SUBSURFACE EFFECTS IN A CO_2 ENGINEERED GEOTHERMAL SYSTEM THERMOSIPHON

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SUMMARY - Engineered geothermal systems (EGS) present an opportunity to expand the scope of geothermal implementation worldwide. Differences from traditional geothermal systems indicate that design modifications may improve their potential. A change that has been proposed is the use of CO_2 as a heat extraction fluid for the reservoir. CO_2 has the benefit of being a non-polar fluid (indicating no salt dissolution in a CO_2-rich phase), favourable transport properties (particularly low viscosity), and a large buoyancy effect (due to operation in the supercritical phase). The disadvantage of CO_2 is the larger mass flows required, leading to increased influence on the system of wellbore frictional pressure losses. Compared to a water-based system where fluid flows are dominated by viscous flow through a porous reservoir, CO_2-based systems will have significant contributing effects from turbulent wellbore friction, viscous reservoir flow, and buoyancy effects. Each of these can dominate to varying degrees depending on process design and operating parameters. Their effect on the manner in which a CO_2-based system operates makes a pure thermodynamic comparison with more traditional approaches problematic. Economic comparison of different designs is necessary.

1 CO2-BASED EGS SYSTEMS

The standard engineering assumption for EGS be to use water as a heat extraction fluid, however water may not provide the optimum economics. Carbon dioxide is the only cheap, abundant alternative with favourable properties. The characteristics making CO_2 a potential competitor are:

- Abundance – as geothermal reservoir flow can involve significant losses of heat extraction, a large source of fluid is needed.
- Sequestration potential – there are economic benefits involved in storage of CO_2 in the reservoir (providing it is appropriately sealed) through carbon credit schemes.
- No process equipment fouling issues – as CO_2 is a non-polar fluid with low solubility of ionic compounds, a geothermal plant utilising CO_2 will not have the issues with precipitation in process equipment often encountered in traditional hydrothermal power generation. Note that this changes when a water phase is also present.
- Buoyancy drive – a CO_2-based system would have high-density fluid in the injection well and low-density fluid in the production well, providing additional impetus for flow through the reservoir and decreasing pumping requirements.
- Suitable thermodynamic & transport characteristics – while the heat capacity and density of CO_2 are lower than water, the viscosity is also lower, allowing similar flows of thermal energy when utilising CO_2

A design of a CO_2 thermosiphon is shown in Figure 1. Of note is the ability for the innate buoyancy drive to supply the motive requirements for the system, allowing a simpler design of surface plant (no need for a large pump)

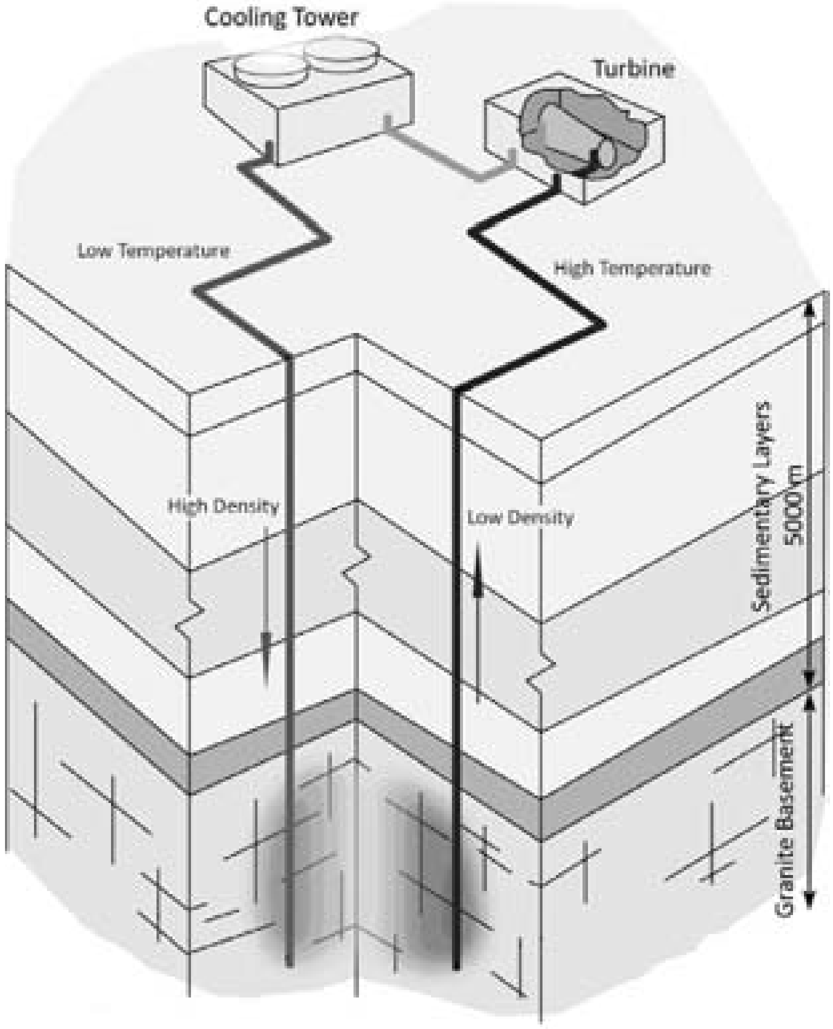

Figure 1: Example of CO_2 thermosiphon system

2 SUBSURFACE EFFECTS

There are three significant phenomena that affect fluid pressure change in the subsurface for a CO_2-based EGS: buoyancy, turbulent wellbore friction, and viscous reservoir friction. These are discussed below. Note that these effects are also present for water, however the magnitude of their effect on CO_2 is very different. Wellbore analysis is based on equation 1.

$$\Delta h = g\Delta z \quad (1)$$

Equation 1 is derived from the first law of thermodynamics for an internally reversible, adiabatic system with negligible kinetic energy change. Pressure change is given by equation 2, calculated from static pressure change and frictional losses.

$$\Delta P = \rho g \Delta z - \Delta P_f \quad (2)$$

Viscous Reservoir Flow

Flow through the reservoir of an EGS system is either through small cracks or porous media, which can be approximated at a simple level through the Darcy flow equation (3).

$$\Delta P = -\frac{\dot{m}\mu\Delta L}{\rho\kappa A} \qquad (3)$$

Note that pressure drop across a reservoir will be proportional to the fluid viscosity and density; a significant advantage of CO_2 as a heat extraction fluid is its low viscosity.

Wellbore Friction

Wellbore flow operates in the turbulent flow regime (Reynolds number is >10^6), as given by equations 4 and 5.

$$\Delta P_f = f\frac{\Delta z}{D}\rho\frac{V^2}{2} \qquad (4)$$

$$f = \left[-1.8\log\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\varepsilon}{3.7D}\right)^{1.11}\right]\right]^{-2} \qquad (5)$$

Note that friction factor is a dependant on epsilon, D, and Re. In general, within the turbulent regime, pressure losses are proportional as given in equation 6.

$$\Delta P_f \propto \left\{\rho^{0.75}, \mu^{0.25}, z, Q^{1.75}, D^{-4.75}\right\} \qquad (6)$$

Turbulent wellbore friction losses for CO_2 are larger in the production wellbore due to lower density compared to the injection well. CO_2 generally will have much higher wellbore frictional pressure losses than water due to a larger flow-rate required for equivalent heat extraction (due to lower heat capacity).

Buoyancy Effect

There is an additional thermodynamic component affecting fluid flow – the buoyancy derived from a density difference between the fluid in the injection and production wellbores. If we consider a case of constant fluid density, each wellbore has a change in pressure (neglecting friction) given by equation 7.

$$\Delta P = \rho g\Delta z \qquad (7)$$

Taking both wells into account, there is a net change in pressure due to density differences given in equation 8.

$$\Delta P_{net} = \frac{\rho_{inj}}{\rho_{prod}} g\Delta z \qquad (8)$$

For higher reservoir temperatures, the density is lower in the production wellbore, leading to a greater buoyancy effect.

3 SYSTEM ANALYSIS

Overall subsurface effect & comparison with water

The above components of pressure change have been assessed numerically with variation in a number of parameters (permeability, wellbore diameter & roughness, reservoir temperature and depth). From this analysis, it is seen that the process can opesrate in a manner that provides a net pressure *gain* through the subsurface, either removing the need for pumping equipment, or allowing the pressure to be harnessed to provide work output.

For some specifications, CO_2 can extract the same heat as a water-based system without a pump; the comparative benefit increases as reservoir permeability decreases, and wellbore diameter increases. Note however, that due to the thermodynamics of the buoyancy effect, the low static pressure loss in the production wellbore is coupled with a large temperature drop; this can be as large as 70 or 80°C in extreme cases. Of additional importance here is the theoretical potential for direct use of produced CO_2, offsetting the lower production temperature by removing the need for heat transfer to a secondary power generation fluid.

The conclusion from the differences between CO_2 and H_2O in terms of the pressure and thermodynamic effects is that a purely thermodynamic comparison is unreliable. On a basis of heat extraction capability, the temperature losses in the production wellbore for CO_2 need to be taken into account, and for direct usage of produced fluids, the simpler plant design of a CO_2-based system is of key importance. A cost-based comparison of competing designs will be necessary to properly contrast their features.

Despite this, some interesting details can be noted:

- CO_2 outperforms H_2O in the viscous flow regime of the reservoir (particularly when acceleration is included, which it is not in this analysis)
- CO_2 suffers compared to water in wellbore frictional losses, particularly in the production well
- CO_2 has large buoyancy drive; but this also means that temperature drops in the production well.
- The temperature-pressure relation of the buoyancy effect means that there is a trade-off for CO_2-based systems – there is a continuum possible production fluid properties, from producing at high flows, low pressure, and low temperature, through to lower flows, but higher production pressure and temperature. This may allow for some tailoring of production characteristics depending on whether the power plant aims for direct fluid use or a binary cycle.
- In general, CO_2 has an advantage for low permeability reservoirs where large energy is required for forcing H_2O through,; this can be amplified through larger diameter wells, and making sure the well casing roughness is low

Of significance is the neglect in this analysis of the mutual solubilities of CO_2 and H_2O; the assessment has been based on a dry CO_2-filled reservoir. A future analysis of the effects on the wellbore of combined CO_2/H_2O flows (i.e. the influence on density of the presence of water, and the change in flow relations if two phases are present) is necessary. It can be envisaged that in an initially saturated reservoir, CO_2 could act as a buoyancy-driven gas lift.

4 CONCLUSIONS

Use of CO_2 as a heat extraction fluid presents a number of benefits and challenges. The thermodynamic properties of CO_2 lead to different subsurface operation of an EGS system compared to water, specifically in terms of the pressure changes within the system. These differences lead to difficulty comparing the fluids from a purely thermodynamic standpoint, and necessitate economic analysis of the EGS power plant design. Basic reservoir analysis indicates that CO_2's advantages compared to water are most prominent for low permeability reservoirs.

5 REFERENCES

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., 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

Lemmon, E. W., Jacobsen, R. T., Penoncello, S. G. and Friend, D. G. (2000) Thermodynamic Properties of Air and Mixtures of Nitrogen, Argon, and Oxygen from 60 to 2000 K at Pressures to 2000 MPa. *Journal of Physical and Chemical Reference Data,* **29**, 331pp.

Lemmon, E. W. and Span, R. (2006) Short Fundamental Equations of State for 20 Industrial Fluids. *Journal of Chemical Engineering Data,* **51**, 785pp.

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**, 351pp.

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. *Journal of Physical and Chemical Reference Data,* **25**, 1509pp.

Tester, J. W. (2006) *The Future of Geothermal Energy*. MIT, Boston.

The International Association for the Properties of Water and Steam. (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. (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.