Experiments and appraisal to investigate the effect of CO_2/water volume combined with gravity flow characteristics in the Delft area sand reservoirs

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1 Executive Summary (restricted)

The activities in WP3.5.2 are mostly performed within the framework of DUT Post-Doc and student activities associated to the Delft geothermal project (DAP). In September 2012 Dr. H. Salimi left the university. Till then he had the lead in this part of the work package. Theory development & Modelling The new model to combine geothermal heat mining and co-injection of CO_2 in the reservoir; phase behaviour of CO_2 and water through space and time at varying P,T, is tested and improved with respect to the transition zones, heterogeneity of the reservoir and input parameters as expected for a field case. Furthermore, trapping zones and trapping effects have been modelled for non-isothermal multi-phase flow. In addition, the work has undergone several iteration of 2D/3D improvement and presented during the Cato meeting in spring 2012.

- *Surface & sub-surface integration*. Salimi and students also started a new study to connect the surface and sub-surface activities. An inventory of the surface facilities/activities (power plant, capture options, transport and storage) is under way. On-going work: MSc-thesis D. Reyes Lasteri: Implementation and combining of surface and sub-surface modules for the energy/exergy characterization of CO_2-geothermals at the Delft University Geothermal Concession.
- *Developments in drilling.* In September Delft University approved the proposition to develop a geothermal plant that will be combined with the (to be renovated) congenial power plant of the university. The water is used for grid heating of various buildings that will be renovated in the coming four years. The second step, CCS, was kept out of this decision.
  - The powerplant is to be renovated in such way, that capture research and development can be implemented.
  - Delft is now talking with financial and operational partners. These negotiations have to be completed at the end of spring 2013.
- *MSc/BSc-reports* written in 2012 are available from the Delft University Library repository. The relevant reports are:
  - R. Logister: Geochemical work on fluid composition (salinity) and behaviour at changing temperatures.
  - C. den Boer: The effect of dissolved methane on subsurface flow for heat production from geothermal aquifers.
  - R.C.A. Smit: Optimization of geothermal well doublet placement.
  - E. van Dalen: Heat flow experiments and modelling.
  - T. van der Ende: Mineral Scaling in Geothermal Wells
  - Q. de Zeeuw: Modeling two-phase fluid and heat flow in geothermal wells.
  - F.W.G.M. van Beuningen: Determination of the applicability of the distributed optical-fiber temperature sensing technique for geothermal energy production within the DAP - Delft Geothermal Project.

Distribution List

(this section shows the initial distribution list)

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Document Change Record

(this section shows the historical versions, with a short description of the updates)

Version	Nr of pages	Short description of change	Pages
3.5.2-D05	1 - 23	On-going work on field development of the doublets, associated petrophysical results and modelling work	6 - 23

Table of Content

2 Applicable/Reference documents and Abbreviations

2.1 Applicable Documents

(Applicable Documents, including their version, are the “legal” basis to the work performed)

	Title	**Doc nr**	**Version**
AD-01d	Toezegging CATO-2b	FES10036GXDU	2010.08.05
AD-01f	Besluit wijziging project CATO2b	FES1003AQ1FU	2010.09.21
AD-02a	Consortium Agreement	CATO-2-CA	2009.09.07
AD-02b	CATO-2 Consortium Agreement	CATO-2-CA	2010.09.09
AD-03g	Program Plan 2013	CATO2-WP0.A-D03	2013.04.01

2.2 Reference Documents

(Reference Documents are referred to in the document)

	Title	**Doc no**	**No**
RD-01	Hamidreza Salimi, Karl–Heinz Wolf, and Johannes Bruining. 2012. Negative-Saturation Approach for Compositional Flow Simulations of Mixed CO_2–Water Injection into Geothermal Reservoirs Including Phase Appearance and Disappearance. *SPE Journal* **17** (2): 502-522. DOI: 10.2118/142924–PA.		
RD-02	Hamidreza Salimi and Karl–Heinz Wolf. 2012. Integration of Heat–Energy Recovery and Carbon Sequestration. *International J. of Greenhouse Gas Control* **6:** 56-68. DOI: 10.1016/j.ijggc.2011.11.010.		
RD-03	Hamidreza Salimi, Karl–Heinz Wolf, and Johannes Bruining. 2012. Negative Saturation Approach for Non–Isothermal Compositional Two–Phase Flow Simulations. *Transport in Porous Media* **91** (2): 391-422. DOI: 10.1007/s11242–011–9851–5.		
RD-04	Hamidreza Salimi, Karl-Heinz Wolf, Johannes Bruining, The influence of capillary pressure on the phase equilibrium of the CO2–water system: Application to carbon sequestration combined with geothermal energy, International Journal of Greenhouse Gas Control, Volume 11, Supplement, November 2012, Pages S47-S66, ISSN 1750-5836, 10.1016/j.ijggc.2012.09.015.		

Invited talks, presentations and abstracts

Hamidreza Salimi, Karl-Heinz Wolf, and Johannes Bruining. 2012. Integration of the Delft Geothermal Projects and Carbon Sequestration" at the 8th CATO–2 Day in Utrecht University, Utrecht, The Netherlands, 21 June 2012

Hamidreza Salimi, Karl-Heinz Wolf, and Johannes Bruining. 2012. The Influence of Capillary Pressure on Phase Equilibrium of Mixed CO2-Water Injection into Geothermal Reservoirs Including Phase Appearance and Disappearance. Paper SPE 153886 to be presented at the SPE EUROPEC/EAGE Annual Conference and Exhibition, Copenhagen, Denmark, 4–7 June.

Hamidreza Salimi, Karl-Heinz Wolf, and Johannes Bruining. 2011. Integration of Heat–Energy Recovery and Carbon Sequestration" at the 7th CATO–2 Day in Utrecht University, Utrecht, The Netherlands, July 2011

Hamidreza Salimi, Karl–Heinz Wolf, and Johannes Bruining. 2011. Negative Saturation Approach for Compositional Flow Simulations of Mixed CO_2–Water Injection into Geothermal Reservoirs, Including Phase Transition and Disappearance. Paper SPE 142924 presented at the SPE EUROPEC/EAGE Annual Conference and Exhibition, Vienna, Austria, 23–26 May, 2011. Doi: 10.2118/142924-MS. Publ: Society of Petroleum Engineers. ISBN: 978-90-73834-12-5. URL: http://www.onepetro.org/mslib/app/Preview.do?paperNumber=SPE-142924-MS&societyCode=SPE

Hamidreza Salimi, Karl–Heinz Wolf, and Johannes Bruining. 2011. Non–Isothermal Compositional Flow Simulations of Mixed CO_2–Water Injection into Geothermal Reservoirs. Presented at the European Geosciences Union (EGU) General Assembly 2011 Conference, Geophysical Research Abstracts, Vol. 13, EGU2011–379, Vienna, Austria, Vienna, Austria, 23–26 May. URL: http://meetingorganizer.copernicus.org/EGU2011/EGU2011-379.pdf

Hamidreza Salimi, Karl–Heinz Wolf, and Johannes Bruining. 2011. Negative Saturation Approach for Non–Isothermal Compositional Flow Simulations of Mixed CO_2–Water Injection into Geothermal Reservoirs, Including Phase Transition and Disappearance. Poster C8 presented at the INTERPORE2011 conference, Bordeaux, France, 29–31 March.

- "Nonisothermal Compositional Simulations of Mixed CO_2–Water Injection into Geothermal Reservoirs" at the SP3 Underground Storage and Monitoring meeting of the Dutch national R&D program for CO_2 capture, transport and storage (CATO–2), TU Delft, The Netherlands, Feb 2011.
- Hamidreza Salimi, Remco Groenenberg, and Karl–Heinz Wolf. 2011. Compositional flow simulations of mixed CO_2-water injection into geothermal reservoirs: Geothermal energy combined with CO_2 storage. In: Proc. 36th Workshop on geothermal Reservoir Engineering, Stanford Univ., Stanford, CA, USA, 13 p. (SGP-TR-191), 31 January – 2 February 2011 Publ.: ISBN: 978-1-61782-788-4.
  URL: http://ere.stanford.edu/pdf/IGAstandard/SGW/2011/salimi.pdf

2.3 Abbreviations

(this refers to abbreviations used in this document)

DAP	Delft Aardwarmte Project or Delft Geothermal Project

3 Heat-Energy Recovery and Carbon Sequestration

a*bstract on phase modelling*:

Cold mixed CO_2-water injection into hot-water reservoirs can be used for simultaneous geothermal-energy (heat) production and subsurface CO_2 storage. This work studies this process in a 2D geothermal reservoir for a homogeneous reservoir, a layered reservoir, and a heterogeneous reservoir represented by a stochastic-random field. We give a set of simulations for a variety of CO_2-injection concentrations. In this process, often regions of two-phase flow are connected to regions of single-phase flow. Different systems of equations apply for single-phase and for two-phase regions. We develop a solution approach, called the non-isothermal negative saturation (NegSat) solution approach, to solve efficiently non-isothermal compositional flow problems (e.g., CO_2-water injection into geothermal reservoirs) that involve phase disappearance, phase appearance, and phase transition. The advantage of the solution approach is that it circumvents using different equations for single-phase and two-phase regions and the ensuing unstable switching procedure. In the NegSat approach, a single-phase multi-component fluid is replaced by an equivalent fictitious two-phase fluid with specific properties. The equivalent properties are such that in the single-phase aqueous region, the extended saturation of a fictitious gas is negative.

We discussed the salient features of the simulations in detail. When two phases are present at the injection side, heterogeneity and layering lead to more CO_2 storage compared to the homogeneous case because of trapping. In addition, layering avoids movement of the CO_2 to the upper part of the reservoir and hence reduces the risk of leakage. Our results also show that heterogeneity and layering change the character of the solution in terms of useful-energy production and CO_2 storage. The simulations can be used to construct a plot of the recuperated useful energy versus maximally stored CO_2. Increasing the amount of CO_2 in the injection mixture leads to bifurcation points at which the character of the solution in terms of energy production and CO_2 storage changes. For overall injected CO_2 mole fractions less than 0.04, the result with gravity is the same as the result without gravity. For larger overall injected CO_2 mole fractions, however, the plot without gravity differs from the plot with gravity due to early breakthrough of a supercritical-CO_2 tongue near the cap rock. The plot of the useful energy (exergy) versus the CO_2 storage capacity in the presence of gravity shows a *Z*-shape. The top horizontal part represents a branch of high exergy recovery and a relatively lower storage capacity, whereas the bottom part represents a branch of lower exergy recovery and a higher storage capacity.

4 Modeling Experiments and Appraisal to Investigate the Effect of CO_2/Water Concentrations and Volumes Combined with Gravity Flow Characteristics in the Delft Area Sand Reservoirs. The Influence of Capillary Pressure on the Phase Equilibrium of the CO_2-Water System: Application to Carbon Sequestration Combined with Geothermal Energy

In this work, we include the capillary-pressure effect in the phase-equilibrium calculation of the CO_2-water system. Our rationale to investigate the influence of capillary pressure on the phase equilibrium of the CO_2-water system is that the effect might substantially influence the CO_2-storage capacity and CO_2-trapping mechanism in less permeable zones of reservoirs. Our hypothesis is that inclusion of capillary pressure in VLE reduces the solubility of CO_2 in the aqueous phase and increases the solubility of water in the CO_2-rich (non-wetting) phase. We use thermodynamics to determine the range of capillary pressures for which discernable effects occur in the fluid-phase equilibrium compositions and densities. Subsequently, we quantify the capillary-pressure effect on the CO_2 storage capacity and heat-energy recovery for CO_2-water injection into geothermal reservoirs. Our interest is in the capillary-pressure range between 0 and 100 bars for temperatures between 293 and 372 K and bulk (wetting-phase) pressures between 25 and 255 bars. For this purpose, we have implemented capillary pressure in the PRSV equation of state.

To examine for which values of the injected CO_2 concentrations inclusion of capillary pressure in the phase-equilibrium calculations shows an influence on the displacement process of the CO_2-water system, we simulate mixed CO_2-water injection into a geothermal reservoir. In this way, synergy is established between geothermal-energy production and subsurface CO_2 storage. We apply the non-isothermal negative saturation (NegSat) solution approach (Salimi et al. 2012a, 2012b, 2012c) to solve efficiently non-isothermal compositional CO_2-water flow that involves phase appearance, phase disappearance, and phase transitions. The advantage of this solution approach is that it circumvents using different equations for single-phase and two-phase regions and the ensuing unstable switching procedure. In this paper, we use the simulation results of mixed CO_2-water injection for various injected CO_2 concentrations to give a complete overview of optimal heat recovery and maximally stored CO_2 for a selected heterogeneity structure derived from the Delft Sandstone Member (Salimi et al. 2011a).

The objectives of this study are (1) to construct a thermodynamic model in which the influence of capillary pressure on the phase equilibrium of the CO_2-water system is included; (2) to quantify conditions for which inclusion of capillary pressure can substantially shift the thermodynamic properties of the CO_2-water system; and (3) to assess inclusion of capillary pressure in the phase equilibrium on the efficiency of CO_2 sequestration and heat-energy recovery for mixed CO_2-water injection into a geothermal reservoir.

The results show that capillary pressure promotes interfacial evaporation. Capillary pressure reduces the CO_2 solubility in water and the aqueous-phase density up to 64% and 1.3%, respectively, whereas it increases the water solubility in the CO_2-rich phase and the CO_2-rich-phase density up to 3,945% (1.0 + 39.5 = 40.5 times) and 1,544%, respectively. Capillary pressure shifts the CO_2 liquid-vapor transition and consequently the upper critical point of the CO_2-water system to a lower pressure. The intensity of the shift depends on the value of the capillary pressure and the bulk pressure.

For mixed CO_2-water injection into a geothermal reservoir, the influence of capillary pressure on the phase equilibrium reduces both the heat recovery up to 37% and the CO_2-storage capacity up to 37%. We construct a plot of the recuperated heat energy versus the maximally stored CO_2 for a variety of conditions; we compare the results including and excluding the effect of capillary pressure in the phase-equilibrium calculations. We also provide a cursory evaluation of the energy and economics of mixed CO_2-water injection into a geothermal reservoir.

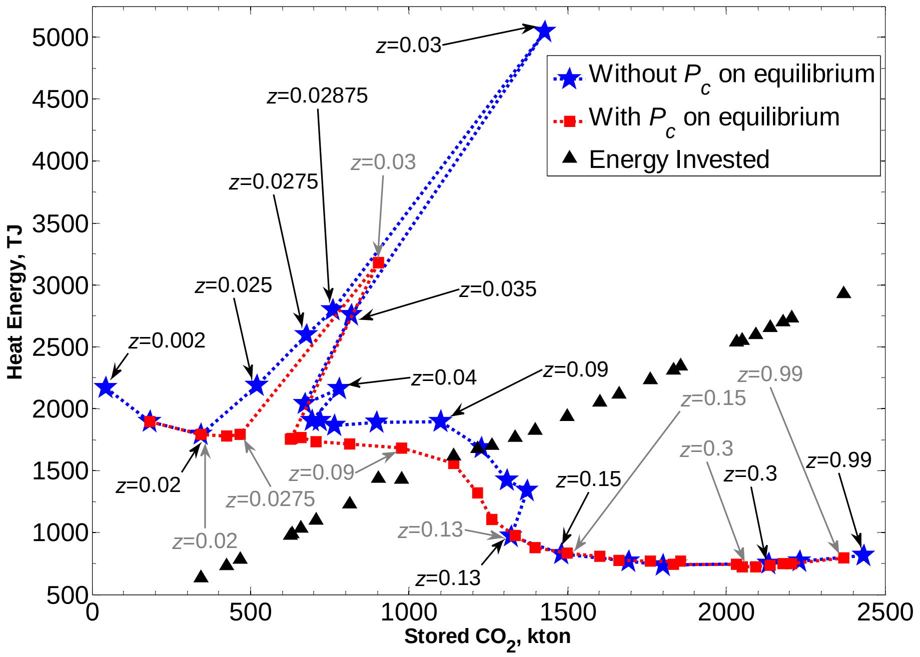

Figure 1—Cumulative heat-energy production and energy invested versus maximally stored CO_2 at the end of the process. We use *z* to denote the overall injected CO_2 mole fraction. The trend from left to right represents an increase in the injected CO_2 mole fraction. The point that corresponds to cold-water injection (i.e., no CO_2) is located on the y-axis (not shown here).

Fig. 1 plots two curves for the recuperated heat energy versus the maximally stored CO_2 at the end of the process: (1) the curve with the blue-star points excludes the capillary pressure in the phase-equilibrium calculations and (2) the curve with the red-square points includes the capillary pressure in the phase-equilibrium calculations. The figure includes the results for various overall injected CO_2 mole fractions. In Fig. 1, the black-triangular points represent the total energy consumed for each case including the capillary pressure in the phase-equilibrium calculations. For all cases, the initial reservoir conditions, water-injection rate, and injection temperature are the same. However, the overall injected CO_2 mole fraction is different for each case. Along the blue-stars and red- square curves, the overall injected CO_2 mole fraction essentially increases from left to right. With no added CO_2, the criterion to end the project is cold-water breakthrough, while if any amount of CO_2 is added, the criterion to end the project is when CO_2, dissolved into the aqueous phase, breaks through. If the entire pore volume of the reservoir were filled with CO_2 at T = 353.15 K and P = 220 bars, a total CO_2-storage capacity of 13,678 ktonnes would be attained. When no CO_2 were added, a total geothermal-energy production of 16,492 TJ (1 T = 10^{12}) could be achieved.

Table 1 shows the CO_2-breakthrough time, cumulative CO_2 mass injected up to the CO_2-breakthrough time (i.e., stored CO_2), and cumulative heat-energy production for each red-square point in Fig. 1.

Table 1 The CO_2-breakthrough time, cumulative CO_2 injection, and cumulative heat-energy production for the heterogeneous cases.

Overall Injected CO_2 mole fraction, dimensionless	CO_2-breakthrough time, months	Cumulative CO_2 injection (storage), kton	Cumulative energy production, TJ
0.01	235	183.1	1896.1
0.02	221	343.4	1794.4
0.025	219	423.8	1782.8
0.0275	220	467.4	1792.3
0.03	390	902.3	3181.5
0.04	220	626.4	1754.5
0.05	232	631.1	1757.2
0.06	246	658.3	1768.5
0.07	254	706.9	1737.2
0.08	262	811.7	1713.8
0.09	266	957.4	1681.4
0.10	252	1141.2	1561.8
0.11	213	1214.9	1318.7
0.12	176	1262.5	1108.0
0.13	150	1334.5	975.7
0.14	129	1396.5	878.5
0.15	116	1497.8	832.7
0.16	106	1600.6	807.0
0.17	96	1663.3	777.5
0.18	90	1759.9	772.0
0.19	85	1855.5	771.3
0.20	77	1833.3	740.2
0.25	62	2032.3	740.6
0.30	53	2049.3	725.3
0.35	49	2093.8	726.5
0.40	47	2139.2	736.5
0.45	46	2179.9	748.4
0.50	45	2205.5	749.8
0.99	44	2369.4	793.6