 \cdot \theta^6} \quad (4)$$

218

219 where $\theta = T_b/T_c$, both temperatures in K, and P_c in bar.

220

221 Binary interaction parameter k_{ij} was determined as a function of temperature by
 222 either fitting the experimental data or using PPR78, a predictive version of Peng-Robinson
 223 equation of state based on a group contribution method developed by Jaubert and
 224 collaborators [91–96]. In this fully predictive method, the binary interaction parameter is
 225 given by:

226

$$\begin{aligned}
227 \quad k_{ij}(T) = & \left\{ \left[-\frac{1}{2} \sum_{k=1}^{N_g} \sum_{l=1}^{N_g} (\alpha_{ik} - \alpha_{jk})(\alpha_{il} - \alpha_{jl}) A_{kl} (298.15/T)^{\left(\frac{B_{kl}}{A_{kl}} - 1\right)} \right] - \right. \\
228 \quad & \left. \left[\frac{\sqrt{a_i(T)}}{b_i} - \frac{\sqrt{a_j(T)}}{b_j} \right]^2 \right\} \cdot \left(2 \cdot \frac{\sqrt{a_i(T)a_j(T)}}{b_i b_j} \right)^{-1} \quad (5)
\end{aligned}$$

229

230 where N_g represents the total number of functional groups considered by the method, α_{ik} is
231 the occurrence of group k in component i divided by N_g , and A_{kl} and B_{kl} are group
232 parameters. A total of 21 functional groups for PR78 have been defined [91–96].

233 Results obtained from PR EOS fitting are presented in Figure 5 for all investigated
234 temperatures. This figure also depicts the phase envelope description obtained by the
235 predictive PPR78 EOS version. Fitted and predicted binary interaction parameters are listed
236 in Table 7. The models describe the system phase behavior qualitatively, with significant
237 deviations in the LL and critical regions. This is expected because of the limited
238 representation of high asymmetric systems by PR EOS, especially using classical mixing
239 rules and only the attractive binary interaction parameter [7,97]. However, a good
240 description of low-pressure LLV is obtained at 293.15 K [98].

241 As one can note in Table 7, there are no significant differences between fitted and
242 predicted interaction parameters. The PPR78 seems to correctly predict the temperature-
243 dependent k_{ij} for diphenylmethane and carbon dioxide, based on the aromatics functional
244 groups considered by the model [91,99]. Fitted and predicted binary interaction parameters
245 are in accordance with results reported in the literature for such systems [99]. Optimized
246 A_{12} and B_{12} for the PPR78 EOS can be obtained by fitting these parameters to the tuned
247 temperature-dependent k_{ij} using Eq. 6, as follows:

248

$$k_{ij}(T) = \left\{ \left[A_{ij} \cdot (298.15/T)^{\left(\frac{B_{ij}}{A_{ij}} - 1 \right)} \right] - \left[\frac{\sqrt{a_i(T)}}{b_i} - \frac{\sqrt{a_j(T)}}{b_j} \right]^2 \right\} \cdot \left(2 \cdot \frac{\sqrt{a_i(T)a_j(T)}}{b_i b_j} \right)^{-1} \quad (6)$$

250

251 In this equation, the molecules i and j on the binary mixture are treated as a single group

252 [100,101]. The optimal values obtained were $A_{12} = 131.81$ MPa and $B_{12} = 133.74$ MPa.

253 These results can help to improve the group parameters considered in PPR78.

254

255

256 **4. Conclusions**

257 The phase behavior of carbon dioxide and diphenylmethane mixtures was investigated by

258 measuring liquid – vapor, liquid – liquid, liquid – liquid – vapor, and liquid – solid phase

259 equilibria. The isopleth and p,x phase diagram were constructed from these measurements.

260 Results suggest that this mixture exhibits a type III phase behavior in the van Konynenburg

261 and Scott classification scheme. Liquid – liquid and liquid – liquid – vapor insolubilities

262 were detected at carbon dioxide content above 60.18 mol %. Peng-Robinson equation of

263 state qualitatively describes the experimental phase behavior using temperature-dependent

264 attractive binary interaction parameters, with maximum deviations in the liquid – liquid and

265 critical regions.

266

267 **6. References**

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601

602 Table 1. Fluid phase transitions reported in literature for mixtures of *n*-paraffins and
 603 methane or carbon dioxide.

System	Type of equilibria	Type of Phase diagram	References
$\text{CH}_4 + \text{n-C}_{(i)}\text{H}_{(2i+2)} / i \in [2 - 5]$	LVE	I	[18–20]
$\text{CH}_4 + \text{n-C}_6\text{H}_{14}$	LVE/ LLE/LLVE	V	[21–24]
$\text{CH}_4 + \text{n-C}_7\text{H}_{16}$	LVE/ LLE/LLVE	IV	[25,26]
$\text{CH}_4 + \text{n-C}_{(i)}\text{H}_{(2i+2)} / i \geq 8$	LFE/SLFE	III	[27–35]
$\text{CO}_2 + \text{n-C}_{(i)}\text{H}_{(2i+2)} / i \in [2 - 6]$	LVE	I	[36–38]
$\text{CO}_2 + \text{n-C}_{(i)}\text{H}_{(2i+2)} / i \in [7 - 11]$	LVE/LLE/LLVE	II	[39–45]
$\text{CO}_2 + \text{n-C}_{12}\text{H}_{26}$	LVE/ LLE/LLVE	- ^a	[46]
$\text{CO}_2 + \text{n-C}_{13}\text{H}_{28}$	LVE/ LLE/LLVE	IV	[47,48]
$\text{CO}_2 + \text{n-C}_{(i)}\text{H}_{(2i+2)} / i \in [14 - 21]$	LVE/ LLE/LLVE	III	[41,46,49–53]
$\text{CO}_2 + \text{n-C}_{(i)}\text{H}_{(2i+2)} / i \geq 22$	LFE/SLFE	III	[54–61]

604 ^a Phase behavior not defined [8]

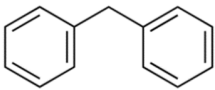
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609 Table 2. CAS registry number, molecular structure, purity, and suppliers of the chemicals.

Compound	CAS Reg. No.	molecular structure	purity, %	supplier
carbon dioxide	124-38-9	CO ₂	99.995 ^a	Linde
diphenylmethane	101-81-5		99.9 ^b	Sigma-Aldrich

610 ^a molar composition. ^b mass composition reported by the supplier (certificated by gas

611 chromatography)

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614 Table 3. Chemicals molecular weight, melting temperature (T^m), and normal boiling
615 temperature (T^b).

Compound	MW	T^m / K	T^b / K
diphenylmethane	168.23	299.0	537.5

616

617 Table 4. Pressure of phase transition p at a given temperature T in different mixtures of
618 global CO₂ composition $z_{CO_2} \pm U(z_{CO_2})$ in mol % with its expanded ($k = 2$) uncertainty $U(p)$.

$T \pm$ 0.1 / K	$p /$ MPa	$U(p) /$ MPa	transition type	$T \pm$ 0.1 / K	$p /$ MPa	$U(p) /$ MPa	transition type	$T \pm$ 0.1 / K	$p /$ MPa	$U(p) /$ MPa	transition type
$z_{CO_2} = 20.13 \pm 0.09$ mol %				$z_{CO_2} = 30.21 \pm 0.09$ mol %				$z_{CO_2} = 40.20 \pm 0.08$ mol %			
293.3	2.27	0.02	L→LV	292.8	3.35	0.02	L→LV	292.8	4.43	0.02	L→LV
307.5	2.75	0.02	L→LV	308.3	4.21	0.03	L→LV	308.0	5.70	0.03	L→LV
323.4	3.32	0.03	L→LV	322.9	5.08	0.03	L→LV	322.9	7.07	0.03	L→LV
338.1	3.91	0.03	L→LV	337.5	6.04	0.03	L→LV	337.5	8.45	0.03	L→LV
357.9	4.66	0.03	L→LV	357.1	7.30	0.03	L→LV	357.5	10.28	0.04	L→LV
377.2	5.29	0.03	L→LV	377.3	8.45	0.04	L→LV	377.2	11.99	0.04	L→LV
$z_{CO_2} = 50.18 \pm 0.07$ mol %				$z_{CO_2} = 60.18 \pm 0.03$ mol %				$z_{CO_2} = 70.17 \pm 0.03$ mol %			
292.9	5.30	0.02	L→LV	293.2	5.70	0.03	LL→LLV	292.9	5.62	0.03	LL→LLV
308.0	7.12	0.04	L→LV	298.0	6.51	0.02	LL→LLV	297.4	6.37	0.02	LL→LLV
323.1	9.20	0.04	L→LV	303.2	7.08	0.03	LL→LLV	302.9	7.00	0.02	LL→LLV
337.8	11.32	0.04	L→LV	306.5	7.70	0.03	UCEP	292.7	52.4	0.3	LL→LLV
357.6	13.90	0.04	L→LV	293.2	15.4	0.1	L→LL	297.4	39.9	0.2	L→LL
377.5	16.27	0.04	L→LV	298.1	13.61	0.09	L→LL	302.9	32.56	0.09	L→LL
				303.0	12.73	0.07	L→LL	308.0	28.91	0.06	L→LL
				306.5	12.63	0.02	L→LL	312.9	27.11	0.05	L→LL
				307.0	12.63	0.02	L→LL	322.9	24.64	0.03	L→LV
				308.0	12.58	0.06	L→LL	337.6	24.46	0.03	L→LV
				313.4	12.88	0.05	L→LL	357.3	26.02	0.03	L→LV
				323.4	13.97	0.04	L→LV	376.7	28.00	0.03	L→LV
				338.0	16.13	0.04	L→LV				
				358.0	19.18	0.03	L→LV				
				376.9	21.56	0.03	L→LV				
$z_{CO_2} = 75.15 \pm 0.02$ mol %				$z_{CO_2} = 80.13 \pm 0.02$ mol %				$z_{CO_2} = 85.10 \pm 0.01$ mol %			
292.8	5.57	0.03	LL→LLV	293.1	5.61	0.03	LL→LLV	293.1	5.63	0.03	LL→LLV
298.0	6.43	0.02	LL→LLV	298.2	6.45	0.02	LL→LLV	298.0	6.40	0.02	LL→LLV

303.0	7.00	0.02	LL→LLV	303.2	7.04	0.02	LL→LLV	303.2	7.01	0.02	LL→LLV
297.4	54.40	0.21	L→LL	303.3	57.77	0.16	L→LL	303.2	70.9	0.2	L→LL
303.1	42.79	0.14	L→LL	307.9	50.88	0.15	L→LL	308.2	61.0	0.2	L→LL
308.1	37.04	0.10	L→LL	312.9	43.49	0.12	L→LL	313.2	52.5	0.2	L→LL
313.4	33.20	0.06	L→LL	317.9	37.88	0.08	L→LL	317.6	44.6	0.1	L→LL
322.7	29.86	0.03	L→LV	322.9	33.90	0.04	L→LL	322.8	37.68	0.04	L→LL
338.1	28.40	0.02	L→LV	327.8	32.20	0.02	L→LV	328.2	35.69	0.02	L→LV
357.6	29.11	0.02	L→LV	338.0	31.06	0.02	L→LV	338.0	34.63	0.02	L→LV
377.7	30.53	0.02	L→LV	357.5	30.96	0.02	L→LV	357.5	33.33	0.02	L→LV
				377.0	32.40	0.02	L→LV	377.2	33.39	0.02	L→LV

$z_{CO_2} = 90.07 \pm 0.01 \text{ mol } \%$

$z_{CO_2} = 95.03 \pm 0.01 \text{ mol } \%$

292.8	5.62	0.03	LL→LLV	293.0	5.53	0.03	LL→LLV
297.9	6.39	0.02	LL→LLV	298.0	6.35	0.02	LL→LLV
303.3	7.04	0.02	LL→LLV	303.2	6.96	0.02	LL→LLV
				292.8	17.87	0.13	V→LV
297.7	69.43	0.30	L→LL	297.7	18.12	0.13	V→LV
303.2	54.48	0.27	F→FF	303.2	18.42	0.09	V→LV
308.2	41.99	0.08	F→FF	307.7	18.62	0.06	V→LV
322.7	33.70	0.04	F→FF	322.8	20.06	0.04	V→LV
338.0	32.60	0.03	V→LV	338.0	22.33	0.04	V→LV
357.5	31.15	0.03	V→LV	357.8	25.09	0.03	V→LV
377.2	32.70	0.03	V→LV	377.2	27.66	0.03	V→LV

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626 Table 5. Fluid-solid transition temperature at a given pressure p with its expanded ($k = 2$)
 627 uncertainty $U(T) = 0.42$ K

$p \pm 0.1$ / MPa	T / K	$p \pm 0.1$ / MPa	T / K
$z_{CO_2} = 20.13 \pm 0.09$ mol %		$z_{CO_2} = 30.21 \pm 0.09$ mol %	
12.0	293.71	23.2	292.71
20.7	296.01	42.9	298.00
29.9	298.00	35.9	296.01
34.9	299.80		
$z_{CO_2} = 40.20 \pm 0.08$ mol %		$z_{CO_2} = 50.18 \pm 0.07$ mol %	
38.6	293.01	52.3	293.01
48.4	295.51		

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631 Table 6. Interpolated data of transition pressure p at isothermal conditions from data
632 reported in Table 4.

T/K	p/MPa	transition type	T/K	p/MPa	transition type	T/K	p/MPa	transition type
$z_{\text{CO}_2} = 20.13 \pm 0.09 \text{ mol } \%$			$z_{\text{CO}_2} = 30.21 \pm 0.09 \text{ mol } \%$			$z_{\text{CO}_2} = 40.20 \pm 0.08 \text{ mol } \%$		
293.15	2.25	L→LV	293.15	3.32	L→LV	293.15	4.42	L→LV
308.15	2.80	L→LV	308.15	4.24	L→LV	308.15	5.77	L→LV
323.15	3.35	L→LV	323.15	5.16	L→LV	323.15	7.13	L→LV
338.15	3.89	L→LV	338.15	6.08	L→LV	338.15	8.48	L→LV
358.15	4.62	L→LV	358.15	7.30	L→LV	358.15	10.29	L→LV
378.15	5.35	L→LV	378.15	8.52	L→LV	378.15	12.10	L→LV
$z_{\text{CO}_2} = 50.18 \pm 0.07 \text{ mol } \%$			$z_{\text{CO}_2} = 60.18 \pm 0.03 \text{ mol } \%$			$z_{\text{CO}_2} = 70.17 \pm 0.03 \text{ mol } \%$		
293.15	5.30	L→LV	293.15	15.43	L→LL	293.15	50.90	L→LL
308.15	7.27	L→LV	308.15	12.52	L→LL	308.15	28.93	L→LL
323.15	9.25	L→LV	323.15	14.01	L→LV	323.15	24.62	L→LV
338.15	11.22	L→LV	338.15	16.15	L→LV	338.15	24.50	L→LV
358.15	13.85	L→LV	358.15	19.01	L→LV	358.15	26.08	L→LV
378.15	16.48	L→LV	378.15	21.86	L→LV	378.15	28.24	L→LV
$z_{\text{CO}_2} = 75.15 \pm 0.02 \text{ mol } \%$			$z_{\text{CO}_2} = 80.13 \pm 0.02 \text{ mol } \%$			$z_{\text{CO}_2} = 85.10 \pm 0.01 \text{ mol } \%$		
308.15	36.92	L→LL	308.15	50.48	L→LL	308.15	60.97	L→LL
323.15	29.75	L→LV	323.15	33.93	L→LL	323.15	37.37	L→LL
338.15	28.40	L→LV	338.15	31.04	L→LV	338.15	34.80	L→LV
358.15	29.14	L→LV	358.15	31.29	L→LV	358.15	33.14	L→LV
378.15	30.58	L→LV	378.15	32.52	L→LV	378.15	33.13	L→LV
$z_{\text{CO}_2} = 90.07 \pm 0.01 \text{ mol } \%$			$z_{\text{CO}_2} = 95.03 \pm 0.01 \text{ mol } \%$					
293.15			293.15	17.89	V→LV			
308.15	41.99	F→FF	308.15	18.67	V→LV			
323.15	33.69	F→FF	323.15	20.10	V→LV			
338.15	32.58	V→LV	338.15	22.36	V→LV			
358.15	31.14	V→LV	358.15	25.12	V→LV			
378.15	32.90	V→LV	378.15	27.90	V→LV			

633

634 Table 7. Critical temperature, critical pressure, and acentric factor for chemical compounds

compound	P_c , MPa	T_c , K	ω
CO ₂ ^a	7.380	304.20	0.225
diphenylmethane ^b	2.979	767.0	0.475

635 ^a from NIST webbook database [87]. ^b P_c and T_c from NIST webbook database [87] and ω

636 calculated from Eq. (4).

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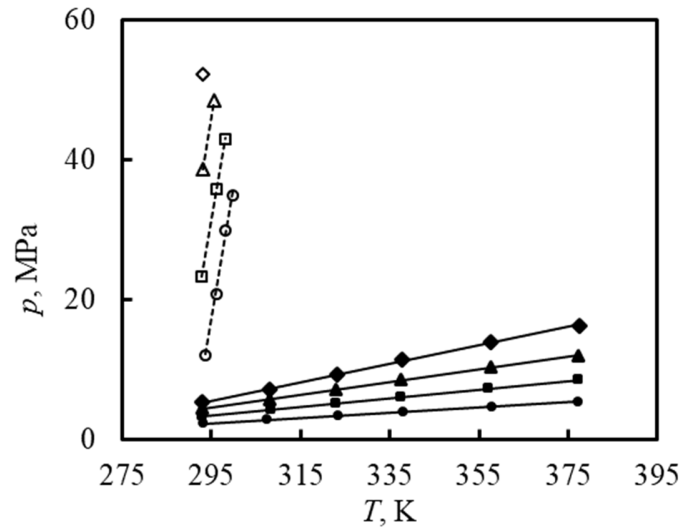
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641 Table 8. Fitted and predicted binary interaction parameters obtained at different
642 temperatures for PR and PPR78 models.

<i>T</i> , K	Fitted <i>k_{ij}</i>	PPR78 <i>k_{ij}</i>
293.15	0.0996	0.0973
308.15	0.0979	0.0949
323.15	0.0961	0.0934
338.15	0.0946	0.0927
358.15	0.0924	0.0925
378.15	0.0900	0.0930

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646 Figure 1. Isophletic pT phase diagram for the CO_2 – diphenylmethane mixtures with bubble
 647 point pressures (L→LV, solid symbols) and liquid – solid phase transitions (L→LS, unfilled

648 symbols) at several feed compositions. ●, ○: $z_{CO_2} = 20.12$ mol %; ■, □: $z_{CO_2} = 30.20$
 649 mol %; ▲, △: $z_{CO_2} = 40.20$ mol %; and: ◆, ◇: $z_{CO_2} = 50.18$ mol %. Lines included for

650 eye-guide.

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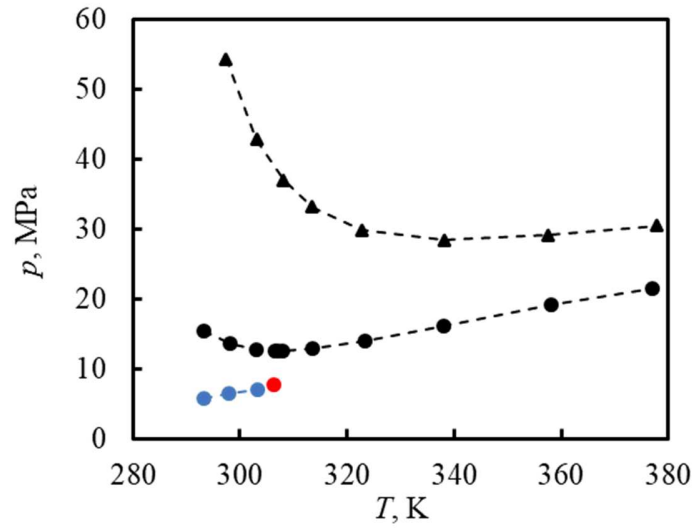
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663 Figure 2. Isophletic pT phase diagram for the CO_2 – diphenylmethane mixtures with phase
 664 transitions at several feed compositions. Biphasic envelope (L→LV and L→LL) for ●:
 665 $z_{CO_2} = 60.18$ mol %; and ▲: $z_{CO_2} = 75.15$ mol %. ●: Liquid – liquid – vapor equilibrium
 666 (LL→LLV) for $z_{CO_2} = 75.15$ mol %; and ●: LLV triphasic UCEP. Dashed lines included
 667 for eye-guide.

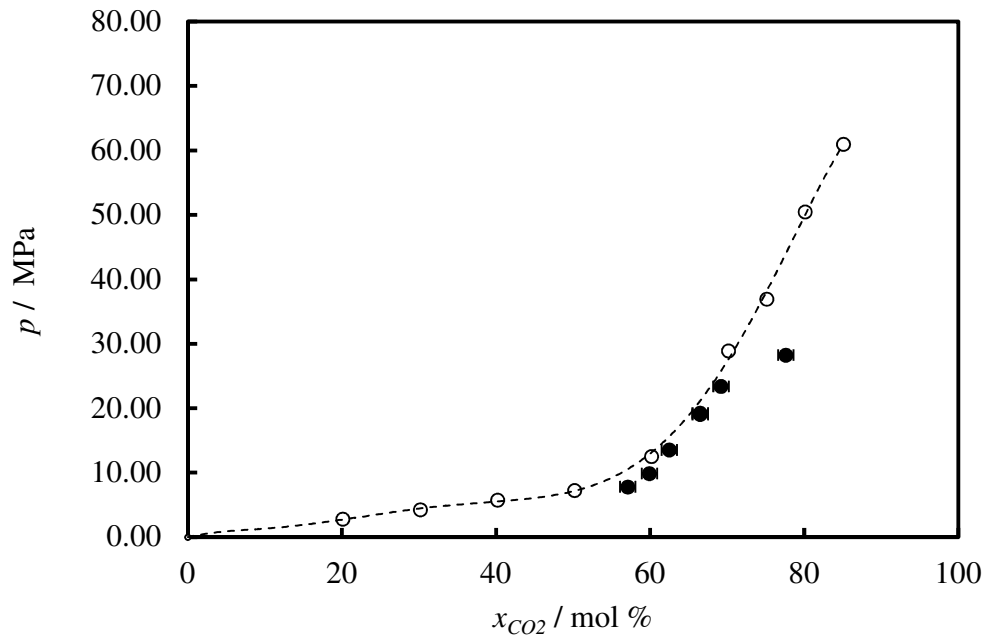
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674 Figure 3. Comparison between liquid phase composition reported by Chung et al. [75] (●)

675 and the present work (○)for carbon dioxide and diphenylmethane binary system at 308.15

676 K.

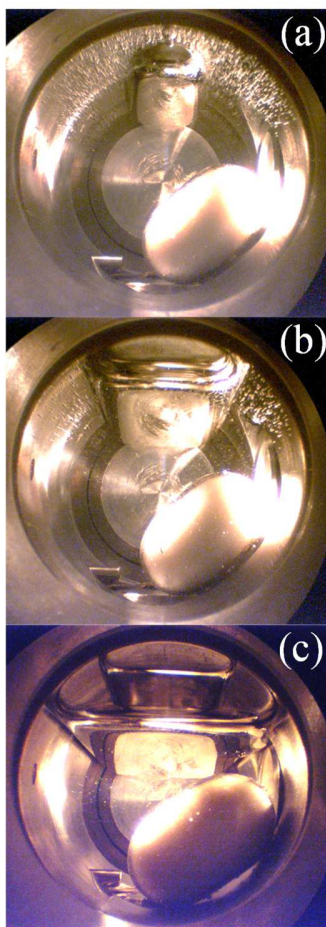
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683 Figure 4. Observed phase equilibria during isothermal depressurization of CO₂ and
684 diphenylmethane mixtures: (a) liquid – liquid equilibrium for $z_{CO_2} = 60.18$ mol % at 293.2
685 K and 10.0 MPa; (b) liquid – liquid – vapor equilibrium for $z_{CO_2} = 60.18$ mol % at 293.2 K
686 and 5.70 MPa; (c) liquid – liquid – vapor equilibrium for $z_{CO_2} = 75.15$ mol % at 292.8 K
687 and 5.57 MPa.

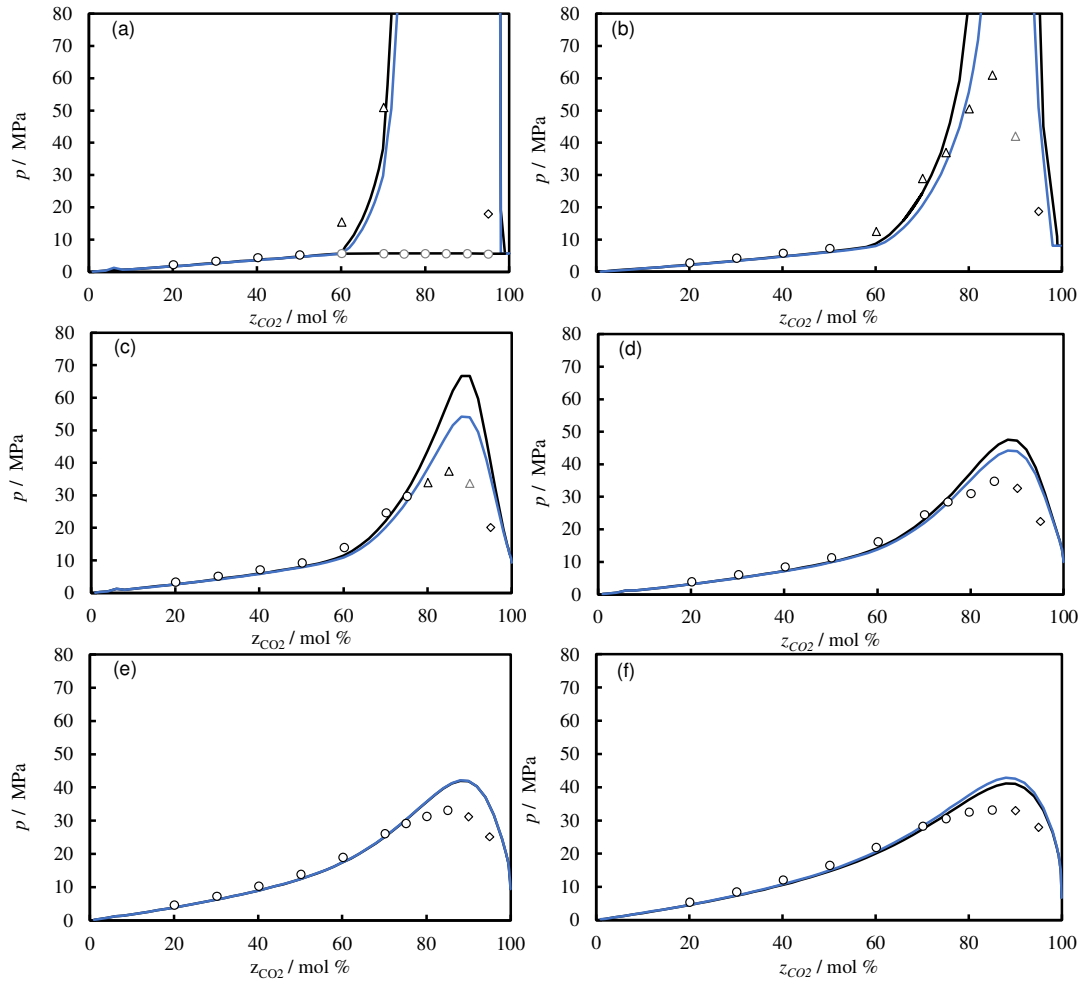
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694 Figure 5. Isothermal interpolated p - z_{CO_2} diagram at different temperatures $T = 293.15$ K (a);
 695 $T = 308.15$ K (b); $T = 323.15$ (c); $T = 338.15$ K (d); $T = 358.15$ K (e); and $T = 378.15$ K (f)
 696 compared to modelling results from PR EOS with fitted binary interaction parameters from
 697 Table 7 (black line), and PPR78 model (blue line). Experimental L→LV in black circles
 698 (○); L→LL in black triangles (△), F→FF in gray triangles (△); LL→LLV in gray circles
 699 (○); and V→LV in diamonds (◇).

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Fluid phase equilibria in asymmetric model systems.

Part I: CO₂ + diphenylmethane

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Graphical Abstract

