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# Use of CO2 as Heat Transmission Fluid to Extract Geothermal Energy: Advantages and Disadvantages in Comparison with Water

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## ABSTRACT

Use of $CO_2$ as heat transmission fluid to extract geothermal energy is currently considered as a way to achieve $CO_2$ resource utilization and geological sequestration. As a novel heat transmission fluid, the thermophysical property of $CO_2$ is quite different from water. It has many advantages, such as larger mobility and buoyancy resulted from the lower density and viscosity. This will reduce the consumption of driving pressure of the circulation, and save the energy consumption of external equipment. The cycle even can be achieved by siphon phenomenon under a negative circulating pressure difference.

However, there are still some disadvantages for $CO_2$ as a kind of heat transmission fluid, such as small heat capacity, leading to carry less heat at the same mass flow rate. At the same time, if temperature and pressure change, it will cause a more complex flow and thermodynamic processes because of the lager expansion and compression coefficient for $CO_2$. Lager compressibility makes it possible to get high temperature at the bottom of the injection well, but lager expansion coefficient makes the temperature drops rapidly during the extraction process. Therefore, how to scientifically control the production pressure to guarantee the temperature at the head of production well to be high enough and then improve the efficiency of heat extraction is the key problem to be further studied and solved.

Here, a classic idealized "five-spot" model coupled with wellbores is set up according to the geological and geothermal conditions and parameters of the central depression of Songliao basin. Our purpose is to (1) explore the flow and thermodynamics process of supercritical CO2 as heat transmission fluid, analyze the heat recovery mechanism, (2) compare the heat extraction efficiency of CO2 with water, and evaluate the advantages and disadvantages using CO2, (3) optimize the temperature and pressure of injection and production and other parameters for CO2, and (4) determine the favorable range of temperature and pressure of geothermal reservoirs, and provide a theoretical basis for the selection of heat transmission fluid. Results from this work may be useful for future field design of a $CO_2$-geothermal system.

## 1. INTRODUCTION

The enhanced geothermal system (EGS) is defined as an engineered reservoir that has been created to extract economical amounts of heat from geothermal resources of low permeability and/or porosity (MIT, 2006). As part of an effort to reduce atmospheric emissions of carbon dioxide ($CO_2$), a novel concept of operating the EGS using $CO_2$ instead of water as the working fluid ($CO_2$-EGS) and achieving simultaneous geologic sequestration of $CO_2$ has been proposed and evaluated (Brown, 2000; Pruess, 2006).

In recent years, a similar concept, so-called the $CO_2$-plume geothermal (CPG) system, has been proposed (Randolph and Saar, 2011). The CPG system utilizes existing, naturally porous, high-permeability geologic formations (reservoirs) for geothermal energy recovery. The major benefit of the CPG system over the EGS is that the CPG system does not require hydro-fracturing, which helps increase fracture permeability but may induce seismicity. The EGS has encountered considerable unfavorable conditions and socio-political issues (resistances). Consequently, the CPG that can use the $CO_2$ sequestration site to recovery geothermal energy may be practical. In this paper, $CO_2$-based geothermal system can be referred for both the CPG and the $CO_2$-EGS.

Pruess (2006, 2008) performed fundamental numerical studies to evaluate the heat extraction performance of two fluids. He got the conclusion that under certain thermal conditions, the heat extraction rate of $CO_2$ can be 50% higher than water. $CO_2$ fluid flow in wellbore was considered under some restrictions, or the flow in wellbore was treated as isenthalpic flow. The heat exchange between wellbore and surrounding geological formation was not considered, Joule-Thomson effect in wellbore was noticed. It was concluded that the favorable properties for $CO_2$ are having (1) large expansibility, which would generate large density differences between injection and production wells, and provide buoyancy force and then reduce power consumption, (2) lower viscosity, would lead to a larger mass flow rate, and (3) lower reactivity, or, $CO_2$ is not likely to react with rock compare to water.

Atren et al. (2009) analyzed power generation from a doublet $CO_2$ geothermosiphon system without considering frictional effects, indicating that $CO_2$-EGS could generate similar amounts of power as a water-EGS but with simpler surface equipment. Atren et al. (2010) took frictional loss into account, and indicated that the $CO_2$-EGS would be less effective at energy extraction than a water-EGS for conditions used in past EGS trials. They also discussed the effects of diameter of well and permeability of reservoir, and concluded that $CO_2$ is superior to water in lower permeability reservoir and larger wellbore. The previous studies discussed were performed under many restrictions especially for the flow in wellbore. The properties of $CO_2$ make the processes in the wellbore totally different from those in the reservoir. The previous wellbore-decoupled model could not capture important features of the entire processes. Pan et al. (2014) developed a fully coupled wellbore-reservoir simulator called T2well, which is based on TOUGH2. The program considers the wellbore and reservoir as an integrated system. The program was used to study $CO_2$ and brine leakage along wellbore (Pan et al, 2011a; Hu et al, 2012). This coupled model is a significant advance for studies of $CO_2$

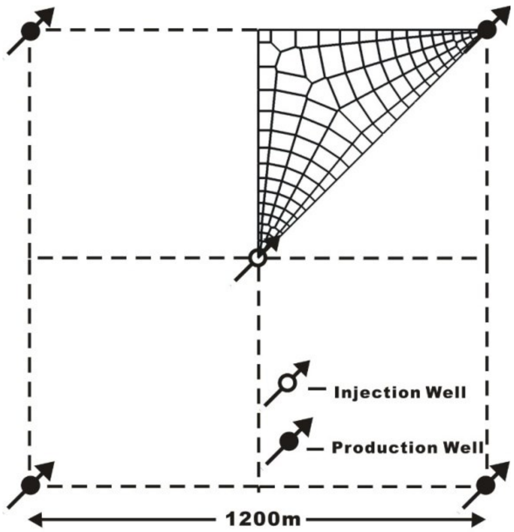
multiphase flow and thermodynamics in both wellbore and reservoir, and is a very useful tool for design and optimization of $CO_2$-based geothermal system.

In this work, we performed well-reservoir coupled simulation using T2well to (1) explore the fluid and thermal dynamics of supercritical $CO_2$ as heat transmission fluid in the circulation, and analyze the heat recovery mechanism, (2) compare the heat extraction efficiency of $CO_2$ with water, and evaluate the advantages and disadvantages using $CO_2$, and (3) optimize the temperature and pressure of injection and production and other parameters.

## 2. PROBLEM SETUP

### 2.1. Model Setup

A great deal of specific and detailed information will be required to assess the feasibility of injecting $CO_2$ as a heat transmission fluid at any particular site, and to develop engineering designs for $CO_2$-based geothermal systems. Before moving into site-specific investigations, general features and issues should be explored. This can be done by investigating deep brine systems that abstract site-specific features and thereby attempt to represent characteristics that are common to many such systems. Here, geological characteristics and physic-thermo conditions are mainly extracted from the central depression of Songliao Basin, Northeastern China. The basin has the highest geothermal gradient and heat flow among sedimentary basins in China (Hou et al., 2009), and can meet the temperature require for geothermal development. We treat the reservoir as a naturally porous media.



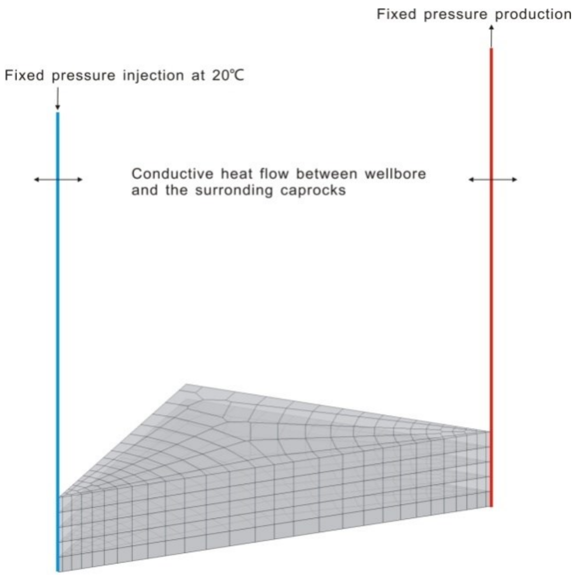




**Figure 1: Left: Overview of the five-spot well pattern with computational grid for modeling a 1/8 symmetry domain. Right: 3-D sketch of the model**

In this study, we built a 3-D, five-layer (vertically) 'five-spot' model to compare the behavior of $CO_2$-based with water- geothermal system. The symmetry of the five-spot well pattern allows to limit the model to a 1/8 symmetry domain, as shown in Figure 1, which reduce significantly computational burden. The wellbore is also considered as 1/8, perforating both wells open to all layers. The geological and thermo-physical conditions are extracted from the Songliao Basin site. The geothermal reservoir we considered is sandstone formation with 150m thickness. Two basic models were considered. For the first one, $CO_2$ is injected into a reservoir initially filled with $CO_2$ ($CO_2$-model). For the second model, water is injected into a reservoir initially filled with water (water-model). The initial conditions are the same for both, 36.7 MPa and 150C$^o$.

Normally the reservoir is initially filled with water. $CO_2$ injection into the reservoir displaces water, it will take quite long time to dry the formation out and to create a $CO_2$ reservoir. For comparing the two fluids more directly and making the problem simple to study we used the two models, and the process of $CO_2$-water displacement is not discussed here. In fact, the $CO_2$ reservoir can be viewed a reservoir after operation of $CO_2$ injection and storage project, or an existed natural $CO_2$ reservoir.

Pressures at the injection wellhead and production wellhead maintained constant at all the time, their values are given in Table 1. The two cases have the same pressure difference between injection and production wellheads. The higher injection pressures of 128 bar for $CO_2$ was to keep at supercritical state. The injection temperatures for both cases are 20℃. Because of symmetry, all sides of simulation domain are considered as no flow boundaries, but allow the heat exchange between wellbore and surrounding geological formation by using a semi-analytical solution.

### Table 1: Geometric and hydrogeological specifications for the simulation

| Formation | |
|---|---|
| thickness | 150 m |

| | |
|---|---|
| permeability | $3.2\times10^{-14}$ m$^2$ |
| rock grain density | 2650 kg/m$^3$ |
| rock specific heat | 920 J/kg/°C |
| rock thermal conductivity | 2.51 W/m/°C |
| Initial Conditions | |
| Reservoir fluid | all water/all $CO_2$ |
| temperature | 150 °C |
| pressure | 367 bar |
| Production/Injection | |
| pattern area | 1.44 km$^2$ |
| injector-producer distance | 848.5 m |
| injection temperature | 20 °C |
| injection pressure | 25 bar(for water)/128bar(for $CO_2$) |
| production pressure | 5 bar(for water)/108bar(for $CO_2$) |

**2.2. Simulation approach**

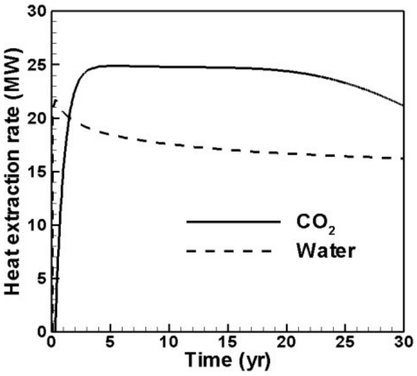
We use a fully coupled wellbore-reservoir simulator, T2well (Pan et al., 2011b; Pan and Oldenburg, 2014), developed based on multiphase fluid and heat flow code TOUGH2 V2 (Pruess, 2004). The module we choose to describe the equation of state is ECO2h (Spycher and Pruess, 2010). T2well considers the wellbore and reservoir as an integrated system. Different sets of governing equations are used to describe the multiphase flow in the wellbore and in the reservoir. In the wellbore, the flow is governed by 1-D momentum equation. While in the reservoir, it is governed by multiphase Darcy's Law (Pan and Oldenburg, 2014). Because the 1-D momentum equation for the multiphase flow in the wellbore is difficult to solve, so DFM (Drift flux model) was introduced to provide an efficient way to approximate the complex two-phase flow in the wellbore. For energy balance equation in the reservoir, because the velocity is so small, kinetic energy is ignored. While in the wellbore, kinetic energy and gravitational potential energy are included in the energy balance equation.

## 3. RESULTS AND DISCUSSION

**3.1 Comparison of heat extraction rate and flow**

According to Pruess (2006), we calculate the heat extraction rate as Equation (1), where F and h represent the mass flow rate and specific enthalpy. The thermal energy extracted using two fluids over time is presented in Figure 2. The heat extraction rate basically keeps stable during 5 to 20 years for two fluids. Using $CO_2$ more thermal energy can be extracted than water, it is mainly due to the larger mass flow rate. The larger flow rate is resulted from larger mobility. Mobility can be represented as the ratio of density to viscosity (see Figure 4). The flow rate of $CO_2$ is about four times as water (Figure 3). However, the difference of thermal energy extracted is not so significant, because changes in the specific enthalpy of change for $CO_2$, from injection wellhead to production wellhead is much smaller than water (we'll discuss it in next chapter).

$$G = F_{pro}h_{pro} - F_{inj}h_{inj} \tag{1}$$



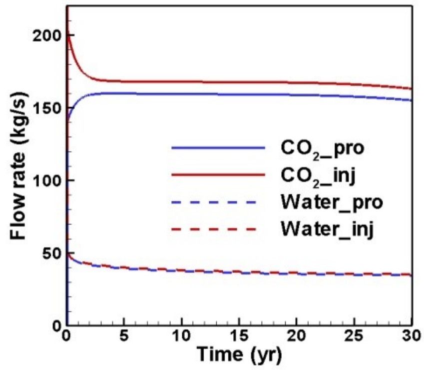




**Figure 2: Comparison of heat extraction rate**

**Figure 3: Comparison of flow rate of injection and production well**

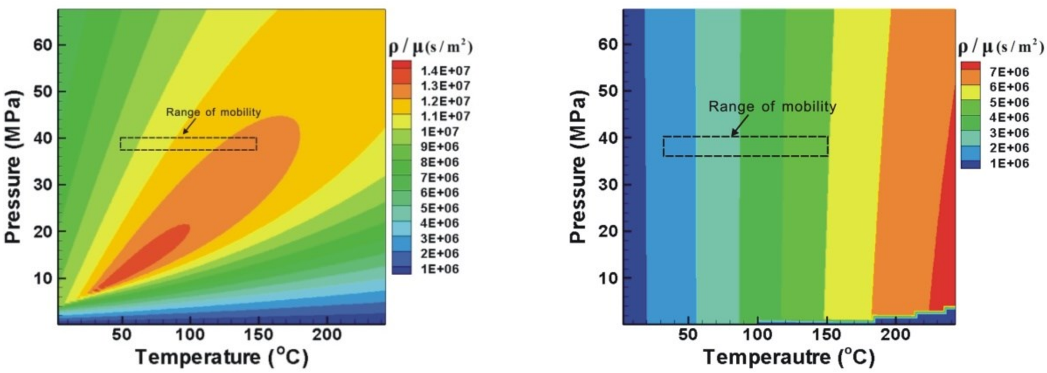



**Figure 4: Ratio of density to viscosity for CO2 (left) and water (right)**

### 3.2 Change of specific enthalpy

Figure 5 shows specific enthalpy change profile for the two fluids, during circulation from the injection wellbore, the reservoir, to the production wellbore. The enthalpy change in the wellbore contains two parts (Equation 2): (1) the work done by gravitational potential energy, and (2) the heat exchange between the wellbore and surrounding geological formation, which is calculated as Equation (3) (Pan et al, 2009; Luo et al., 2014).

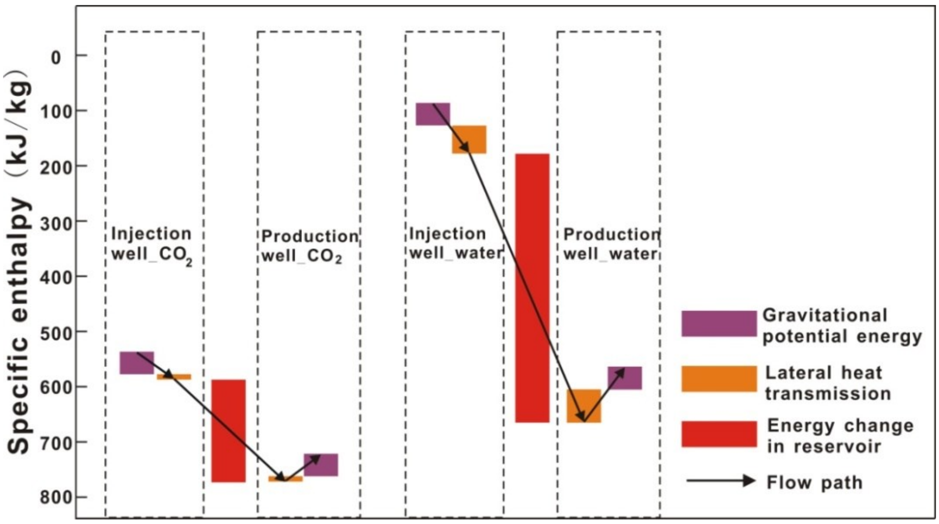



**Figure 5: Enthalpy change per one kilogram fluid in wellbores and reservoir after 10 years ($CO_2$: left), and (water: right)**

$$\Delta h = g\Delta z - \frac{\Delta v^2}{2} + q \tag{2}$$

$$q = \frac{-4\pi\lambda_s (T_f - T_{s,i})}{\ln(\frac{2.246\lambda_s t}{C\rho r^2})} \tag{3}$$

The specific enthalpy change due to gravitational potential energy is the same for both fluids after steady-state. Along the injection wellbore from the top to bottom, the potential energy increases. Along the production wellbore from the bottom to top, the potential energy decreases, and the absolute values are the same as along the injection. $CO_2$ has larger mass flow rate and lower density, so the velocity is much higher than water, especially in production well. Therefore, the lateral heat exchange is much smaller than water. The energy gain from reservoir of $CO_2$ in terms of same mass (1 kg) is much smaller than that of water.

Figure 6 shows the specific enthalpy under different pressure and temperature conditions for $CO_2$ and water. The reference state (zero enthalpy) was chosen as (T,P)=(20℃, 100bar) (Pruess, 2006). The red line shows the flow path from the injection wellhead to production wellhead after 10 years of operation.

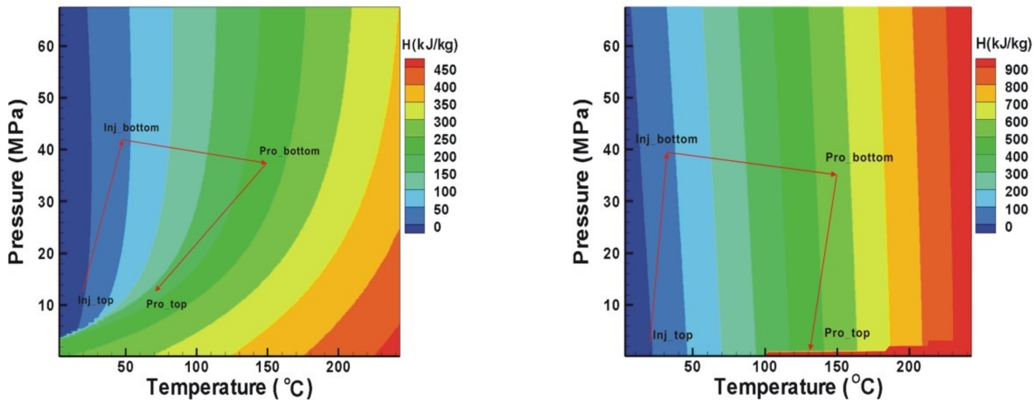



**Figure 6: Specific enthalpy variations with pressure and temperature, left for $CO_2$ and right for water.**

The specific enthalpy of water is mainly controlled by temperature, pressure has little effect. However, that of $CO_2$ is affected by both temperature and pressure. We can see that the $CO_2$ temperature at injection well bottom is about 50℃, while, water is 32℃. Higher temperature is not conducive to extract heat from reservoir, so this is one of disadvantages of $CO_2$. The temperature distribution simulated is shown in Figure 7. The temperature near injection well is higher for the $CO_2$ case, and temperature close to the bottom of the reservoir is lower than those at the reservoir top. This is because as Pruess (2008) pointed out, cold dense for $CO_2$ fluid is diverted towards the bottom. So it is easier to breakthrough at close to the reservoir bottom. For the same reason, from production well bottom to wellhead, is almost an isenthalpic process, as fluid flows upward, the pressure reduces. For water, temperature is almost keep constant, but for $CO_2$, there is a drastically drop in temperature. This is a disadvantage of $CO_2$ as a working fluid, and lower temperature may not meet the demand for generating electricity.

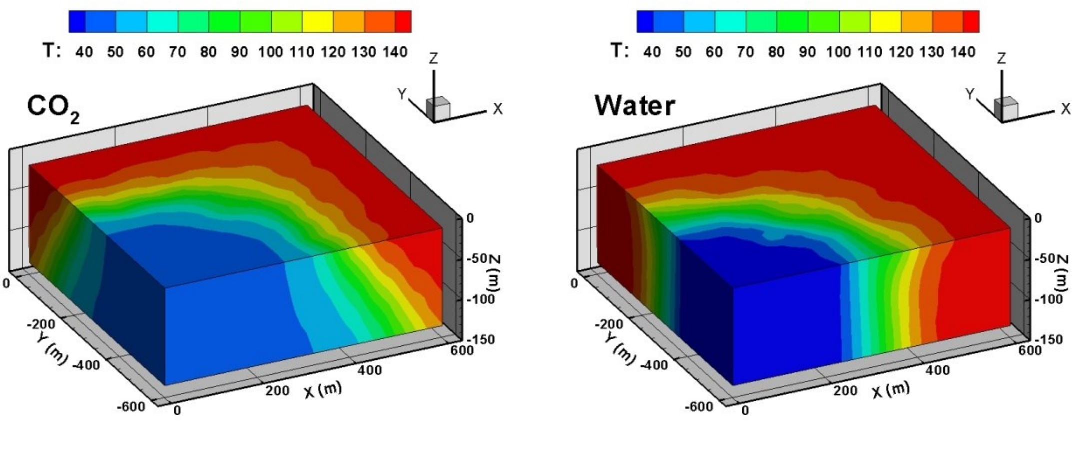



**Figure 7: Temperature distribution obtained from simulations after 30 year**

### 3.3 Change of pressure

Because of distinct thermodynamics properties of two fluids, there exist quite some differences in flow processes. The pressure changes for $CO_2$ and water during the operation are shown in Figure 8, We assume the initial reservoir pressures for the two cases are the same, but two fluids are injected at different pressures (see Table 1). From Figure 8, it can be seen that the frictional loss for $CO_2$ is much larger than water in wellbores, partly due to the larger flow rate. While the main pressure loss for water case is in the reservoir. The pressure change due to gravity in injection and production well for water are almost the same. However for $CO_2$, because of the difference of density of cold and warm $CO_2$, the pressure change due to gravity for $CO_2$ in injection and production well is different, 34MPa in the injection well and 18MPa in the production well. That is why the $CO_2$-based geothermal system can be achieved by siphon phenomenon under the negative circulating pressure difference (Atrens et al., 2010).

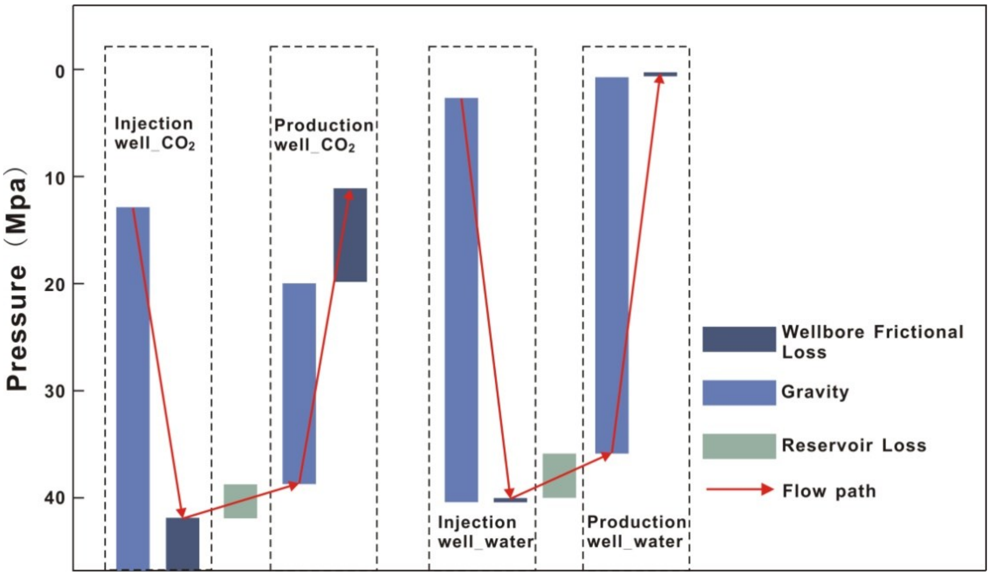



**Figure 8: Pressure change in wellbores and reservoir at 10 year for the two working fluids.**

## 4. EFFECTS OF PARAMETERS CHANGE

### 4.1 Permeability

The heat extraction rate and flow rate for different permeabilities are depicted in Figure 9. For water, heat extraction and flow rate increase significantly as permeability increases. This is also true for permeability reduction case, $k*10^{-1}$, using $CO_2$. Therefore, for lower permeability reservoirs, the advantage of $CO_2$ becomes more noticeable, and we can conclude that $CO_2$ is more suitable for low-permeability reservoirs compared to water.

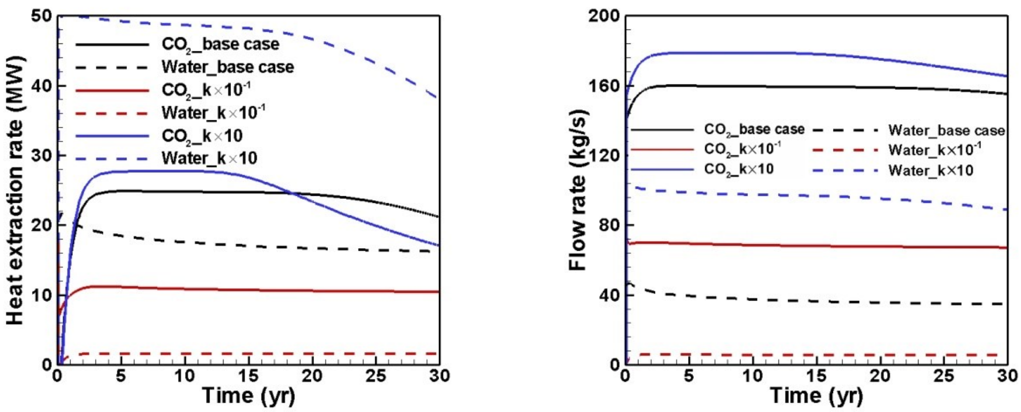



**Figure 9: Heat extraction rate (left) and flow rate of at the production well (right) for different permeabilities.**

To explain this phenomenon, we analyzed the pressure change pattern of three cases, as shown in Figure 10. We can see, for the $k*10^{-1}$ case, because of the lower velocity, the pressure due to friction in wellbore significant decreases, the main pressure loss turn into the reservoir loss. To the k*10 case, although the reservoir become lower, the production wellbore frictional loss become larger.

So, we can conclude that, $CO_2$ has great compressibility, when the flow rate reaches a certain value, the wellbore frictional loss become the main constraint to mass flow rate. However, for water, even the permeability gets larger, compared to loss in reservoir, the wellbore loss is also insignificant. For water, the maximum flow rate is controlled by properties of the reservoir, while the $CO_2$ is controlled by the wellbores.

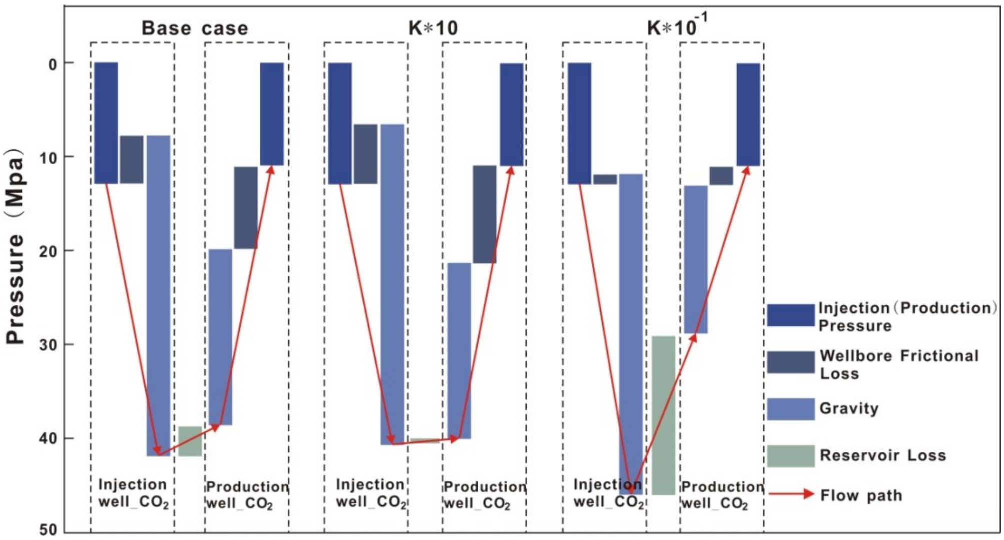



**Figure 10: Pressure change in wellbores and reservoir for different permeability cases (obtained after 10 years)**

Figure 11 depicts temperatures at the top and bottom of the production well. For the base case and k*10$^{-1}$ case, the temperature can keep stable for a long time. While, the temperature for the k*10 case drops rapidly after about 15 years. The reason is the higher permeability more likely leads to breakthrough at bottom of reservoir, as discussed before. So for the higher permeability reservoirs the stable operation of the system cannot be guaranteed.

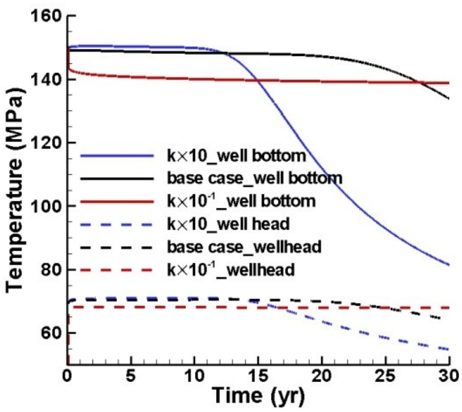



**Figure 11: Temperature at the top and bottom of the production well**

### 4.2 Injection pressure

In these comparisons, we set production pressure the same as before (see Table.1), change injection pressure in order to create different pressure drop between injection and production wellheads. As shown in Figure 12, heat extraction of water is more sensitive to injection pressure than that of $CO_2$. Under different injection pressures, the change tendency and scope of flow rate for the two fluids are nearly the same. However, as to specific enthalpy, as discussed before, unlike $CO_2$ specific enthalpy of water is little affected by pressure (Figure 6). The increase in flow rate is compensated by the change of specific enthalpy of injection. So, when the production pressure is constant, $CO_2$ is more superior to water under low pressure difference, and can even be operated under negative pressure difference.

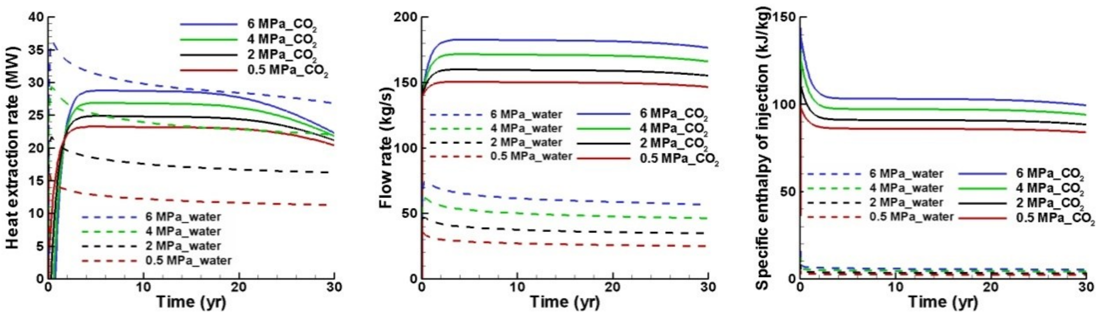



**Figure 12: Heat extraction rate (left), flow rate (middle), specific enthalpy of injection (right) for different pressure differences.**

## 5. CONCLUSION

We have performed wellbore-reservoir coupled numerical simulations, based on geological and thermo-physical conditions of Songliao Basin of China. From the numerical analysis, we can draw the following conclusions.

1. In the base case, heat extraction rate of $CO_2$ is slightly higher than water. The mass flow rate of $CO_2$ is nearly four times as water, because the heat extraction quantity per kilogram of $CO_2$ is less than water.

2. The specific enthalpy change in wellbore contains two parts, the work done by gravity and heat transmission between well and surrounding rocks. Because of the specific thermophysical properties of $CO_2$, the specific enthalpy change is so small relative to its intrinsic specific enthalpy, so we regard the wellbore flow as isenthalpic process. In production, the temperature decrease significantly with pressure, the outlet temperature at the production wellhead is much lower than water. This is a disadvantage of $CO_2$

3. The main pressure loss for water is within reservoir. While for $CO_2$, except for the case of extremely low permeability, the main loss is the frictional loss in the wellbores. Under this circumstance, increases in permeability cannot conduce to heat extraction rate and have an adverse effect on stable operation. The advantage of $CO_2$ is more noticeable in low permeability reservoirs. All these behaviors of $CO_2$ basically owes to its compressibility.

4. Water is more sensitive to injection pressure change than $CO_2$. When the production pressure is constant, $CO_2$ is more superior to water under low pressure difference, and can even be operated under negative pressure difference.

5. Besides the disadvantages we discussed above, the higher injection and production pressure for $CO_2$ cost more energy but if we make the pressure lower, the production temperature will decrease. Another disadvantage is that larger wellbore diameter is needed to inject $CO_2$, which is costly as well.

6. Some portion of $CO_2$ in the circulation can be lost to the surrounding geological environments, which is a benefit for storing $CO_2$, a greenhouse gas.

The range of problems concerning the $CO_2$-based geothermal systems is very broad. The present simulation results and conclusions are specific to the conditions and parameters considered. The “numerical experiments” give a detailed understanding of the dynamic evolution, and provide useful insight into fluid flow and thermal processes along the wellbores and in the reservoir. Results and conclusion may be useful for future field design of a $CO_2$-geothermal system.

## ACKNOWLEDGEMENT

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