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Advancing CO_2 Plume Geothermal: A Preliminary Investigation of Key Success Factors

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ABSTRACT

Numerous studies have shown that CO_2 plume geothermal (CPG) contributes to the goal of simultaneously utilizing and storing CO_2. The system employs supercritical CO_2 as the heat-carrying fluid in natural porous media to achieve the extraction of geothermal resources while storing CO_2 geologically. This work investigates key success factors for advancing CO2 plume geothermal. We look at reservoirs' geologic, reservoir, and thermophysical characteristics and quantitatively evaluate how they support heat extraction using CO_2 stored in porous media. We use a three-dimensional numerical simulator to model the impact of each property studied on cumulative CO2 produced. The result showed that permeability and anisotropy significantly influenced how much CO_2 could be extracted from the reservoir. From a geological perspective, sensitivity analyses reveal the influence of dip on CO_2 extraction and the need for optimal well placement. The study describes optimal development strategies for different reservoir thicknesses.

1. INTRODUCTION

One of the challenges limiting large-scale deployment and a large number of CO_2 capture projects is that CCUS projects are considered expensive and not economically attractive (Shen et al., 2022; Gibbins et al., 2008). The ability to utilize the captured CO_2 and simultaneously sequester it may improve the economic attractiveness of CCUS (Budinis et al., 2018). Several authors (Brown, 2000; Pruess, 2006; Luo and Jiang, 2014; Okoroafor et al., 2022) have studied the thermal performance of an enhanced geothermal system (EGS) with supercritical carbon dioxide (CO_2). Their simulation results show that the thermophysical properties of CO_2 in the supercritical state make it quite attractive for heat mining. In contrast with the EGS model based on a complex fracture system, the CO_2 plume geothermal takes full advantage of the greater compressibility, expansibility, and lower viscosity of CO_2. In addition, the fluid loss in the system will indirectly achieve the purpose of geological storage of CO_2 (Randolph et al., 2010, 2011).

The CO_2 plume geothermal system is still in the research and demonstration phases. To maximize net power, reservoir properties as well as surface facilities' optimization, have become the focus of research. Adam et al. (2020) proposed that correctly sized well spacing will provide the greatest average power over time. The work by Adam (2020) highlighted that over-spacing wells affect the average power less than under-spacing them. This opinion is also demonstrated by Wei et al. (2015). The increase in well spacing reduces the pressure gradient between wells while increasing the maximum amount of geothermal resources that can be extracted by the plume geothermal system and the heat exchange time between the working fluid and the reservoir, weakening the effect of heat loss on the heat extraction and reducing the negative effect of the plume migration. Feng, et al. (2013) conducted a field-scale investigation suggesting that high temperature and permeability are the keys to heat mining in the Songliao basin. In particular, the study specified that when the permeability decreases, the sensitivity increases rapidly as the permeability decreases. This was cited as due to the increased heat loss in the reservoir as the production well flow rate increases with permeability. As a result, a smaller enthalpy difference will appear between the production well flow and the injection well flow, thus decreasing the effects of permeability changes on the thermal extraction rate.

As research on CO_2 plume geothermal systems continues to improve, various factors have been proposed to influence the magnitude of heat extraction. However, previous studies only study a few parameters to optimize the model computing time. This study begins a comprehensive investigation of various properties, including geology, reservoir, and thermophysical properties, which cohesively shows the effect of key factors that could advance CO_2 plume geothermal.

2. METHODOLOGY

A hypothetical CO_2 plume geothermal system was modeled within an aquifer with a reservoir top depth of 1500 meters. The fluid circulation was achieved with a vertical injector and a vertical producer. The perforated interval of the injection well is fixed at 1/4 of the reservoir thickness to the bottom of the aquifer, i.e., for the reservoir thickness of 400 m, the perforated interval is at 100 m from the bottom of the reservoir. The length of the production well is approximately half of the injection well, placed higher than the injection well to ensure any CO_2 that migrates upwards is produced. A three-dimensional flow and heat transfer model was used to represent the system, as shown in **Fig. 1**. The X-Y plane is a square of length L 2000 m. The reservoir is assumed to be homogeneous. Permeability anisotropy through the kv/kh ratio is fixed at 0.1 in the base case, but sensitivity analysis was performed on this parameter for different kv/kh ratios. Robertson (1988) proposed the thermal properties of rocks. We considered the reservoir to be sandstone-dominated leading to heat capacity ranges from 1 kJ/kg/K to 2 kJ/kg/K. Other thermophysical properties taken from Robertson (1988) include rock thermal conductivities of 1.5 W/m/K to 4.2 W/m/K, and 2200 kg/m^3 to 2800 kg/m^3 as the rock density. The initial surface temperature of the system was kept at 15 °C, and CO_2 was injected under a supercritical state of temperature 35 °C and pressure 75 bar. The geothermal gradient of 0.02 °C /m, 0.034 °C /m, and 0.04 °C /m were also considered during the simulation. Finally, we examined dips at -2°, 0°, 10°, and 15°. Table 1 and Table 2 summarize the Base Case numerical setting and all the parameters used for the sensitivity study.

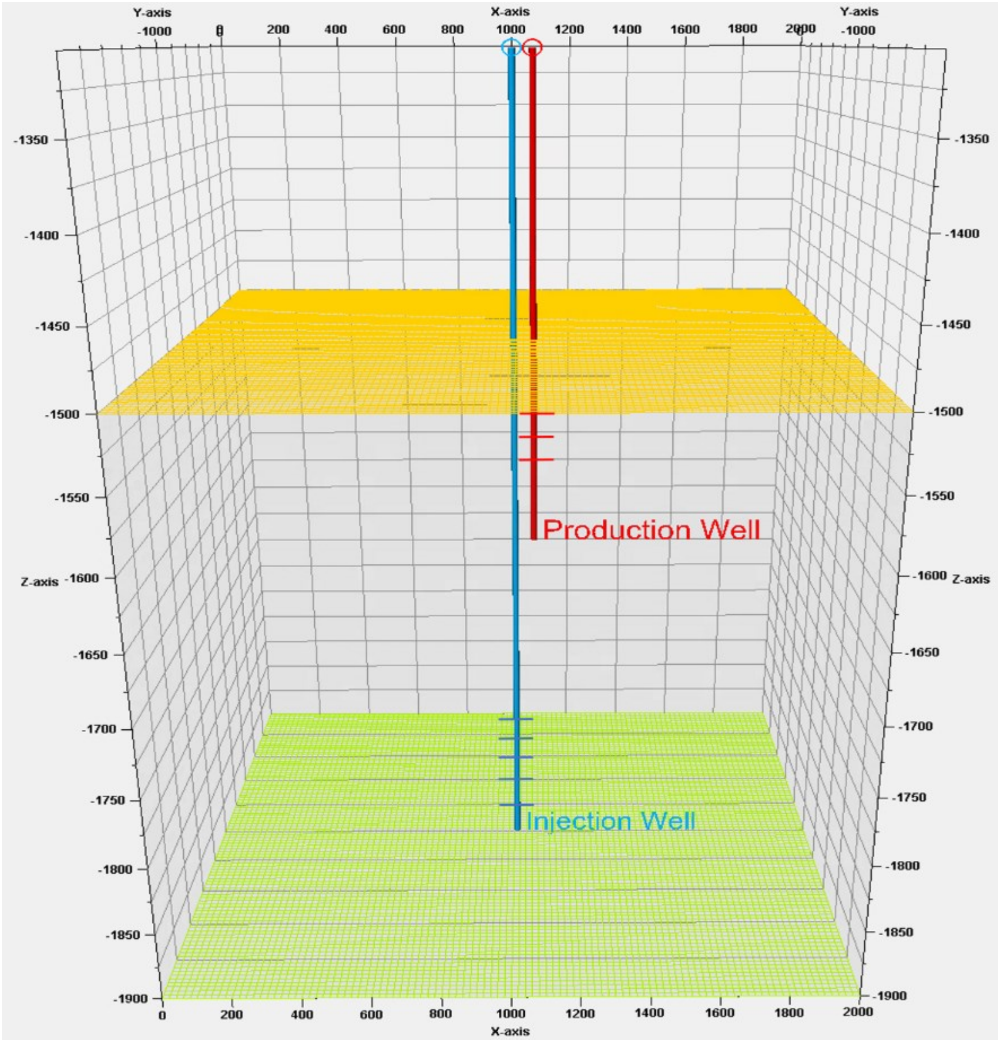

Figure 1: The three-dimensional model representing the CO_2 Plume Geothermal System.

Table 1

Nomenclatures and numerical setting of the Base Case.

Symbol	Description	Value	Unit
h	Thickness of aquifer	400	m
kh	Horizontal permeability	250	md
kv/kh	Permeability anisotropy	0.1	frac
Φ	Porosity of the formation	0.2	frac
Kr	Thermal conductivity of rock	2.89	W/m/K
Cr	Specific heat capacity of rock	1	kJ/kg/K
ρr	Rock density	2650	kg/m3
γ	Geothermal gradient	0.034	°C/m
δ	Dip	0	°

Table 2

Parameters used for sensitivity study.

Parameters	Value	Unit
h	50, 100, 200, 300, 400	m
kh	10, 50, 250, 500, 1000	md
kv/kh	0.1, 0.3, 0.5, 0.75, 1	frac
Φ	0.1, 0.2, 0.3	frac
Kr	1.5, 2.89, 4.2	W/m/K
Cr	0.84, 1, 1.5	kJ/kg/K
ρr	2200, 2650, 2800	kg/m3
γ	0.02, 0.034, 0.04	°C/m
δ	0, -2, 10, 15	°

The Eclipse 300 simulator was adopted for modeling because it has been demonstrated to be suitable for modeling geothermal systems (Stacey and Williams et al., 2017). The initial temperature of the reservoir is derived from the average ambient temperature in Dallas (15 °C) plus the product of the geothermal gradient and the depth of the reservoir (Adams et al., 2014). A direct CPG system was assumed at the surface, including a turbine, cooler, condenser, producer and injector, and a surface pump, as shown in **Fig. 2**. CO_2 is injected for 2.5 years. In the first 3 months, 0.25 MT/yr CO_2 is injected. In the second 3 months, 0.5 MT/yr of CO2 is injected. In the months that follow up until 2.5 years, 1 MT/yr of CO_2 is injected. The producer is opened after 2.5 years until 7.5 years when the simulations were completed. The results are analyzed to construct the cumulative CO_2 production curve from the producer after then.

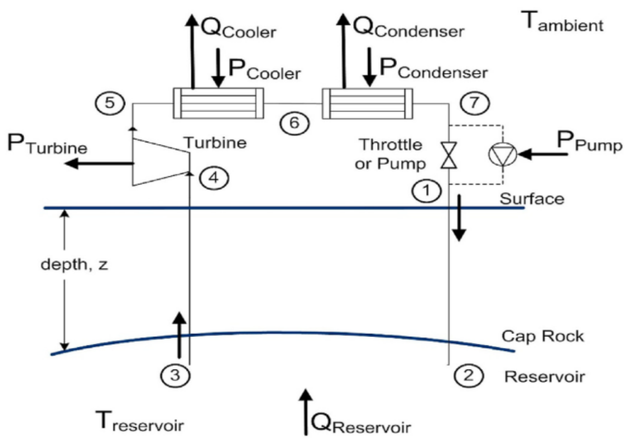

Figure 2: A direct CPG system schematic at the surface (Adams et al., 2021).

3. RESULTS AND DISCUSSION

The fundamental thermodynamics equation is sufficient to quantify heat extraction in a CO_2 plume geothermal system. The expression of the formula is:

$$Q = \dot{m}C_p\Delta T$$

Where $\dot{m}$ is the mass flow rate, $C_p$is the specific heat capacity, and ΔT stands for the temperature difference before and after heat transfer.

We further derive the mass flow rate to be the product of the mass density of the fluid and the volumetric flow rate stated by the equation below:

$$\dot{m} = \rho \cdot \dot{V}$$

The volumetric flow rate is defined by the limit:

$$\dot{V} = \lim_{\Delta t \to 0} \frac{\Delta V}{\Delta t} = \frac{dV}{dt}$$

Observing the direct relationship between the heat extraction, mass flow rate, and volumetric flow rate, we considered that the cumulative volume of CO_2 produced will be directly related to the cumulative heat extracted. Hence, we investigate how the parameters can impact the CO_2 volume that could be produced.

3.1 Optimal CO_2 production for given different reservoir thickness

We simulated the cumulative gas production over time for thicknesses of 50 m, 100 m, 200 m, 300 m, and 400 m. The production well was set to open 2.5 years after CO_2 injection. From **Fig. 3**, with January 2026 as the cut-off date, the smaller the reservoir thickness, the faster the CO_2 production increases. This phenomenon depends on how quickly the CO_2 reaches production well. In the case of the 400 m reservoir, for example, growth only starts to gain momentum at the end of the 4-year phase. Although the CO_2 plume takes much longer to migrate from the perforated interval of the injection well to the production well, the slope is more in line with exponential growth in terms of the trend after that. As of 7.5 years, its production has surpassed that of the 100-meter thickness case, which was growing rapidly at the beginning, and is close to parity with the 200-meter thickness case.

We noted that although the 50-m reservoir is limited by the volume of gas injection that it can sustain, the final CO_2 production is significant. Compared to the late stage of injection and recovery in the 100-m reservoir thickness case, the production has continued to increase after about 6 years. Combined with the gas production curve of the 300-m reservoir that possesses the optimal CO_2 production, the smaller thickness of the reservoir is more favorable for short-term CPG projects. In contrast, larger thickness reservoirs require more sustained investment and development time and may eventually pay off more abundantly.

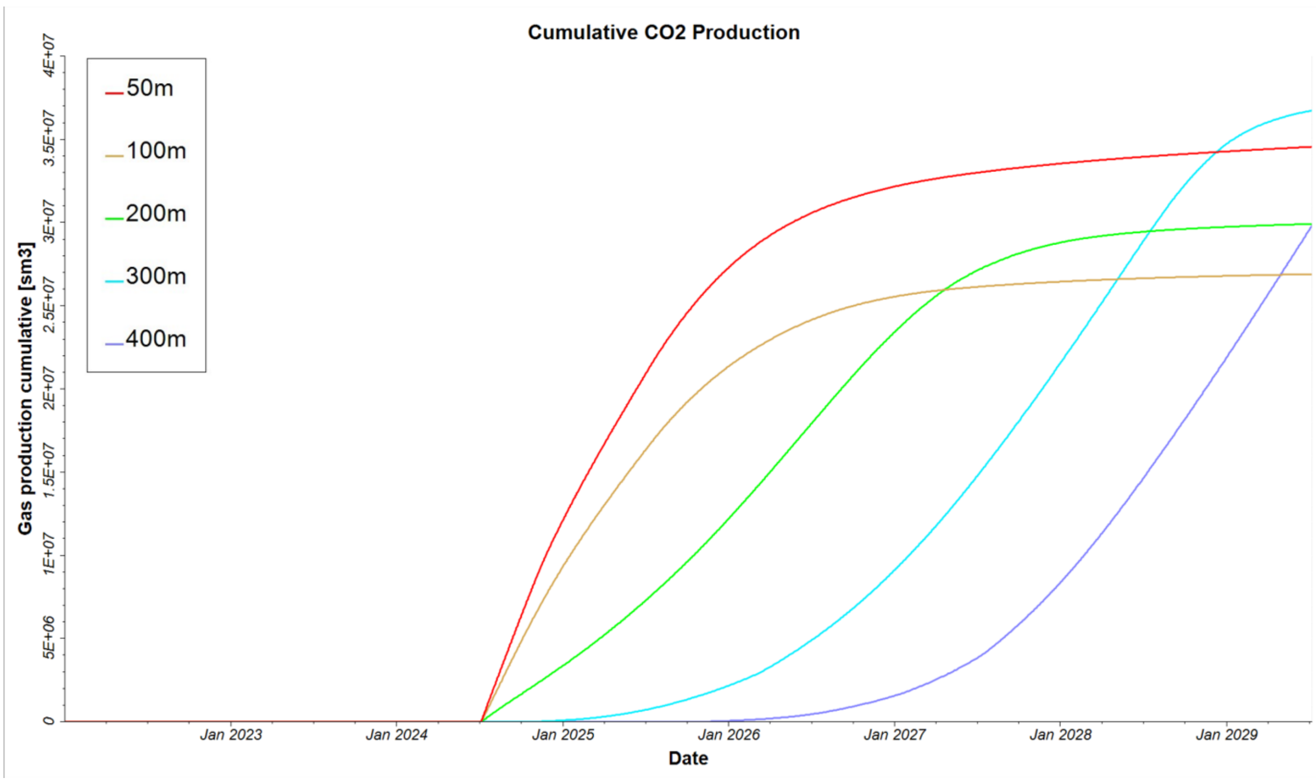

Figure 3: Cumulative CO_2 production for given various thicknesses of the reservoir.

3.2 Permeability anisotropy has impact on CO_2 production

Several studies (Feng, et al., 2013; Wei et al., 2015) have shown that high permeability reservoirs benefit from excellent percolation rates, which greatly enhance heat extraction. Our study showed that for the given reservoir thickness of 400 m, a high permeability was favorable to ensure production of CO_2 (**Fig. 4**). However, when we evaluated these permeabilities for different kv/kh ratios, we found that the cumulative CO_2 production for the 50 mD case was much higher than the other cases if the kv/kh ratio was 1 (**Fig. 5**). This implies that there exists a combination of permeability and kv/kh ratio that maximizes the cumulative CO_2 yield. Larger permeability reservoirs would be better for CPG if they have small kv/kh ratios while lower permeability reservoirs would benefit from having large kv/kh ratios.

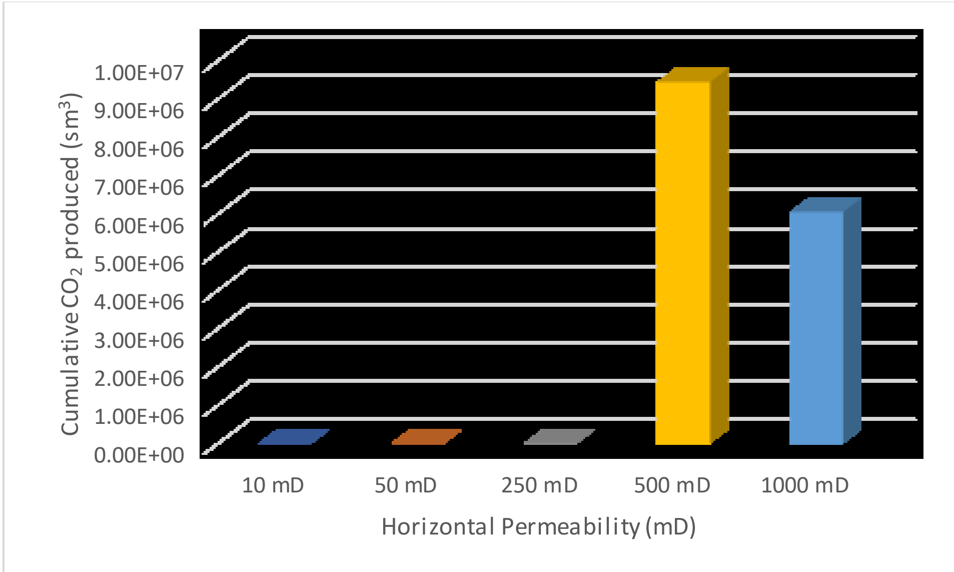

Figure 4: Cumulative CO_2 production over 4 years for given various horizontal permeability.

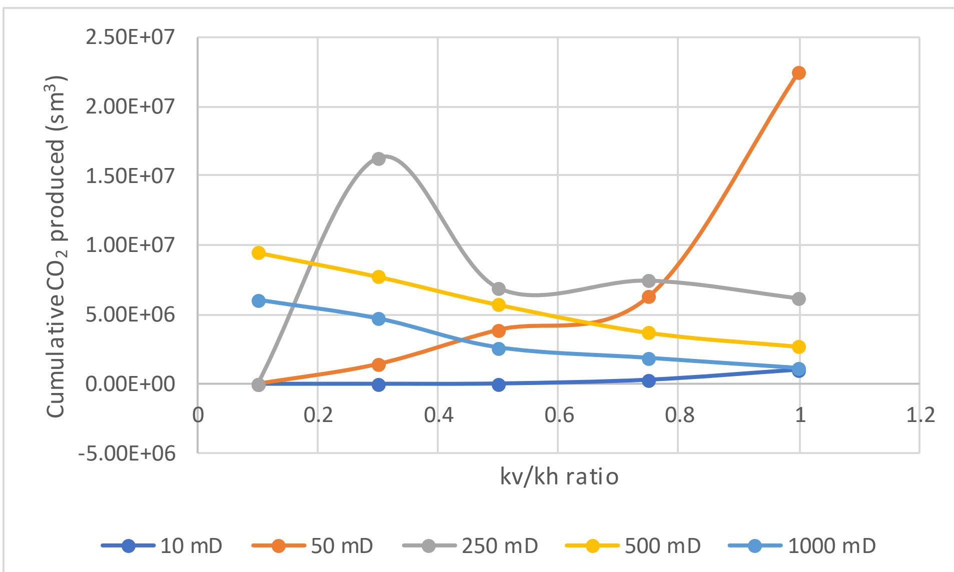

Figure 5: Cumulative CO_2 production over 4 years for different permeability anisotropy (kv/kh) ratios.

3.3 Changes in heat capacity do not significantly affect cumulative CO_2 production

Regarding thermophysical parameters, we focused on the heat capacity's influence on heat extraction. Based on the base case (1 kJ/kg/K), we added two new cases: 1.5 kJ/kg/K and 2 kJ/kg/K. The most intuitive impression given by **Figure 6** is that as the heat capacity increases, CO_2 production yields. However, we observed that the rate of change is only between 10^3 and 10^4. Recalling the sensitivity on kv/kh ratio, there were values in the range of 10^7. This indicates that if a reservoir has a large heat capacity, more CO_2 can be extracted but this is not a significant parameter compared to other geological factors.

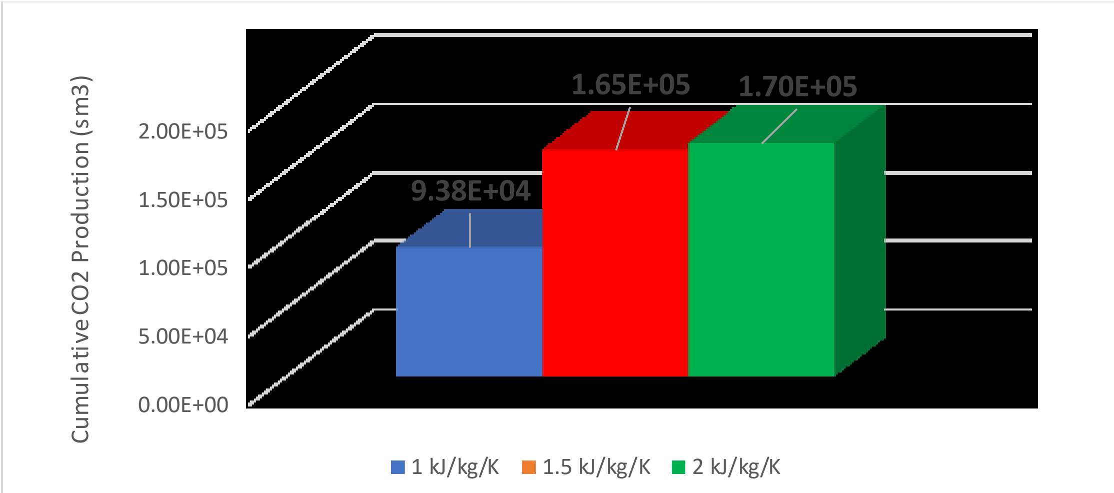

Figure 6: Cumulative CO_2 production over 4 years for given various heat capacities.

3.4 CO_2 production is highly dependent on the magnitude and direction of the dip angle

Considering the influence of the geological structure on the system, three cases are given at -2°, 10°, and 15° with a base case at dip of 0°. As in **Figure 7** we observed that the larger the dip, the less gas produced. It is also noteworthy that when the inclination angle is 15°, there is minimal CO_2 production within 7.5 years. Observing the trajectory of the CO_2 plume in the Dip-15° case (**Fig. 8**), the gas goes from the injection well, diagonally to the top of the reservoir without passing the production well. This phenomenon indicates that the direction of CO_2 plume migration depends on the dip path rather than vertical movement at all times. Therefore, the dip is also a very important success factor, and proper well placement strategies should be considered to maximize CO_2 extraction from dipping reservoirs.

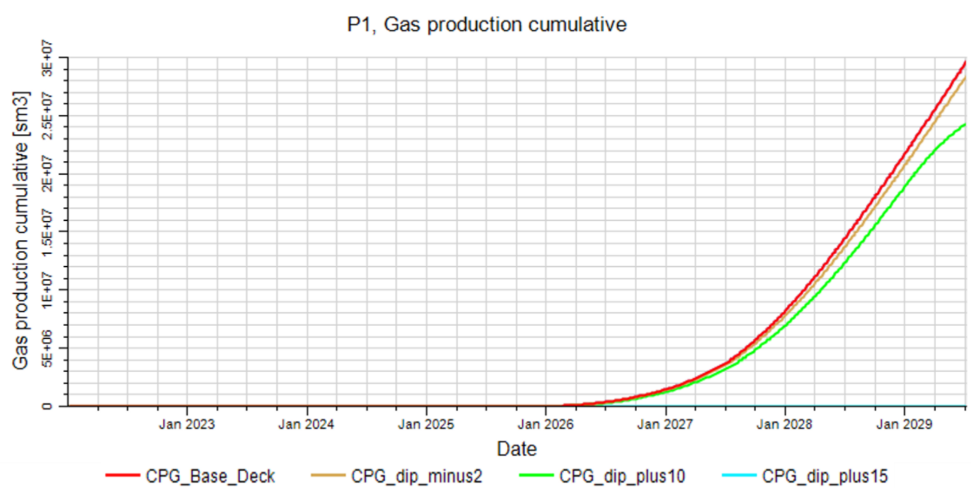

Figure 7: Cumulative CO_2 production over 7 years for given various dips.

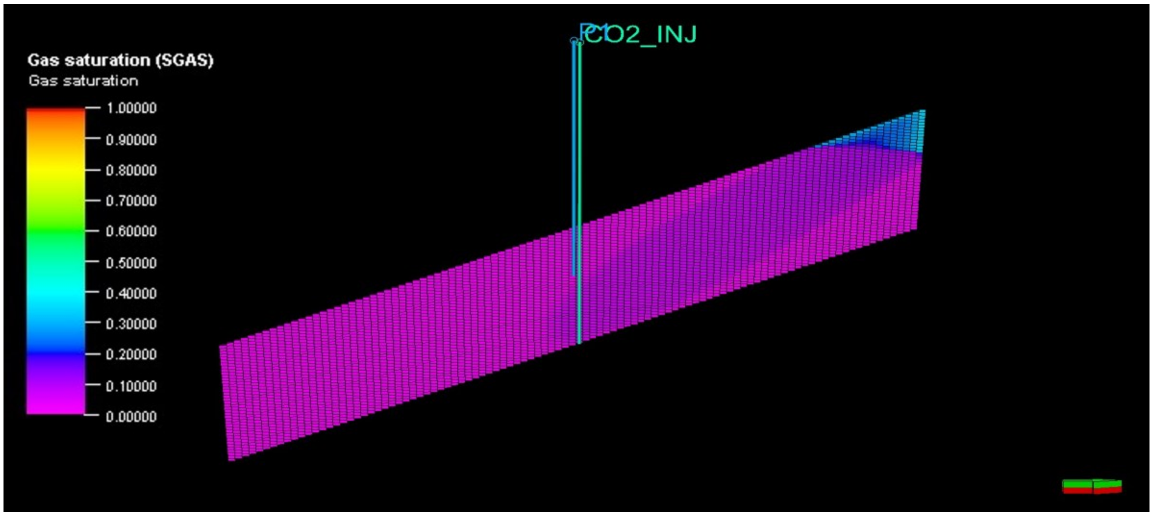

Figure 8: Final timestep of CO_2 plume migration at dip of 15°

4. CONCLUSIONS

This paper examines various sensitivity tests to find the cumulative CO_2 production for thickness, horizontal permeability, kv/kh ratio, heat capacity and reservoir dip. Based on the findings, key success factors have been determined.

Small-thickness reservoirs are suitable for short-term geothermal reservoir investment projects. The advantage is that the initial CO_2 production growth rate is fast, and the growth rate can still be reasonable at the end. In contrast, large-thickness reservoirs expect sufficient development time and stable investment, and despite the insignificant initial CO_2 growth rate, the potential for exploitable final production is huge.

Reservoirs with horizontal permeabilities in the range of 50 mD to 250 mD are suitable for CPG. Excessively larger permeability lead to accelerated migration of CO_2 away from the production well. To minimize this migration, large permeability reservoirs with low kv/kh ratios should be considered. Reservoirs with small permeabilities (such as 10 mD) may not be ranked high, unless it is know that they have high kv/kh ratios that limit lateral migration of CO_2 but support upward migration of CO_2.

We determined that the heat capacity of the rock was not a significant parameter impacting the cumulative CO_2 that could be extracted for a CPG project.

The dip determines the migration direction of the CO_2 plume and the cumulative production. The greater the dip magnitude, the lower the cumulative CO_2 produced if the well is placed at the center of the reservoir. Because the gas moves along the dip path rather than the vertical direction, care should be taken in well placement when selecting steeply dipping sites.

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