Role of Fluid Pressure in the Production Behavior of Enhanced Geothermal Systems with CO_2 as Working Fluid

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Keywords: enhanced geothermal systems (EGS), heat transmission, CO_2 storage, numerical simulation.

Abstract

Numerical simulation is used to evaluate mass flow and heat extraction rates from enhanced geothermal injection-production systems that are operated using either CO_2 or water as heat transmission fluid. For a model system patterned after the European hot dry rock experiment at Soultz, we find significantly greater heat extraction rates for CO_2 as compared to water. The strong dependence of CO_2 mobility (= density/viscosity) upon temperature and pressure may lead to unusual production behavior, where heat extraction rates can actually increase for a time, even as the reservoir is subject to thermal depletion.

Introduction

There has been increasing interest in the novel concept of operating enhanced geothermal systems (EGS) with high pressure (supercritical) CO_2 instead of water as heat transmission fluid. Originally proposed by D. Brown (2000), this concept may offer opportunities for reducing atmospheric emissions of CO_2, a greenhouse gas, while avoiding difficulties encountered in water-based EGS experiments, such as water losses (Abé et al., 1999), and strong mineral dissolution and precipitation reactions (Durst, 2002; Bächler, 2003; Xu and Pruess, 2004; Rabemana et al., 2005). The latter give rise to the twin problems of short-circuiting flow paths from injector to producer with premature thermal breakthrough on the one hand, formation plugging on the other. CO_2 is not an ionic solvent, and no significant dissolution-precipitation reactions would be expected in the "core" of an EGS operated with CO_2, where all aqueous phase has been removed by dissolution into the flowing CO_2 stream (Fouillac et al., 2004).

Evaluating the feasibility and suitability of using CO_2 as heat transmission fluid requires an understanding of the relevant transport and thermophysical properties of CO_2, as well as an assessment of chemical interactions of CO_2-based fluids with different mineral assemblages. In a previous study we evaluated thermophysical properties, including the temperature and pressure dependence of density, viscosity, and specific enthalpy, as well as compressibility and expansivity, and found considerable advantages of CO_2 in terms of reservoir heat extraction efficiency and wellbore hydraulics as compared to water (Pruess, 2006). We also performed a first quantitative exploration of the heat extraction and mass flow behavior of EGS operated with CO_2, using numerical simulation. Studies for a hypothetical fractured reservoir patterned after the Soultz system in eastern France (Baria et al., 2005; Dezayes et al., 2005) showed

approximately 50 % larger heat extraction rates for CO_2 as compared to water for a reservoir temperature of 200 ^oC, with the advantage of CO_2 increasing for lower reservoir temperature. These observations were explained in terms of the strong increase of water viscosity with decreasing temperature. For a water-based system, much of the pressure differential between injection and production wells is used up to move the very viscous fluid in the vicinity of the injection well. In contrast, viscosity of CO_2 increases much less with lower temperatures, so that a greater fraction of the applied pressure drop is available at the production well. In addition, CO_2 flow in the low-temperature region surrounding the injection well is facilitated by the substantial density increase of CO_2 with decreasing temperatures.

The simulation studies reported in (Pruess, 2006) compared CO_2 and water-based EGS for a fixed initial reservoir pressure of 500 bar. For the temperature and pressure conditions of interest to EGS, thermophysical properties of water (density, viscosity, specific enthalpy) depend primarily on temperature, with only weak dependence on pressure. In contrast, thermophysical properties of CO_2 are strong functions of pressure as well. It is the main purpose of this paper to explore the dependence of EGS-CO_2 production behavior on fluid pressures. We also address some issues that had not been considered in our previous studies, including heat exchange with cap and base rocks, and space discretization errors when modeling flow of supercritical CO_2 in fractured media.

This study focuses on energy production from CO_2-EGS. Issues of fluid loss and associated CO_2 storage and storage integrity are of course very important and will be addressed in a future publication.

Energy Recovery from CO_2-EGS

As in our previous work we consider an idealized fractured reservoir problem with parameters representative of conditions at the European EGS site at Soultz (Table 1; Pruess, 2006). Assuming a five-spot well configuration, the computational grid needs to cover only 1/8 of the domain (see Fig. 1). All simulation results will be scaled and reported on a “full well” basis. We use a two-dimensional parallel five-point grid of 36 square blocks with 70.71 m side length. The reservoir is assumed fractured with three orthogonal fracture sets of 50 m spacing. The matrix blocks are assumed to have negligible permeability, but will provide the main inventory of thermal energy. Matrix-fracture heat exchange is modeled using the method of “multiple interacting continua” (MINC; Pruess and Narasimhan, 1985), with subgridding of matrix blocks into five continua, for a total of 5x36 = 180 grid blocks. Fluid circulation is established by applying an overpressure of 10 bar at the injection side, and an underpressure of -10 bar at the production side, relative to original reservoir pressure. We monitor produced flow rate F and net heat extraction rate G, calculated as $G = F(h - h_{inj})$, where h is produced specific enthalpy, and h_{inj} is specific enthalpy at injection conditions of T = 20 ^oC. All simulations were done with our general-purpose reservoir simulator TOUGH2, augmented with a fluid property module “EOSM” that can describe all phase combinations of water-CO_2 mixtures within experimental accuracy, including pure water and pure (anhydrous) CO_2 in supercritical, liquid, and gaseous conditions (Pruess, 2004a, b). However, simulations reported here are either for "CO_2 only" or "water only" systems. Mixtures of CO_2 and water would be encountered during the early (development) phase of an EGS-CO2, as well as in the periphery of an EGS operated with CO_2 (Fouillac et al., 2004), and have not been considered here.

Table 1. Parameters for five-spot fractured reservoir reference case.

Formation		Flow Specifications	
thickness	H = 305 m	reservoir fluid	all CO_2, or all water
fracture spacing	D = 50 m	initial temperature	T_{in} = 200 °C
permeable volume fraction	f = 2%	initial pressure	P_{in} = 45 - 500 bar
permeability	$k = 50.0 \times 10^{-15}$ m^2	pattern area (Fig. 1)	A = 1 km^2
porosity in permeable domain*	ϕ_f = 50%	injector-producer distance	L = 707.1 m
rock grain density	ρ_R = 2650 kg/m^3	injection temperature	T_{inj} = 20 °C
rock specific heat	c_R = 1000 J/kg/°C	injection pressure (downhole)	$P_{inj} = P_{in}$ + 10 bar
rock thermal conductivity	λ = 2.1 W/m/°C	production pressure (downhole)	$P_{pro} = P_{in}$ - 10 bar

* we include some wall rock in the definition of the fracture domain

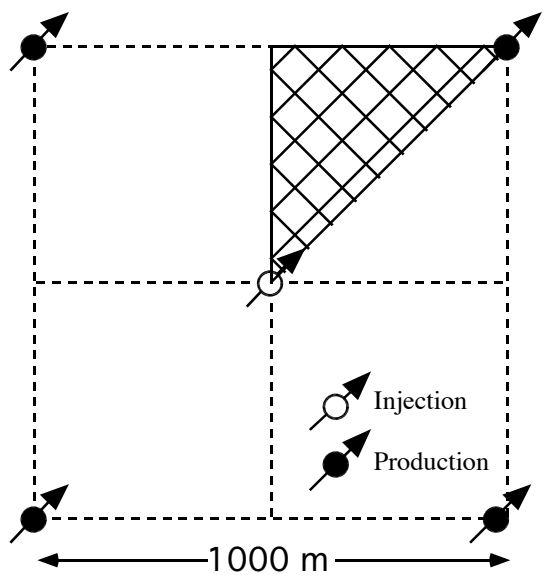

Figure 1. Five-spot well pattern with computational grid for modeling a 1/8 symmetry domain.

Fig. 2 shows simulated heat extraction rates for an initial reservoir temperature of 200 ^oC and pressures of 500, 200, 100, and 45 bar, respectively. Although in "normal" crustal conditions temperatures approaching 200 ^oC will only be encountered at depths of 5 km or more, such temperatures may be found at shallower depths, corresponding to smaller ambient fluid pressures, in the caprock or margins of hydrothermal systems. Such systems may provide early targets of opportunity for EGS. For comparison, we also simulated heat extraction performance of water-based systems for the same T,P-conditions and reservoir parameters. It turns out that the production behavior of water-based systems is rather insensitive to initial reservoir pressure, and the single curve labeled "water" in Fig. 2 represents the performance of water-based EGS over

the entire range of pressures considered. It is seen that heat extraction rates for systems using supercritical CO_2 ($P > P_{crit} = 73.82$ bar) are considerably larger than for water-based systems. For sub-critical CO_2 (P = 45 bar) a much lower heat extraction rate is obtained, as was expected due to the much lower density of gaseous as compared to supercritical CO_2. This low-pressure case was included only for completeness; it is not of practical interest and will not be considered further.

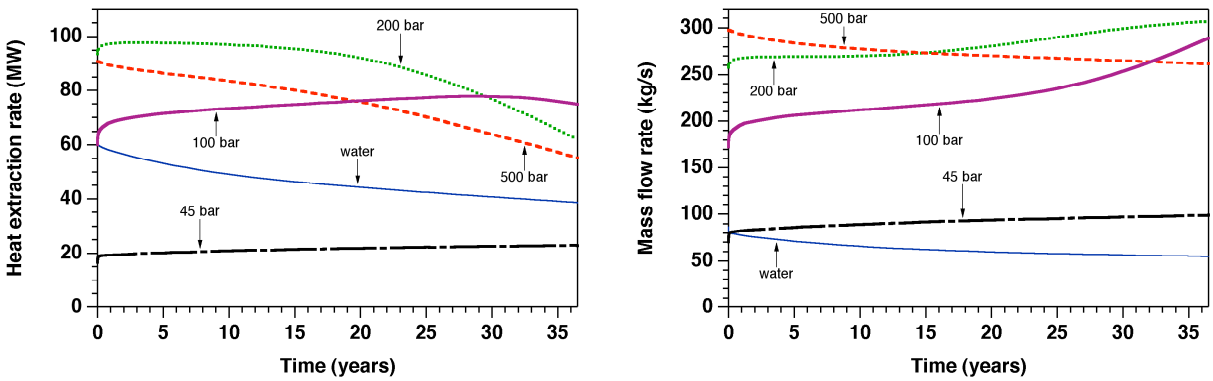

Figure 2. Simulated heat extraction (left) and mass flow rates (right) of CO_2-EGS (full well basis) for different reservoir pressures at T = 200 ^oC. The curve labeled "water" shows the production behavior of a water-based system, which is insensitive to reservoir pressure.

The time dependence of heat extraction rates when using CO_2 as working fluid shows some unusual features. For the 500 bar case there is a monotonic decline over time, in line with general expectations that, when injection and production pressures are held constant, heat extraction rates will decline over time as the reservoir heat inventory is being depleted. However, for a reservoir pressure of 200 bar heat extraction rates remain almost constant for the first 15 years, and for P = 100 bar there actually is a continuous increase over time up to 30 years, followed by a slow decline. For both P = 100 and 200 bar reservoir pressure, there is a continuous increase in mass production rates over time. This surprising behavior can be understood from the peculiar dependence of CO_2 mobility $m = \rho/\mu$ (density/viscosity) on temperature and pressure (Fig. 3). The heavy dashed lines in Fig. 3 indicate the range of thermodynamic conditions, from initial reservoir temperature of 200 ^oC to injection temperature of 20 ^oC, that will be encountered during fluid circulation. It is seen that at 500 bar pressure, declining reservoir temperatures will cause the mobility of CO_2 to decline also. This feature gives rise to the decline of mass flow rate over time for the 500 bar case. For P = 200 bar there is a moderate and for P = 100 bar there is a strong increase in fluid mobility over time, when temperatures decline over part of the injector-producer flow path (Fig. 3). This causes mass flow rates to increase, helping to stabilize (P = 200 bar) or even increase heat extraction rates (P = 100 bar).

Heat Transfer from Cap and Base Rocks

The simulations presented so far all assumed "no flow" (mass or heat) conditions at the top and bottom reservoir boundaries. However, even if the permeability of cap and base rocks is negligibly small, there would still be a possibility of conductive heat transfer to the EGS reservoir as temperatures decline from continued fluid circulation. In order to assess these effects, we have performed additional simulations in which heat exchange between the EGS

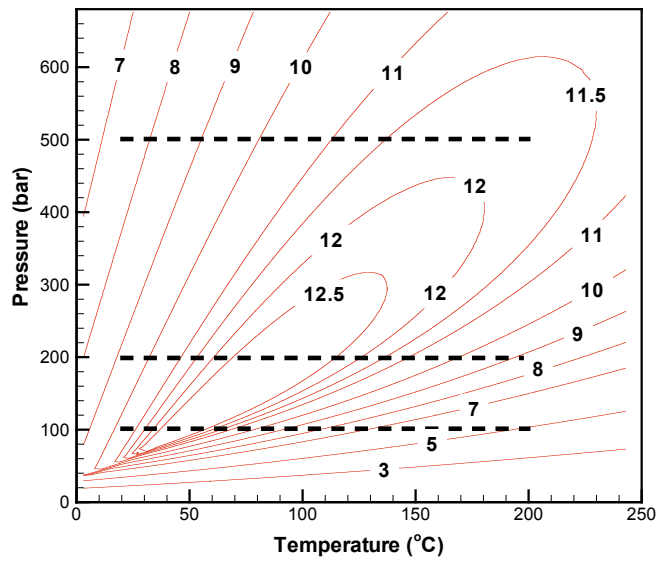

Figure 3. Mobility $m = \rho/\mu$ of CO_2 in units of 10^6 sm^{-2} as function of temperature and pressure. The heavy dashed lines indicate the range of thermodynamic conditions encountered at the different initial reservoir pressures.

reservoir and cap and base rocks is modeled by means of the semi-analytical technique of Vinsome and Westerveld (1980). Results for initial reservoir conditions of (T, P) = (200 °C, 200 bar) are shown in Fig. 4. Including heat exchange with cap and base rock increases heat extraction and production temperature, as expected, but the differences are not large and kick in only after about 15 years of fluid circulation.

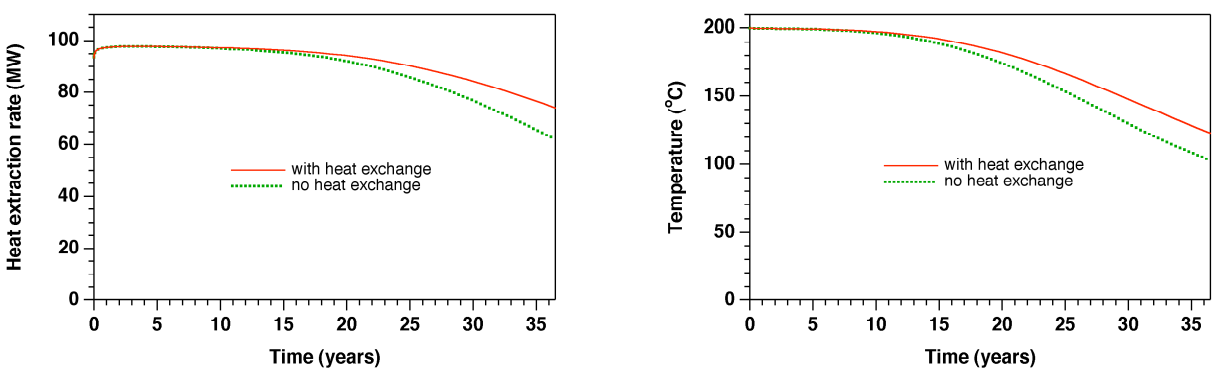

Figure 4. Heat extraction rates (left) and production temperatures (right) for an EGS reservoir of supercritical CO_2 at (T, P) = (200 °C, 200 bar), comparing simulations with and without inclusion of heat exchange with cap and base rocks.

Space Discretization Effects

The simulations performed above use a rather coarse space discretization. For the 1/8 of the five-spot modeled, our five-point parallel grid has 36 blocks (5x36 = 180 blocks after MINC

discretization), and divides the injector-producer distance of 707.1 m into 10 grid increments of 70.71 m each. In an effort to examine the possible sensitivity of results to space discretization effects, additional calculations were performed for a grid with 144 blocks (5x144 = 720 blocks after MINC discretization), corresponding to a spatial resolution of 32.14 m. Simulated rates of mass flow and heat extraction for reservoir conditions of (T, P) = (200 ^{o}C, 200 bar) for both CO_2 and water are shown in Fig. 5. Differences between the coarse and fine grids are surprisingly small.

The weak sensitivity of fractured reservoir simulations to grid spacing has been noted previously (Pruess and Wu, 1993). It is explained by a compensation of space discretization errors between global flow through the fracture system, and local heat exchange between matrix blocks and fractures. Indeed, if the cold front emanating from the injection well advances too rapidly because of coarse space discretization, this will cause cooler conditions in the fractures downstream, and will induce rates of heat transfer from the matrix blocks to increase, thus partially compensating for the lower temperatures.

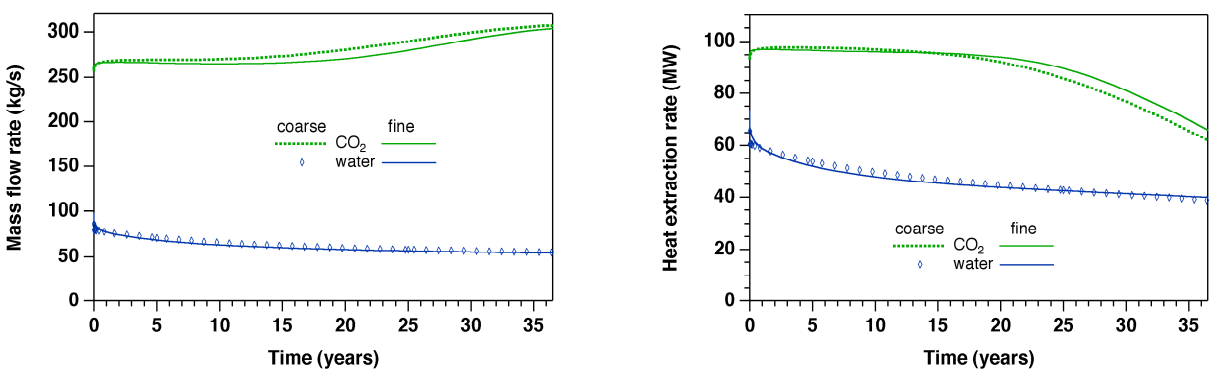

Figure 5. Comparison of mass flow (left) and heat extraction rates (right) for reservoir conditions of (T, P) = (200 ^{o}C, 200 bar) for both CO_2 and water for simulations using coarse and fine grids, respectively.

Concluding Remarks

Numerical simulation results presented in this paper confirm advantages of CO_2 over water as heat transmission fluid for enhanced geothermal systems (EGS), predicting larger energy extraction rates for CO_2 for the same applied pressures in injection and production wells. The mobility (= density/viscosity) of CO_2 depends in complicated fashion on both temperature and pressure, which gives rise to unusual features in the time dependence of mass flow and heat extraction rates. For certain reservoir pressures, heat extraction rates can actually increase for a time, due to strong increases in fluid mobility, even as the reservoir is being depleted thermally.

The present study has focused on the energy extraction aspects of EGS with CO_2. Future work must also address CO_2 losses, as well as the question whether CO_2 lost from the main reservoir will remain contained safely and securely, perhaps through a combination of dissolution in the aqueous phase and formation of solid carbonates of low solubility (Fouillac et al., 2004).

Acknowledgement
Thanks are due to Tianfu Xu for a review of the manuscript. This work was supported by Contractor Supporting Research (CSR) funding from Berkeley Lab, provided by the Director, Office of Science, and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Geothermal Technologies, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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