PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31 - February 2, 2011
SGP-TR-191

COUPLED WELLBORE AND 3D RESERVOIR SIMULATION OF A CO_2 EGS

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ABSTRACT

Three dimensional injection-production reservoir flows of CO_2 Engineered Geothermal System (EGS) were coupled with wellbore flow simulations. The 3D reservoir simulations used a modified ECO2N module of TOUGH2 to analyze CO_2 mass and heat flow rates while the wellbore flow simulations determined the injection and production parameters at the wellhead (i.e. pressure and temperature).

The effects of different operational and reservoir parameters were also investigated.

INTRODUCTION

Literature on CO_2 EGS is limited compared to conventional-water based EGS. Most of the literatures available are 1D and 2D thermodynamic and exergy analyses (Atrens, Gurgenci, & Rudolph, 2008, 2009a, 2009b; Brown, 2000; Pruess, 2006, 2007, 2008; Pruess & Azaroual, 2006; Reichman, Bresnehan, Evans, & Selin, 2008; Remoroza, Moghtaderi, & Doroodchi, 2009). Very few literatures exist for 3D reservoir simulations of CO_2 EGS (Pruess, 2008; Pruess & Spycher, 2010; Remoroza, Moghtaderi, & Doroodchi, 2010) and none coupled with wellbore flows. This paper will present coupled wellbore and 3D reservoir flows in CO_2 EGS.

NUMERICAL METHODS

A numerical procedure that uses a modified ECO2N TOUGH2 module in CO_2 EGS reservoir simulations were performed and validated by Remoroza et al (2010). The same procedure was adapted in this study. The assumptions in this study are infinitely large reservoir, repeating units of 5-spot well configuration in 1 km^2 area (4 production wells centered around 1 injection well), and single phase fluid flow in the reservoir.

Table 1 shows the formation, wellbore, and reservoir parameters used in the 3D reservoir simulations.

Table 1 Formation, wellbore, and reservoir parameters used in the simulations.

Parameter	***Values***
Thickness, m (6 layers, 55 m bottom layer)	305
Fracture spacing, m	50
Nos. of Multiple Interacting Continua	5
Permeability, x10^{-15} m^2	50
Porosity	
Fracture	50%
Rock matrix	2%
Rock grain density, kg/m^3	2650
Rock specific heat,kJ/kg	1000
Rock thermal conductivity, W/m ^{o}C	2.1
Reservoir temperature, ^{o}C	200
Reservoir pressure, MPa	20, 35, 50
Injection bottomhole temperature, ^{o}C	20, 35
Injection bottomhole pressure, MPa	21, 36, 51
Production bottomhole pressure, MPa	19, 34, 49
Well diameter, m	0.2315
Wall pipe roughness, micron	40

In wellbore calculations, it was assumed that the wells are vertical and the depth corresponds approximately to the hydrostatic pressure of the reservoir (i.e. 2 km for 20 MPa reservoir pressure, 3.5 km for 35 MPa and soon). Adiabatic fluid flow in the well are described by the following equations,

$$P_{inj} = P_{bot,inj} + \Delta P_{f,well} - \sum \rho g \Delta z$$

$$P_{prod} = P_{bot,prod} - \sum \rho g \Delta z - \Delta P_{f,well}$$

$$\Delta P_{f,well} = \sum \left[f \frac{8 \Delta z \dot{m}^2}{\pi^2 \rho D^5} \right]$$

$$f = \left[-1.8 \log \left[\frac{6.9}{R_e} + \left(\frac{\varepsilon}{3.7D} \right)^{1.11} \right] \right]^{-2}$$

P_{inj} = wellhead injection pressure

$P_{bot,inj}$ = bottomhole injection pressure

P_{prod} = wellhead production pressure

$P_{bot,prod}$ = bottomhole production pressure

$\Delta P_{f,well}$ = wellbore frictional losses
Δz =depth increment of the wellbore
$\dot{m}$ = mass flow rate
f = Darcy-Weisbach friction factor
ρ = density
R_e Reynolds number
ε = pipe roughness
D = pipe diameter
g = gravitational constant, 9.81 m/s^2

Wellbore flows were calculated using Engineering Equation Solver (EES). Temperatures and pressures at the wellheads were calculated from the given mass flow rates, temperatures and pressures at the bottom of the wells-which are the results from 3D reservoir simulation runs.

EES calculates thermodynamic properties of carbon dioxide using the fundamental equation of state developed by (Span & Wagner, 1996) and viscosity and thermal conductivity based on the work by (Vesovic, Wakeham, Sengers, Watson, & Millat, 1990). EES gives thermodynamic properties of water using the 1995 Formulation for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use issued by The International Association for the Properties of Water and Steam (IAPWS) (Wagner & Pruss, 2002).

The total energy available to do mechanical work or the exergy was calculated based on the exergy associated with fluid enthalpy change.

$$x_H = (h - h_0) - T_0(s - s_0)$$

Where x_H = specific exergy
h = specific enthalpy
s = specific entropy
T = temperature in Kelvin
The subscript 0 denotes initial conditions.

RESULTS AND DISCUSSION

This study and prior studies have shown the rapid thermal decline of the reservoir when production wells are drilled through all the layers of the reservoir compared to when the production well is drilled only into the top 50 m layer (Pruess, 2008; Remoroza, et al., 2010). In this regard, we will only present 3D reservoir simulation results where the injection wells are drilled through all layers of the reservoir and the production wells drilled only at top 50 m layer.

Figure 1 shows the comparison of mass and heat extraction rates of CO_2 and H_2O at 20 MPa and 200 ^oC reservoir conditions simulated using 20 ^oC bottomhole injection temperatures. It shows that CO_2 mass and heat extraction rates are much higher compared to H_2O. However, H_2O wellhead production temperature approaches that of reservoir temperature while CO_2 production wellhead temperature is lower at ~180 ^oC and sharply declining after 25 years of production (Figure 2).

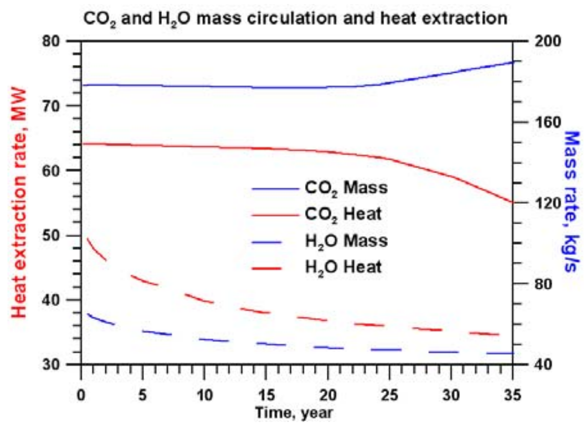

Figure 1 CO_2 and H_2O mass and heat extraction rates at 20 MPa, 200 ^oC reservoir conditions and 20 ^oC injection bottomhole temperature.

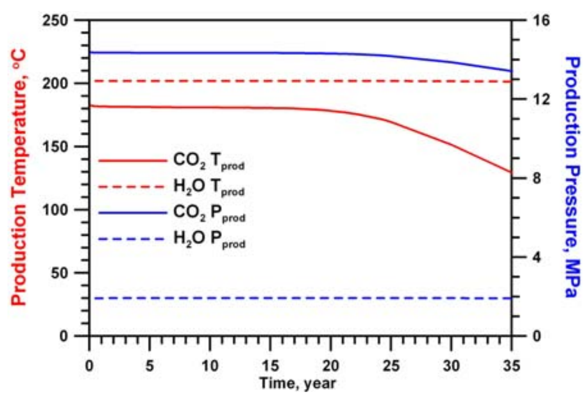

Figure 2 Wellhead production temperature and pressure of CO_2 and H_2O based EGS at 20 MPa and 200 ^oC reservoir conditions simulated using 20 ^oC bottomhole injection temperature.

Figure 3 shows that the total exergy is higher for CO_2 at ~14.5 MW and stable for up to 25 years compared to H_2O with ~11 MW declining to 8 MW in the same period. However, CO_2 wellhead injection temperature is ~ 11 ^oC while H_2O wellhead injection temperature is ~24 ^oC (not shown).

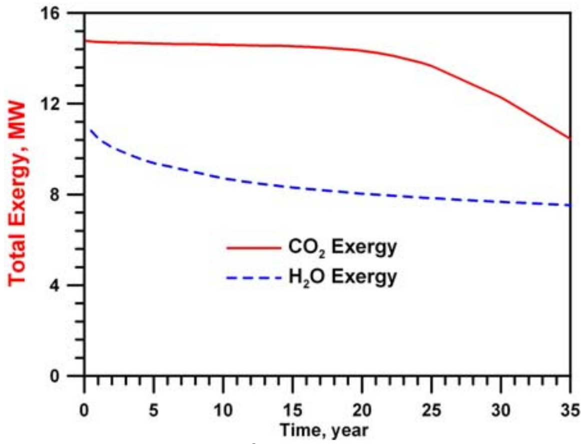

Figure 3 Total exergy of CO_2 and H_2O based EGS at 20 MPa and 200 °C reservoir conditions simulated using 20 °C bottomhole injection temperature.

The effect of injection temperature on CO_2 total exergy is shown in Figure 5. It shows that higher injection temperature gives lower total exergy. Bottomhole injection temperature of 35 °C at the reference 20 MPa and 200 °C reservoir conditions gives a higher wellhead injection temperature at ~23 °C (Figure 5) with similar wellhead production temperature at ~180 °C.

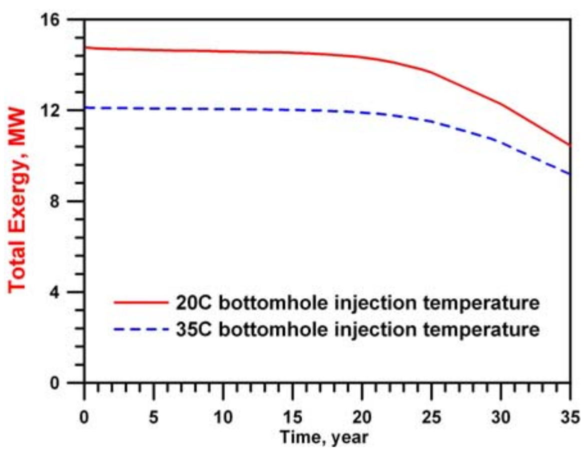

Figure 4 Effect of bottomhole injection temperature on CO_2 total exergy.

The effect of reservoir pressure is shown in Figure 6, simulated using 200 °C reservoir and 35 °C bottomhole injection temperatures. It shows that the optimum total exergy that can be generated is ~14 MW. Wellhead production temperature at 35 MPa reservoir pressure is ~ 173 °C while it is ~ 170 °C at 50 MPa (not shown).

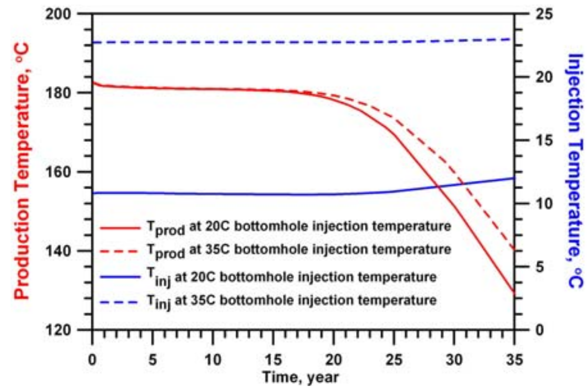

Figure 5 The corresponding wellhead injection and production temperatures given the bottomhole injection temperature.

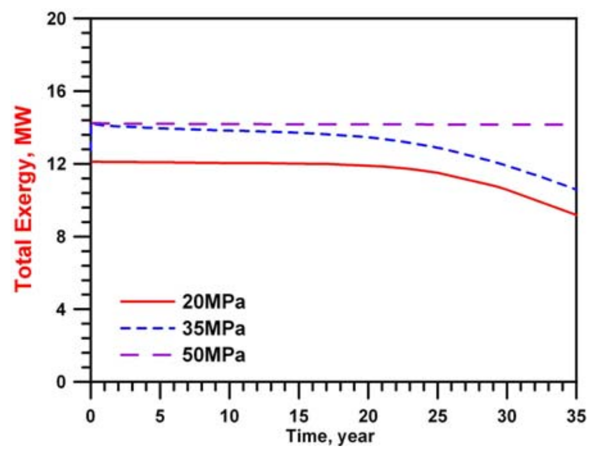

Figure 6 Effect of reservoir pressure on total exergy generation.

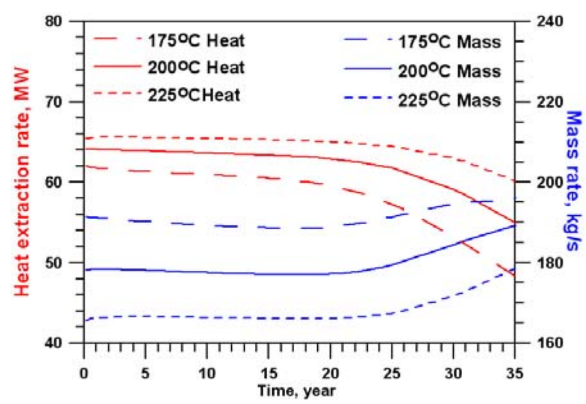

Figure 7 Effect of reservoir temperature on CO_2 mass and heat extraction rates.

The effect of reservoir temperature on CO_2 mass and heat extraction rates is shown in Figure 7. Figure 8 shows the effect on total exergy. As expected, higher reservoir temperature generates a higher total exergy. The simulations used the reference 20 °C bottomhole injection temperature and 20 MPa reservoir pressure. The calculated wellhead production temperature of the 225 ^oC reservoir is ~209 ^oC while that of 175 ^oC reservoir temperature is ~ 153 ^oC.

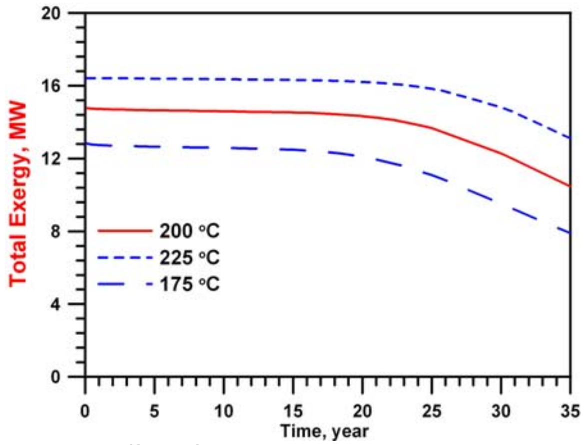

Figure 8 Effect of reservoir temperature on CO_2 total exergy generation.

The CO_2 wellhead production pressures are greatly affected by reservoir pressure (Figure 9) and only slightly by reservoir temperature (Figure 10).

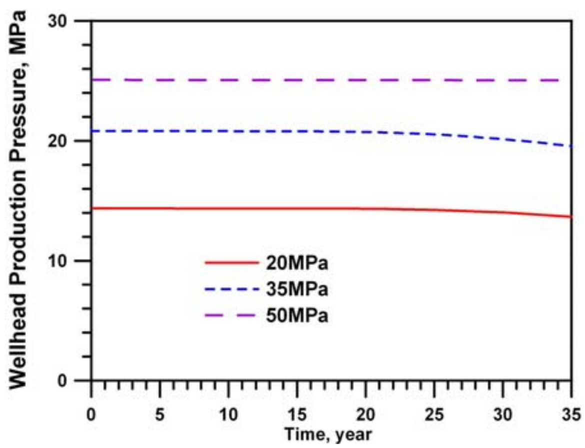

Figure 9 Effect of reservoir pressure on CO_2 wellhead production pressures.

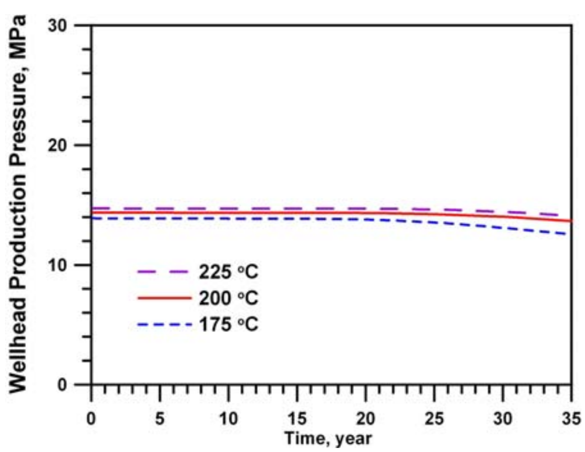

Figure 10 Effect of reservoir temperatures on CO_2 wellhead production pressures.

The wellhead injection pressure increases with increasing reservoir pressure (Figure 11) and decreases with increasing reservoir temperature (Figure 12). These simulations are in reference to a targeted 20 ^oC bottomhole injection temperature.

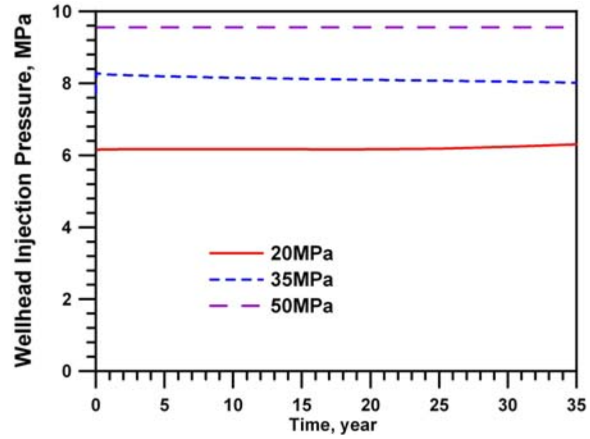

Figure 11 Effect of reservoir pressure on CO_2 wellhead injection pressure.

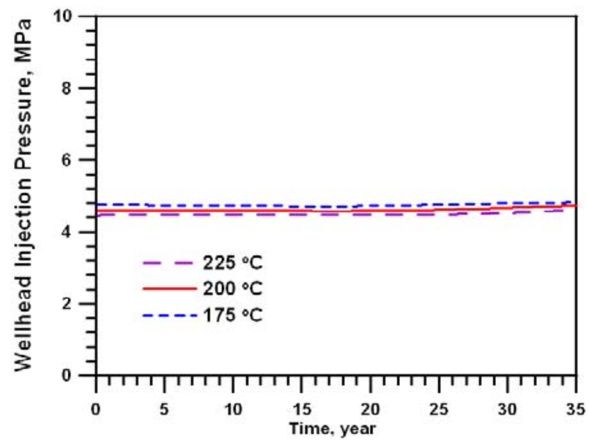

Figure 12 Effect of reservoir temperature on CO_2 wellhead injection pressure.

CONCLUSION AND RECOMMENDATIONS

The results of the coupled wellbore and reservoir simulations show that CO_2 based EGS can generate exergy similar to and sometimes at par with H_2O based EGS. The total exergy that can be generated in 1 km^2 area of a geothermal reservoir with at least 305 meter thick layer is 12-16 MW depending on temperature and depth (pressure). It is desirable to operate at deeper and hotter reservoirs based on the simulation results.

CO_2 wellhead production pressures correlate strongly with and are more than half of reservoir pressures. The wellhead injection pressure required is always less than the production pressure; therefore, natural thermosiphon cycle is technically feasible.

The hotter the geothermal reservoir is, the lower the wellhead injection pressure required and the higher the total exergy that can be generated.

To further advance our knowledge of CO_2 EGS, geochemical (fluid-rock interaction) and material studies (turbine and well design) should be done to determine the overall feasibility of using this system for power generation.

ACKNOWLEDGEMENT

The authors wish to thank Priority Research Centre for Energy, University of Newcastle for supporting this study.

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