Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Reinjection of CO2 into Geothermal Fields

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Key words: Carbon dioxide, NCG injection, carbon capture, geothermal.

ABSTRACT

In this study, reinjection of NCGs (non-condensable gases) released from geothermal plants was investigated. NCGs are formed mainly from CO_2 (>%98), so we will call NCGs as CO_2 from now on. The purpose of this study is to protect the environment, prevent geothermal plants from being subject to the carbon tax, and from providing them from taking a share from the carbon reduction revenues. These goals will be achieved by injecting CO_2 into the geothermal reservoir with reinjected water. Furthermore, it was observed that the productivity of the wells would be reduced with a decrease in the partial pressure of CO_2 in the reservoir for fields emitting CO_2, even if the reservoir pressure and temperature is stable. Thus, the reinjection of CO_2 into the geothermal reservoirs will make a major contribution to sustainable production as well as environmental protection. Here, unlike many carbon capture projects, CO_2 is not injected into the reservoir in the gas phase, but after being dissolved in the reinjected water. In the study, CO_2 released into the atmosphere from the geothermal plant is compressed up to a value above the dissolution pressure via a compressor and is injected with water into the injection well. As a study case, the wells of the 11.7 MW binary power plant Dora-II were examined in the case of CO_2 reinjection into the reservoir by using TOUGH2 modelling.

The elevated pressures in the injection wells increase the operating costs of the pump and the compressor. Therefore, it was concluded that the complete dissolution of CO_2 is the optimum solution to decrease the operating cost and reinjection pressure.

In the case of implementing the method mentioned in geothermal fields, the geothermal plants emitting carbon dioxide will take carbon reduction revenue and not pay a carbon tax. Furthermore, since partial pressure of carbon dioxide remained stable, it will be possible to generate much more energy in the field by preventing the reduction of productivity of wells.

1. INTRODUCTION

CO_2 in the geothermal systems may originate from volcanic activities or thermal degradation of carbonate rocks followed by heating. A carbonate rock (XCO_3) is thermally degraded and decomposed into $XO_{(k)}$ and $CO_{2(g)}$ by heating (1). Then, CO_2 dissolves into the geothermal fluid under pressure.

$$XCO_{3\,(s)} \xrightarrow{\text{heat}} XO_{(s)} + CO_{2\,(g)} \tag{1}$$

Hoşgörmez and Özcan (2915) revealed that the origin of the CO_2, in the Middle Anatolian, Turkey, is thermogenic decarbonization of limestones. Due to low density, CO_2 rises to the surface, it is emitted from faults and soil naturally, and a part of it dissolves into groundwaters. A study (Aksoy, et al., 2015) performed in a geothermal field located in Menderes Metamorphics, showed that the natural emissions from the field were 11 g/m^2.day. This field's area was 25 km^2, and the total natural emissions were about 11.4 t/h CO_2, which is equal to the carbon dioxide emission of 20 MW coal-fired power plants.

CO_2 is found as ions in the water of the geothermal reservoir. However, the concentration of dissolved CO_2 decreases towards the surface because of the hydrostatic pressure of water. Where the pressure reaches the flashing point, CO_2 bubbles occur, these expand and as a result, the density of the fluid decreases. CO_2 runs as if it is a gas-lift pump and provides more production from wells. And then, CO_2 moves with steam. After condensing steam, both binary and steam turbine plants release CO_2 to the atmosphere. When recycled, CO_2 -poor water is reinjected into the geothermal reservoir, CO_2 content in the reservoir starts to decrease. Finally, production wells are affected, and this leads to a decline in production.

CO_2 reductions have been realized in many geothermal fields. Armannsson et al. (2005) divided geothermal power plants into nine categories. Only 3% of the 6648 MW total capacity power plants had CO_2 emission over 500 g/kWh. But the most important result of their study was the CO_2 decrease in the Larderello (Italy) field, which has been operated to produce electricity for over one hundred years. The study concluded that the difference between the gas discharge resulting from the power production and the gas released naturally was insignificant. Another study (ESMAP, 2016) reported that during the production of six geothermal power plants in Iceland, the emission of CO_2 dropped from 375 to 50 g/kWh. A similar result of a study conducted at a power plant in Turkey with a capacity of 45 MW revealed the drop in CO_2 emission from 55 to 40 tons/h, after five years of electricity production (Pluto, 2016).

Geothermal fields in Turkey contains a high level of CO_2. CO_2 content released per electricity generation is 2-3 times higher than the coal-fired thermal power plants (Aksoy, 2014). Thus, this is a drawback of electricity production from geothermal energy that is accepted as clean and environmentally friendly until recently. In case of full implementation of the Kyoto Protocol; geothermal plants are going to be subjected to the carbon tax.

Fortunately, with the realization of the research presented here, no carbon tax will be paid, and even a share could be taken from the carbon reduction tax. On the other hand, CO_2 emissions in geothermal power plants are the result of a natural phenomenon, and it is argued if it should be included in the carbon inventory or not. For example, Italy (Ármannsson, 2003) decided not to consider CO_2 emission from geothermal plants as anthropogenic and did not include it in their inventory of anthropogenic airborne material.

In this study, the effect of the CO_2 is investigated by the TOUGH2 simulator for two cases: CO_2 is *i)* dissolved into reinjected water, *ii)* emitted to the atmosphere. For this study, we used the data of the Dora-II geothermal power plant.

2. SOLUBILITY OF CO_2 IN GEOTHERMAL FLUIDS

Salinity, pressure, and temperature variations are of great importance for this dissolution event to happen. According to Henry's law, more pressure should be applied in order to dissolve more CO_2 into the fluid. However, gas solubility is also a function of temperature and salinity, and less CO_2 dissolves in the fluid as a result of an increment in temperature and salinity.

Studies of Ellis and Golding (1963), Sutton (1976), Bowers and Helgeson (1983), Duan et al. (1992), Duan and Sun (2003), Spycher et al. (2003), and Duan et al. (2006) were analyzed for CO_2 solubility. Among these studies, CO_2 solubility decreased in saline solutions with 5000 ppm NaCl when its concentration is 1.3%, based on Ellis and Golding (1963), Duan et al. (1992), Duan and Sun (2003), and Duan et al. (2006) equations.

Figure 1 represents the temperature - partial pressure graph of 5000 ppm NaCl and 1.3% CO_2, representing the Dora-II geothermal waters obtained from the geothermal power plant with a capacity of 11.7 MW. Considering that the temperature of the injected water is 70 °C, the pressure required to dissolve all the produced carbon dioxide in the injected fluid will be between 20-22 bar.

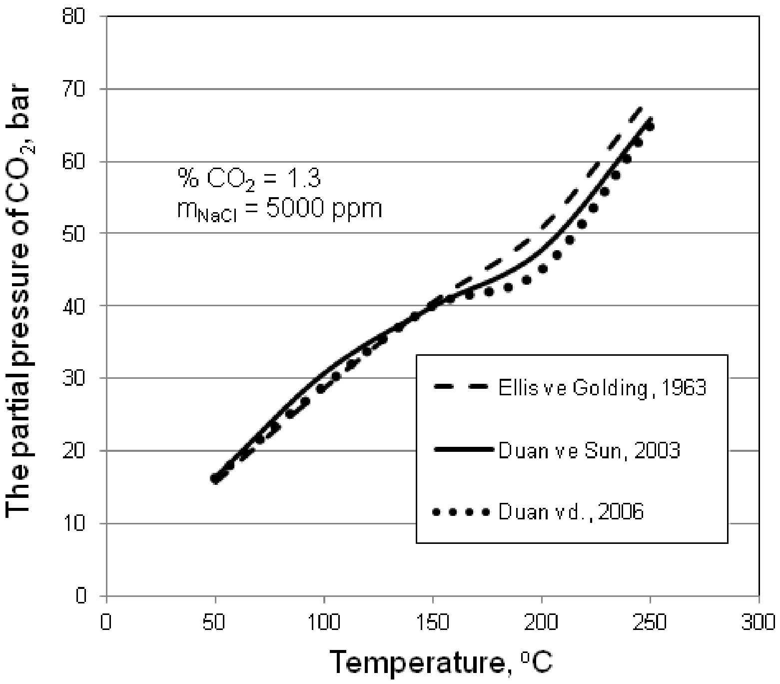

Figure 1: CO_2 solubility of geothermal fluids.

The Aydin-Salavatli geothermal field was used as a base for the comparison. Temperature and partial pressure of CO_2 were calculated for the amount of CO_2 to be dissolved by using salinity, and ionic strength values of the water monitored at this field (Figure 1). It is observed that curves are close to each other at temperatures below 150ºC in the studies performed by Ellis and Golding (1963), Duan and Sun (2003), and Duan et al. (2006). On the other hand, at temperatures above 150ºC, it can be seen from the curve given in Duan et al. (2006) that more is dissolved than the values reported in the Ellis and Golding (1963) study. The reinjection temperature for geothermal projects is usually below 150ºC. Therefore, any of these equations could be used for the calculations. The equation of Ellis and Golding (1963) was preferred for CO_2 solubility due to ease of use.

2.1 Dissolution Kinetics of CO_2 in Geothermal Fluids

It is also important to know how long it takes for carbon dioxide to dissolve in water. If the dissolution process requires a long period of time, the fluid will flow into a two-phase state in the well and also will enter the reservoir as a two-phase fluid. If the dissolution process occurs at the surface, and the fluid enters the well into the two-phase state, it needs to be converted into a single-phase fluid at the reservoir inlet. Reactions occurring during dissolution are expressed as follows.

$$CO_{2(g)} \leftrightarrow CO_{2(aq)} \quad (2)$$

$$CO_{2(aq)} + H_2O \leftrightarrow H_2CO_3 \quad (3)$$

The reaction rate constant is a parameter that changes depending on the temperature. Therefore, the reaction rate constant at an appropriate temperature can be calculated by using the Arrhenius equation (4). "E_a" and "R" in equation 4 are activation energy and gas constant, respectively. The activation energy value reported in the literature is 55 kJ/mol (Crittenden et al., 2012).

$$k_{80} = k_{25}\exp\left(-\frac{E_a}{R}\left(\frac{1}{353.15} - \frac{1}{298.15}\right)\right) \quad (4)$$

The rate constant "k" is found to be 1.37 since the reinjection water temperature at the field sampled in the project is 80˚C. Solubility half-life variations of CO_2 of carbon dioxide dissolution in the water at different temperatures are given in Figure 2. In here, $k_{0^\circ C}$ and $k_{25^\circ C}$ were obtained from the literature (Zhang, 2008), and $k_{60^\circ C}$, and $k_{80^\circ C}$ from Equation 4. It can be seen that 99% of carbon dioxide hydration occurs within 0.0073 seconds. It follows from this that the dissolution of CO_2 in water takes place almost instantly, and the mixture flows as a single-phase (liquid) entering the well. It also enters the reservoir in a single-phase as long as the dissolution pressure is exceeded. This also shows that this is a useful and feasible study as a process.

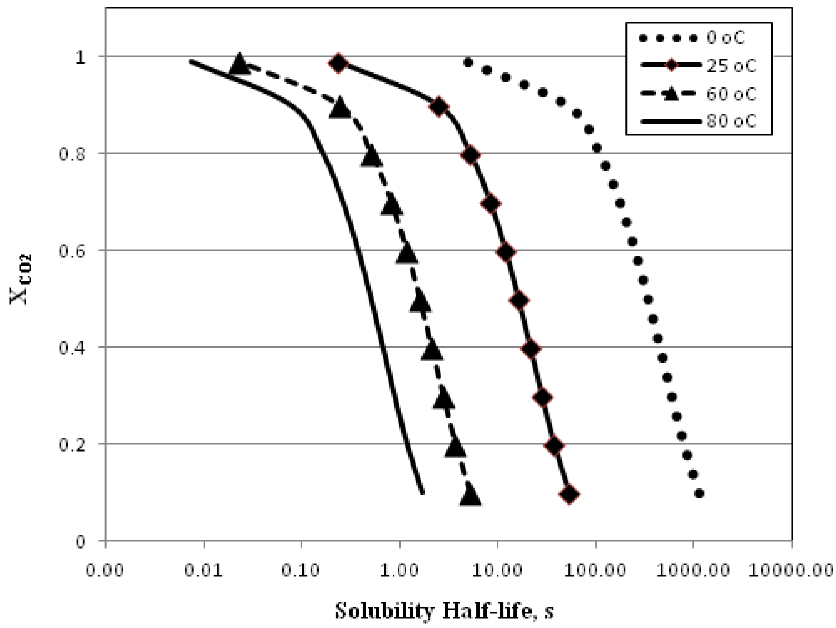

Figure 2: Solubility half-life of CO_2.

2.2. pH-CO2 Relationship for Geothermal Fluids

CO_2 is a gas that dissolves easily in water, while carbonates in the form of HCO_3^-, CO_3^{-2}, H_2CO_3 are formed as a result of the reaction between water and CO_2 (Eq. 5-7).

$$H_2O + CO_2 \leftrightarrow H_2CO_3 \quad (5)$$

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad (6)$$

$$HCO_3^- \leftrightarrow CO_3^{-2} + H^+ \quad (7)$$

CO_3^{-2} ions in the Equation 7 may cause precipitation in the reservoir due to a combination with divalent cations (such as Mg^{+2}, Ca^{+2}, Fe^{+2}) present in the geothermal fluid and consequently forming carbonated solid compounds (such as magnesite, calcite, siderite). In case of precipitation of these solid compounds, this may cause a decrease in the permeability of the reinjection wells used in the projects intended for underground storage of CO_2 in geothermal fields, and consequently block them. Injection pressures and reinjection costs may increase as a result of a decrease in permeability of the reinjection wells. So, after a certain time, reinjection pressure starts to increase. The presented reactions will take place in which conditions should be investigated in order not to confront such a problem.

The ion type of carbonates dissolved in water will depend on the partial pressure of CO_2 (P_{CO2}) and pH of the fluid (Figure 3). Bicarbonate (HCO_3^-) ions become dominant for pH between 6-10, whereas carbonic acid (H_2CO_3) for pH<6, and carbonate (CO_3^{-2}) for pH>10. In Figure 3, it is seen that pH values of the reservoir fluid shift to the left as the temperature increases. In the projects realized on reinjection of CO_2 mixture within the geothermal fluid, carbonate present in the injected mixture should be in carbonic acid form and pH should be kept in the relevant interval in order to prevent mineral precipitations that could be formed with a combination of carbonate with divalent cations.

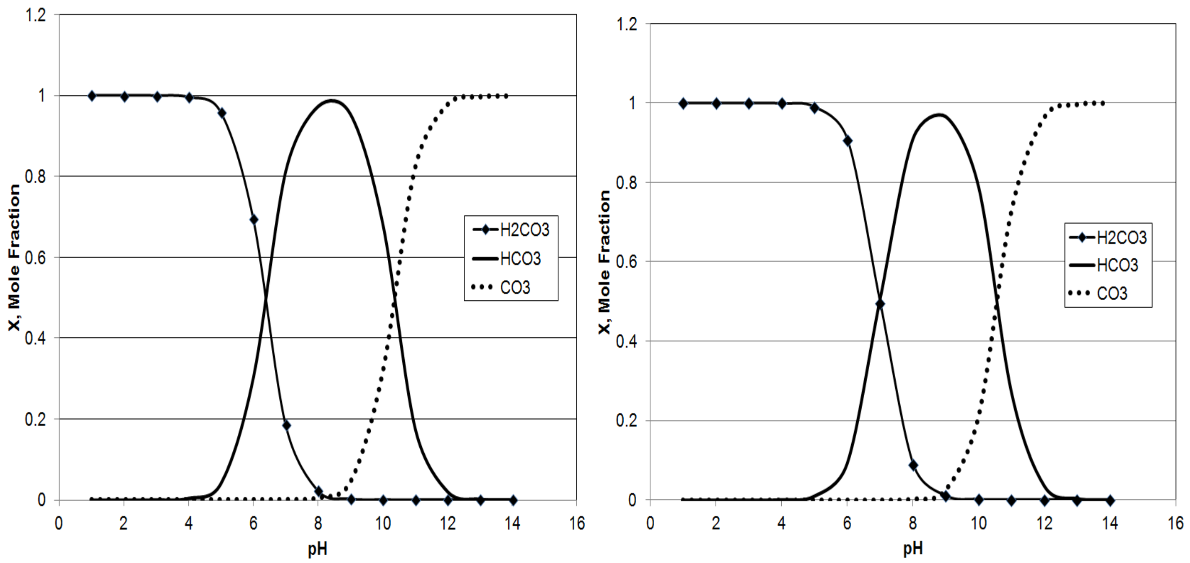

Figure 3: pH-CO_2 equilibrium (left and right charts demonstrate curves of the carbonate forms for 25°C and T>150°C, respectively).

3. CASE STUDY: REINJECTION OF CO_2 WITH GEOTHERMAL FLUID

The largest (in size and output) regional heat flow in Turkey is found in the Menderes Metamorphic Massif (Serpen and Mıhcakan, 1999). Several recent grabens have been formed within the MMM, where all the geothermal fields are of medium-to-high enthalpy, with temperatures in the 120–240°C range. The thermal fluids are of alkaline-bicarbonate compositions, have high-CO_2 contents and show evidence of water-rock interactions and mixing with shallow waters (Ozgur and Pekdeger, 1995; Vengosh et al.,2002; Ozen et al., 2005). More than 40 geothermal power plants have been operated, which are a total capacity of near 1200 MW in the MMM. These power plants have high CO_2 emission varying between 0.4-1.3 CO_2 kg/MW (Aksoy, 2014; Aksoy et al., 2015).

In this study, as mentioned earlier, water and gas samples taken from the Dora-II plant wells of the Aydin-Salavatli geothermal field and its neighborhood were utilized for this study. Operating conditions of the Dora-II are shown in Figure 4. The power plant runs with the AS3 and AS4 named production wells; these wells' have temperatures of 171°C and 174°C, respectively. On the wellheads, steam-gas and brine are separated at 12.6 bar-g and sent to the heat exchanger of the power plants. At the outlet of the heat exchangers, the temperature of the condensate and brine is about 80°C. CO_2, leaving from the steam-gas mix, is directed to a commercial CO_2 factory to produce industrial liquid and dry-ice CO_2. In Figure 4, fluid coming out from the production wells (AS3 and AS4) separates into hot water and steam due to pressure drop in the separator. These separated phases are brought together at 170°C. Steam and brine are injected into the reinjection wells (ASR4 and ASR5) at 80°C after mixing with the fluid, while CO_2 taken from the plant with a flow rate of 9.8 t/h is sent to the CO_2 factory. Then, liquid CO_2 and dry-ice are produced for the industrial gas market. Zero-emission production is carried out in this plant by means of a CO_2 factory. There are no CO_2 factories in most geothermal plants in Turkey, since lower market capacity when comparing produced CO_2 from geothermal power plants. As a result, all geothermal power plants not selling their gas to CO_2 factories are directly releasing CO_2 into the atmosphere.

In this study, therefore, reinjection of 9.8 t/h CO_2 into the reservoir after dissolving into a fluid to be injected at a temperature of 80°C was investigated.

Sampled gases from AS3 and AS4 wells were analyzed using gas chromatography. This study found that 99% is CO_2 and the rest is H_2S (<1%) and rare amounts of hydrocarbon gases. The value of $\delta^{13}C$ in CO_2 is measured as 3.38-4.71 %. According to the graph presented by Hoefs (1997), the source of the CO_2 should be degradation of marine carbonates.

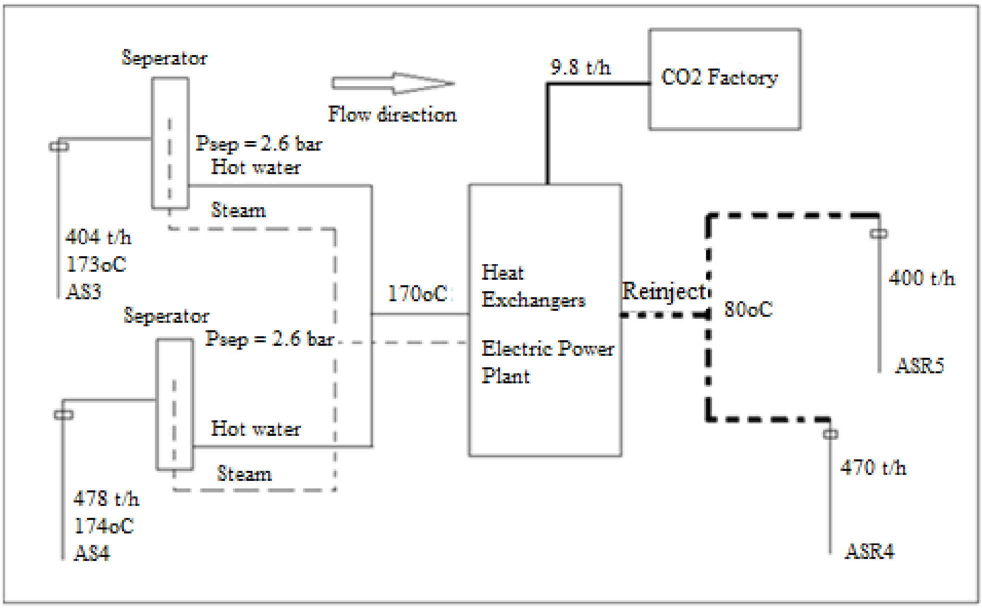

Figure 4: Operating conditions of the plant; flow rate, pressure and temperature values.

Variation of dissolution pressure and pH of the reinjection fluid at a temperature of 80°C in the Dora-II plant are given in Table 1 as a function of the injected amount of CO_2.

Table 1: Dissolution pressure (80°C, x_m = 0.056 M).

CO_2 amount in reinjected water, %	P_f, bar	pH
0.7	13.1	5.7
1.3	23.9	5.4
2.7	50.5	5.1

As seen in Table 1, dissolution pressure increases with an increase in the amount of CO_2 to be dissolved. The pressure of CO_2–water system should be kept at 13.1 bar and above when 0.7% of CO_2 is required to be dissolved. In case that all CO_2 produced in the plant is required to be injected, the CO_2/water ratio will be 1.3%, and the system pressure becomes 23.9 bar. If 2.7% of CO_2 is required to be dissolved in the fluid to be reinjected, the pressure that should be applied becomes at least 50.5 bar. The solution becomes more acidic as the amount of dissolved CO_2 increases. The pH of dissolved CO_2 fluid decreases to 5.4 for 1.3% and to 5.1 for 2.7% when pH is 5.7 for 0.7%. According to the pH values calculated, there is a low risk emerging that it may dissolve the carbonate rocks as the environment becomes more acidic. However, this situation does not pose any problem for the geothermal system.

The CO_2-water injection system designed for injection of CO_2 after dissolving in the fluid is presented in Figure 5. In this system, there is a pump at the right side according to the hot water and flow chart in the plant output (the reinjected water). The pressure is 10 bars, the temperature is 80°C, and the flow rate 870 t/h at the pump inlet while the flow rate changes depending on the amount of CO_2 in the fluid to be injected. The gas compressor shown in Figure 5 compresses CO_2 gas at 10 bars, 35°C, and with a flow rate of 9.8 tons up to the dissolution pressure. The compressed CO_2 and hot water are put into a mixer providing CO_2 mix homogeneously and, then, dissolve. The inlet temperature of CO_2 is 35°C, and this temperature increased with compression. Therefore, this causes a small amount of increase in temperature of the reinjected water.

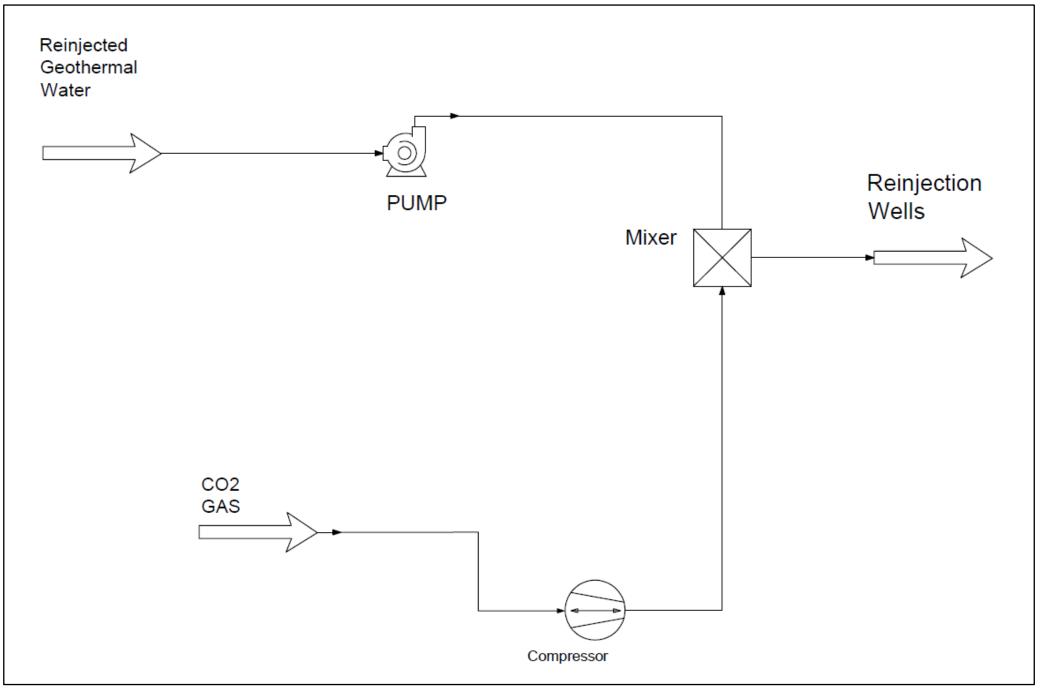

Figure 5: CO_2 injection system.

Pump efficiency and compressor efficiency values were assumed to be 0.8 and 0.75, respectively in the designed system. CO_2 is found in a pure gaseous phase and free from water vapor at the compressor inlet. Therefore, a slug catcher may be needed at the compressor inlet.

In case all CO_2 is dissolved in the injected fluid; all of CO_2 with a flow rate of 9,800 kg/h is dissolved into the fluid with a flow rate of 337 t/h and injected into the injection well. The plant outlet temperatures are 80°C and 110°C for the geothermal water and CO_2, respectively. The pressure needed for the dissolution of the whole CO_2 is 50.5 bars. Mixture temperature becomes 83.3°C following dissolution. This system requires a pump with a power of 545 kW in order to increase the pressure of 337 t/h hot water from 10 bars to 50.5 bars. Also, a compressor with a power 498 kW is needed to compress 9,800 kg/h CO_2 at a temperature of 35°C and a pressure of 10 bars to 50.5 bars.

As can be seen, CO_2 can dissolve in water; however, the compressor and pump powers should also be increased with an increase in CO_2 concentration, which is a problem that requires a solution.

4. INVESTIGATION OF BEHAVIOR OF THE GEOTHERMAL FLUID REINJECTED AFTER CO_2 DISSOLUTION IN THE RESERVOIR

The following scenarios were performed in order to investigate the reinjection behavior of the geothermal fluid after CO_2 dissolution in the reservoir.

Scenario I: The production in each production well is 100 kg/h. 1.1% of the CO_2 present in the produced fluid is released into the atmosphere. The fluid is reinjected at a temperature of 80°C. The produced fluid is injected with a CO_2 deficiency of 1.1%. There is 0.2% of CO_2 as dissolved in the injected fluid at the operating pressure (12.6 bars) of the separator.

Scenario II: Production is made as in Scenario I; however, all emerging CO_2 is injected to the reservoir after it is dissolved in the reinjected fluid. In Scenario II, the production and reinjection are equal in mass, and no CO_2 loss is available. Again, the rate of CO_2 in the injected water is found to be 1.3%.

With both scenarios, variations in partial pressure and concentration of CO_2 in the reservoir are calculated with Petrasim-Tough2 (Pruess et al., 1992) for a time interval of 50 years. Results are given in Figure 6.

In Figure 6, it is seen that there is an interesting difference in CO_2 partial pressure and concentration occurring in the reservoir depending on the scenarios. Under Scenario-I conditions which is the case where 1.1% of the produced 1.3% CO_2 is released to the atmosphere, CO_2 partial pressure and concentration rapidly decrease in the reservoir. The CO_2 concentration decreases from 1.3% to about 1% for the first nine years. This decrement continues in subsequent years and becomes 0.5% after 20 years and 0.35% after 40 years. Although CO_2 released into the atmosphere is negligible in mass and the reservoir pressure is maintained by reinjection, the release of CO_2 into the atmosphere causes a rapid decrease in the CO_2 concentration and the CO_2 partial pressure in the reservoir. This situation adversely affects production.

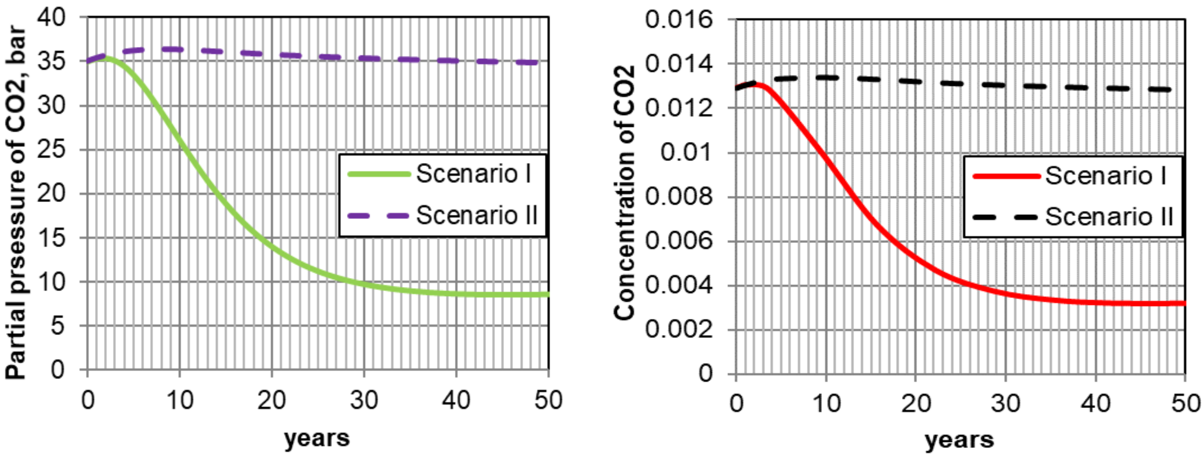

Figure 6: Under Scenario I and II conditions, variations in partial pressure and concentration of CO_2 in the reservoir.

5. CONCLUSIONS

Geothermal fields in Turkey contains a high level of CO_2. Dissolved CO_2 in geothermal fluids emerges as a by-product, and most of it is released into the atmosphere. Geothermal power plants sometimes releasing 2-3 times higher CO_2 concentrations than the coal-fired thermal power plants poses financial, technical, and social risks for the geothermal resources known as clean and environmentally friendly. Geothermal projects are expected to take part in carbon trading; however, the risk of carbon tax adversely affects the financial viability of projects. High CO_2 emissions are given by geothermal resources which are known as clean and environmentally friendly causes a decrease in public support for the geothermal projects.

In this study, reinjection of carbon dioxide released from geothermal plants into the geothermal system was investigated by dissolving in the reinjected water.

In this study, the Aydin-Salavatli geothermal field was taken as basis in order to explain the CO_2 solubility in the fluid under a certain temperature and pressure. All of the produced CO_2 was dissolved, and the water-CO_2 mixture was reinjected by utilizing water-gas and steam samples of this field. In this dissolution process, it was seen that there is no risk of mineral precipitation in the reinjection well and reservoir.

Furthermore, in the long term, CO_2 injection will make a greater contribution to total energy production. It will prevent the partial gas pressure drop, which will occur in time in the reservoir. It will be a useful and feasible practice to reinject the CO_2 produced from the geothermal systems to the geothermal system for a clean and environmentally friendly production. It is also a sustainable, steady production, and will produce much more energy production from the geothermal reservoir.

The model simulation carried-out in this study indicated that carbon dioxide in the reservoir decreased over time because the CO_2-depleted water was injected into the reservoir. As a result, CO_2 emissions also reduced. Armansson (2005), ESMAP (2016), Pluto (2016) are consistent with the observed results of the studies. Presumably, as the amount of CO_2 in the reservoir reduces, the natural CO_2 outflows in the geothermal fields will reduce, and the geothermal power plants will reach net negligible levels of CO_2 emissions.

CO_2 injection is highly effective on the economic feasibility of CO_2 projects. When full (100%) injection of the produced CO_2 is taken into account, the only way to keep the dissolution pressure at the lowest level is to dissolve CO_2 homogenously in the entire injected water. In addition to the contribution made by CO_2 injection by preventing a reduction in production, carbon revenues to be earned with the carbon fees in the voluntary market will also provide financial support to the investments and business. It may give support for the reduction of greenhouse gas emissions for which Turkey will be responsible via The Kyoto Protocol, and income may be supplied from this reduction trade.

As a result of the research and studies performed, it was concluded that the dissolution of the produced carbon dioxide into the reservoir is necessary. This is not only for environmental or financial concerns but also for sustainable production.

In order to determine the net CO_2 emissions caused by geothermal power generation, it would be useful for the above discussions to measure the natural CO_2 emission. From this, it could be found the net emission amount before and during commissioning and even after the power generation is completed in the geothermal fields.

ACKNOWLEDGEMENTS

This study was conducted with the support of Master Thesis by Graduate School of Natural and Applied Science of Dokuz Eylul University and TUBITAK with the project number 112M942. We would like to thank TUBITAK for the support.

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