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A study on the possibility of mineral formation in CO_2 geothermal power generation using THC simulation

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INTRODUCTION

CO_2-EGS has been proposed as a novel concept of geothermal power generation. The system utilizes CO_2 instead of water as heat transfer fluid. Its potential advantages include greater heat extraction efficiency compared to water and the storage of unrecovered CO_2 in underground geological formations. Although many researchers have investigated this concept, its implementation has not yet been realized. When CO_2-EGS is implemented in Japan, injecting CO_2 into geothermal reservoirs containing water (i.e., hydrothermal reservoirs) would be expected due to high precipitation conditions. CO_2-plume geothermal (CPG) has been investigated by Randolph and Saar (2011), focusing on sedimentary layers saturated with water at lower temperature ranges (~120 °C) than geothermal reservoirs (~250). Generally, it is considered that the mineral reactions will vary significantly with reservoir temperature and pressure, potentially could cause formation of mineral shells due to geochemical reactions. However, studies on the possibility of mineral formation in CO_2 geothermal power generation have not yet been conducted enough. In this study, THC numerical simulations were performed to investigate mineral formation and heat extraction efficiency, in case where CO_2 is injected as a heat transfer fluid into a geothermal reservoir composed of volcanic rocks saturated with water.

1 METHOD

1.1 Numerical model

We have created a three-dimensional model assuming a geothermal reservoir that exists underground in a volcanic area in Japan. A schematic diagram of the reservoir used in this study is shown in Figure 1-a, while a bird's-eye view of the model is shown in Figure 1-b. Here we assumed a reservoir of which the size is 8500 m long, 8000 m wide and 500 m thick. As for the wells, assuming an initial stage of a project, two conditions were set that there should be one injection well (CO_2 injector) and one/three production wells (heated CO_2 producer). The location of the injection well was set in the center of the reservoir (horizontal plane) in a section of 100 m from the lower edge of the reservoir. The location of the production well is 100 m from the upper edge of the reservoir with a horizontal separation of 500 m from the injection well. The modeling region in this analysis was set to half of the reservoir area shown by the dashed green line in Fig. 1-a from the flow symmetry in the reservoir. The side boundary of the model was set as an open boundary, which allows CO_2, partially unrecovered in the production well, to flow out of the model. Under these conditions, the CO_2 recovery rate in the production well was calculated. For the analysis, we used an in-house program (Yamamoto et al., 2017) that was parallelized TOUGHREACT V2.0 with MPI and compatible with the ECO2N V2.0 module, which can take CO_2 at high temperatures and pressures into consideration.

1.2 Reservoir condition and geochemical condition

The basic reservoir physical properties in this study were set with reference to Pruess (2006). The initial pressure of the reservoir is 10 MPa, and the temperature is respectively 150 °C and 190 °C at the upper and lower edges of the reservoir. It is considered that the existence of a complete hot dry rock at a depth of 1000 m in a volcanic area in Japan is unlikely due to the weather conditions with high precipitation and geological conditions such as many natural cracks. In other words, the pores of the reservoir would be initially saturated with water (hot water). In this study, the double porosity model was applied considering that the reservoir is a fractured medium. In addition, considered also was the decrease in permeability when the porosity decreases due to mineral precipitation (cubic rule).

For the reservoir rocks, andesite which is often observed as a rock that constitutes a geothermal reservoir in Japan is assumed. The proportion of primary and secondary minerals were set with reference to Utomo (2021).

As geochemical database, Thermoddem (BRGM, 2020) was used basically. Note that some minerals were given non-equilibrium conditions based on USGS data (Palandri, 2004). Numerical simulations were conducted for two cases: one with a single, and the other with three production wells arranged to encircle an injection well. In each case, both the thermal-hydraulic-chemical calculation (THC simulation which considers geochemical reactions) and thermal-hydraulic calculation (TH simulation which doesn't consider geochemical reactions) were performed, highlighting the effect of chemical reactions on the results.

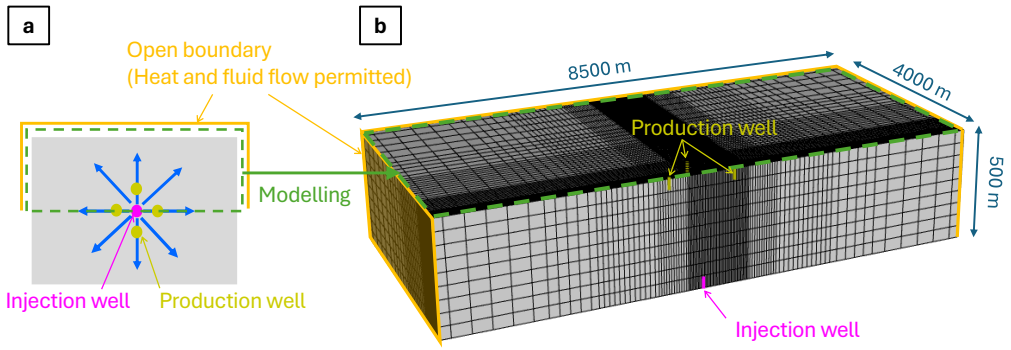


Figure 1. 3-D reservoir model used in this study: a schematic diagram; b bird's-eye view

2 RESULTS

As an example of results of three production wells case, Figure 2 shows some contours (CO_2 saturation, temperature, volume fraction of calcite, permeability and pH) created for the fracture grids two years after the commencement of the CO_2 injection. It is clearly seen from these contours that the injected CO_2 quickly

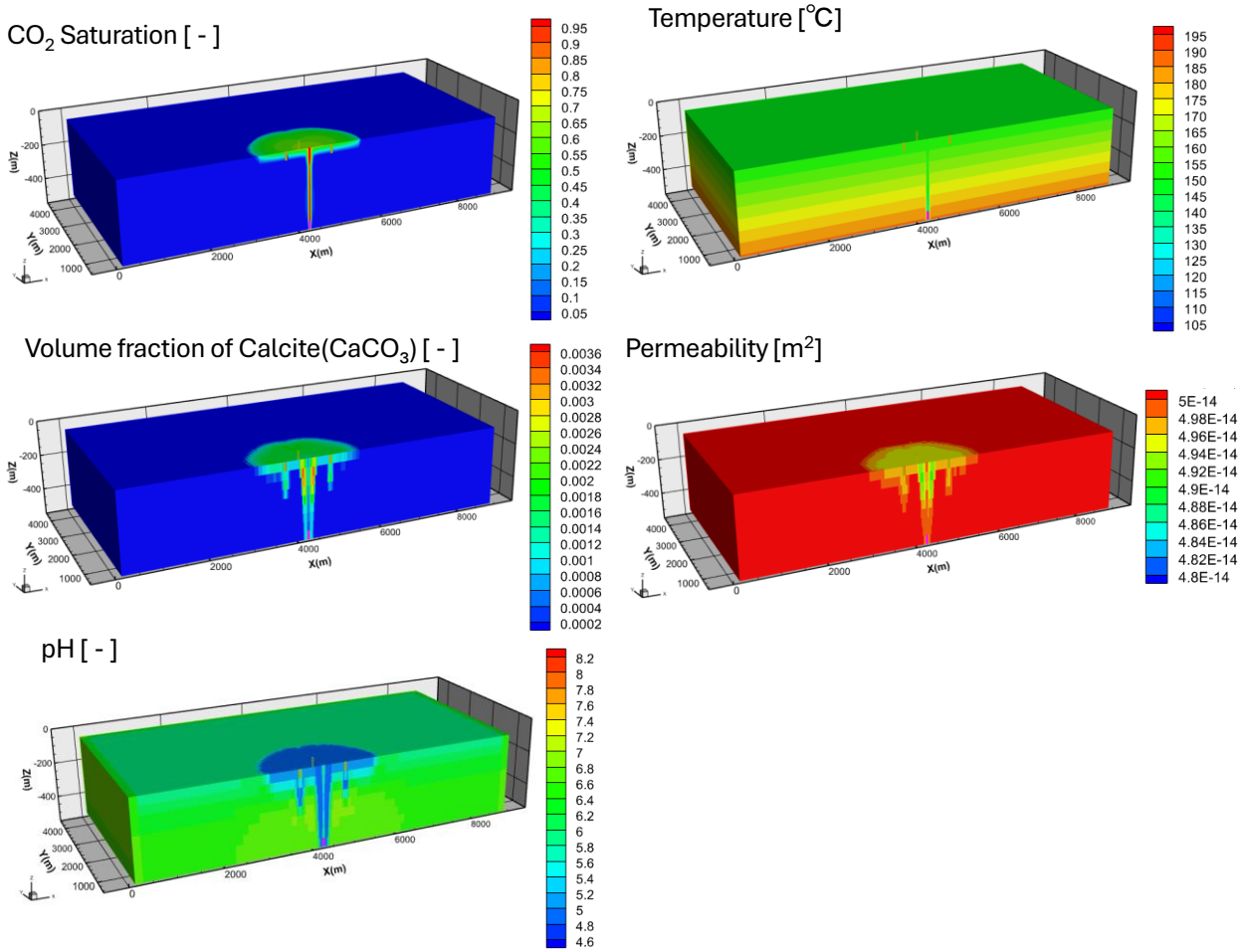


Figure 2. Contours of CO_2 saturation, temperature, volume fraction of calcite, permeability, and pH in the fractured zone two years after the commencement of CO_2 injection (three-production wells).

migrated vertically upwards due to buoyancy, and that it then migrated horizontally after reaching the top of the reservoir. The temperature of the CO_2 plume at the production wells became similar to that of the upper side of the reservoir when the CO_2 plume migrated upwards in the reservoir, even though the temperature at the CO_2 injection point was high (lower side of the reservoir). Regarding mineral reaction, precipitation of the calcite and permeability decrease occurred along the CO_2 plume. It was shown in this study that more mineral precipitation occurred at the upper side than lower side of the reservoir.

Fig. 3 shows the time series change in mass flow rate in a production well when multiple production wells are arranged. The solid lines in the figure show the change in the mass flow rate of water, CO_2, and the sum of water and CO_2 with THC simulation. The dashed lines show those with TH simulation. From this figure, it was confirmed that the proportion of CO_2 in the production fluid increased significantly about 0.5 years after CO_2 injection start, and the recovery rate of injected CO_2 at the production well achieved approximate 70% (approx. 30% when water was injected from other study).

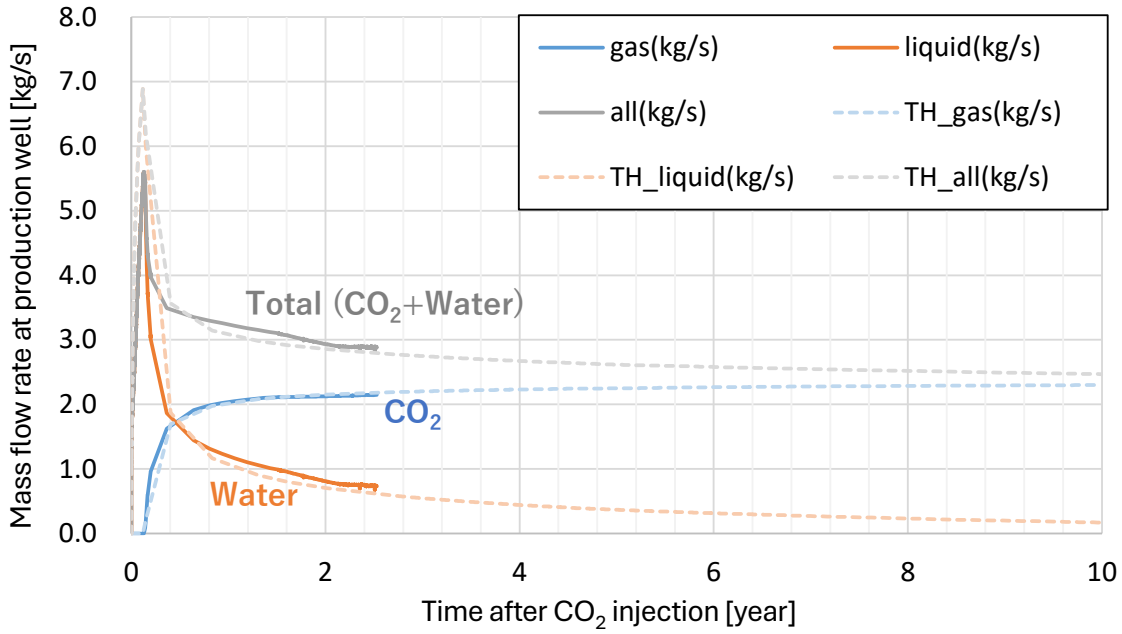


Figure 3. Time series change in mass flow rate of CO_2, water and sum of them at three production wells. Solid lines show the results from a THC simulation whereas dotted lines show the results from a TH simulation (non-consideration of geochemical reaction).

3 DISCUSSION

As mentioned above, it was found that the injected CO_2 into the reservoir rapidly migrated upwards by buoyancy, and then flowed laterally. In addition, it was confirmed that more mineral precipitation such as carbonates occurs in the upper side of the reservoir at relatively low temperatures. Here, this study hypothecates that there is a cap-lock layer above the reservoir. If mafic rocks exist as caprock formations in volcanic areas, it is thought that some of the CO_2 migrated upwards in the reservoir could increase the CO_2 concentration in the water in the caprock layer. As a result, geochemical reactions with the mafic rocks could occur in the caprock layer under not so high temperature, which would lower permeability due to mineral precipitations such as calcite. Similarly, in the horizontal direction within the reservoir, more mineral precipitation could occur in the transition region from the high to the low temperature. From the discussion above, the injection of CO_2 into a reservoir composed of igneous rocks in a volcanic area may result in a region of lowered permeability due to mineral precipitation both in cap-lock located upper-side and also in the horizontal direction of the reservoir. Thus, the recovery rate of injected CO_2 could be improved by forming a region of lowered permeability like a shell surrounding the high-temperature area.

On the other hand, the simulation results revealed that the CO_2 temperature in the production well is not as high as that at the lower side of the reservoir. This suggests that CO_2 temperature in the production well is limited at low temperature at the upper side of the reservoir. This result also indicates that when determining the depth range for reservoir formation in CO_2 geothermal power generation, the temperature of the production fluid may be constrained by the temperature at the depth the production well will be set up, rather than by the temperature at the injection depth.

In the fractures near the injection well, the increase in CO_2 saturation progressed faster than the decrease in temperature. It is therefore thought that the fractures are almost saturated with CO_2 at the low temperature stage when more mineral precipitation would occur. In other words, for the case of andesite, which does not have a fast reaction rate, decrease in permeability due to precipitation of carbonate wouldn't occur in the fractures near the injection well, rather minerals mainly precipitate in the matrix part. This is indicated in the results of this study, in which there was no significant difference in the flow rate of CO_2 in the production well up to two years after the start of injection, whether or not considering the geochemical reaction.

4 CONCLUSION

Applying CO_2-EGS as a new geothermal power generation system that uses CO_2 as a heat medium instead of water in Japan, we investigated the possibility of mineral formation and the heat harvesting efficiency when CO_2 is injected into a geothermal reservoir composed of water-saturated andesite by thermal-hydraulic-chemical (THC) coupled numerical simulation. It was revealed that CO_2 injected into the reservoir quickly migrates upwards in the reservoir due to buoyancy and then migrates in the lateral direction. Since mineral precipitation occurred along CO_2 plume in the upper side of the reservoir at a lower temperature than at the injection point, it may be thought to contribute to the decrease in permeability of the cap-lock layer (*e.g.*, like self-sealing). On the other hand, it was found that the CO_2 temperature at the production well is limited by the upper side of the reservoir and that it is not as high as the temperature at the injection point. Furthermore, the simulation results reveal that the increase in CO_2 saturation in the fractures near the injection well progressed faster than the decrease in temperature. This means that the fractures are almost saturated with CO_2 at the low temperature stage when minerals precipitate actively, so that clogging due to mineral precipitation is unlikely to occur.

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