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Carbon sequestration potential of the Habanero reservoir when carbon dioxide is used as the heat exchange fluid

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ABSTRACT

The use of sequestered carbon dioxide (CO_2) as the heat exchange fluid in enhanced geothermal system (EGS) has significant potential to increase their productivity, contribute further to reducing carbon emissions and increase the economic viability of geothermal power generation. Coupled CO_2 sequestration and geothermal energy production from hot dry rock (HDR) EGS were first proposed 15 years ago but have yet to be practically implemented. This paper reviews some of the issues in assessing these systems with particular focus on the power generation and CO_2 sequestration capacity. The Habanero geothermal field in the Cooper Basin of South Australia is assessed for its potential CO_2 storage capacity if supercritical CO_2 is used as the working fluid for heat extraction. The analysis suggests that the major CO_2 sequestration mechanisms are the storage in the fracture-stimulation damaged zone followed by diffusion into the pores within the rock matrix. The assessment indicates that 5% of working fluid loss commonly suggested as the storage capacity might be an over-estimate of the long-term CO_2 sequestration capacity of EGS in which supercritical CO_2 is used as the circulation fluid.

1. Introduction

It is widely accepted that anthropogenic carbon dioxide (CO_2) emissions into the atmosphere is one of the major causes of global warming (Metz et al., 2005). Although the ultimate solution is to move away from our dependency on fossil fuels, it is unlikely that this dependency will be eliminated in the near future. Various techniques have been explored to capture and store emitted CO_2 including natural sequestration of CO_2 in plants and carbon in soil and the storage of CO_2 in geological reservoirs or geological sequestration (Huisingh et al., 2015).

Broadly speaking, geological storage refers to any method that results in the permanent storage of CO_2 beneath the surface of the Earth. This could include injection of CO_2 underground purely for the purpose of storage (e.g. in a depleted oil or gas field) or the use of CO_2 as a working fluid to assist/enhance industrial production whilst simultaneously achieving the permanent storage of CO_2. Over the past decade or so much research has focused on the latter category because of the additional financial benefit, which makes it more likely that large-scale commercial operations will be established using techniques in this category (Xie et al., 2014).

Most of the work in the use of CO_2 to assist/enhance production has been in CO_2 enhanced oil recovery (CO_2-EOR), CO_2 enhanced gas recovery (CO_2-EGR), CO_2 enhanced coal-bed methane recovery (CO_2-ECBM), CO_2 enhanced shale gas recovery (CO_2-ESGR), CO_2 enhanced geothermal system (CO_2-EGS), CO_2 enhanced uranium leaching (CO_2-EUL), and CO_2 enhanced saline water recovery (CO_2-EWR) (Li et al., 2015a). A detailed discussion of these techniques was documented in ACCA21 (2014). Of these techniques, CO_2-EOR is perhaps the most developed and there are many commercial operations in Canada, China and USA (Manrique et al., 2010; ACCA21, 2014; Lv et al., 2015). The other techniques are still mainly in the development stage although research has, to date, demonstrated their significant potential (ACCA21, 2014; Li et al., 2015b).

CO_2 has different phases and it readily becomes a supercritical fluid ($scCO_2$) as it reaches its critical point at a temperature of 31.1 °C and a pressure of 7.38 MPa. In its supercritical state, CO_2 has some desirable properties that make it very useful in a wide range of industrial applications. For example, the density (ρ) of $scCO_2$ is a little less than that of water but it has a much lower viscosity (μ, ρ/μ of $scCO_2$ is about 1.7 times that of water at a temperature of 200 °C),

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higher compressibility and expandability (i.e. higher expansion coefficient), and a surface tension of almost zero. These properties make it much easier for $scCO_2$ to flow within pores or fractures in rock masses and make $scCO_2$ almost an ideal working fluid for reservoir fracture stimulation, pressure expulsion (e.g. for EOR, EGR, ESGR, EWR) or fluid circulation (e.g. for EGS). The $scCO_2$ is also a strong extraction solvent for heavy oil or other organic matter and, when mixed with oil, it reduces significantly the viscosity and density of oil and therefore can enhance significantly the recovery rate (EOR). The high compressibility and expandability of $scCO_2$ make it easier to maintain a high buoyancy force within the reservoir so as to enhance the production rate (EGS, EOR, EGR). For CO_2-EGS, $scCO_2$ has the added advantage of reducing scaling in both the reservoir and the circulation system, which is a serious problem in geothermal applications. The $scCO_2$ is much less likely to dissolve in-situ minerals compared with the highly corrosive brine normally encountered in EGS reservoirs. During the process of enhancing production, $scCO_2$ will dissipate from the injection well, become trapped within the pores or fractures in rock masses, react with other minerals or dissolve in water and hence achieve permanent geological storage.

This paper assesses the CO_2 storage capacity for CO_2-EGS, taking the Habanero reservoir as an example. In EGS, the working fluid normally considered is water (or brine). Brown (2000) was the first to suggest the use of $scCO_2$ as a working fluid for EGS. He identified three major advantages of using $scCO_2$ instead of water as the working fluid taking the Fenton Hill reservoir as an example: (1) the buoyancy force is equivalent to adding an additional 22 MPa of pressure difference between the injection and production wells and hence increases the mass production rate significantly; (2) as it does not dissolve minerals in the reservoir, its use could potentially eliminate the scaling problem in the system; (3) hot dry rock (HDR) reservoirs with temperatures in excess of the critical temperature for water (374 °C) could be developed without the problems associated with dissolving silica, which could increase the thermodynamic efficiency of surface power-conversion units. Brown (2000) also noted that the low heat capacity of $scCO_2$ (40% of the heat capacity of water) is an unfavourable property as the heat that can be absorbed per unit weight of $scCO_2$ is lower than that of water. Although no modelling work was done, Brown suggested that, after taking into account the additional production rate and the higher buoyancy force (hence less power is needed to drive the fluid circulation), a CO_2-EGS should produce approximately the same power as a water-based system if all other conditions are equal.

EGS reservoirs are pressurised in the heat production process. The higher pressure within the reservoir compared with its surroundings will force the fluid to diffuse into the surrounding rock masses through faults, fractures and pores. In general, this fluid loss is not recoverable unless the reservoir is negatively pressured for a long period of time. It is, therefore, possible to achieve permanent storage of CO_2 in this application if $scCO_2$ is used as the working fluid. EGS are normally created in geological formations with very low permeability, either within the crystalline rock or in the sedimentary layer directly above the basement rock (heat source). In this case, the reservoir must be stimulated to create fracture networks and hence a permeable reservoir with a permeability suitable for heat production. Within this context, the estimation of CO_2 storage capacity for a given stimulated reservoir and operating scenario is important in optimising the design not only for energy production, but also for the required storage capacity. In the work by Brown (2000), a figure of 0.3 kg/s (~9460 t/a) of CO_2 per 1 MW of electric power generated was given as a prediction for the sequestration capacity of EGS reservoirs, although no detail was given on how this figure was obtained.

2. Enhanced geothermal systems (EGS)

EGS have the potential to provide substantial amount of renewable energy due to the vast extent of the heat resources throughout the world (MIT, 2006; Xie et al., 2014). These resources, however, are in general located at significant depths (3–5 km below the surface) within geological formations of low permeability. For example, although crystalline rocks have significant radiogenic heat, their permeability is at the micro-Darcy or even nano-Darcy scale (Selvadurai et al., 2005; Bear and Cheng, 2010; Bundschuh and Suárez-Arriaga, 2010). The permeability of sedimentary rocks overlaying radiogenic heat sources is generally higher but at the milli-Darcy scale or less (Bundschuh and Suárez-Arriaga, 2010). Direct circulation of flow through these types of rocks for heat mining is obviously difficult if not impossible and requires the additional step of fracture stimulation to create fracture networks within the reservoir, hence the term EGS is used to describe these types of (enhanced) reservoirs. The fracture network generated by the stimulation should connect the injection and production wells to form significant flow pathways for the geothermal fluid. The permeability of open (stimulated) fractures is generally several magnitudes greater than that of the rock matrix and thus stimulation is expected to increase the permeability of the reservoir by several orders of magnitude. This level of increase in permeability is crucial for creating technically and commercially viable geothermal reservoirs. For commercial viability, an EGS reservoir should be able to achieve a flow rate of at least 100 L/s.

The depth and re-engineering of the reservoir impose many significant technical challenges for the commercial exploitation of EGS. The outcomes from major EGS projects around the world over the past 40 years are very mixed (Tenzer, 2001). The world's first EGS project, starting in the early 1970s, was at Los Alamos in New Mexico and was successful in the sense that it proved the concept by achieving flow circulation between injection and production wells through the stimulated fractures. The Phase II system produced 4–6 MW of geothermal power by circulating the fluid at a rate of approximately 6 L/s at an injection pressure of around 27 MPa. The project stopped in 1995 mainly due to budget shortfalls (Duchane and Brown, 2002; Brown et al., 2012). The Rosemanowes project in the UK achieved a production rate of 16.7 L/s at an injection pressure of 10 MPa with a three-well configuration during its Phase 2C stage, but the project was terminated in 1991 following the inability to seal the reservoir during the Phase 3 stimulation (Parker, 1999). The Ogachi HDR project in Japan achieved a low circulation rate of about 2 kg/s at a wellhead pressure of 13 MPa with a two-well configuration after multiple stimulations of the two wells. The project was stopped in 2002 for financial reasons (Kaieda et al., 2005). The Hijiori project in Japan suffered a similar fate and the project was stopped in 2002 despite having established a circulation between a four-well system with a production rate of 6.7 kg/s at an injection pressure of 8.1 MPa (Oikawa et al., 2001; Matsunaga et al., 2005). The European Community Soultz-sous-Forêt HDR project in France continues to operate. The pilot electricity plant was constructed in 2007 with a capacity of 1.5 MW and the latest published figures (for 2011) report a production rate of 23–26 L/s and a net electrical power of 100 kW was produced. The thermal power produced was 8474 kW and the gross power produced was 655 kW, suggesting a utilisation efficiency of around 7.8% (Albert et al., 2012). This project has taken more than 20 years and significant investments from the European Union to bring it to this stage. The project is regarded as an R&D project at this stage as it is still not commercially viable, although it does demonstrate the potential of HDR EGS. Geodynamics' Cooper Basin project in South Australia was started in 2002 (Weidler, 2005; Baisch et al., 2006). Four wells were drilled and the final Habanero 4 (H4) well was