Accepted Manuscript

Title: A fast method to equilibrate carbon dioxide with brine at high pressure and elevated temperature including solubility measurements

Authors: R.M. El-Maghraby, C.H. Pentland, S. Iglauer, M.J. Blunt

Please cite this article as: R.M. El-Maghraby, C.H. Pentland, S. Iglauer, M.J. Blunt, A fast method to equilibrate carbon dioxide with brine at high pressure and elevated temperature including solubility measurements, *The Journal of Supercritical Fluids* (2010), doi:10.1016/j.supflu.2011.11.002

Brine/CO₂ mixing set-up

A fast method to equilibrate carbon dioxide with brine at high pressure and elevated temperature including solubility measurements

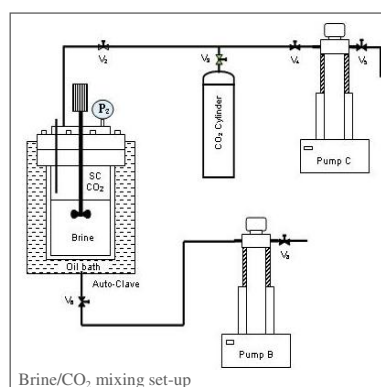R. M. El-Maghraby[1*], C.H. Pentland[1,2], S. Iglauer[1,3], M.J. Blunt[1]

[1] Department of Earth Science and Engineering, Imperial College London SW7 2AZ, United Kingdom

[2] Current address Shell Global Solutions International

[3] Current address Curtin University, Department of Petroleum Engineering, 26 Dick Perry Avenue, 6151 Perth, Australia

- We introduce a fast and easy methodology to equilibrate CO_2 and brine in the liter range.

- Equilibration was reached in 60 minutes.

- This is an important step for CO_2 storage studies and experiments.

- Solubility of CO_2 in brine was measured using isothermal depressurization method.

- Comparing our solubility data with the literature shows its consistence.

*Manuscript

A fast method to equilibrate carbon dioxide with brine at high pressure and elevated temperature including solubility measurements

R. M. El-Maghraby[1*], C.H. Pentland[1,2], S. Iglauer[1,3], M.J. Blunt[1]

[1] Department of Earth Science and Engineering, Imperial College London SW7 2AZ, United Kingdom
[2] Current address Shell Global Solutions International
[3] Current address Curtin University, Department of Petroleum Engineering, 26 Dick Perry Avenue, 6151 Perth, Australia

* Corresponding author
e-mail: r.el-maghraby09@imperial.ac.uk

Abstract:

We introduce a fast, easy and reliable methodology, using a stirred reactor, to equilibrate carbon dioxide with brine and measure the solubility of carbon dioxide in the aqueous phase at high pressure (9MPa) and elevated temperature (33, 50 and 70°C) conditions at the litre scale. The solubility of carbon dioxide in brine was measured using an isothermal depressurization method and compared with data in the literature. This methodology can be used in petroleum engineering, carbon storage and chemical engineering applications.

Keywords: Equilibration of Brine/CO_2, Solubility of CO_2, CO_2 Storage, supercritical CO_2, dissolution trapping.

1. Introduction

Long term storage of carbon dioxide (CO_2) in deep saline aquifers has been proposed to mitigate global warming [1]. Saline aquifers are abundant and geographically widespread with huge storage capacities [2-4]. The CO_2 will likely be stored as a supercritical (sc) phase at depths of 800 m or more [2], which maximizes the stored mass of CO_2.

When CO_2 is injected into geological formations there are a number of trapping mechanisms which prevent its migration and subsequent escape to the atmosphere. These are: stratigraphic and structural trapping, geochemical trapping, solubility trapping, and capillary trapping [5]. These mechanisms are the subject of active research, and preparing an equilibrated mixture of carbon dioxide and brine is an important step for many of these experiments (see, for instance, [6-8]).

We present here a methodology with which CO_2 can be rapidly equilibrated with brine at the litre-scale at high pressure and elevated temperature conditions representative of geological storage formations. This method could also be used to equilibrate other fluids if their viscosities are not too high, e.g. oils can be mixed with CO_2 for petroleum engineering studies or CO_2 can be mixed with other solvents (e.g. acetone, dichloromethane, diethyl ether, monoethanolamine, etc.) for chemical engineering applications.

In addition, the equilibrium solubility of CO_2 in brine was measured with an accurate isothermal depressurization method. The results were consistent with literature data. Solubility data is crucial for assessing not only the effectiveness of solubility trapping but the equilibration methodology outlined is a crucial step in capillary trapping experiments which rely on immiscible phase displacements [6, 9].

2. Experimental Equipment and Conditions

2.1 Experimental Apparatus

An equilibration reactor (1200 mL C276 autoclave with gas entrainment stirrer – Parr Instruments Co., IL, USA) was used to establish equilibrium between the CO_2 and brine phases. High precision syringe pumps (Teledyne ISCO 1000D, Lincoln, NE, USA) maintained pressures with high accuracy. The brine composition we used was 5wt % NaCl and 1wt % KCl in deionized water. *Figure 1* shows the experimental apparatus.

2.2 Experimental Procedure

2.2.1 Rapid establishment of CO_2/brine equilibrium

Three steps were developed to prepare brine saturated with CO_2 and CO_2 saturated with water vapour. During the first step $scCO_2$ was prepared in a syringe pump C, and a water heating jacket was used to heat the pump to the desired temperature (33°C, 50°C or 70°C). Pump C and all tubing were vacuumed for 20 min, then high pressure gaseous CO_2 (5MPa at 15°C) was transferred to pump C from a CO_2 cylinder by operating pump C in constant refill mode (the pump is driven by a stainless steel piston which was initially set to 0 ml volume which is driven back to full capacity, i.e. 1015 ml). When pump C was completely filled with CO_2 gas at the gas cylinder pressure, it was then pressurized to experimental pressure (9MPa); at these thermophysical conditions $scCO_2$ was generated.

During the second step, the reactor was heated to experimental conditions in an oil bath, then vacuumed and filled with de-aerated brine using a high precision syringe pump B. The reactor was then pressurized up to our experimental condition using pump B. The reactor is connected to the $scCO_2$ pump C operating at the same pressure, then 500 ml from the brine volume in the reactor were displaced by $scCO_2$ from pump C (pump was set to constant pressure mode) and withdrawing brine with pump B (pump was set to constant refill flow rate mode).The reactor is then isolated from pump B.

In the third step CO_2 and brine were brought to equilibrium inside the reactor by stirring with a stirrer at 200 rpm. The stirrer is a mixing shaft attached to a magnetic motor and has a gas entrapment design. It essentially pushes the lighter phase ($scCO_2$) into the bottom phase (brine) and generates a large surface area between the fluids by splitting the CO_2 into many small bubbles. This maximization of the contact surface and turbulent flow assured rapid equilibration.

The pressure was maintained constant during the dissolution process with pump C set to constant pressure mode. The pressure in the reactor was monitored using a pressure transducer (Rosemount 3051S pressure transmitter, Rosemount, USA) and pressure readings were logged on a computer. In addition the volume and pressure of pump C were logged to monitor $scCO_2$ volume balances.

Additional CO_2 was pumped into the vessel during the equilibration process because the CO_2 dissolved reducing the pressure. Equilibrium is reached if no more CO_2 is pumped into the reactor and no change in pump C volume is detected. Equilibration was completed in 60 minutes; however for subsequent experiments [6-8] the system was left overnight to stabilize.

2.3 Isothermal depressurization

The solubility of CO_2 in brine was measured in two steps by using the isothermal depressurization method.

In *step 1* pump B was cleaned and vacuumed, then filled with de-aerated brine. The brine was pressurized to 9 MPa and the brine volume (V_{B1}) was noted. The pressure was reduced gradually to atmospheric pressure. The volume (V_{B2}) in pump B was recorded after depressurization to atmospheric pressure.

In *step 2* pump B was emptied and vacuumed for 20 minutes, then a volume of CO_2 saturated brine (V_{M1}) – (same volume as for the pressurized de-aerated brine (V_{B1}) (*equation 1*)) - was transferred from the reactor to pump B by operating pump C in constant pressure mode and allowing CO_2 to displace some of the brine to pump B operating in constant refill mode.

$$V_{M1} = V_{B1} \qquad (1)$$

This was conducted at constant pressure and temperature to prevent CO_2 separating out of solution during the transfer process. After the required amount of CO_2 saturated brine was transferred, pump B was isolated. Then the CO_2-saturated brine mixture in pump B was expanded at constant temperature (33°C, 50°C or 70°C) by reducing the applied pressure gradually. Starting with an operating pressure of 9 MPa, the pressure was reduced gradually until atmospheric pressure was reached. The volume (V_{M2}) in pump B was noted.

Dead volumes in the system were measured carefully and taken into account for volume balance calculations.

The isothermal expansion method is based on the concept that for a given volume of brine saturated with CO_2, the CO_2 is released if the pressure is reduced isothermally. If the volume of CO_2 saturated brine is known before depressurization (V_{M1}) and the total brine volume is known after depressurization (V_{M2}), then the amount of CO_2 that separated out of solution (V_{CO2}) can be calculated by subtracting the two volumes (*equation 2*). We can then calculate the solubility of CO_2 in brine at this condition.

$$\text{Volume of } CO_2 \text{ dissolved in the brine } (V_{CO2}) = V_{M2} - V_{M1} \quad (2)$$

But to measure the solubility we have to consider two points to get an accurate measurement of solubility by using the isothermal depressurization method. First as the pressure is reduced, water vapor co-exists with CO_2 gas above the liquid phase. Second the brine volume will change with pressure reduction due to compressibility. Equation 2 is therefore modified:

$$V_{CO2} + \Delta V_B + V_{WV} = V_{M2} - V_{M1} \quad (3)$$

where V_{WV} is the volume of water vapour above the liquid phase and ΔV_B is the change in brine volume with pressure due to compressibility.

So, s*tep 1* was introduced to account for the compressibility of the brine and the amount of water vapour that will form on top of the liquid when the pressure is reduced. By isothermal depressurization of de-aerated brine we can know V_{B1} and V_{B2} and from *equation 4* we can compute the sum of ΔV_B and V_{WV}

$$\Delta V_B + V_{WV} = V_{B2} - V_{B1} \qquad (4)$$

Two assumptions were made. The first was assuming that the effect of CO_2 presence on top of the liquid phase in *step 2* on the amount of water vapour is negligible. Secondly we assumed that the CO_2 present in the brine will not change its compressibility. Substituting *equation 4* into *equation 3* results in

$$V_{CO2} + V_{B2} - V_{B1} = V_{M2} - V_{M1} \qquad (5)$$

Rearranging *equation 5* we get the actual amount of CO_2 dissolved in the brine at the given operating conditions,

$$V_{CO2} = V_{B1} - V_{B2} + V_{M2} - V_{M1} \qquad (6)$$

Knowing the volume of CO_2 dissolved in the brine we can calculate the number of moles of CO_2 using the Peng–Robinson equation of state [10]. The density of brine was obtained from the literature [11]. At atmospheric pressure there is still some CO_2 dissolved in the brine; this has been calculated to be 0.0098 mole CO_2/ kg brine at 70 °C, 0.0162 mole CO_2/ kg brine at

50 °C, and 0.0239 mole CO_2/ kg brine at 33 °C based on literature models [12, 13] and was added to the total obtained solubility.

3. Results and Discussion

We tested the reactor for three thermophysical conditions (9 MPa/33°C, 9 MPa/50°C and 9 MPa/70°C) and measured CO_2 solubilities in brine for a range of pressures (9 MPa, 7.58 MPa, 3.44 MPa and 0.34 MPa) at three temperatures (33°C, 50°C and 70°C). Our results are displayed in *Table 1*.

A similar solubility measurement has been described in the literature [8], although the way we account for water vapor is different. In [14] the separated CO_2 gas from the equilibration mixture was bubbled through concentrated sulfuric acid solution to condense the water vapor. In [15, 16] water vapor in the gas phase was not considered.

CO_2 solubility in brine at 70°C and 9 MPa was measured three times to check experimental reproducibility (0.842 ± 0.0138) mole CO_2/kg brine). The low standard deviation (≈ 1.6%) demonstrates that the isothermal depressurization method is highly reproducible.

Our results are consistent with solubility data available in the literature (*Table 2, Figures 2 and 3*) [12, 14-27]. Only one brine of the same composition has been studied in the literature [22]; other data for similar brine compositions and operating conditions are also listed. It is interesting to note that a solution containing KCl will dissolve more CO_2 than a solution containing an equal concentration (wt.%) NaCl [16]; so 6 wt.% NaCl solution will dissolve less CO_2 than a 5wt% NaCl/1wt.% KCl solution. In general at constant pressure and temperature the solubility decreases with increase in salinity (*Figure 3*).

4. Conclusions

A methodology to equilibrate brine with CO_2 at the litre-scale was presented. In two easy and fast steps we rapidly equilibrated supercritical CO_2 and brine at high pressure and elevated temperature. This method can be applied to a wide range of temperatures and pressures. We focus here on equilibrating brine and $scCO_2$ as this is most relevant for carbon storage studies [6, 9, 28]. However, we suggest that different fluids can also be saturated with CO_2 by using this method, e.g. in chemical engineering applications. Volumes in the liter range can be equilibrated in approximately one hour which is fast turn over compared with other mixing methods proposed.

The solubility of CO_2 in brine was measured by using the isothermal expansion method. This method has proven to be accurate and fast when compared to the available methods and data in the literature (Figures 2 and 3).

Acknowledgments

References

[1]   Intergovernmental Panel on Climate Change (IPCC), IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2005.

[2]   A. Firoozabadi, P. Cheng, Prospects for subsurface CO_2 sequestration, AIChE Journal, **56** (2010), pp. 1398-1405.

[3]   A. Kopp, H. Class, R. Helmig, Investigations on CO_2 storage capacity in saline aquifers Part 1. Dimensional analysis of flow processes and reservoir characteristics, International Journal of Greenhouse Gas Control, **3** (2009), pp. 263–276.

[4]   S. Bachu, Sequestration of CO_2 in geological media: criteria and approach for site selection in response to climate change, Energy Conversion and Management, **41** (2000), pp. 953-970.

[5]   S. E. Gasda, J. M. Nordbottenb, M. A. Celia, The impact of local-scale processes on large-scale CO_2 migration and immobilization, Energy Procedia, **4** (2011), pp. 3896-3903.

[6]   C. H. Pentland, R. El-Maghraby, S. Iglauer, M. J. Blunt, Measurements of the capillary trapping of supercritical carbon dioxide in Berea sandstone, Geophysical Research Letters, **38** (2011), L06401.

[7]   J. C. Perrin, M. Krause, C. W. Kuo, L. Milijkovic, S. M. Benson, Core-Scale experimental study of relative permeability properties of CO_2 and brine in reservoir rocks, Energy Procedia, **1** (2009), pp. 3515-3522.

[8]   T. Suekane, T. Nobuso, S. Hirai, M. Kiyota, Geological storage of carbon dioxide by residual gas and solubility trapping, International Journal of Greenhouse Gas Control, **2** (2008), pp. 58-64.

[9]   C. H. Pentland, S. Iglauer, R. El-Maghraby, Y. Tsuchiya, H. Okabe, M. J. Blunt, Measurement of Carbon Dioxide Capillary Trapping in Core Analysis, Proceedings of SPE 2nd International Conference on CO_2 Capture, Storage, and Utilization; SPE 138476, New Orleans, Louisiana, USA, 2010.

[10]   McCain, W.D., The properties of petroleum fluids, Tulsa: Penn Well Corporation, 1990.

[11]   S. Mao, Z. Duan, The P, V, T, x properties of binary aqueous chloride solutions up to T = 573 K and 100 MPa, The Journal of Chemical Thermodynamics, **40** (2008), pp. 1046-1063.

[12]   Z. Duan, R. Sun, An improved model calculating CO_2 solubility in pure water and aqueous NaCl solutions from 273 to 533 K and from 0 to 2000bar, Chemical Geology, **193** (2003), pp. 257-271.

[13]   Z. H. Duan, R. Sun, C. Zhu, I. M. Chou, An improved model for the calculation of CO_2 solubility in aqueous solutions containing Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-}, Marine Chemistry, **98** (2006), pp. 131-139.

[14]   J. A. Nighswander, N. Kalogerakis, A. K. Mehrotra, Solubilities of carbon dioxide in water and 1 wt.% NaCl solution at pressures up to 10 MPa and temperatures from 80 to 200° C, J. Chemical and Engineering Data, **34** (1989), pp. 355-360.

[15]   Z. Li, M. Dong, S. Li, L. Dai, Densities and solubilities for binary systems of carbon dioxide + water and carbon dioxide + brine at 59° C and pressures to 29 MPa, J. Chemical and Engineering Data, **49** (2004), pp. 1026-1031.

[16]   Y. Liua, M. Houa, G. Yanga, B. Han, Solubility of CO_2 in aqueous solutions of NaCl, KCl, $CaCl_2$ and their mixed salts at different temperatures and pressures, Journal of Supercritical Fluids, **56** (2011), pp. 125-129.

[17]   H. S. Kiepe, K. Fischer, J. Gmehling, Experimental determination and prediction of gas solubility data for CO_2 + H_2O mixtures containing NaCl or KCl at temperatures between 313 and 393 K and pressures up to 10 MPa, Industrial & Engineering Chemistry Research, **41** (2002), pp. 4393-4398.

[18]   S. Bando, F. Takemura, M. Nishio, E. Hihara, M. Akai, Solubility of CO_2 in aqueous solutions of NaCl at (30 to 60)° C and (10 to 20) MPa, J. Chemical and Engineering Data, **48** (2003), pp. 576-579.

[19]   A. N. Sabirzyanov, R. A. Shagiakhmetov, G. R. Gabitov, A. A. Tarzimanov, F. M. Gumerov, Water solubility of carbon dioxide under supercritical and subcritical conditions, Theoretical Foundations of Chemical Engineering, **37** (2003), pp. 51-53.

[20]   D. Koschel, J. Y. Coxam, L. Rodier, V. Majer, Enthalpy and solubility data of CO_2 in water and NaCl (aq) at conditions of interest for geological sequestration, Fluid Phase Equilibria, **247** (2006), pp. 107-120.

[21]   W. S. Dodds, L. F. Stutzman, B. J. Sollami, Carbon dioxide solubility in water, Industrial and Engineering Chemistry, 1 (1956).

[22]   M. Trusler , D. Vega-Maza, Solubility of CO_2 in aqueous solutions of either NaCl and KCl or $MgCl_2$ and densities of the CO_2-saturated solutions at temperatures of (308 to 423) K and at pressures up to 40 MPa, to be published.

[23]   N. Akinfieva, L. Diamond, Thermodynamic model of aqueous CO_2-H_2O-NaCl solutions from -22 to 100° C and from 0.1 to 100 MPa, Fluid Phase Equilibria, **295** (2010), pp. 104-124.

[24]   N. A. Darwish, N. Hilal, A simple model for the prediction of CO_2 solubility in H_2O– NaCl system at geological sequestration conditions, Desalination, **260** (2010), pp. 114-118.

[25]   N. Spycher, K. Pruess, A Phase-Partitioning Model for CO_2-Brine Mixtures at Elevated Temperatures and Pressures: Application to CO_2-Enhanced Geothermal Systems, Transport in Porous Media, **82** (2010), pp. 173-196.

[26]   X. Ji, S. P. Tan, H. Adidharma, M. Radosz, SAFT1-RPM Approximation Extended to Phase Equilibria and Densities of CO_2-H_2O and CO_2-H_2O-NaCl systems, Industrial & Engineering Chemistry Research, **44** (2005), pp. 8419-8427.

[27]   N. Spycher, K. Pruess, CO_2-H_2O Mixtures in the Geological Sequestration of CO_2. II. Partitioning in Chloride brines at 12-100° C and up to 600 bar, Geochimica Acta, **69** (2005), pp. 3309-3320.

[28]   C. H. Pentland, R. El-Maghraby, A. Georgiadis, S. Iglauer, M. J. Blunt, Immiscible Displacements and Capillary Trapping in CO_2 Storage, Proceedings of the Greenhouse Gas Control Technology Conference 2010, Amsterdam, The Netherlands, 2010.
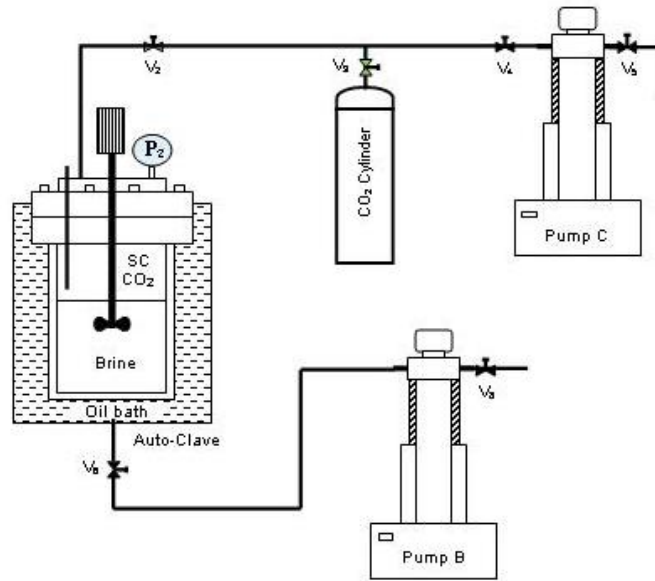
Figure 1: Experimental apparatus for brine-CO_2 equilibrium.
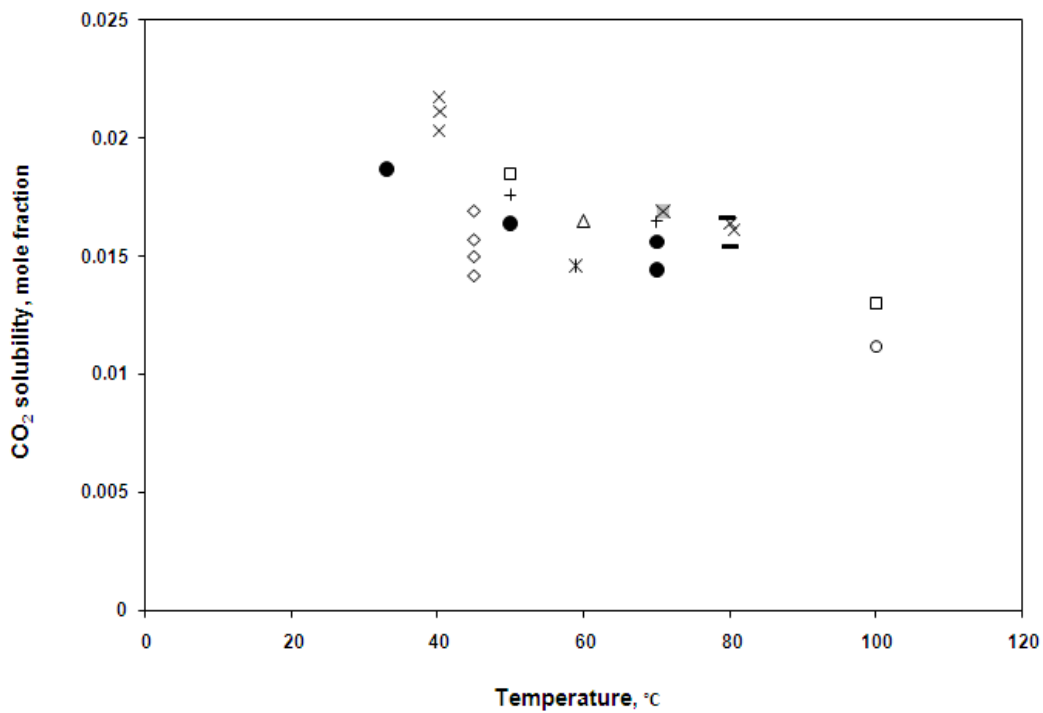
Figure 2: Solubility data for CO_2 in brine with different salinities at CCS pressures (between 8.4-10.5 MPa) versus temperature – solid symbols are our measurements and open symbols are literature data;(━) Nighswander et al (1989) [14], (*) Li et al. (2004) [15], (◊) Y. Liua et al. (2010) [16], (x) Kiepe et al (2002) [17], (Δ) Bando et al. (2003) [18], (□) Sabirzyanov et al (2003), [19] (○) Koschel et al (2006 [20], (+) Dodds et al (1956) [21], (**X**) M. Trusler, et.al. (to be published) [22], (●) Our measurements.
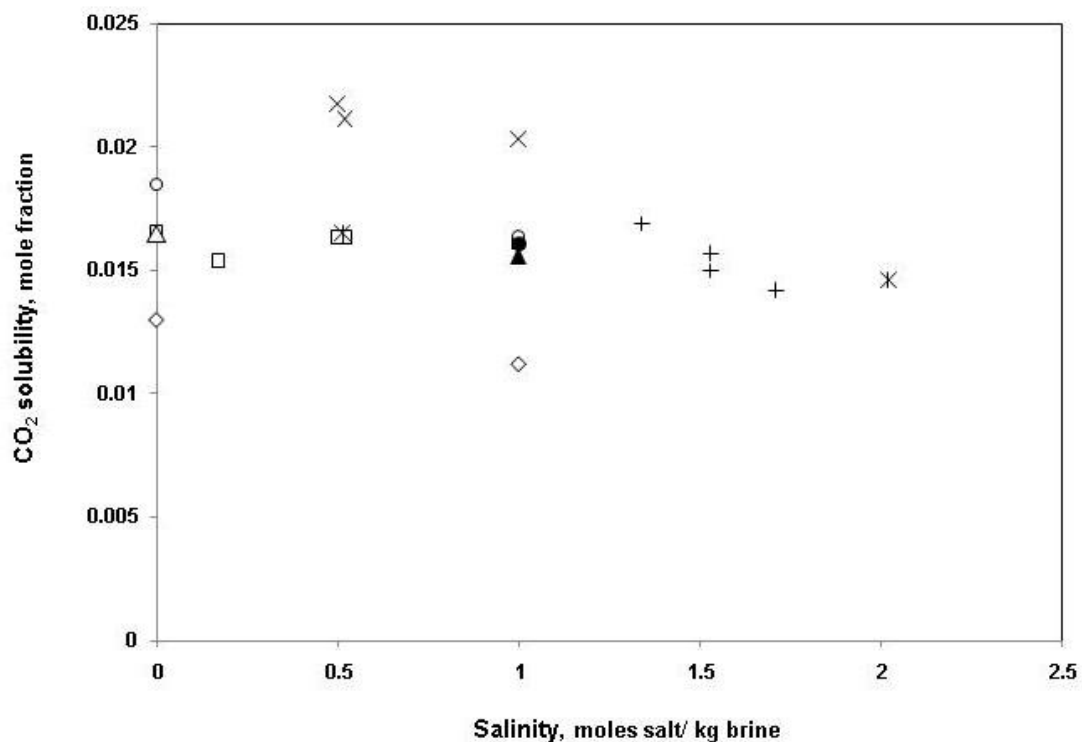
Figure 3: Solubility data for CO_2 in brine versus salinity at CCS temperatures (between 33-100°C) and pressures (between 8.4-10.5 MPa). Solid symbols are our measurements and open symbols are literature data (◊) T= 100°C and p= 10.20 (±0.28) MPa [19, 20], (□)T= 80.1 (±0.3) °C and p = 9.51 (±0.57) MPa [14,17], (Δ) T= 70°C and p= 9 MPa [21, (▲)our measurement], (*)T= 59.5 (±0.71) °C and p = 10.19 (±0.27) MPa [15, 18], (○) T= 50°C and p = 9.5 (±0.58) MPa [19-21, (●) our measurement], (+) T= 45°C and p= 9.8 (±0.86) MPa [16] (x) T= 40.3°C and p = 8.47 (±0.21) MPa [17].

Table 1: Solubility data for CO_2 dissolved in brine measured using the isothermal de-pressurization method. The salinity was constant with 0.856 moles NaCl and 0.134 moles of KCl per kilogram water.

T (°C)	P (MPa)	Solubility of CO_2 (mole CO_2/ kg brine)	Mole fraction of dissolved CO_2
70	9	0.857	0.0159
70	9	0.836	0.0155
70	9	0.832	0.0154
70	7.58	0.78	0.0144
70	3.44	0.39	0.0073
70	0.34	0.045	0.0008
50	9	0.886	0.0164
33	9	1.015	0.0187

Table 2: Solubility data of CO_2 in water for different salinities and operating conditions from the literature.

Reference	T (°C)	P (MPa)	Salinity (wt. %)	Salinity (moles salt/ kg brine)	Solubility of CO_2 (mole CO_2/ kg brine)	Mole fraction of CO_2
Experimental data						
J. A. Nighswander, et.al. (1989) [14]	79.7	10.18	0	0	0.9376	0.0166
	80.1	9.94	1% (NaCl)	0.171 (NaCl)	0.8631	0.0154
Z. Li, et.al. (2004) [15]	59	10.38	8.05% (Weyburn brine)	2.021 (Weyburn brine)	0.7666	0.0146
Y. Liua, et.al.(2010) [16]	45	10.09	10% (NaCl)	1.71 (NaCl)	0.7432	0.0142
	45	10.09	10 % (KCl)	1.34 (KCl)	0.893	0.0169
	45	10.58	5 % (NaCl)& 5% (KCl)	0.86 (NaCl)& 0.67(KCl)	0.825	0.0157
	45	8.59	5 % (NaCl)& 5% (KCl)	0.86 (NaCl)& 0.67(KCl)	0.784	0.0150
J. Kiepe, et.al. (2002) [17]	40.38	8.43	3 % (NaCl)	0.52 (NaCl)	1.1738	0.02112
	80.08	9.24	3 % (NaCl)	0.52 (NaCl)	0.9048	0.01636
	40.31	8.28	3.7 % (KCl)	0.5 (KCl)	1.2000	0.02174
	80.08	8.74	3.7 % (KCl)	0.5 (KCl)	0.8981	0.01636
	40.31	8.7	7.5 % (KCl)	1 (KCl)	1.0862	0.02031
	80.55	9.45	7.5 % (KCl)	1 (KCl)	0.8574	0.0161
S. Bando, et.al. (2003) [18]	60	10	3 % (NaCl)	0.514 (NaCl)	0.9127	0.0165
R. Sabirzyanov, et.al. (2003) [19]	50	10	0	0	1.0471	0.0185
	100	10	0	0	0.7317	0.013
D. Koschel, et.al. (2006) [20]	50.1	10	5.8% (NaCl)	1 (NaCl)	0.8891	0.0164
	100.1	10.4	5.8% (NaCl)	1 (NaCl)	0.6040	0.0112
W. Dodds, et.al. (1956) [21]	70	9	0	0	0.9320	0.0165
	50	9	0	0	0.9953	0.0176
M. Trusler, et.al. (to be published) [22]	70.9	13.69	5% (NaCl)& 1% (KCl)	0.86 (NaCl)& 0.13 (KCl)	0.9147	0.0169
Theoretical data						
N. Akinfiev & L. Diamond (2010) [23]	70	9	5.8% (NaCl)	1	0.75	0.0138
N. Darwish, N. Hilal (2010) [24]	50	9	5.8% (NaCl)	1	0.9	0.0166
N. Spycher & K. Pruess (2010) [25]	50	9	5.8% (NaCl)	1	0.9	0.0166
	90	9	5.8% (NaCl)		0.7	0.0129
X. Ji, et.al. (2005) [26]	60.15	9	3 % (NaCl)	0.5292	0.9033	0.0163
	80.15	9	3 % (NaCl)	0.52	0.8460	0.0153
N. Spycher & K. Pruess (2005) [27]	60	9	3 % (NaCl)	0.5	0.85	0.0154
Z. Duan & R. Sun (2003) [12]	60.15	10	5.8% (NaCl)	1	0.8405	0.0155