Exergetic performance and power conversion of a CO_2 thermosiphon

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Engineered geothermal systems (EGS) supply the potential to produce a significant capacity of base-load renewable electricity. In EGS that are not hydraulically connected to a source of water recharge off the opportunity to use CO_2 as a heat extraction fluid instead of H_2O. CO_2 offers the advantages of ease of flow through the subsurface reservoir, an innate buoyancy driving simplifying surface equipment design, and lower dissolution of compounds that lead to fouling in wellbores and surface equipment. These advantages are balanced by higher frictional losses within the wellbores, particularly the production wellbore due to the low density of CO_2 in this process component. Here we explore the results of these advantages and disadvantages on the exergy extracted from the geothermal reservoir, and examine the impact of direct use of CO_2 in power conversion equipment.

Keywords: Carbon dioxide, EGS, enhanced geothermal systems, CO2, thermosiphon

Introduction

The use of CO_2 in EGS has been discussed in a number of previous works (Brown 2000; Pruess 2006; Gurgenci, Rudolph et al. 2008; Pruess 2008; Atrens, Gurgenci et al. 2009a). The use of CO_2 in EGS where CO_2 recovered from the underground reservoir is fed directly into a turbine (known as a CO_2 thermosiphon), is significantly different from H_2O flash or binary plants.

A convenient method for comparing power generation systems with significant internal differences is through the usage of exergy. This provides a measure of the maximum theoretical electricity that can be generated from the system. As such, a comparison of the exergy available at the surface can be used as a rough measure to compare the different designs. Exergy available on the surface Ψ is calculated from:

$$\Psi = m(h_{prod} - h_{inj} - T_0 (s_{prod} - s_{inj}))$$

Where h_{prod} and s_{prod} are the enthalpy and entropy of fluid exiting the production wellhead, h_{inj} and s_{inj} are the enthalpy and entropy entering the injection wellhead, and T_0 is the reference temperature (ambient temperature is used).

The enthalpy and entropy at the injection and production wellheads is calculated by methods described in previous work (Atrens, Gurgenci et al. 2009b).

Exergy Recovery

Fluid flow of CO_2 compared to water as calculated from modelling methods in previous work is shown in figure 1 (for a reservoir of hydraulic impedance as per Soultz-sous-Foret). Much larger flow-rates of CO_2 then H_2O can be achieved due to its lower viscosity in the reservoir, particularly in the region near the injection well (where the viscosity of water is much higher).

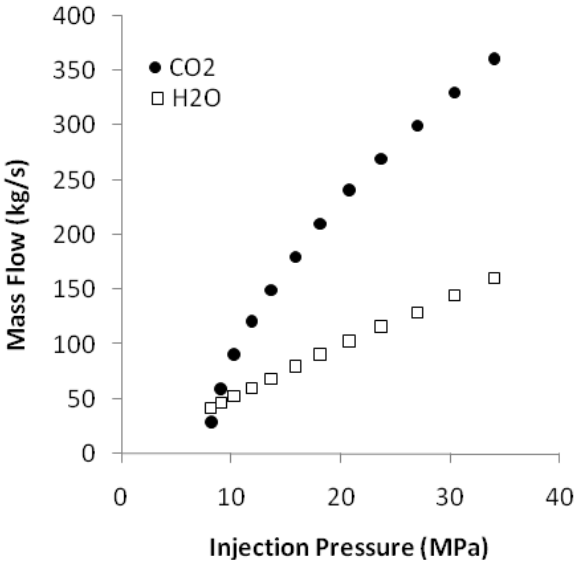

Figure 1: Injected fluid flow-rates

However, due to larger pressure drop in the production well, in conjunction with the lower heat capacity of CO_2 compared to water, CO_2 will extract less exergy than water under most conditions. This situation can be changed through increase in production well diameter size. This change has very large effects on the CO_2, significantly reducing the pressure drop in the production well leading to higher exergy recovery. As well diameters generally used are an appropriate size for the volumetric flows likely for water, the effects on exergy extraction of water are negligible. Exergy extracted for a base reference case, and with two larger diameter casing sizes for CO_2-based systems is shown in figure 2.

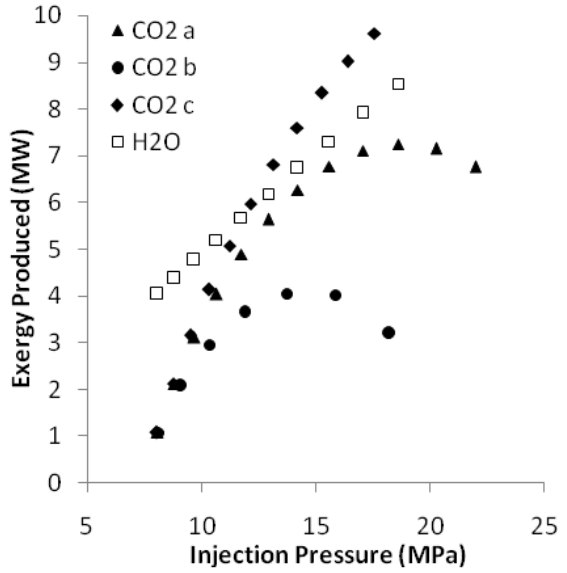

Figure 2: Exergy produced at the surface by the different fluids; (a) for reference casing internal diameter size of 0.2313 m; (b) for internal diameter of 0.3 m; (c) for internal diameter of 0.4 m

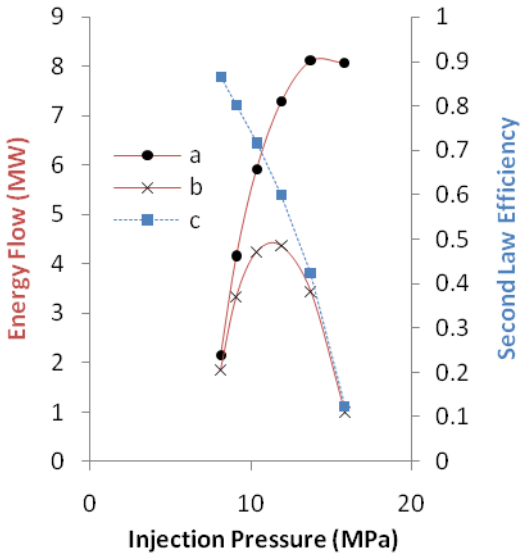

Figure 3: Energy recov ery considerations for CO_2 for the reference case; (a) Exergy produced at the surface; (b) Electricity generated; (c) Second law efficiency of the overall process.

Power Conversion

The ability to extract exergy from the subsurface reservoir is not the only issue of critical importance to an EGS power plant. Also important is the capability to convert the exergy extracted into electricity in an effective manner.

Because CO_2 in a thermosiphon plant configuration is used directly in power conversion equipment, the impact of production pressure on the ability to convert available exergy into electricity is significant. This means that as flow-rates through the subsurface are increased (and exergy extraction is increased), the ability to convert the exergy extracted into electricity is reduced (due to the reduced difference in pressures between the production wellhead and the injection wellhead). This leads to the relationship between turbine work and exergy produced as shown in figure 3. This is based on an assumed isentropic efficiency of the turbine of 85%, while in reality higher isentropic efficiency may be achievable. The second law efficiency shown in this figure represents the proportion of the actual work out of theoretical maximum work achievable in an ideal case.

This relationship can be improved through the addition of a recompression system. In such a case, the turbine exhaust would be designed at a lower operating pressure, and the effluent from the turbine would be recompressed after cooling, and prior to reinjection. The thermodynamic relationship of this process change is shown in figure 4.

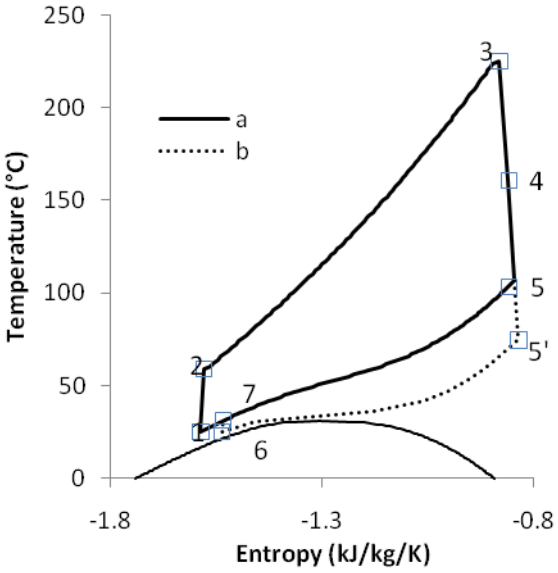

Figure 4: Temperature-entropy diagram showing (a) CO_2-based EGS basic power cycle; and (b) recompression modification. Point (1) indicates the injection wellhead and heat exchanger outlet, point (2) indicates the base of the injection well and the entry to the reservoir, point (3) indicates the base of the production well, point (4) indicates the production wellhead and turbine inlet, and point (5) indicates the turbine exhaust and cooling system inlet. Point (5') indicates the turbine exhaust with recompression modification, point (6) indicates the compressor inlet, and point (7) indicates the compressor outlet.

Process modification in this manner leads to performance as shown in figure 5. This represents a significant improvement in electricity recovery, and indicates a worthwhile process modification.

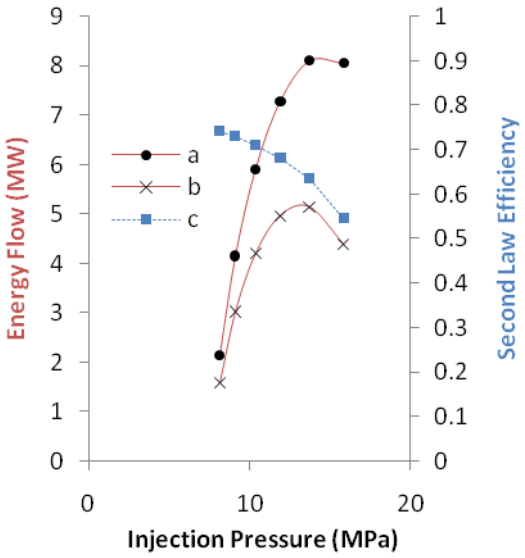

Figure 5: Energy recov ery considerations for CO_2 as in figure 3, with recompression process modification; (a) Exergy produced at the surface; (b) Electricity generated; (c) Second law efficiency of the overall process.

Reference Case

The reference case used in this work utilises data as given in table 1.

Table 1: Reference Case Data

Parameter	Value
Depth (m)	5000
Reservoir Length (m)	1000
Reservoir Temperature (°C)	225
Injection Temperature (°C)	25
Reference Temperature (°C)	25
Min. Reservoir Width (m)	0.73
Max Reservoir Width (m)	251
Depth (m)	5000
Hydraulic Impedance (MPa.s/L)	0.2
Reservoir Pressure (MPa)	49
Wellbore roughness, ε (m)	0.0004
Wellbore Diameter (m)	0.231
Isentropic Efficiency, η_{II}	0.85

References

Atrens, A. D., Gurgenci, H., Rudolph, V., 2009a, CO2 thermosiphon for competitive power generation, Energy & Fuels **23**(1): 553-557.

Atrens, A. D., Gurgenci, H., Rudolph, V., 2009b, Exergy analysis of a CO2 thermosiphon, Thirty-fourth workshop on geothermal reservoir engineering, Stanford University, Stanford, California

Brown, D. W., 2000. A hot dry rock geothermal energy concept utilizing supercritical CO2 instead of water. Twenty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

Gurgenci, H., V. Rudolph, et al., 2008. Challenges for geothermal energy utilisation. Thirty-Third Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

Pruess, K. (2006). "Enhanced geothermal systems (EGS) using CO2 as working fluid—A novel approach for generating renewable energy with simultaneous sequestration of carbon." *Geothermics* **35**: 351–367.

Pruess, K. (2008). "On production behaviour of enhanced geothermal systems with CO2 as working fluid." Energy Conversion and Management **49**: 1446-1454.