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EXERGY ANALYSIS OF A CO2 THERMOSIPHON

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ABSTRACT

Engineered geothermal systems (EGS) present an opportunity to expand the implementation of geothermal power. There has been some interest in the possible application of CO_2 as a heat extraction fluid in these systems instead of water, due to a variety of inherent benefits, including being a non-polar fluid, low viscosity at the temperatures and pressures within the reservoir and a large buoyancy effect. The buoyancy effect in particular indicates the potential for a simple surface plant design, or "CO_2 thermosiphon". Balancing these advantages, CO_2 has some drawbacks, leading to lower thermodynamic performance in the overall system. This is mostly due to a combination of lower heat capacity, and large frictional losses due to gas-phase flows in the production wellbore. Here we explore some of the thermodynamics underlying this characteristic, and explore some scenarios that could be expected to offset it. Ultimately, economic analysis will be necessary to determine in what cases CO_2 would be applicable as a geothermal heat extraction fluid. This should give some indication as to which geothermal resources may benefit from the usage of CO_2.

INTRODUCTION

As part of the development and research into Engineered Geothermal Systems (EGS) as a commercial source of geothermal power, there has been some interest in the use of carbon dioxide as a heat extraction fluid. CO_2 offers a number of significant advantages as a geothermal fluid which have been discussed in detail in other works (Brown, 2000; Pruess, 2006; Gurgenci et al, 2008; Atrens et al, 2009), including:

- Low solubility of salts (decreasing the potential for scale precipitation in wellbores and surface equipment)
- Potential for chemical and geological sequestration of CO_2 within the reservoir
- Possibility of direct use of produced CO_2 in turbomachinery, instead of using a binary plant design
- Capability of deriving the motive force to move the fluid in a cycle from the difference in static pressures between the injection and production wellbores, removing the necessity of large pumping equipment (a "CO_2 thermosiphon", shown in Figure 1)
- Favourable transport properties over the thermodynamic conditions of the reservoir, leading to greater heat extraction rates

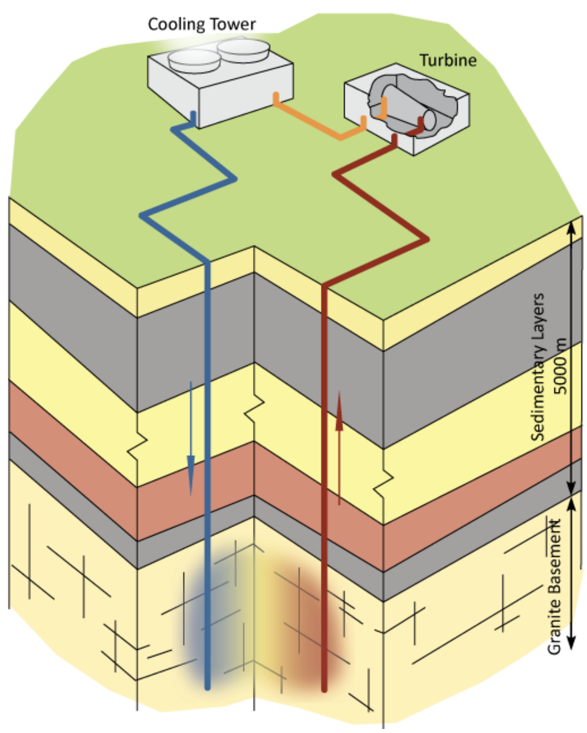

Figure 1: CO2 thermosiphon

This paper is an analysis of the exergy produced from a CO_2 thermosiphon and a water-based geothermal system under similar conditions. Particular attention has been given to the thermodynamic and transport characteristics of the wellbore flows.

PROCESS ANALYSIS

To illustrate the differences inherent in the subsurface thermodynamics of the CO_2 thermosiphon compared to water-based systems, this discussion will detail the injection and production operations of the geothermal system separately. The injection component will include the injection wellbores and fluid flow through the reservoir; the production component will include only the production wellbores. The overall effects of the subsurface will be discussed in context of power produced from the design.

Injection Aspects

This section of the CO_2 thermosiphon system is illustrated in Figure 2, and is considered on a basis of flow from the injection wellhead through to the exit of the reservoir system at the production well base.

For this analysis, it was assumed that the fluid must exit the geothermal reservoir at pressures greater than or equal to the reservoir pressure. Therefore, effective injection into the geothermal reservoir has two constraints. Fluid pressure at the exit of the reservoir is defined by the reservoir pressure, and the maximum temperature at the exit is defined by the temperature of the reservoir.

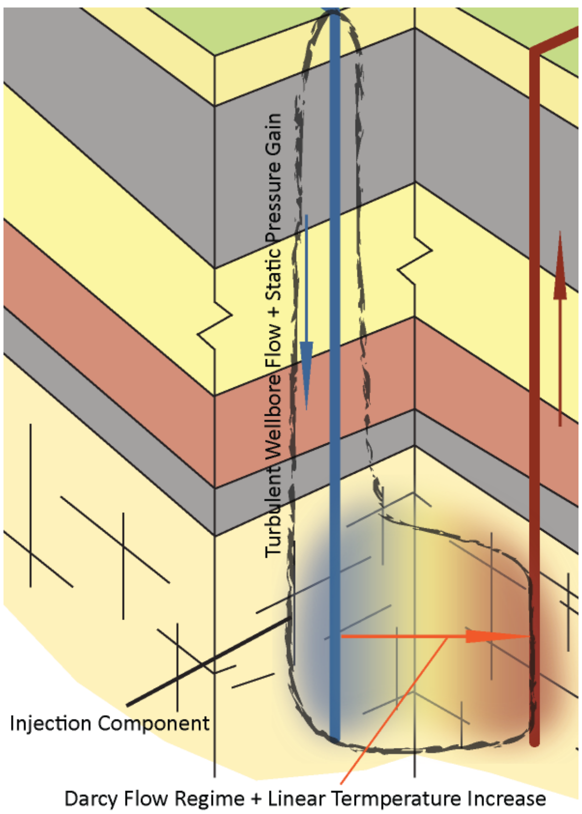

Figure 2: Injection Components of the thermosiphon

To simplify analysis, it was assumed that the most efficient injection of fluid into the reservoir will provide output fluid equal to reservoir pressure and temperature. If the output of the injection section of the system is defined in this manner, the section is controlled by the relationship between the conditions at the injection wellhead, and mass flow through the system.

The wellbore is assumed to operate as pipe flow with negligible heat transfer and kinetic energy, and with frictional losses as defined by White (2003). The reservoir is modeled as Darcy flow through geometry of constant cross-sectional area and linearly increasing temperature. From this, the relationship between injection conditions and mass flow through the injection system can be derived :

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

$$\Delta P_{f,well} = f \frac{\Delta z}{D} \rho \frac{V^2}{2} = f \frac{8\pi^2 \Delta z \dot{m}^2}{\rho D^5}$$

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

$$\Delta P_{f,res} = -\frac{\dot{m}\mu \Delta L}{\rho \kappa A}$$

These, and other equations involved in the modelling are calculated iteratively along the depth of the wellbores and the length of reservoir, using Helmholtz free energy equations of state (Span and Wagner, 1996; IAPWS, 1996; IAPWS 2007);

The major assumptions underlying this analysis are the lack of heat transfer from the wellbore to the surroundings, and the use of constant cross-sectional geometry for the reservoir. The former assumption was considered reasonable for injection wellbore flows as the temperature differential compared to the surroundings is relatively small. The assumption about the reservoir will definitely cause inaccuracies in the results of the analysis. This assumption was made to keep computational times low. It effectively makes the reservoir component act as an impedance measure, with the value (K.A – permeability × cross-sectional area) calibrated to get pressure drops for water flows similar to past EGS trials.

Equation Set 1 shows that the injection operation is dominated by the tradeoff between the static pressure increase over the depth of the injection wellbore, and the frictional losses from the viscous flow through the geothermal reservoir. Both water and CO_2 behave in a similar manner (in terms of temperature and pressure changes) through the injection component of the system, but CO_2 outperforms water in terms of having a much smaller pressure drop. This is largely due to the lower μ/ρ ratio of CO_2 through the reservoir system, leading to a much smaller pressure drop. Furthermore, the effects of injection pressure have beneficial amplifying effects in a non-linear manner on the injection flows of CO_2. In comparison, increases in water pressure act only to offset pressure drop experienced in the reservoir. Figure 3 shows the relationship between the surface pressure and the mass flow through the system achieved by the two fluids in the injection component of the system.

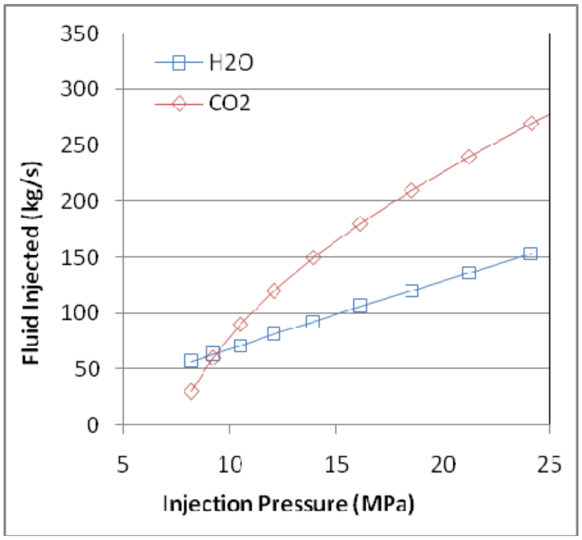

Figure 3: Injectivity of CO_2 and H_2O

This graph shows the mass flow advantage of CO_2 (although not in proportion to its lower heat capacity). This analysis is covering a very simplified reservoir system, using simplified analysis of both the wellbore flow and the reservoir. Near-wellbore acceleration effects are likely to play an important role (and need to be considered in future research), but are likely to affect the H_2O-based system more for the injection regime, due to the higher μ/ρ ratio of water at that point in the system.

Production Aspects

The production section of the system is examined purely in terms of the production wellbore. For this component, the initial conditions are defined as the reservoir temperature and pressure. Based on adiabatic flow in a vertical pipe, the relation between mass flow rate and the pressure drop can be defined. This calculation method is exactly the same as that for the wellbore in the injection section [Equation Set 2]:

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

This system of modeling gives the relationship between produced fluid and production pressure as shown in Figure 4.

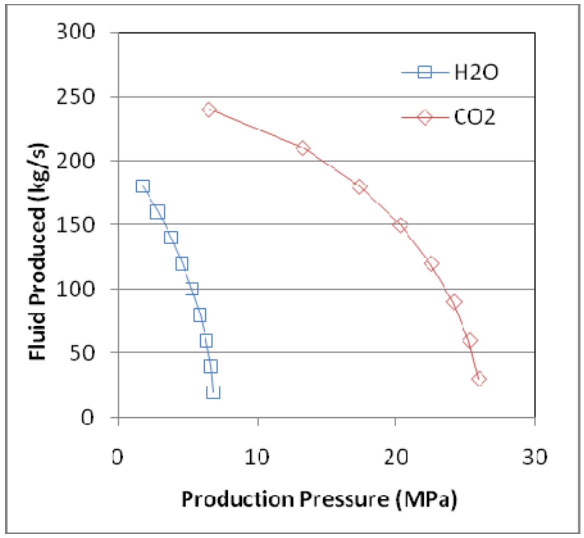

Figure 4: Productivity of CO_2 and H_2O

The two fluids behave very differently during the production operation – CO_2 has large pressure and temperature drops, while H_2O pressure losses are mostly equivalent to potential energy change. This is because water is in a compressed liquid phase, and CO_2 is in a supercritical/superheated gas phase.

For water, the relationship between production pressure and fluid produced is more linear. This is because of the incompressible nature of the fluid flow. It should be noted however, that vaporization of the water at some point in the wellbore would significantly change this. This should likely be avoided in EGS, if significant scaling in the wellbore is to be prevented.

For CO2, the system is non-linear, due to the supercritical nature of the fluid. This makes frictional pressure drops significant, and they increase quickly with increasing mass flow. This leads to large pressure decreases, leading to temperature decreases due to their relationship in gas-phase thermodynamics. This is amplified by further expansion of the supercritical phase as pressures drop, accelerating the flow. From a conceptual standpoint, it can be considered that the enthalpy losses from expansion are the energy driving the motive force of the thermosiphon. It is notable in the production operation of the system that dramatic effects on the CO_2-based system can be achieved from changes in wellbore diameter and roughness.

Note also that heat losses have been neglected for this analysis; while they were of much less significance for the injection operation, here heat loss could be significant, particularly depending on the geology of the strata surrounding the wellbore. Heat loss is likely to be lower for the CO_2 thermosiphon than for the water-based system, due to the lower temperatures and heat capacity of the CO_2 flow, leading to smaller driving forces for any heat transfer, but this is a topic that needs further assessment.

Combined Analysis of Injection and Production

The injection and production operations can be combined, as they share the same conditions at the reservoir exit. If any of the three parameters of injection pressure, production pressure, or mass flow rate are set, the other two can be explicitly calculated. Therefore the performance of the system over a range of surface operational control can be examined. This has been conducted on a basis of total exergy produced by the field, divided by the total number of wells (including injection wells).

If this is conducted on a single-production-well and single-injection-well basis, with a reasonably standard set of parameters (given in Table 1), CO_2 underperforms compared to H_2O in exergy production, as shown in Figure 5:

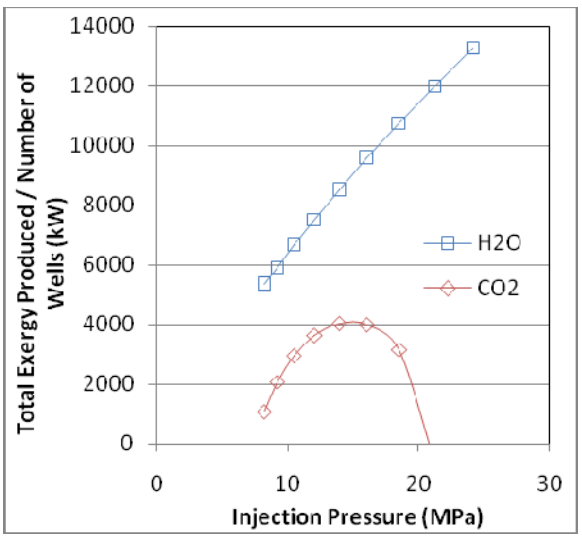

Figure 5: Exergy production for CO_2 and H_2O for reference parameters

Parameter	Value
Depth	5000 m
Reservoir Length	1000 m
Reservoir Temperature	225 °C
Injection Temperature	25 °C
K.A (inverse impedance)	2.1E-9 m^4
Reservoir Pressure	Hydrostatic (49.05 MPa)
Wellbore roughness (ε)	0.0004 m
Wellbore Diameter	0.2315 m
Dead state temperature	25 °C

Table 1: Parameter values for reference state

This may be offset by the ancillary benefits of using CO_2 as a cycle fluid (as mentioned in the introduction), depending on the associated costs and benefits.

COMPARITIVE IMPROVEMENT

For the base case discussed here and minor variations of ±20% in the values of reference parameters CO_2 underperforms in exergy production compared to water. However, there are a number of different cases where it might be expected to become comparable:

- Reservoirs with significantly higher impedance
- Through the use of a greater number of production wells than injections wells (to offset energy losses related to high production well velocities)
- Use in shallower geothermal systems
- Processes designed with smoother and/or larger wellbores

Low Permeability Reservoirs

Because CO_2 has the advantage of much lower reservoir pressure drop (and because the major component of impedance in water-based EGS is reservoir pressure drop), it would be expected that CO_2 would perform comparatively better in lower permeability reservoirs. For significant changes in impedance (i.e. reservoir permeability or cross-sectional area), the effect on CO_2 and the water-based system are shown in Figure 6.

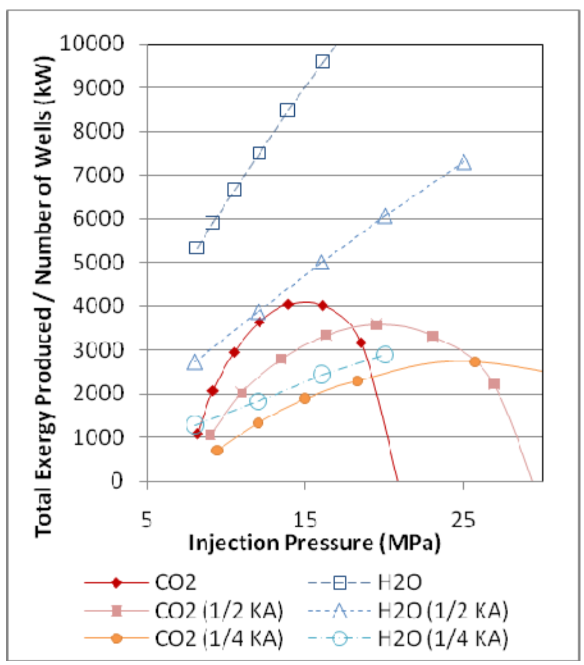

Figure 6: Effect on per-well exergy production of permeability changes

The exergy production of the fluids becomes closer as the permeability decreases. Note that while water can to some extent offset the decrease in permeability with increased injection pressure, there are physical limitations of pumping equipment.

Injection to Production Well Ratio

Because the majority of wasted energy in the CO_2 thermosiphon is from friction in the production wellbore, and because CO_2 is effective at injection and flowing through the reservoir, it would not be unreasonable to operate a reservoir with a number of production wells greater than injection wells. This has an effect as shown in Figure 7.

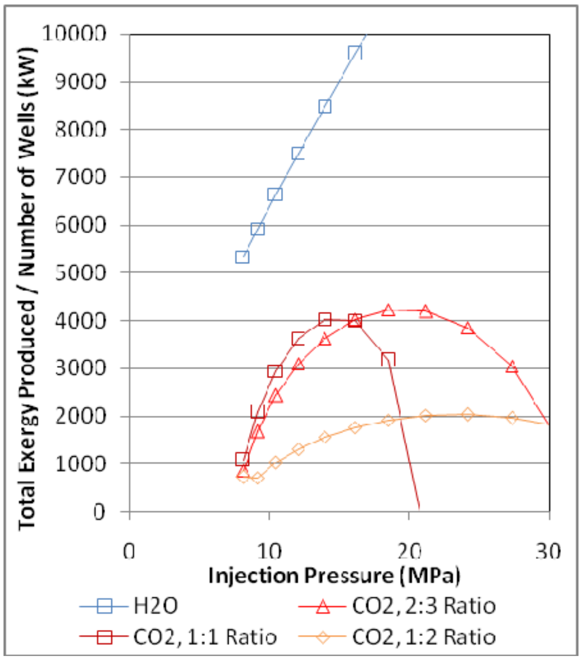

Figure 7: Effect on per-well exery production of changing the Ratio of injection wells to production wells in a CO_2 thermosiphon

The large drop-off in performance for the 1:2 ratio is due to the addition of an extra production well without a significant increase in performance. The large pressures needed to flow more CO_2 through the reservoir decrease the potential energy that can be generated.

A 2:3 five-spot layout of wells will achieve a slightly higher exergy production per well. This comes at the expense of higher surface operating pressures. Depending on economics, this may still be worthwhile, particularly as it may result in access to a greater reservoir volume than repeating doublets. This may result in slower temperature decline of the reservoir.

Shallower EGS

Some EGS may utilise shallower, lower temperature geothermal resources. While these have a greater likelihood of initially containing water or have water influx, they may be suitable for deployment of a CO_2 thermosiphon. The shorter production wellbore length, combined with lower temperatures (leading to lower densities and velocities in the production well) would be expected to have a beneficial effect on the CO_2 thermosiphon compared to water-based systems. Figure 8 depicts the performance of two systems for a 150 °C temperature resource situated 3000 m below the surface (all other parameters the same as for the base case).

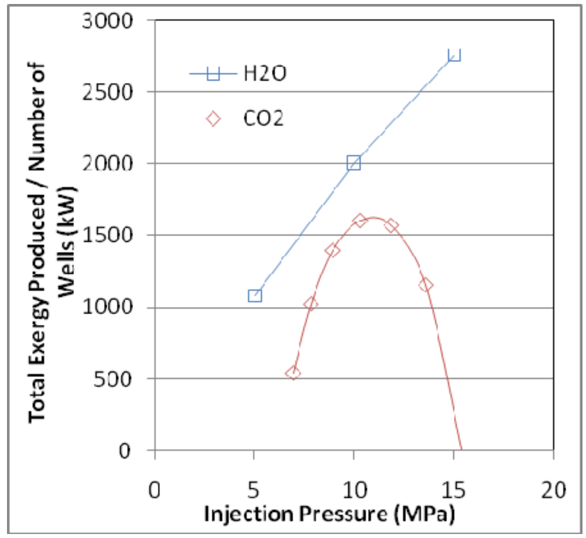

Figure 8: Comparison of the CO2 thermosiphon with a water-based system on application to a shallower EGS

Note that the exergy produced per well is significantly lower than for the deeper reservoirs. The CO_2 thermosiphon does perform here more similarly to the water-based system, but still has less exergy produced. It may be useful in a case such as this to consider the lower complexity of the CO_2 thermosiphon in terms of number of units of equipment in the surface plant. A simple plant design operating at relatively low injection pressures may be appropriate for a lower-grade shallow EGS (particularly if permeability is low).

Wellbore Changes

The significance of changing the wellbore characteristics are, unlike the previous scenarios, not capital-cost-neutral. Decreasing the wellbore surface roughness will assist in decreasing pressure drop, but the effect is relatively minor on the overall process efficiency. Drilling larger-diameter may cost more, but does have a significant effect on the operation of the CO_2 thermosiphon. Figure 9 shows the effect of doubling the wellbore diameter. Note that it is doubled for both the CO_2 thermosiphon and for the water-based system (although the effect on the water-based system is negligible).

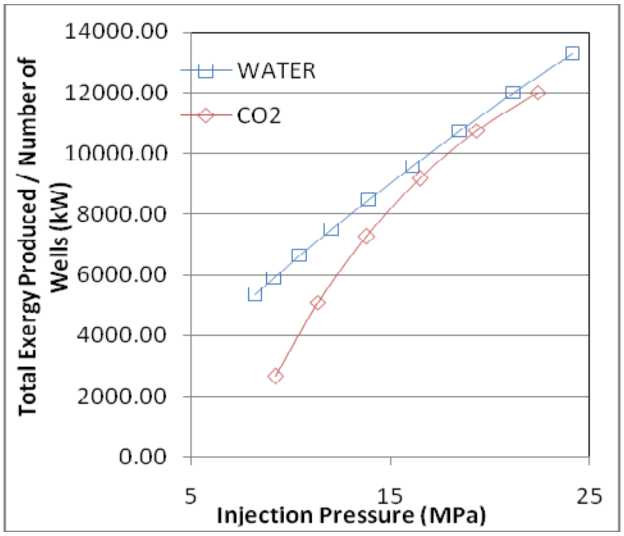

Figure 9: Effect of doubled wellbore diameter on the exergy production of the CO_2 thermosiphon

Figure 9 shows that if larger wellbores are used, CO_2 can be comparitively productive. The costs of this would need to be weighed up against the compartive benefits of utilising CO_2.

DISCUSSION

For the reference case, the CO_2 thermosiphon underperforms compared to H_2O. This is because despite the advantages mentioned in the introduction, CO_2 also possesses some disadvantages compared to water as a heat extractive fluid. The most significant of these are:

- The comparatively lower heat capacity of CO_2
- The gaseous nature of CO_2 under production wellbore conditions, leading to large frictional pressure drops and an associated temperature decrease along the production well

As part of a comprehensive analysis of the performance of the CO_2 thermosiphon concept over a wide range of reservoir and process conditions and constraints, a number of observations have been made:

- For a majority of cases, CO_2 produce less exergy than H_2O. This is mostly due to a combination of the two disadvantages, whereby the frictional pressure drop prevents a large enough flow of CO_2 from moving through the system compared with water.
- There are some cases where the efficacy of CO_2 increases. In less permeable reservoirs, and for shallower, lower-temperature reservoirs, CO_2 displays an exergy production similar to H_2O
- If a wellbore with much larger diameter is used, the differences in exergy production between the systems are insignificant.

Ultimately, the value of the CO_2 thermosiphon concept is based on its economic value compared to the alternatives. This has not been addressed here, but some indicators of the characteristics of reservoirs likely to be favourable to CO_2 have been indicated.

ACKNOWLEDGEMENTS

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REFERENCES

Atrens, A.D., Gurgenci, H., and Rudolph, V. (2009), "CO2 thermosiphon for Competitive Geothermal Power Generation," *Energy Fuels*, 23, 553-557.

Brown, D.W. (2000), "A Hot Dry Rock Geothermal Energy Concept utilising Supercritical CO2 instead of Water," *Twenty-Fifth 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**, 351-67.

Span, R and Wagner, W. (1996), "A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple-Point Temperature to 1100 K at Pressures up to 800 MPa," *J. Phys. Chem. Ref. Data*,, **25**, 1509-96.

Gurgenci, H., Rudolph, V., Saha, T. and Lu, A. M. (2008), "Challenges for Geothermal Energy Utilisation," *Thirty-Third Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California.

The International Association for the Properties of Water and Steam (IAPWS), (1996), "Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use".

The International Association for the Properties of Water and Steam (IAPWS). (2007), "Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam".

White, F. M. (2003) *Fluid Mechanics*. McGraw-Hill, Boston.