Three Dimensional Reservoir Simulations of Supercritical CO_2 EGS

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Following the work of Pruess (2008) on the production behaviour of CO_2 as a working fluid in EGS, a three dimensional (3D) reservoir sensitivity analysis of CO_2 mass flow and heat extraction rates on injection temperature, rock permeability, rock porosity and reservoir temperature were performed. The 3D reservoir simulations were performed using the TOUGH2 modelling code with the modified ECO2N module.

Keywords: CO_2-EGS, reservoir simulation, TOUGH2, ECO2N

Background of the study

The literature on the application of supercritical CO_2 for Engineered Geothermal System (EGS) is relatively scarece. Most of the available literature are 1D and 2D simulations of the thermodynamic and transport properties as well as exergy analysis (Atrens et al, 2008; Atrens et al, 2009; Atrens et al, 2009; Brown et al, 2000; Pruess et al, 2006; Reichman et al, 2008; Remoroza et al, 2009).

Pruess (2008) performed 2D and 3D reservoir simulations of injection/production behaviour of an EGS operated with CO_2 as working fluid using TOUGH2 with fluid property module "EOSM" which is not commercially available. His simulations examine production behaviour in 2D areal model at different reservoir pressures and then assessed 3D flow effects on energy recovery. Table 1 lists the reservoir and CO_2 injection parameters used by Pruess (2008) and in this study.

The equivalent permeabilities calculated from the Soultz granite inferred from geophysical and flow log analysis range from 5.2 $x10^{-17}$ m^2 to $9.6x10^{-16}$ m^2 (Sausse et al, 2006) while intact granite has 1.6 to $3.8x10^{-19}$ m^2 permeabilities (Selvadurai, 2005). Soultz EGS average equivalent permeability is $5x10^{-16}$ m^2.

Porosities of granite range from 0.2 to 4% (http://www.granite-sandstone.com/granite-physical-properties.html).

This study will expand the previous 3D reservoir simulations of Pruess (2008) by determining the impact of injection and reservoir parameters such as permeability, porosity, reservoir temperature and CO_2 injection temperature on the CO_2 mass flow and heat extraction rates. Also, the applicability of the modified fluid property module ECO2N for EGS will be examined.

Table 1. Reservoir and CO_2 injection/production parameters.

	Pruess (2008)	This study
Formation		
Thickness, m	305 (5 layers)	305 (5 layers)
Fracture spacing, m	50	50
Permeable volume fraction	2%	2%
Permeability in fracture domain, $x10x10^{-15}m^2$	50	0.5, 5 and 50
Nos. of MINC	5	5
Porosity in fracture domain	50%	50%
Permeability in rock matrix, $x10x10^{-15}m^2$	50	0.5, 5 and 50
Porosity in rock matrix		0.2%, 2%
Rock grain density, kg/m^3	2650	2650
Rock specific heat, kJ/kg	1000	1000
Rock thermal conductivity, W/m-^oC	2.1	2.1
Initial conditions		
Reservoir fluid	CO_2, H_2O	CO_2, H_2O
Temperature, ^oC	200	200, 225
Pressure, bar	200	200
Production/Injection		
Production area, km^2	1	1
Fraction of the area modelled	1/8	1/4
Spatial resolution, m	32.14 and 70.1	20.83, 45.45
Injection Temperature, ^oC	20	20, 35
Injection pressure, bar	210 gravity equilibrated from top layer	210 gravity equilibrated from top layer
Production pressure, bar	190 gravity equilibrated from top layer	190 gravity equilibrated from top layer

Methodology

Because the fluid property module used in the only published 3D reservoir modelling of CO_2 flows in EGS is not publicly available; a modified ECO2N fluid property module is used in the present study. ECO2N is a fluid property module for the TOUGH2 simulator (Version 2.0) that was designed for applications to geologic sequestration of CO_2 in saline aquifers (Pruess, 2005). The temperature limitation of this module is $10^oC \leq T \leq 100^oC$. In the modified version of ECO2N the restriction on the upper temperature is removed with the provision that only pure phases like CO_2 or H_2O are present (i.e. no mixture).

The 3D simulations in this study were conducted using TOUGH2 in conjunction with the pre and post-processing graphical interface PetraSim. Because of symmetry, only ¼ of the calculation domain (1 km^2 five-spot well configuration) was simulated in this study (Figure 1). Also, a modified CO2TAB file was used so that wider ranges of pressure and temperature, which are more appropriate for EGS application, can be studied. CO2TAB lists thermodynamic properties of CO_2 at different temperature-pressure conditions which are then used by TOUGH2.

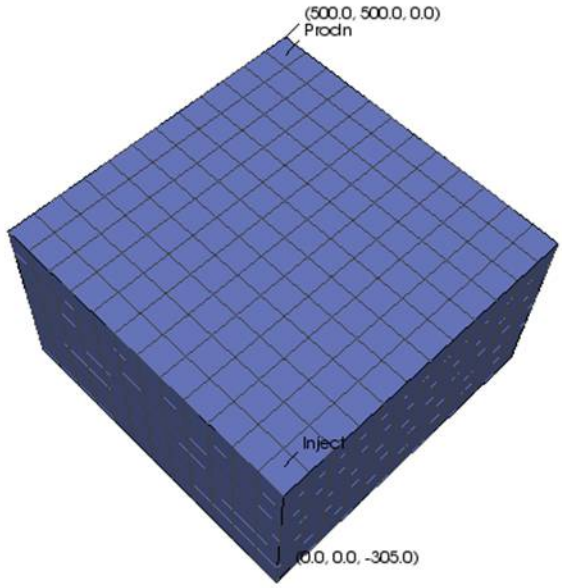

Figure 1: The 1/4 section of the five-spot well configuration showing an injection-production segment.

To validate the use of the modified ECO2N, the result of the previous 3D reservoir simulations were duplicated by finding the appropriate grid size equivalent to the previous model used by Pruess (2008). The previous study did not define rock wall specifications in the definition of fracture domain, i.e. permeability and porosity of the rock matrix. In the first attempt, different permeabilities were used for fracture domain and rock matrix (wall rock). A match was found for configuration where all layers of the production wells are open using a 12x12 areal grid (41.67 m side length) and rock matrix permeability of 1.9×10^{-14} m^2 and porosity of 0.2% (Figure 2). However, for configuration where only the top 50 m of the production well is open, the 12x12 areal grids of the ¼ symmetric model gives higher mass and heat extraction rates (Figure 3).

Doubling the areal grid size to 24x24 (20.83 side length) and defining rock matrix permeability equal to fracture domain permeability (5×10^{-14} m^2) and rock matrix porosity to 0.2% gave an almost perfect match both for CO_2 production well open to all layers (Figure 4) and open only to topmost 50 m layer (Figure 5).

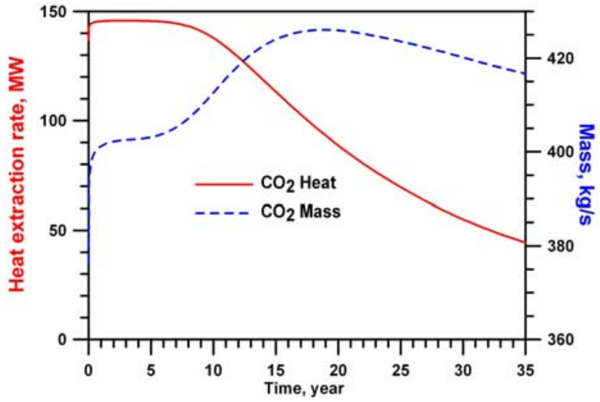

Figure 2: The CO_2 mass and heat extraction rates from this study match the previous study for a CO_2 production well open in all six layers using the ¼ symmetric model having 12x12 areal grids and rock matrix permeability of 1.9×10^{-14} m^2 and porosity of 0.2%.

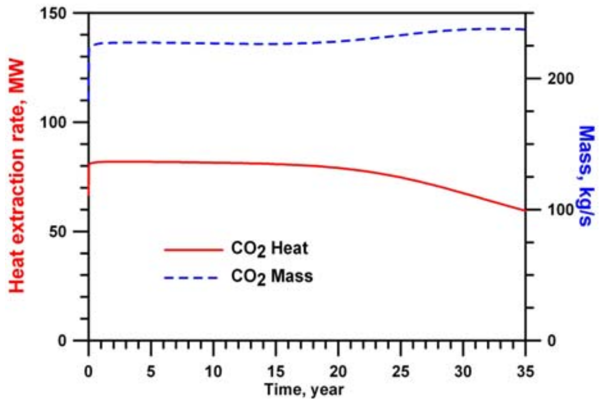

Figure 3: The CO_2 mass and heat extraction rates from this study are higher than the previous study for a CO_2 production well open only in topmost 50 m layer using a ¼ symmetric model having 12x12 areal grids and rock matrix permeability of 1.9×10^{-14} m^2 and porosity of 0.2%.

The reservoir simulation results from the ¼ symmetric model with 24x24 areal grid size was then used as the reference for sensitivity analysis. The result from this section of the study also proved the applicability of modified ECO2N for reservoir simulation of pure phase CO_2 reservoir flows.

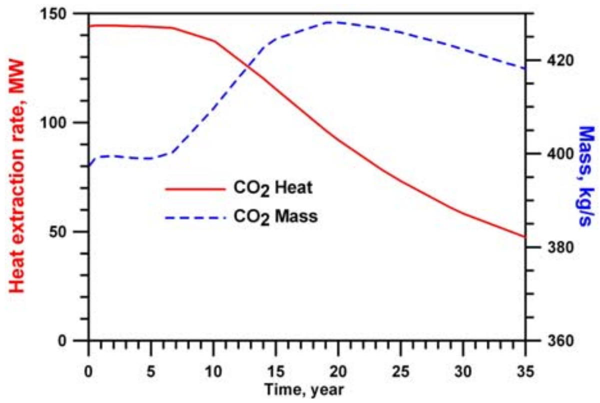

Figure 4: CO_2 mass and heat extraction rates from a ¼ symmetric model having 24x24 areal grids and rock matrix

permeability of 5x10-14 m2 and porosity of 0.2% match the previous study from a CO_2 production well open in all six layers.

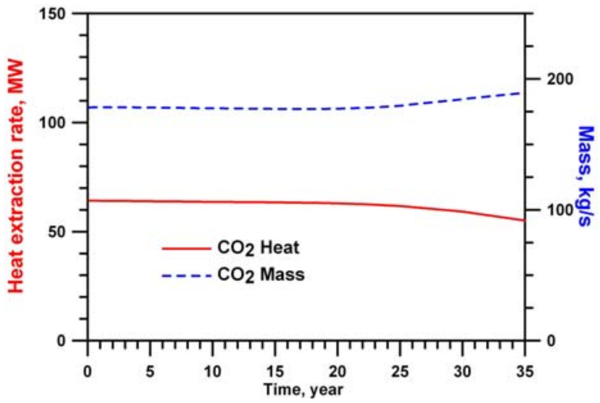

Figure 5: CO_2 mass and heat extraction rates using a ¼ symmetric model having 24x24 areal grids and rock matrix permeability of 5x10-14 m2 and porosity of 0.2% match the previous study from a CO_2 production well open only in topmost 50 m layer.

Results and Discussion

The high CO_2 mass circulation at a reservoir temperature of 200°C for a production well open to all layers initially resulted in very high heat extraction rates and rapid decline of the reservoir thermal content (144 MW to 47 MW) due to thermal depletion of the reservoir. In contrast, H_2O mass circulation was found to be low with a relatively slow decline rates and consequently slow decline in heat extraction rates (24 MW to 16 MW, Figure 6). However, as the previous study recommended, for the case of CO_2 EGS when only the topmost 50 m layer configuration (Figure 5) was used in the analysis stable mass production and heat extraction rate of 64 MW after 2 years were resulted.

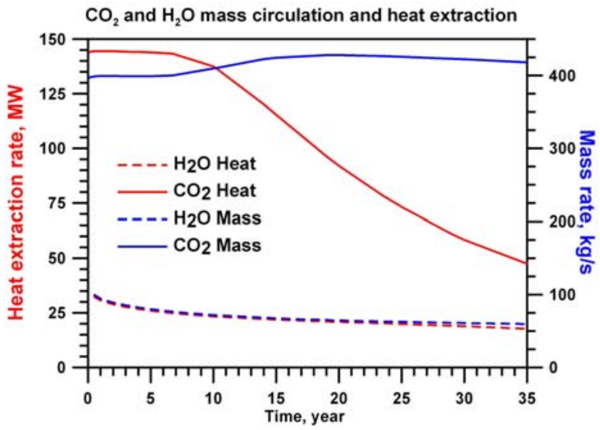

Figure 6: CO_2 and H_2O pure phase mass and heat extraction rates at 200°C reservoir.

The effect of injection temperature on CO_2 mass and heat extraction rates is shown in Figure 7. Increase in injection temperature above the critical temperature (31.4°C) resulted in higher mass production but lower heat extraction rates. The 35°C injection temperature is more or less the appropriate value for regions with arid climate like Australia's EGS locations.

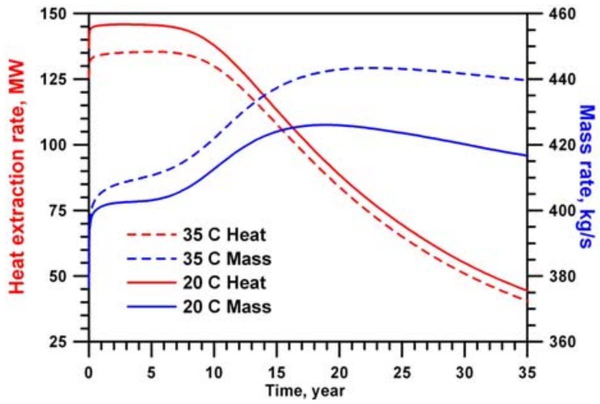

Figure 7: Effect of injection temperature on CO_2 mass and heat extraction rates in a 200°C EGS reservoir.

Rock matrix permeability has dramatic effect on CO_2 mass production. In our studies the mass production rates dropped from ~400 to 185 and 29 kg/s when one and two orders of magnitude decrease in permeability was implemented, respectively. Heat extraction rate, on the other hand, declined to 67 and 11 MW, respectively (Figure 8).

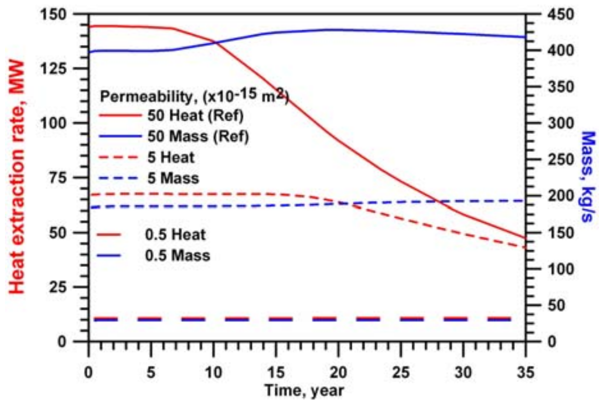

Figure 8: Effect of rock matrix permeabilities on CO_2 mass production and heat extraction rates.

Rock matrix porosity has no significant effect on the CO_2 mass production and heat extraction rates (Figure 9).

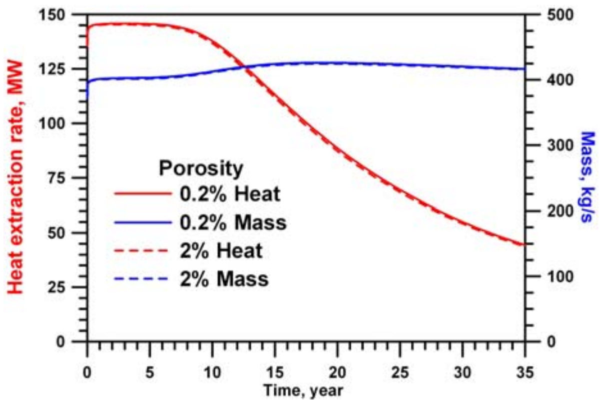

Figure 9: Effect of rock matrix porosity on CO_2 mass production and heat extraction rates.

The average CO_2 mass flow rates did not vary greatly with reservoir temperature (411 kg/s at 200°C, 398 kg/s at 225°C, and 395 kg/s at 175°C). Average heat extraction rates for the 200 and 225°C reservoir temperatures were found to be similar at 117 and 113 MW, respectively. However, at low reservoir temperature, the average heat extraction rate decreased to about 90 MW (Figure 10).

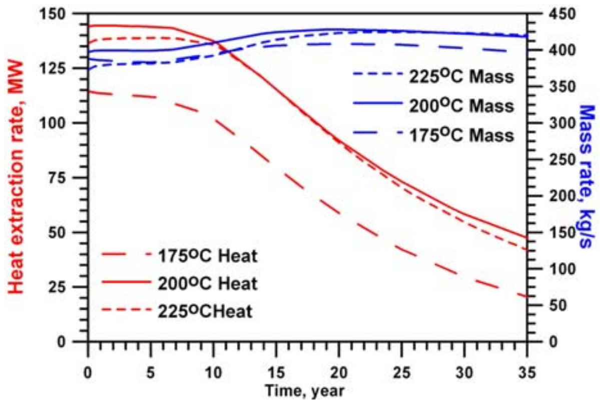

Figure 10: Effect of reservoir temperature on CO_2 mass production and heat extraction rates.

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