Cyclic pumping technique to increase CO₂ sequestration in fractured geothermal reservoirs

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Abstract: Carbon dioxide (CO₂) sequestration in deep geothermal reservoirs is one of the promising techniques to reduce global temperature by decreasing the atmospheric CO₂ content. In this study, a cyclic pumping technique is proposed and applied in an enhanced geothermal system (EGS) for CO₂ sequestration together with heat mining process. Cyclic pumping at higher frequency (small interval of days) can significantly increase the accumulated amount of CO₂ sequestrated. Reducing the pumping frequency results to lower amounts of CO₂ sequestrated, less than using a fixed pumping pressure. The pumping frequency refers to the number of days between maximum to minimum pressure interchange. Furthermore, compared to a fixed low pumping pressure, a cyclic pumping technique improves geothermal heat extraction ratio, thus higher performance of the EGS.

1. Introduction

Efforts to reduce carbon dioxide (CO₂) emissions are highly encouraged as there is a continuous rise in global temperature. Extraction of geothermal energy in deep underground reservoirs can be linked to reduction of non-condensate gas (NCG) by CO₂ sequestration processes. Brown (2000)[1] suggested CO₂ based enhanced geothermal system (CO₂-EGS) in which supercritical CO₂ was used as a working fluid for heat extraction. The idea of using CO₂ as working fluid coupled with CO₂ sequestration and heat mining in geothermal reservoirs has attracted a great deal of attention amongst researchers and industry communities.[2–5] The significance of using supercritical CO₂ has been reported in numerous studies [1,6,7] due to its high heat extraction rate[2,8,9], large expansivity, compressibility, and significant buoyancy force. Moreover, CO₂ sequestration with geothermal heat extraction can help to reduce the project cost by sharing the injection wells used in geothermal heat extraction. [10]

Some test projects of NCG injection have been applied to geothermal fields including Hijiori, [11] and Ogachi [12] in Japan. At these sites CO₂ was dissolved in water at small concentrations prior to injection and CO₂ sequestration was measured based on the percentage composition difference between the injected and produced fluids. Biagi et al. (2015)[13] performed simulation analysis to optimize CO₂ deposit and heat mining in EGS at various injection patterns (fixed rates). The authors showed that the injection scenarios of either constant pressure or constant injection mass rate can help to improve geothermal performance[14] and CO₂ sequestration. Pan et al. (2016) [15] performed simulation studies to assess heat mining with CO₂ sequestration in Mexico’s geothermal reservoirs. The authors showed a significant amount of CO₂ (about 72 million tons) that could be deposited for twenty-one geothermal reservoirs when individual life span of each reservoir is assumed to be 30 years. Well pattern and the reservoir recharge conditions should also be considered when designing an EGS project with CO₂
sequestration. [16] Sun et al. (2016) [4] suggested a technique of injecting CO$_2$ through the tubing, below water outlet from the annulus. The authors showed improved CO$_2$ sequestration and heat extraction rate with the suggested method. The technique also delays the CO$_2$ breakthrough at the production well. Wang et al. (2018) [3] performed a numerical simulation with CO$_2$ and water on the enhanced geothermal system (EGS) and showed the variation of CO$_2$ sequestration and water loss rates for the two systems at fixed injection and production pressures. Numerical analysis performed by Wang et al. (2019) [5] showed that with reduced production pressure and higher injection pressure, the total amount of CO$_2$ sequestration and utilization can be improved at the earlier period of heat mining process.

However, in the above studies, the analysis of CO$_2$ sequestration and heat mining was done at fixed injection pressure throughout the simulation process. In this study, the injection pressure is applied in a cyclic or alternating pattern at a varying frequency of days throughout the simulation period (Figure 2). The cyclic injection pattern is applied to 3D geometric EGS reservoir with doublet well system. The conceptual 3D model is created with multiple intersecting fractures, imitating a real fractured geothermal reservoir. Various parameters related to CO$_2$ sequestration and geothermal heat mining performance are analyzed.

2. Material and Methods

2.1. Variation of CO$_2$ properties with temperature and pressure

CO$_2$ physical properties are sensitive to slight changes in reservoir and surface conditions, therefore a precise model of CO$_2$ variation with temperature and pressure is required to accurately replicate CO$_2$-based EGS. Span and Wagner (1996) [17] proposed an equation of state that is proven to model CO$_2$ density at a wide range of temperature and pressure (216.95 K $< T < 1100$ K, 0.52 MPa $< p < 800$ MPa) with great accuracy. Viscosity and thermal conductivity of CO$_2$ are influenced by pressure and temperature changes. The proposed series of equations by Heidaryan et al. (2011), [18] and Jarrahian and Heidaryan (2012) [19] are used to model these properties. Readers are urged to visit the National Institute of Standards and Technology (NIST) chemistry webbook [20] for detailed clarification on fluid properties variation.

2.2. Description of the thermo-hydro (TH) mathematical model

The mathematical model comprises of matrix and fracture equations describing their individual mass and energy balance equations, which are then coupled together to form a complete system. The basic assumptions can be referred to our previous work [21,22].

The mass balance equation describing the flow in matrix media is expressed as follows

$$\rho \frac{\partial p}{\partial t} + \nabla \cdot (-\rho \frac{k}{\eta} (\nabla p + \rho \frac{g}{\eta} \nabla z)) = Q_m$$  \hspace{1cm} (1)

The mass balance equation for fluid flow in the fracture is given as;

$$a \frac{\partial p}{\partial t} + \nabla \cdot v_j = Q_j$$ \hspace{1cm} (2)

$$v_j = -a \frac{k}{\eta} (\nabla_p + \rho \frac{g}{\eta} \nabla z)$$ \hspace{1cm} (3)

The equivalent energy balance equation considering temperature equality between matrix and fluid in pores is expressed as;

$$((1-\epsilon)\rho_s C_s + \epsilon \rho f C_f) \frac{\partial T_m}{\partial t} = ((1-\epsilon)\lambda_s + \epsilon \lambda_f) \nabla^2 T_m + W_s$$ \hspace{1cm} (4)

In fracture network, the energy balance equations can be expressed as;
\[ a_f \rho_f C_f \frac{\partial T_f}{\partial t} + a_f \rho_f C_f \cdot \nabla_f T_f = a_f \nabla \cdot \left( \lambda_f \nabla T_f \right) + W_f \]  

(5)

2.3. Statement of model validation

Our previous work by Sun et al. (2017, 2018) [21,22] validated the accuracy of the above-proposed models to the analytical model given by Bai (2005)[23] and Cheng et al. (2001) [24]. Good agreement with the numerical model was observed with negligible deviation.

3. Computational model

The geometric model has dimensions of 800m×800m×400m at a depth of 3000m, with multiple fracture network and doublet well system as shown in Figure 2. The injection and production well are separated at a distance of 500m. The initial reservoir temperature is 200 °C, injection temperature at 60°C and no cross heat flux is permitted across the external geometric boundaries. The fluid flow is restricted within the reservoir and no fluid flow across the external model boundaries. The production well is maintained at 12MPa while the injection pressure follows the injection pattern as shown in Figure 1. Other parameters used in the simulation are as listed in Table 1.

Figure 1. Alternating injection pressure patterns with time

Figure 2. Conceptual EGS model

| Parameters          | Symbols | Units | Value     | Parameters          | Symbols | Units | Value     |
|---------------------|---------|-------|-----------|---------------------|---------|-------|-----------|
| Fluid density       | \( \rho_f \) | kg/m\(^3\) | \( f(T,P) \) | Injection temperature | \( T_m \) | K     | 60 °C     |
| Fluid heat capacity | \( C_f \) | J/kg/K | \( f(T,P) \) | Fracture aperture    | \( a_f \) | mm    | 0.35      |

Table 1. Computational parameters
4. Results and discussion

4.1. Analysis of production temperature.

The average production temperature is an important parameter in evaluating the performance and lifespan of a geothermal system. The average outlet temperature at the production well can be obtained by the outlet CO₂ temperature from matrix rock and fracture.[22]

\[
T_{\text{out}} = \frac{\int_{L} v_{f} d_{f} T_{f} dL + \int_{s} u T_{v} d\Gamma}{\int_{L} v_{f} d_{f} dL + \int_{s} u d\Gamma}
\]  

Figure 3 shows the evolution of the average outlet temperature for all cases of the injection pattern. At the beginning of heat mining period, the outlet temperature maintains a stable maximum value for about 1000 days before gradually decreasing. The decline in production temperature indicates the thermal breakthrough of the injected low-temperature CO₂. As shown in Figure 3, small injection pressure (CASE A) delayed the declining rate of the production temperature. Minimum injection pressure results to low fluid velocity in reservoir fracture and matrix systems, resulting in a delayed effect of thermal breakthrough. The cyclic injection mechanism (CASE C to CASE E) displayed no significant difference in the average outlet temperature evolution. Therefore, the frequency in pressure alternation i.e. 15 days, 30 days and 60 days have no impact on the average production temperature trend.

4.2. Heat extraction ratio

Heat extraction ratio is a critical parameter in evaluating the performance of the geothermal reservoir. The heat extraction ratio (\(\eta\)) indicates the extracted thermal energy to the total heat initially stored in the reservoir and can be expressed as; [25]

\[
\eta = \frac{\int_{v_{f}} \rho_{s} c_{s} (T_{r} - T(t)) dv}{\int_{v_{f}} \rho_{s} c_{s} (T_{r} - T_{in}) dv}
\]  

The corresponding evolutions of the heat extraction ratio “\(\eta\)” with extraction time under different injection pattern are illustrated in Figure 4. It can be seen that the cyclic pressure patterns of CASE C, CASE D and CASE E have improved heat extraction ratio than a constant pressure pattern of CASE A. CASE B has the highest heat extraction ratio due a continuous large pressure difference between injector.
and producer wells, making the flow of the reservoir fluids easy in matrix and fracture networks, thus extracting more heat energy. Therefore, compared to a fixed low injection pressure, cyclic pressure alternation improves the heat extraction and performance of the EGS.

![Figure 3](image.png) **Figure 3.** Average production temperature for all cases

![Figure 4](image.png) **Figure 4.** Heat extraction ratio for different injection pattern

### 4.3. Variation in flow rates.

Injection and production rates are key parameters in evaluating the CO$_2$ sequestration, heat production and the corresponding electric energy generated from a geothermal system. CO$_2$ is sensitive to changes in temperature and pressure, therefore the flow process in wellbore greatly impacts the final production flow rate at the surface condition and the injection rate at the reservoir condition. In this study, the values of the production and injection flow rates are obtained at the reservoir conditions i.e. neglecting the fluid heat transfer processes [2] and flow mechanisms in the wellbore. Similar assumptions was adopted by Shi et al. (2018) [25] and Wang et al. (2019)[5] in their research work.

Figure 5 shows the evolution of the production and injection flow rates for different injection pattern. Low injection pressure resulted in reduced flow rates both at injection and production wells (Figure 5a). Higher injection pressure not only pushes a large proportion of injected CO$_2$ to flow out at the production well, but also accounts for the highest flow rate that increases gradually at the injection well. The cyclic injection pressure resulted in continuous alternating flow rates at injection and production wells, but the extent in the difference between maximum to minimum values is significant for the injection rate than production rate. To have a stable output heat and power, the production flow rates must be maintained or varied to a small amount depending on the customer demand. Our proposed method of alternating injection pressure resulted in varying production flow rates. Therefore, we suggest a fixed flow rate at the production well which can easily be achieved by placing a valve at the production wellbore or surface equipment to maintain the flow rate. As shown in Figure 5b to Figure 5d (see the red line in graphs), we recommend a regulated production flow rate far lower than the fluctuating value in the overall production trend at different stages. However, due to the buoyance effect, higher compressibility and expansivity of CO$_2$ [1], the fluctuating magnitudes of production flow rates may be reduced, leading to a stable production rate scheme in the actual geothermal field.
4.4. CO₂ sequestration analysis.

During the heat mining period, CO₂ circulates within the reservoir as a working fluid, filling the fractures and matrix pores. The leakage of CO₂ into the formation that is not accounted for in the well production rate designates the CO₂ sequestered into the reservoir formation. The important parameters for the CO₂ sequestration analysis include fluid loss rate, fluid loss ratio and the cumulative amount of CO₂ sequestration. The fluid loss rate ($q_{loss}$) and fluid loss ratio ($\delta_{loss}$) are calculated as:

$$q_{loss} = q_{inj} - q_{pro} \quad ; \quad \delta_{loss} = \frac{q_{loss}}{q_{inj}}$$

where, $q_{inj}$ and $q_{pro}$ are injection and production flow rates respectively at the reservoir condition, kg/s.

As shown in Figure 6, the cyclic injection pattern of CASE C and CASE D is seen to have higher spikes of fluid loss rate than a constant injection pattern of CASE A or CASE B. For a fixed injection pressure, higher injection pressure (CASE B) had higher fluid loss than a relative lower injection pressure (CASE A). For the cyclic injection pattern, the frequency of the interchange between higher and lower injection pressures had a significant effect to the total amount of CO₂ sequestrated.

Based on Figure 6, cumulative amounts of CO₂ sequestration can be calculated, which are shown in Figure 7. It can be seen that the cyclic pressure pattern with higher frequency interchange of days (CASE
C and CASE D) had higher amounts of CO$_2$ sequestered than a fixed injection pressure. This is to say that the higher frequency of the alternating pressure improves the CO$_2$ sequestration. Alternatively, a higher magnitude of injection pressure at a fixed rate had higher CO$_2$ sequestration than smaller injection pressure. However, much higher injection pressure may have a negative effect on the thermal performance of the geothermal system resulting in an earlier thermal breakthrough at the production well. As shown in Figure 7, the accumulated CO$_2$ sequestered in the formation is higher for CASE C, which is about $3.274 \times 10^{10}$ kg over a period of 11000 days. CASE D, had a total CO$_2$ sequestered of about $3.206 \times 10^{10}$ kg, for the same time period. The decline in the total amount of the CO$_2$ sequestered between CASE C to CASE D is about 2%, resulting from the frequency change of the pumping pressure interval. The decrease of the pumping frequency (CASE C to CASE D) resulted to decline of the accumulated CO$_2$ sequestered of about 15%. Furthermore, a fixed low injection pressure (CASE A) had the least amount of CO$_2$ sequestered ($2.129 \times 10^{10}$ kg).

Figure 6. The fluid loss rate for all cases of the injection pattern.

Figure 7. The cumulative amount of CO$_2$ sequestered in the reservoir.

5. Conclusion
This paper proposed a cyclic injection pattern in fractured geothermal reservoirs to increase the amount the rate and amount of CO$_2$ sequestration. Based on the numerical simulation analysis, the amount of CO$_2$ sequestration can be improved by the cyclic injection pressure technique. Alternation of Injection pressure at high frequency (small interval of days) has more advantage in increasing the cumulated amount of CO$_2$ sequestered in the formation. The decrease in pumping frequency (higher interval of days) decelerates the total amount of CO$_2$ sequestration. Furthermore, in comparison to fixed low injection pressure, the cyclic injection pattern has improved heat extraction rate, thus higher performance of the EGS.

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