The Importance of Phase Transition in Closed Loop Geothermal Power Generation System Using CO_2 as Working Fluid

(CO_2 を駆動流体とする Closed Loop 地熱発電システムにおける相変化の重要性)

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Keywords: Geothermal power, Closed loop system, T2Well, DFM, Numerical Simulation

1.INTRODUCTION

The reasons why conventional geothermal still not make great progress on application and commerce are:

(1) Complex geological condition such as, low reservoir permeability, toxic mineral solution subsidence, groundwater pollution and so on;
(2) Appropriate site selection is limited to result in spreading all over the world slowly;
(3) Geothermal drilling and power projects are too risky to abstract more investment.

In order to promote geothermal power use globally, there have many new methods be proposed and verified by field experiment and numerical simulation. For example, Enhanced Geothermal System (EGS) and ECO2G advocated by GreenFire.

However, EGS is still far from commercialization because of high cost and relatively high risk and concern of seismicity caused by rock fracture. When the two both adopt SCCO2 as working fluid to extract heat, ECO2G has a few advantages compared to EGS:

(1) There is no CO_2 loss during operation;
(2) There is little concern about seismicity;
(3) Can generate revenue is less than half the time with less capital.

Compared with conventional open system geothermal projects, closed-loop circulation using SCCO2 as working fluid (see Fig 1) without contacting the host rock solved existing problem, such as corrosion to the wellbore and surface equipment, pollutant disposal, seismic, subsidence, etc. Here we have carried out mixed convective-conductive fluid-flow modeling using TOUGH2[1] with wellbore flow capability (T2Well[4]) to investigate whether the phase transition occurs along wellbore can provide positive effect for energy extraction or not. Furthermore, sustainability test of the energy output and calculation of the balance between cost and profit in the geothermal power plant under specific conditions, which is simulated in this study.

There were few associations adopting closed-loop system as a primary heat mining method in geothermal power generation, because thermal conduction of closed-loop circulation from hot rock through pipe and into working fluid was limited by many factors (e.g. casing material and drilling technologies). However, recently there have been made many further progresses in reservoir stimulation, drilling technology, and the use of novel working fluids, closed-loop systems regained attention of study and commerce.

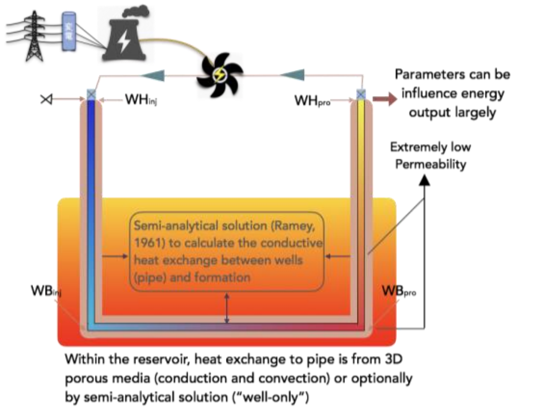

Fig. 1 Conceptual Diagram of an ECO2G System

It is suspected that injection temperature and flow rate of the working fluid strongly control the energy recovery. Therefore, we changed injection temperature and mass flow rate to observe how energy output varies along with injection data change and what a role phase transition plays for energy output by using T2Well model. The geological model which bases on the geothermal resource area in South California's Imperial Valley was used to demonstrate critical factors controlling heat extraction from geothermal systems using a closed-loop heat exchange method built by Lawrence Berkeley National Laboratory.

2.METHODOLOGY

In this paper, we use a T2Well, one from TOUGH2 family, to simulate closed loop circulation that geothermal power generating system. The approach we use for describing wellbore flow is based on the drift-flux model (DFM) (Shi et al., 2005) for one-dimensional (1D) transient two-phase non-isothermal flow of CO_2-water mixtures (here CO_2 only).

2.1. Mass and Energy Conservation

Mass or energy consumptions are expressed as

follows: $$\frac{\partial M^k}{\partial t} = q^k + F^k \quad (1)$$
where k is the index for the mass components, k =1 (H_2O), 2(CO_2), and 3(energy); q^k are source/sink terms for mass or energy components; and F^k are the mass or energy transport balance terms along the borehole.

2.2. Drift-Flux-Model (DFM) in T2Well

The average velocity of gas phase is modeled by the following equations:

$$u_G = C_0 j + u_d \quad (2)$$

where C_0 is the profile parameter to explain the effect of gas saturation and velocity profiles over the pipe cross-section.

3. MODEL

3.1 Well system

It is a U-shaped closed-well (no fluid exchange between the well and the formations). The vertical sections of the well (both injection and production) are marked as "wella", while the horizontal section of the well are marked as "wellb". And the heat exchange between the well and the surrounding formations is calculated numerically since the surrounding formations are discretized in the grid. The grid representing the horizontal section of the well and the surrounding formations was first created as a 3D grid of a vertical well including the surrounding formations using WinGridder and then modify the grid by assigning material based on region and turning gravity direction in WinGridder to make it into a horizontal well.

The closed loop geothermal power generation system consists of a 1100m horizontal pipe within the reservoir underground 2500m, and connected to two 2500m vertical wellbores.

Table 1. Properties of the wellbores.

Parameter	Horizontal well	Vertical well
Length	1100m	2500m
Diameter	0.168m	0.168m
Tube I.D.	0.154m	0.154m
Material	steel	steel
Roughness	4.5×10^{-5}	4.5×10^{-5}

3.2 Reservoir system

Note that the grid in the input file is only a half of the domain because we can save half computational power for the same problem using the symmetry. However, this feature along with other features used in this input file make it impossible for the released version of the T2Well/ECO2N code to run properly. The reservoir is seen as a water-salt-gas geothermal system with permeability at a depth of almost 2500m, and with hydrostatic pressure of 25 MPa and initial reservoir temperature of 250℃. The vertical and horizontal wellbores are in a same product model and are simulated as 1D that heat transfer is by conduction using Ramey's (1962) semi-analytical solution. However, reservoir from overburden to underlying is using standard Darcy's law. There is no advective coupling between the pipe and the reservoir as heat conduction in the reservoir domain is only by heat conduction.

Table 2. Properties of different regions (closed-loop system).

Zone	Porosity(vol%) / Permeability(m^2)	Rock grain Density (kg/m^3)	Rock grain specific heat (J/(kg℃))
Overburden	$5/10^{-15}$	2700	1000
Reservoir	$25.4/10^{-12}$	2700	1000
Underlying	$5/10^{-15}$	2700	1000
Stimulated	$25.4/10^{-10}$	2700	1000

Besides Table.2, we set the same thermal conductivity 4.0 (W/(m℃)) and pore compressibility 7.25×10^{-12} for all zones.

4. ELEMNTS AND INPUT DATA

There are 10792 reservoir elements as surrounding formation and 67 wellbore elements for working fluid circulating to extract heat from ground. Therefore, the closed-loop geothermal system model consists of totally 10859 elements.

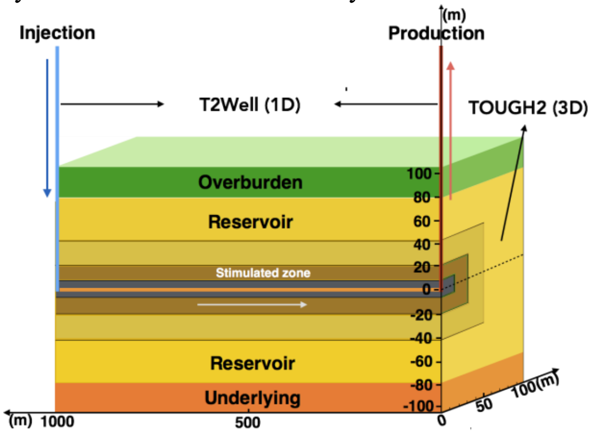

Fig. 2 3D model of the reservoir part in the closed-loop system. (Green is overburden, yellow is reservoir, orange is underlying). Blue line is 1D injection wellbore, orange line is 1D horizontal pipe, red line is 1D production wellbore.

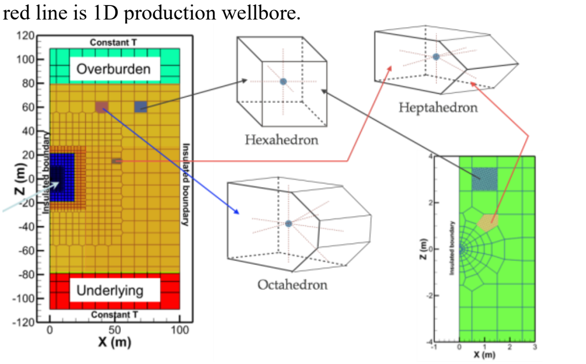

Fig. 3 Three types of cube which are set as element within 3D-domain reservoir.

The purpose we inject liquid CO_2 rather than super--critical is to bring phase transmission into existence.

Table 3. Input information for 3 cases (9 subcases).

	Mass Flow Rate (kg/s)	*Pin (MPa)* / *Pout (MPa)*	T_{inj} (1)	T_{inj} (2)	T_{inj} (3)
Case1	40	7.0 / 6.9	30	40	50
Case2	60	7.0 / 6.9	30	40	50
Case3	80	7.0 / 6.9	30	40	50

5. RESULTS AND DISCUSSION

In Fig 4, We notice low injection temperature cases CaseX(1) have the similar increasing rate on temperature with other cases from inlet until the bottom of production wellbore. But CaseX(1) have the lower decreasing rate on temperature along production wellbore, as a result temperature at outlet of CaseX(1) exceed CaseX(2) and CaseX(3) whose injection temperature are higher than CaseX(1), and the similar law are occurred in Case2 and Case3.

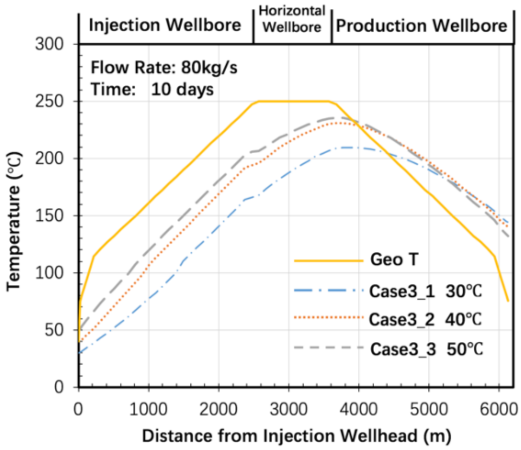

Fig 4. 10-day temperature profile with different injection temperature using Case3 (flow rate: 80kg/s) as an example.

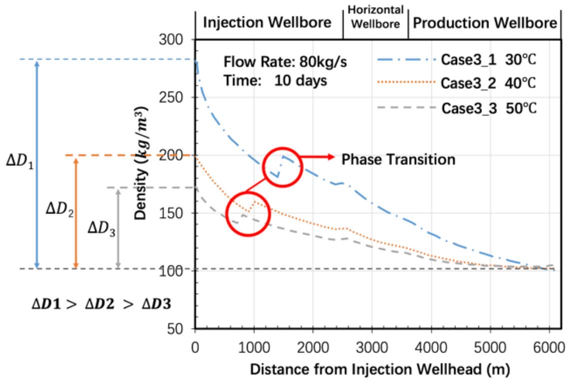

Fig 5. Simulation results of different CO_2 injection temperature on density change in closed loop under different mass flow rate.

The reasons why low injection temperature case gain high outlet temperature are:

(1) As seen in Fig 5, the CaseX(1) have the biggest density different among all cases, therefore CaseX(1) have the greater driving force, which means high velocity (see Fig 6) and less heat loss in CaseX(1).

(2) In Fig 8, the pressure at inlet and outlet have been fixed for all cases, but pressure in CaseX(1) are always higher than other cases. Given they converge to the same value at outlet, we consider pressure energy converts into thermal energy as a result of higher output temperature in CaseX(1) than other cases.

In Fig 5, it is observed there must be an obvious density change occurs in the injection wellbore for all cases, we consider it is the corresponding phenomenon of phase transition according to following indirect reasons:

(1) Apparent change occurs in temperature profile at same depth where obvious density change occurs (see Fig 4);

(2) Thermal cycle (Fig 7) shows there is phase transition occurs because CO_2 enters supercritical from subcritical near the depth where dramatic density change happens;

(3) It is shown in Fig 8, the pressure of CaseX(1) are always higher than CaseX(2) and CaseX(3), because CO_2 at inlet of CaseX(1) are all in liquid state with high density than other cases whose density are close to gas.

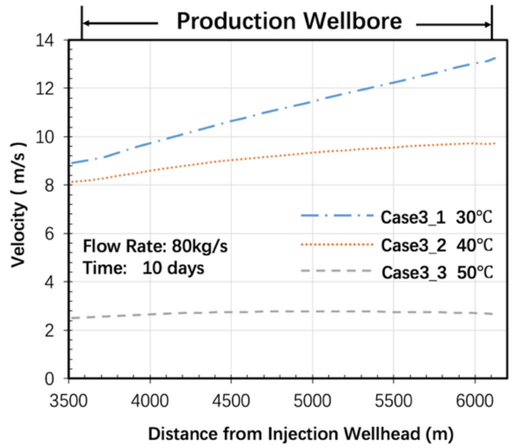

Fig 6. Simulation results of the velocity throughout production wellbore with different injection temperature.

From Fig 9, although we have known that low injection temperature (especially in liquid phase) will extract more energy within certain range, how long the steady energy output can be lasted is need to consider. Therefore, we simulate 1-year operation (see Fig 10) to demonstrate the sustainability for the closed loop geothermal system. And it shows no energy output drop occurs within 1 year.

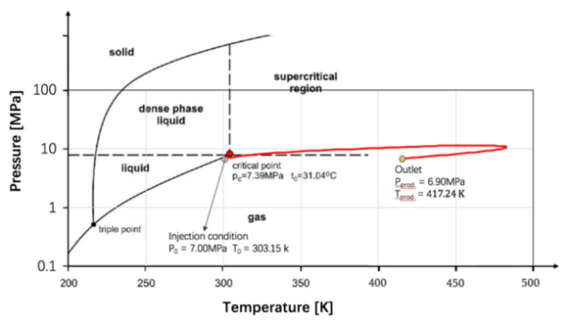

Fig 7. Thermal cycle from inlet to outlet in the CO2 phase diagram under 80kg/s flow rate (Case3_1).

According to Fig 10, in Case2(2) we find the value (about 2.58WM) of energy gain in geothermal operation after 1 year is higher than the value (2.25MW) of energy gain after 10 days, which indicates there is no heat resource decay occurred in the closed loop system within at least a year. But actually, we need to do longer-time simulation in further study.

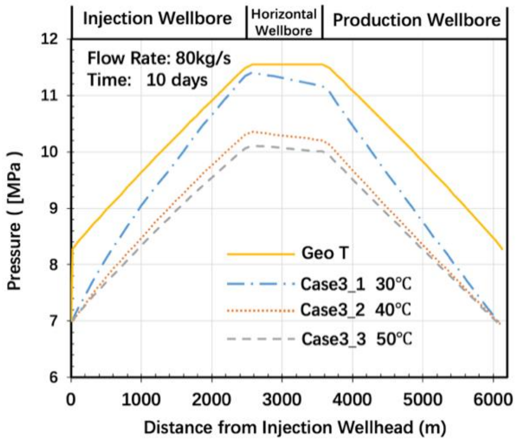

Fig 8. 10-day pressure profile with different injection temperature using Case3 (flow rate: 80kg/s) as an example.

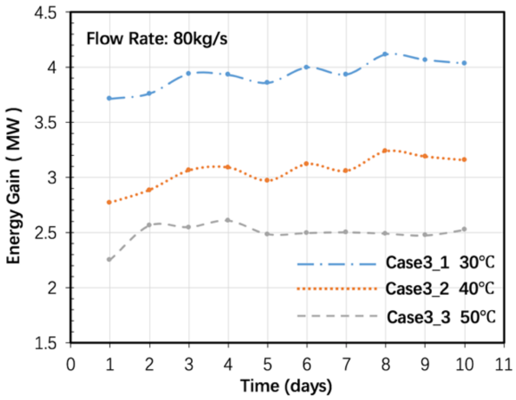

Fig 9. 10-day simulation results of energy gain for various injection temperature under the same flow rate.

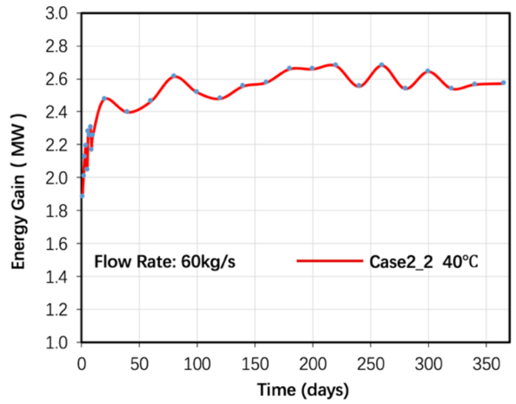

Fig 10. 1-year simulation of energy change profile.

6. COST AND PROFIT

We used an Economic Methodology provided by The Queensland Geothermal Energy Centre of Excellence. Economic analysis of the project is conducted based on standard process engineering cost methodologies. However, the results are volatile and lack of model parameter about applied equipment.

We know it takes \$0.065~0.075/KWH[8]. Compared with conventional unit price of electricity (\$0.2~0.3 /KW)[9], the unit price of electricity by ECO2G method is much lower, which can show economic advantages that ECO2G belongs to.

We need to consider more possible cost that will be necessary for long-time operation (eg. Operating years, maintenance, environmental improvement costs, tax, equipment renewal fee and so on), which are full of uncertainty. Therefore, for giving more appropriate and accurate cost estimation, we must consider more significant factors to complete a long-time calculation.

7.CONCLUSION

In this study, we have used a detailed coupled pipe-reservoir model to investigate the effects of various parameters on the energy gain of CO_2 flowing and the sustainability of steady energy output in a U-shaped well through a reservoir.

Because of phase transition, the energy gain by flowing CO_2 in the pipe is becoming more efficient, rather than injection condition super-/sub-critical whose state is close to gas, injection in liquid phase can cause greater density difference between inlet and outlet as a result of stronger driving force which is explicitly expressed as high velocity that can decrease heat loss time in production wellbore, and in spite of pressure values in inlet and outlet are fixed for all cases, it can keep higher pressure profile from inlet to outlet, which is considered energy conversion exists, pressure energy converts into thermal energy, so that liquid injection cases have more energy gain than other cases.

As a conclusion, low injection temperature and high mass flow rate can bring more benefit to energy gain. Especially, liquid injection condition is better for heat extraction. Meanwhile, we tried to investigate whether the energy output in such a closed loop geothermal system steady or not by simulating 1-year system operation, the results are even there actually slight fluctuation for the values of the energy output occur over time, but it is nearly approach to the steady curve. Furthermore, we need to do more investigation in order to understand why fluctuations exist (see Fig 10).

REFERENCES

[1] Karsten, Curt.O.(1999),LBNL-43134.
[2] Pan, L. (2003). Computers & Geosciences 65 (2014), 46-55.
[3] Lund, J.W.(2003). Geothermics, 32(4), pp.535-543. [4] Pan, L., and C.M. Oldenburg. Computers & Geosciences 65 (2014), 46-55.
[5] Oldenburg, C.M., and L. Pan.(2013) 97(2) 201-221. [6] Oldenburg Curtis, Pan L., Muir Mark et al. (2016) Stanford University, California, February 22-24.
[7] Curtis M. O., Lehua P., Numerical Simulation of Critical Factors Controlling Heat Extraction from Geothermal Systems Using a Closed-Loop Heat Exchange Method, 2016.
[8] Projected 2020 Average Levelized Cost of Electricity of Major Power Sources from US Energy Information Administration, 2016.
[9] Ministry of Economy, Trade and Industry. (2019). https://www.meti.go.jp/press/2018/03/20190322007/20190322007.html.