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# An Experimental Investigation of Feasibility of Supercritical $CO_2$ Geothermal Heat Mining in Low and Medium Temperature Geothermal Reservoir

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**Abstract**

The global warming caused by CO2 emission has drawn worldwide attention, and many countries have committed to achieve carbon neutral around middle of 21st century. Using supercritical CO2 as a heat carrying fluid to produce geothermal resources has a potential to reduce CO2 emission, because it can generate green energy (electricity and direct heating) and store massive amount of CO2 underground simultaneously. Since low and medium temperature geothermal reservoirs are widely distributed, hence applying abovementioned method to these reservoirs may access to more geothermal resource and store more CO2. The objective of this paper is to investigate the feasibility of using supercritical CO2 for heat mining in low and medium temperature geothermal reservoirs.

In this study, we built a large scale high pressure sandpack experimental setup with 83 thermocouples and a heat exchanger to conduct supercritical CO2 heat mining experiments. The sandpack was preheated to a given temperature at a certain pressure, then liquid CO2/water was injected into the sandpack with a certain flow rate for several pore volumes. The temperature distribution inside the sandpack was measured with thermocouples in real-time, as well as the temperature in inlet, outlet and heat exchanger. Different temperatures (80℃, 100℃ and 120℃), pressure (80bar, 100bar and 120bar) and flow rates (25ml/min, 50ml/min and 100ml/min) were utilized to study the heat mining performance of supercritical CO2/water under different conditions. The same experiments with the same inlet pressure were also done to compare the heat mining performance between supercritical CO2 and water.

The experimental results were plotted as heat maps at different pore volumes and revealed the heat transfer mechanism during supercritical CO2/water injection. The heat exchanger is sufficient to compare the performance of different injection scenarios. The injection with higher temperature, pressure and flow rate generate better heat mining performance and achieved higher temperature in the heat exchanger. Supercritical CO2 is a good heat carrying fluid for heat mining, even though it has less heat capacity but lower viscosity allows it can be injected with high flow rate. The experiments with the same inlet pressure showed that supercritical CO2 has higher heat mining efficiency than water in low and medium temperature geothermal reservoirs.

## 1. INTRODUCTION

As a clean energy, geothermal has gained more and more attention from many countries and will play an important role in the future energy map. Compared with solar and wind energy, geothermal can supply stable energy independent of weather conditions, so the electricity generated with geothermal is a stable input for the power grid. Geothermal also can be used directly as heating source during winter. CCS as another solution to reduce carbon emission also has drawn interests from many researchers. This method is to inject carbon dioxide into the underground brine or gas formation to store CO2. This is a net carbon negative method, but does not produce any economic benefits, only relying on a high carbon tax. However, if the CO2 can be used as a heat carrying fluid for geothermal heat mining, we can achieve CCUS (Brown, 2000). The idea behind CCUS is to use carbon dioxide as a resource and aim to generate economic benefits in the process of carbon storage (Pruess, 2006 and 2008). Which can cover some of the costs of capturing and storing of carbon dioxide. Using supercritical CO2 to extract geothermal and store CO2 underground can achieve win-win situation (Cui, 2017).

The traditional geothermal focus more on high temperature geothermal reservoir, while if one technology can be developed to mining the heat energy from low and medium temperature geothermal reservoirs, we may access more geothermal energy since they are widely distributed. Supercritical CO2 has potential to extract the energy from low and medium geothermal reservoirs due to its specially properties. Heat capacity and viscosity is two important parameters for geothermal heat mining, water has higher heat capacity so it can extract more energy from reservoir per unit time, but water has higher viscosity also, which means more energy is needed to reject it underground, However, supercritical CO2 has less viscosity and less heat capacity as well. For instant, at 100℃ and 200bar condition, the ratio of heat capacity, density and viscosity between water and supercritical CO2 is 1,75, 2.06 and 7.57, respectively. Under the constant injection scenario, supercritical CO2 has 7.57 higher flow rate than water, hence it can extract 2.1 time more heat from geothermal reservoir than water. By theoretical calculation, supercritical may have better heat mining potential to produce low and medium geothermal energy than water.

In this study, we have developed a novel high-pressure high-temperature (HPHT) large-scale sandpack setup for heat mining experiment with multiple integrated thermocouples and a heat exchanger. The primary research objective was to investigate the feasibility of heat mining by supercritical CO2 in low and medium temperature geothermal reservoirs by comparing its performance with water under constant flow rate and injection pressure, evaluate the heat mining performance of supercritical CO2 and water in above sandpack setup.

## 2. EXPERIMENTAL SETUP

In order to have a better understanding of heat transfer and temperature distribution during geothermal heating mining process, we have designed and developed an integrated geothermal heat mining setup with a large-scale sandpack and a heat exchanger. Totally 83 thermocouples were applied to monitor the temperature change, especially 15 multipoint thermocouples (each thermocouple has five temperatures measuring points) were inserted into the sandpack to measure the temperature distribution. More details of setup design can be found in Figure 1.

A schematic diagram of the HPHT geothermal heat mining setup is shown in Figure 1. A CO2 siphon tank with initial pressure about 60bar was used as CO2 source, the tank was connected to five accumulators and CO2 was pressurized to certain pressure by pump1. Before CO2 injection CO2 tank was disconnected from accumulators, and pump1 was used to inject CO2 inside the accumulators into the sandpack. Before CO2 was injected into the sandpack, it was cool down to about 10℃ by flowing through a circulator to ensure that all injection cases have the same inlet temperature. A large-scale sandpack with length of 80cm, inside diameter of 10cm and outside diameter of 13cm was manufactured and to mimic geothermal reservoir. The sandpack was filled with quartz sands with mesh of 70, it has porosity of 0.38 and permeability of 10 Darcy. The sandpack was placed inside a heating cabinet, which is thermal isolated from outside, to ensure a constant temperature during the experiment. A heat exchanger with DI water was placed after the sandpack to allow heat transfer from heat carrying fluid (supercritical CO2/water) to water. This can be used as a indicator of heat mining performance. In downstream, two back pressure regulators (BPR) and one flashing cylinders were included. BPR1 was set to a pressure value higher than 71 bar to ensure that CO2 inside the sandpack is under supercritical condition. A flashing cylinder was placed between the sandpack and ventilation to minimize CO2 flashing problem during depressurization process. The maximum working temperature and pressure of this setup is 130 ℃ and 200bar, respectively.

Totally 83 thermocouples was utilized in this system, the red bars with yellow dots in the Figure 1 indicate thermocouples. Four single thermocouples measured the temperature of inlet, outlet, heat exchanger and after heat exchanger, respectively. Another four surface thermocouples (S1, S2, S3 and S4) shown in Figure 2 were used to measure the temperature of sandpack body. Fifteen multipoints thermocouples were inserted into the sandpack to measure the temperature distribution in real time. As shown in Figure 2, each multipoints thermocouple has five measuring points marked from A to E. All thermocouples were connected to thermocouple data logger via cable (red line), which can monitor and record temperature data in real time. Three pressure gauges (P1, P2 and P3) measured pressure of inlet, outlet and after flashing cylinder. A deferential pressure gauges was used to measure the pressure drop across the sandpack. Pictures of the whole setup and each part are shown in Figure 3.

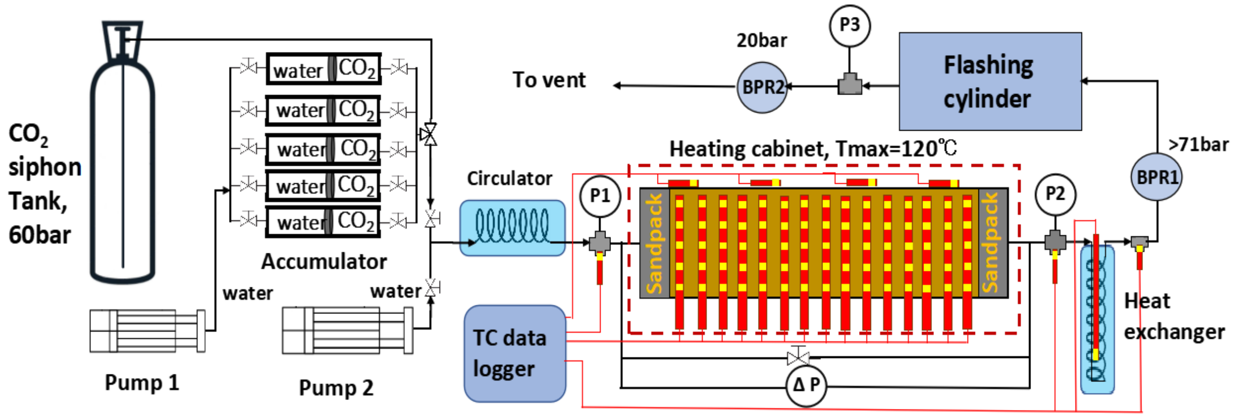


**Figure 1: Schematic diagram of the HPHT geothermal heating mining setup**

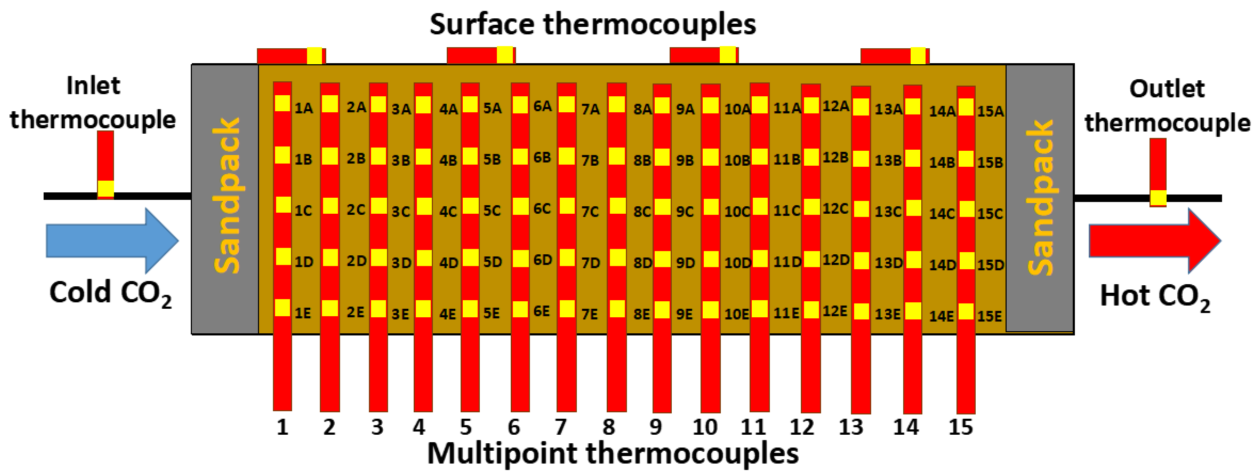


**Figure 2: Zoomed in schematic diagram of the sandpack and multipoint thermocouples.**


**Figure 3 Pictures of the geothermal heat mining setup. 1: whole image of the setup; 2: CO2 tank and pump1; 3: CO2 accumulators; 4: cooling circulator and inlet; 5: sandpack, multipoints thermocouples and heating cabinet; 6: multipoints thermocouple inside the sandpack; 7: surface thermocouple on the sandpack; 8: thermocouple data logger; 9: outlet and heat exchanger; 10: coil inside the heat exchanger; 11: flashing cylinder.**

## 3. EXPERIMENTAL METHODS

Before heat mining experiments, firstly, the sandpack was filled with quartz sands and packed with hammer. The multipoint thermocouples were inserted during packing, then a leak test was done. After the sandpack was connected to the system, a vacuum pump was used to vacuum the whole system and then filled with CO2 under certain pressure. Once the preparation is done, the heating cabinet was set to certain temperature and the sandpack was heated overnight to reach an equilibrium condition. The similar procedure was applied for the cases with water as heat carrying fluid.

For the scenario with supercritical CO2, three temperatures (80℃, 100℃ and 120℃ ), three pressure (80bar, 100bar and 120bar) and three flow rates (25ml/min. 50ml/min and 100ml/min) were applied to obtain a comprehensive image of heat mining. The similar injection scenario was used for the experiment with water as heat carrying fluid, except only one pressure (120bar) was applied. The injection volume for both CO2 and water is about seven liters, which is around 3.256 pore volume. A contrast experiment was also been conducted for both CO2 and water with the same injection pressure, to compare their heat mining performance under the same injection pressure.

During the experiments, the all thermocouple temperature data is recorded in real time, as well as the inlet and outlet pressure and the differential pressure across the sandpack.

## 4. RESULTS AND DISCUSSION

As mentioned above, there were 75 temperature measuring points inside the sandpack and 4 measuring points on sandpack body, hence temperature change of the sandpack during heating mining process can be monitored and recorded. The temperature data then was analyzed and processed, finally the temperature distribution is shown as a heat map. A schematic explanation is shown in Figure 4, 75 grids (15 columns x 5 rows) with different color and values present the temperature distribution of the sandpack. The first column and the last columns grids have the dimension of 3.5cm x 2cm, the rest have the dimension of 5cm x 2cm. The first row and the last row in Figure 4 represent the stainless steel sandpack body, the colored grids shows the body temperature measured with surface thermocouples. By analysis this heat map, we can get insight of sandpack to have better understanding of geothermal heat mining process.

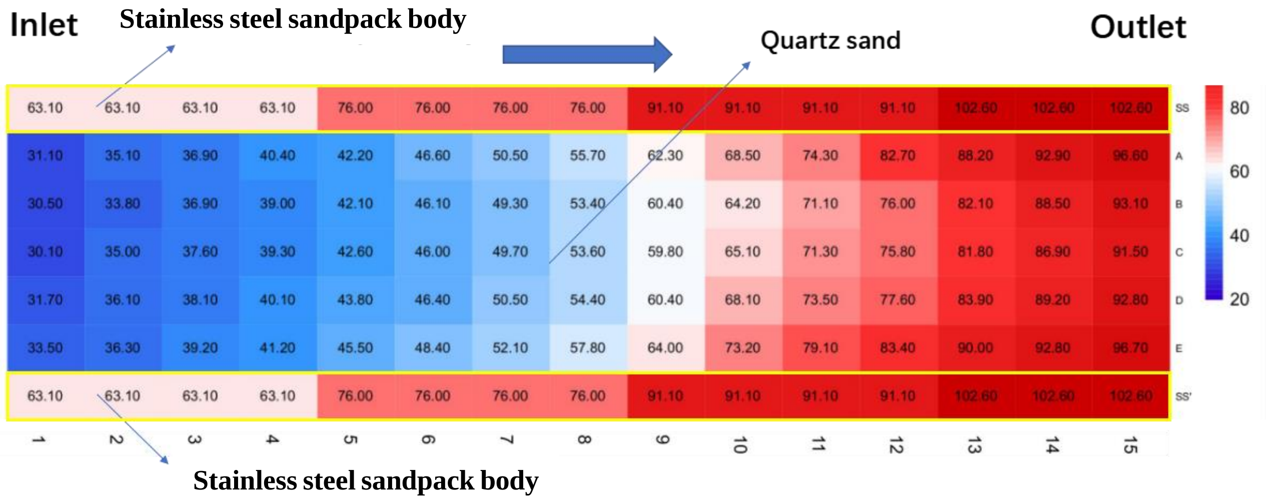


**Figure 4 Schematic explanation of measured temperature distribution for sandpack**

### 4.1 Geothermal heating mining experiments with supercritical CO2

Firstly, the geothermal heating mining experiments with supercritical CO2 were performed with various temperature, pressure and flow rate. Each variable will be discussed separately to investigated their effect on heat mining efficiency.

#### 4.1.1 <u>The Effect of flow rate on heat mining with supercritical CO2</u>

The heat maps for the heat mining cases at different injection pore volume with supercritical CO2 at 120bar and 120℃ with different flow rate (25ml/min, 50ml/min and 100ml/min) are shown in Figure 5-7. As we can see, after cold CO2 is injected into the sandpack, heat was transfer from sand to CO2 and sandpack temperature reduced from inlet for three cases. When more CO2 is injected, the cold CO2 front was pushed deeper toward outlet. The sandpack body close to inlet was cool down as well, lower temperature was observed. The reason is CO2 adsorbed more heat energy from sandpack and body than the energy that body adsorbed from heating cabinet.

The high is the flow rate of injection CO2, the deeper cold CO2 front can reach toward outlet and the lower temperature close to inlet. Due to lower heat capacity of supercritical CO2, only little portion of sandpack heat energy was adsorbed by CO2 and taken out of the sandpack. The temperature of the sandpack close to outlet is still close to the initial temperature 120℃ even for the highest flow rate 100ml/min after more than 3.2PV injection. This also shows that big potential of heat mining when more CO2 can be injected.

The temperature of outlet and heat exchanger versus pore volume injection with different flow rates is shown in Figure 8. Generally, the higher is the flow rate the higher outlet and heat exchanger temperature and the faster heat exchanger temperature increase. However, the difference between 50ml/min and 100ml/min is much less than that between 25ml/min case and 50ml/min. It may indicate that 50ml/min is the most economic flow rate.

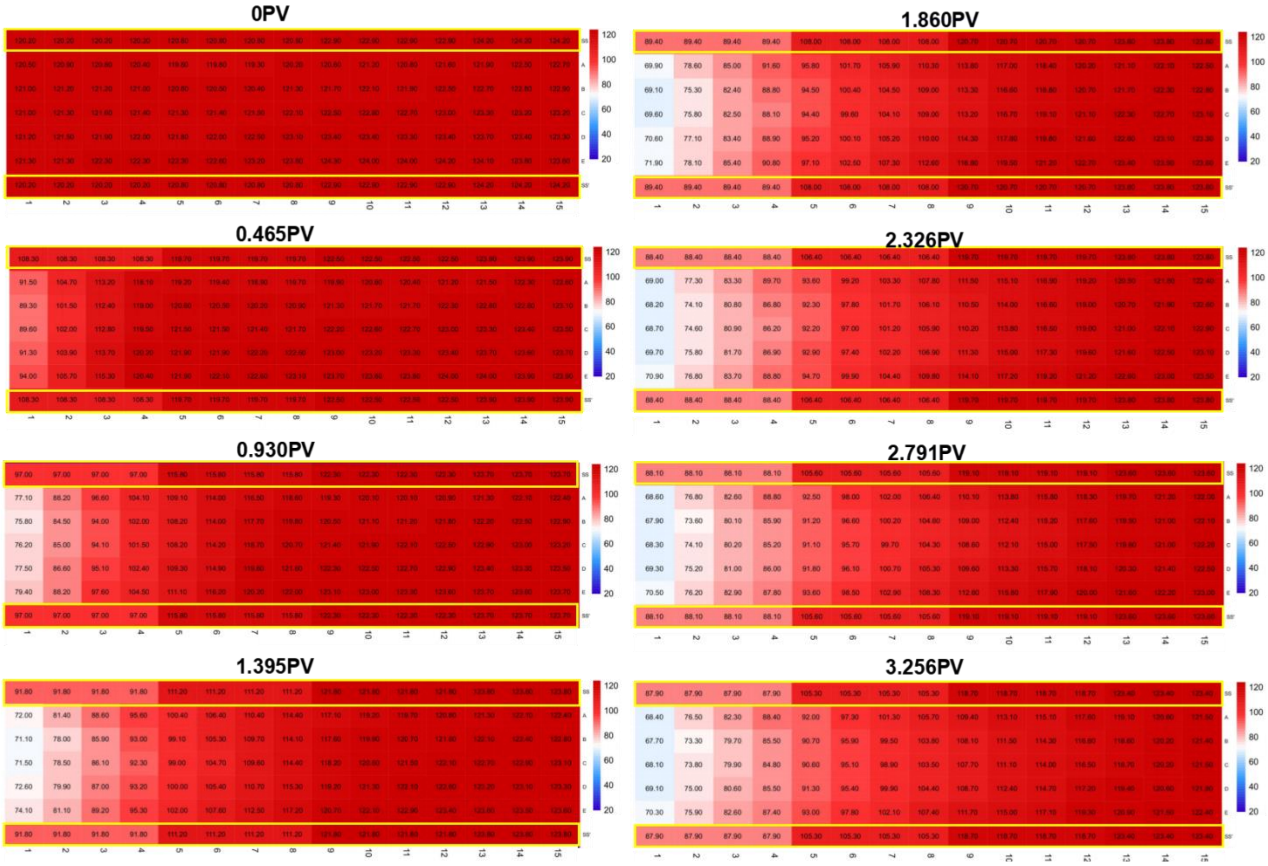


**Figure 5 The heat map of supercritical CO2 heat mining under 120bar, 120℃ and 25ml/min flow rate condition**

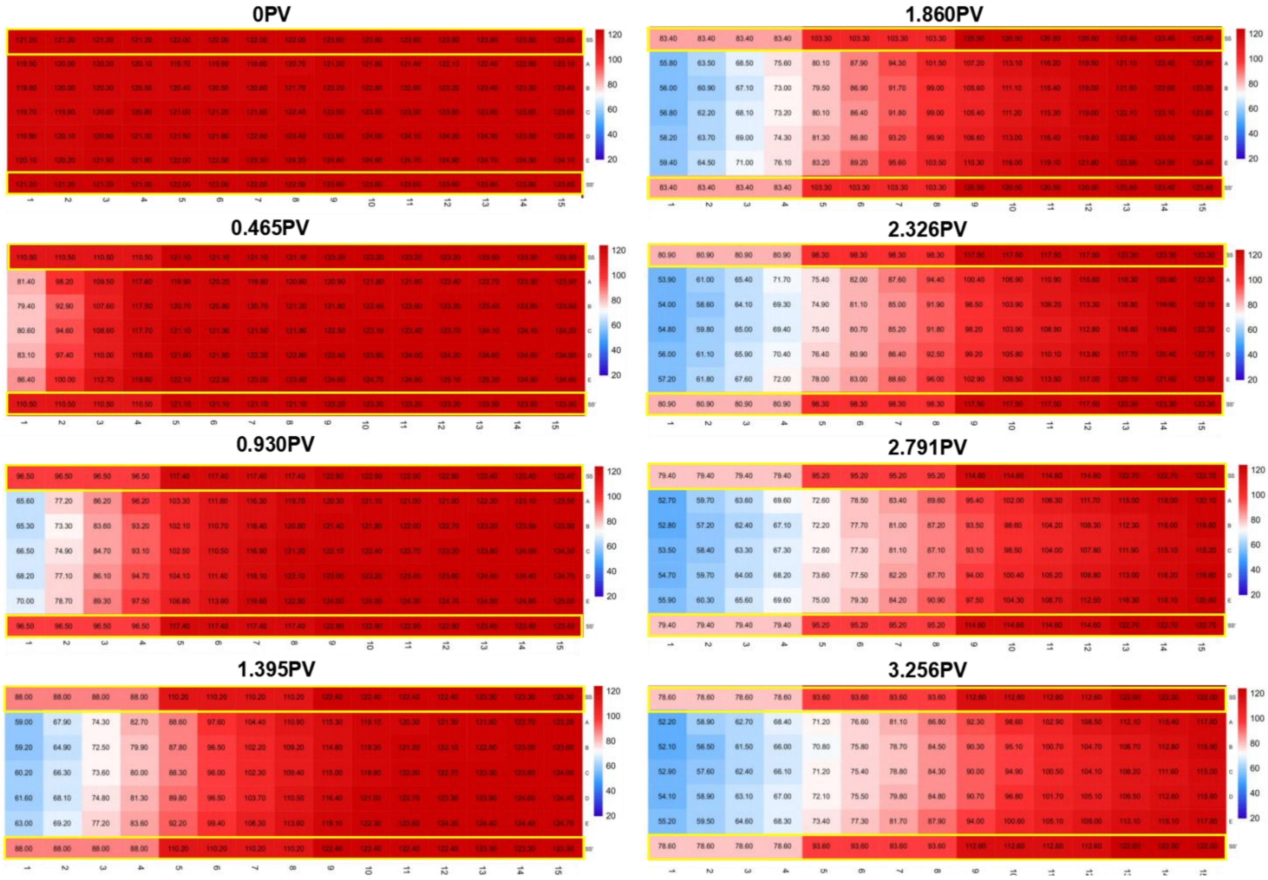


**Figure 6 The heat map of supercritical CO2 heat mining under 120bar, 120℃ and 50ml/min flow rate condition**

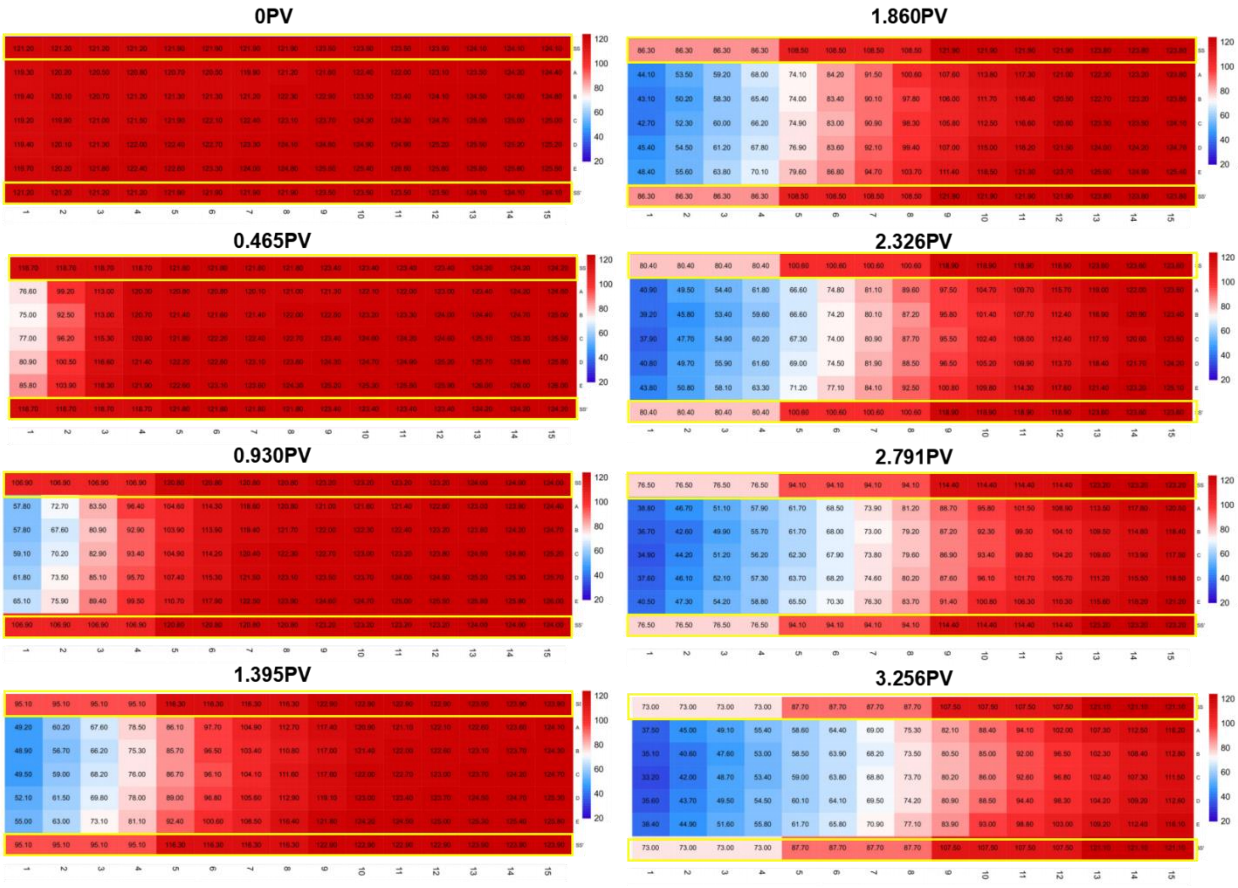


**Figure 7 The heat map of supercritical CO2 heat mining under 120bar, 120℃ and 100ml/min flow rate condition**

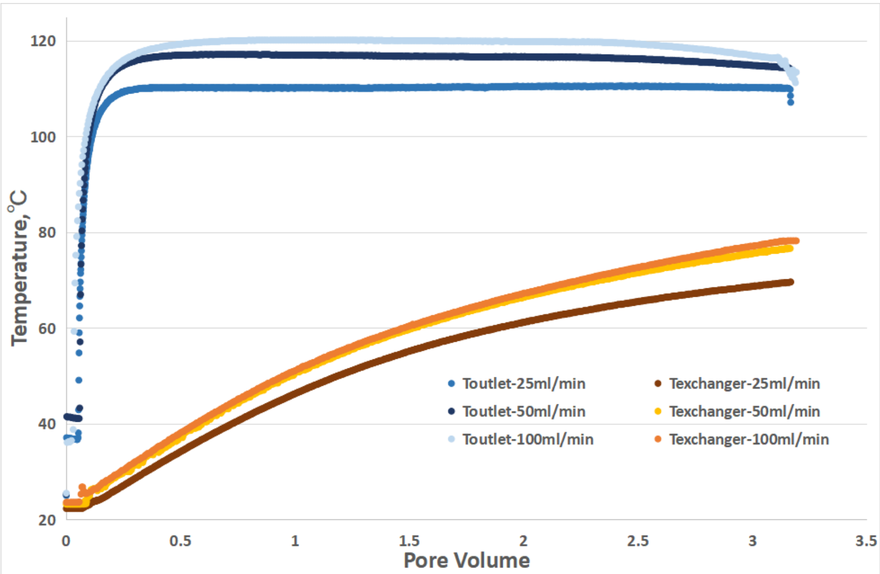


**Figure 8 The temperature of outlet and heat exchanger versus injection pore volume for CO2 case (different flow rate under 120bar and 120℃ condition)**

4.1.2 <u>The Effect of temperature on heat mining with supercritical CO2</u>

The heat maps for the heat mining cases at different injection pore volume with supercritical CO2 at 120bar and 100ml/min flow rate with different temperature (80℃, 100℃ and 120℃) are shown in Figure 9, 10 and 7. Different temperature of the sandpack has a big effect on heat mining, in 80℃ case, cold CO2 front reached 2/3 of sandpack and the outlet end temperature drop from 80℃ to about 70℃. In Figure 11, the outlet temperature of 80℃ case was even lower than heat exchanger temperature at end of injection. This means that CO2 has lost the capacity to heat the water inside heat exchanger, while 100℃ and 120℃ cases still have the potential to heat the heat exchanger. As expected, the result shows that the higher temperature is, the better performance for heat mining.

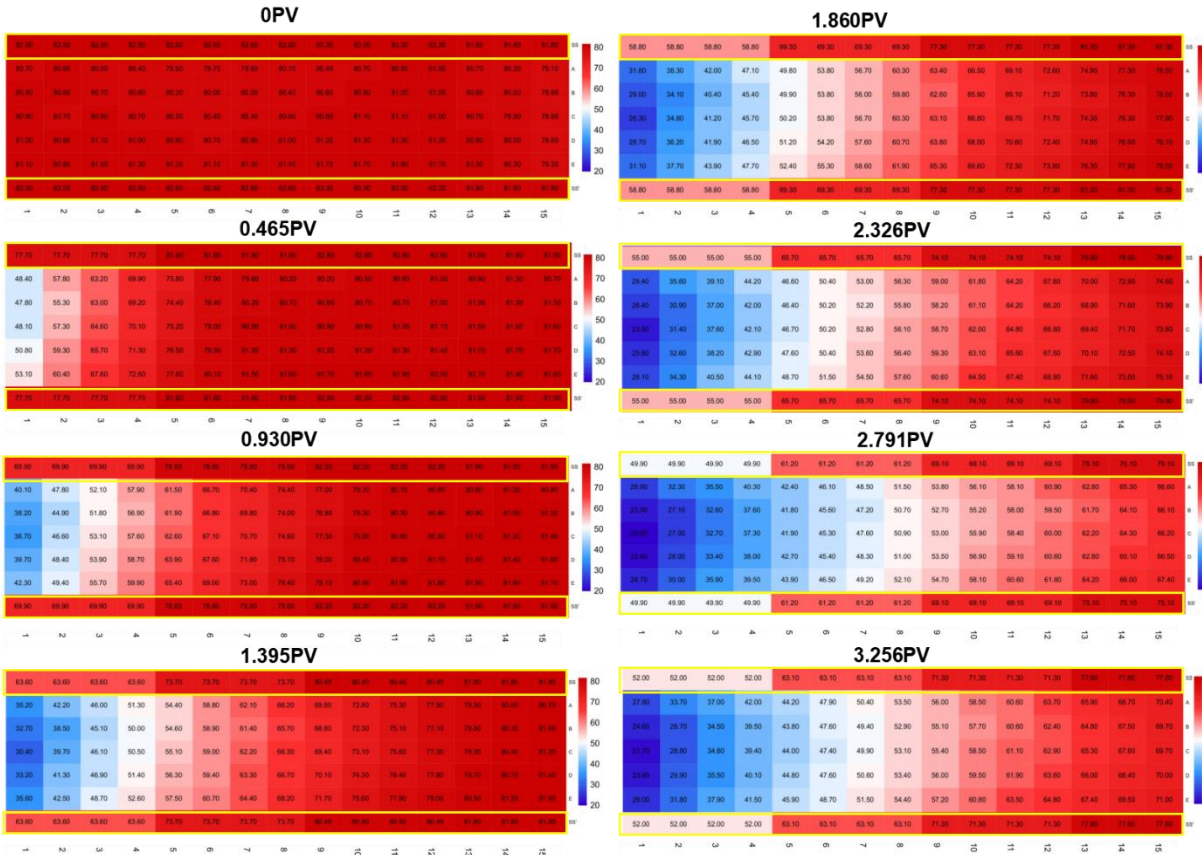


**Figure 9 The heat map of supercritical CO2 heat mining under 120bar, 80℃ and 100ml/min flow rate condition**

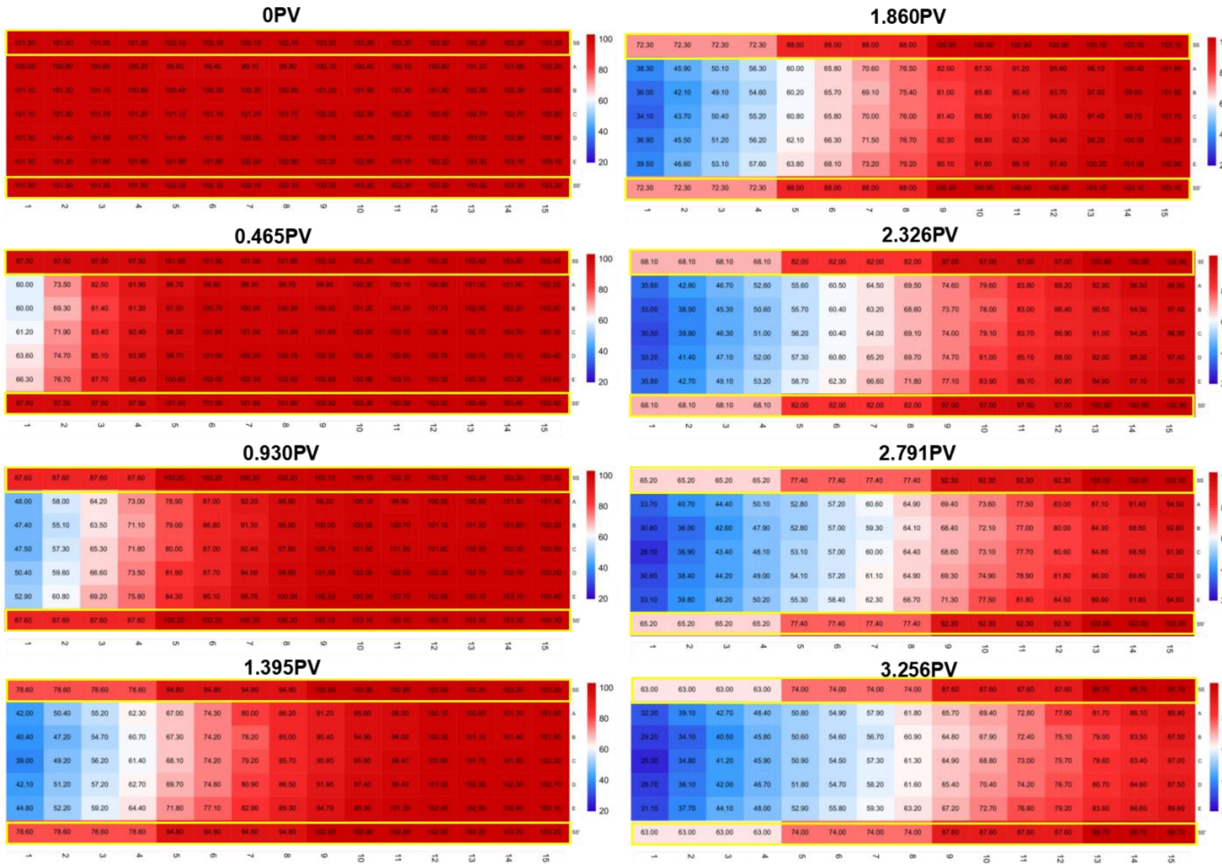


**Figure 10 The heat map of supercritical CO2 heat mining under 120bar, 100℃ and 100ml/min flow rate condition**

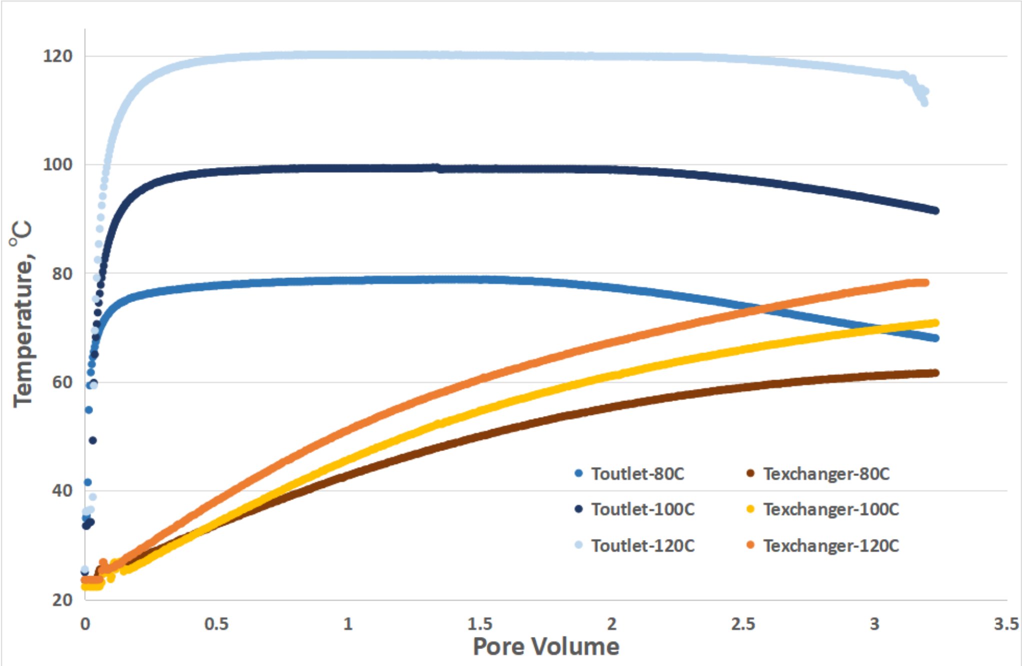


**Figure 11 The temperature of outlet and heat exchanger versus injection pore volume for CO2 case (different temperature under 120bar and 100ml/min flow rate condition)**

4.1.3 <u>The Effect of pressure on heat mining with supercritical CO2</u>

The heat maps for the heat mining cases at different injection pore volume with supercritical CO2 at 120℃ and 100ml/min flow rate with different pressure (80bar, 100bar and 120bar) are shown in Figure 12, 13 and 7. Since the pressure has more effect on CO2 parameter, like density and heat capacity. The higher CO2 pressure give it better heat carrying ability. In Figure 14, the heat exchanger temperature of 120bar is almost 20℃ higher that of 80bar case. This is a significate heat mining performance improvement.

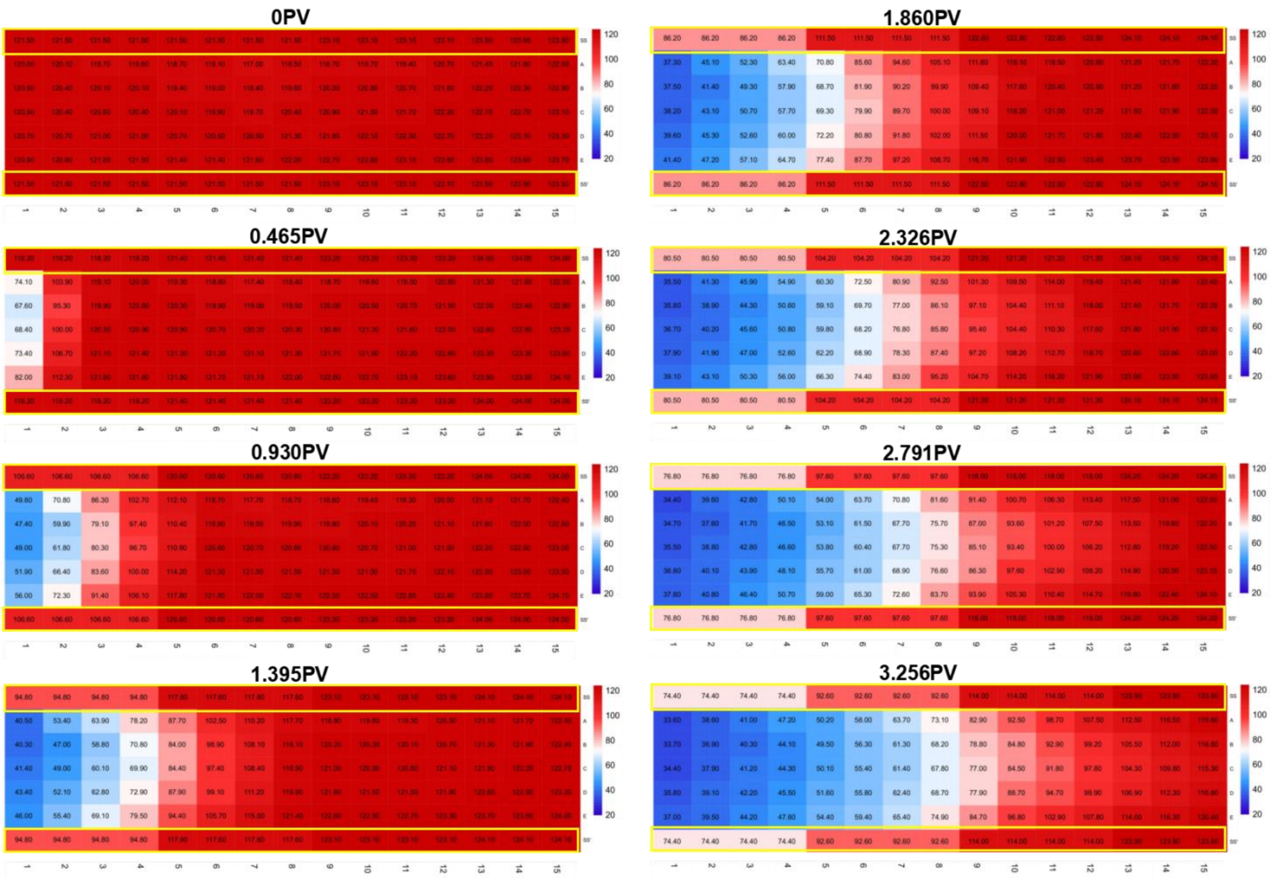


**Figure 12 The heat map of supercritical CO2 heat mining under 80bar, 120℃ and 100ml/min flow rate condition**

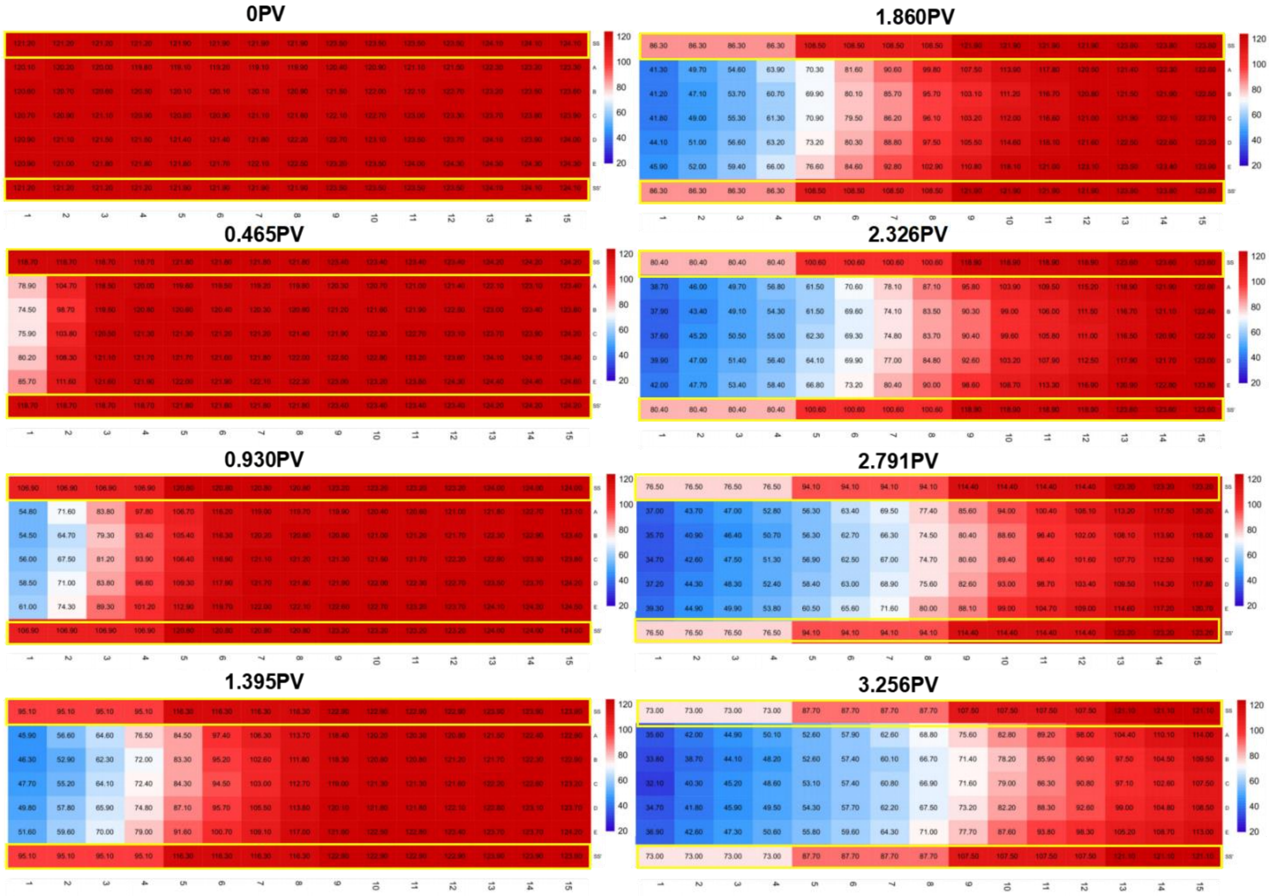


**Figure 13 The heat map of supercritical CO2 heat mining under 100bar, 120℃ and 100ml/min flow rate condition**

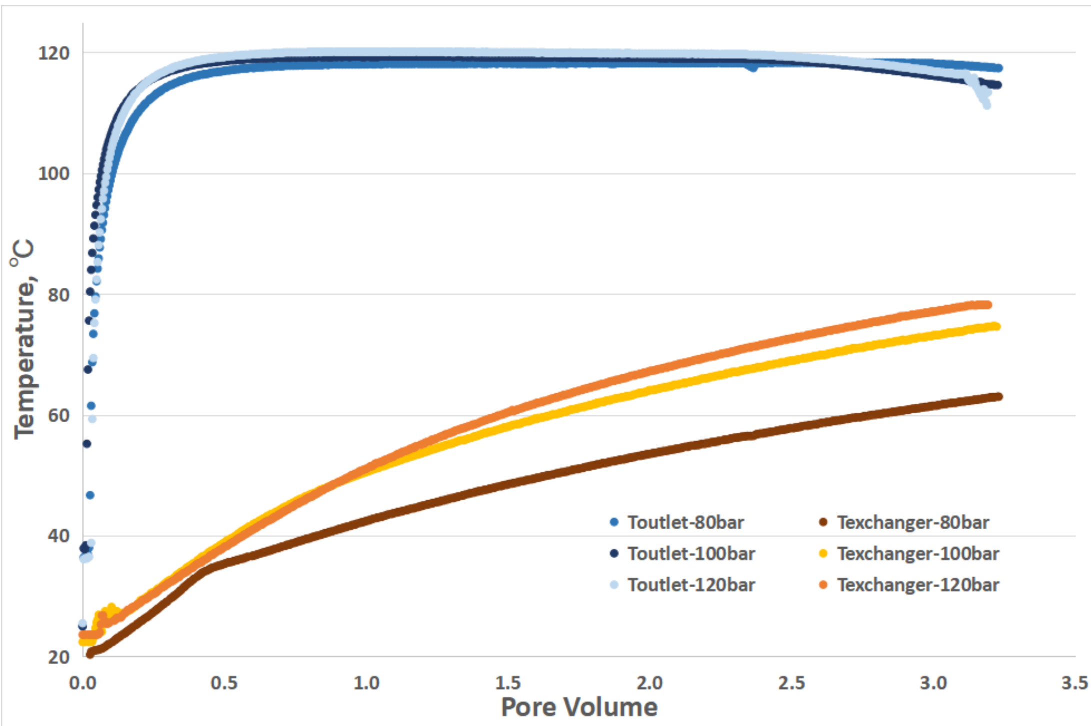


**Figure 14 The temperature of outlet and heat exchanger versus injection pore volume for CO2 case (different pressure under 120℃ and 100ml/min flow rate condition)**

### 4.2 Geothermal heating mining experiments with water

The similar heating mining experiments were also conducted for water, since the pressure has limit effect on water properties, so pressure is constant (120bar) and only temperature (80℃, 100℃ and 120℃) and flow rate (25 ml/min, 50 ml/min and 100ml/min) variables were considered.

4.2.1 <u>The Effect of flow rate on heat mining with water.</u>

The heat maps for the heat mining cases at different injection pore volume with water at 120bar and 120℃ with different flow rate (25ml/min, 50ml/min and 100ml/min) are shown in Figure 15-17. Due to the higher viscosity, we can find a relative obvious piston flooding front in heat map, which is different from CO2 cases. Water has the highest heat capacity, it can adsorb more heat from the sandpack, the high is the flow rate, the more heat was taken and the lower overall sandpack temperature. In Figure 17, some abnormal temperature area be can observed, it shows some kind of discontinuity of temperature distribution. The reason may because the different viscosity caused by temperature difference, thus lead to water breakthrough.

In Figure 18, water cases exhibited similar tend with CO2 cases, the high flow rate is, the high heat exchanger temperature is. However, the gap between the outlet and heat exchanger is reduced, indicating that less potential and large amount of heat energy has been produced.

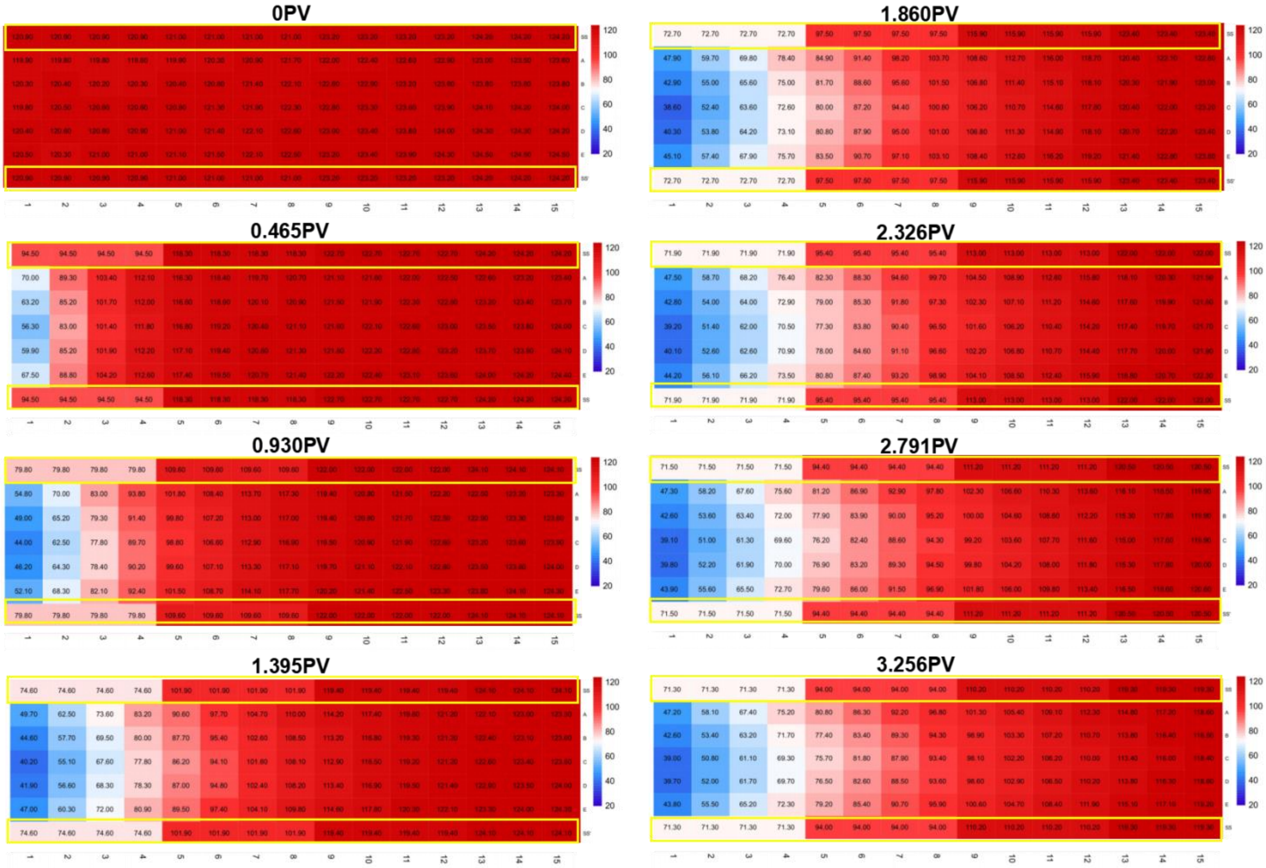


**Figure 15 The heat map of water heat mining under 120bar, 120℃ and 25ml/min flow rate condition**

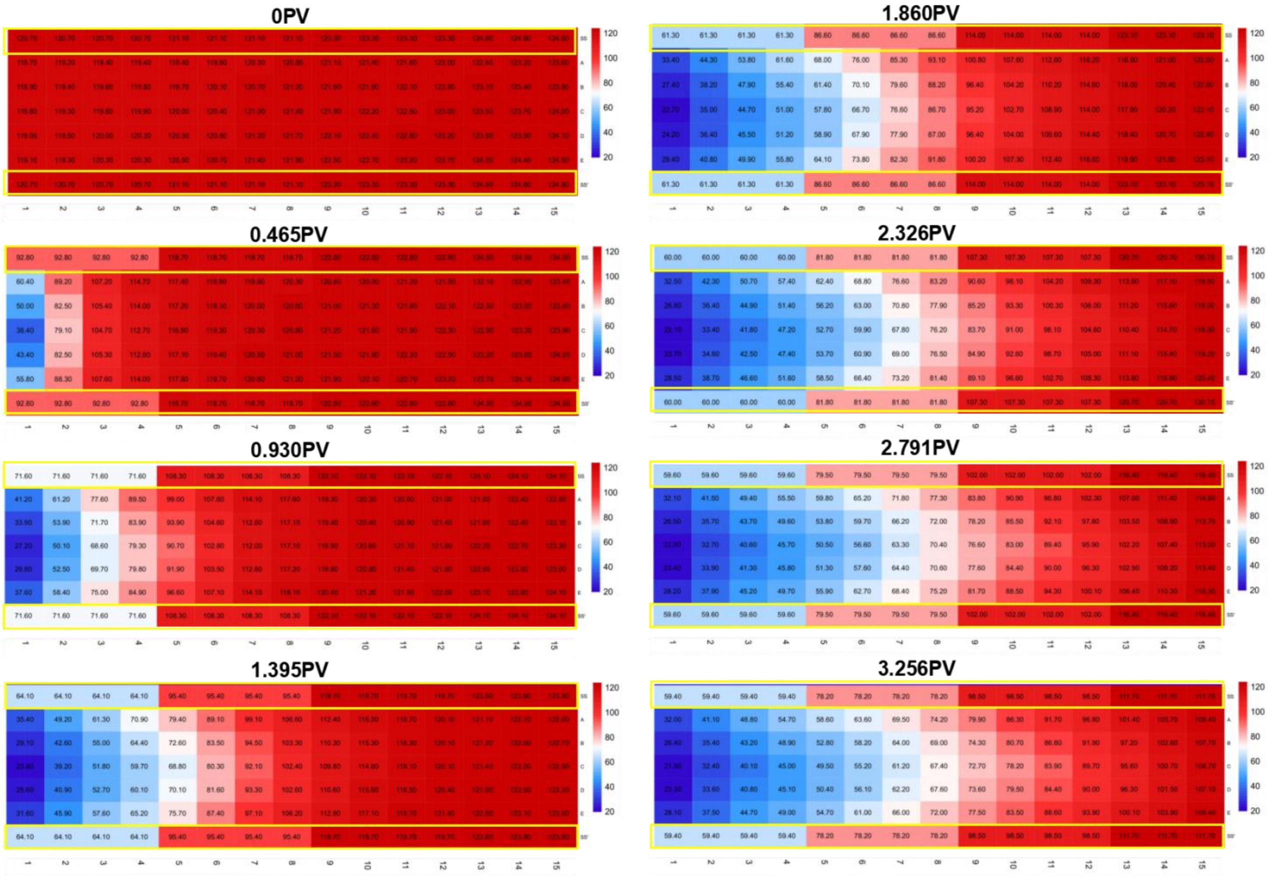


**Figure 16 The heat map of water heat mining under 120bar, 120℃ and 50ml/min flow rate condition**

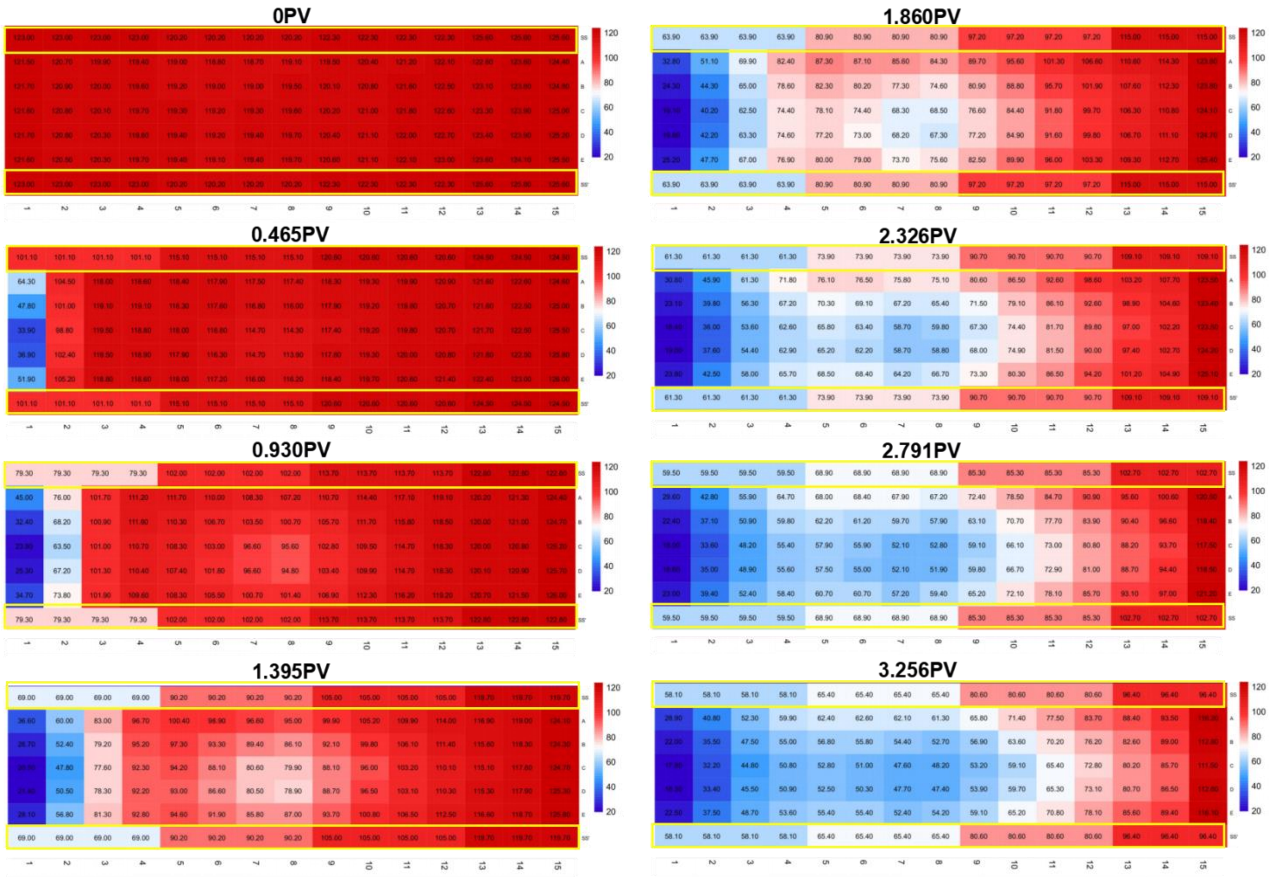


**Figure 17 The heat map of water heat mining under 120bar, 120℃ and 100ml/min flow rate condition**

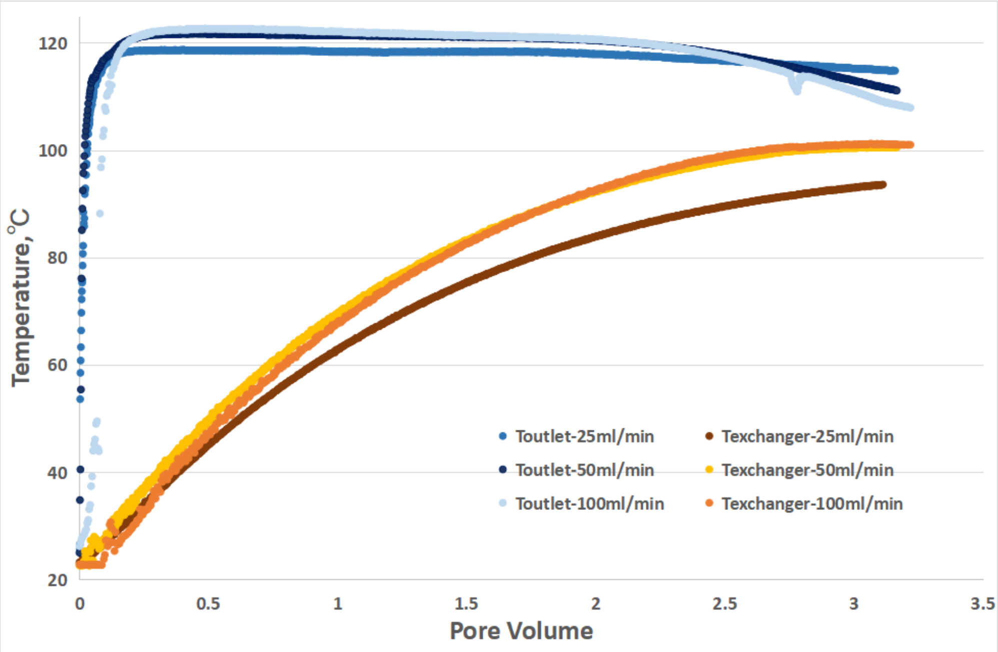


**Figure 9 The temperature of outlet and heat exchanger versus injection pore volume for water case (different flow rate cases under 120℃ and 120bar condition)**

4.2.2 <u>The Effect of temperature on heat mining with water</u>

The heat maps for the heat mining cases at different injection pore volume with water at 120bar and 100ml/min flow rate with different temperature (80℃, 100℃ and 120℃) are shown in Figure 19, 20 and 17. Due to the high heat capacity, in lower temperature cases, water can take heat energy quickly. In Figure 21, after 3 PV injection, the outlet and heat exchange temperature curves crossover for 80℃ and 100℃ cases.

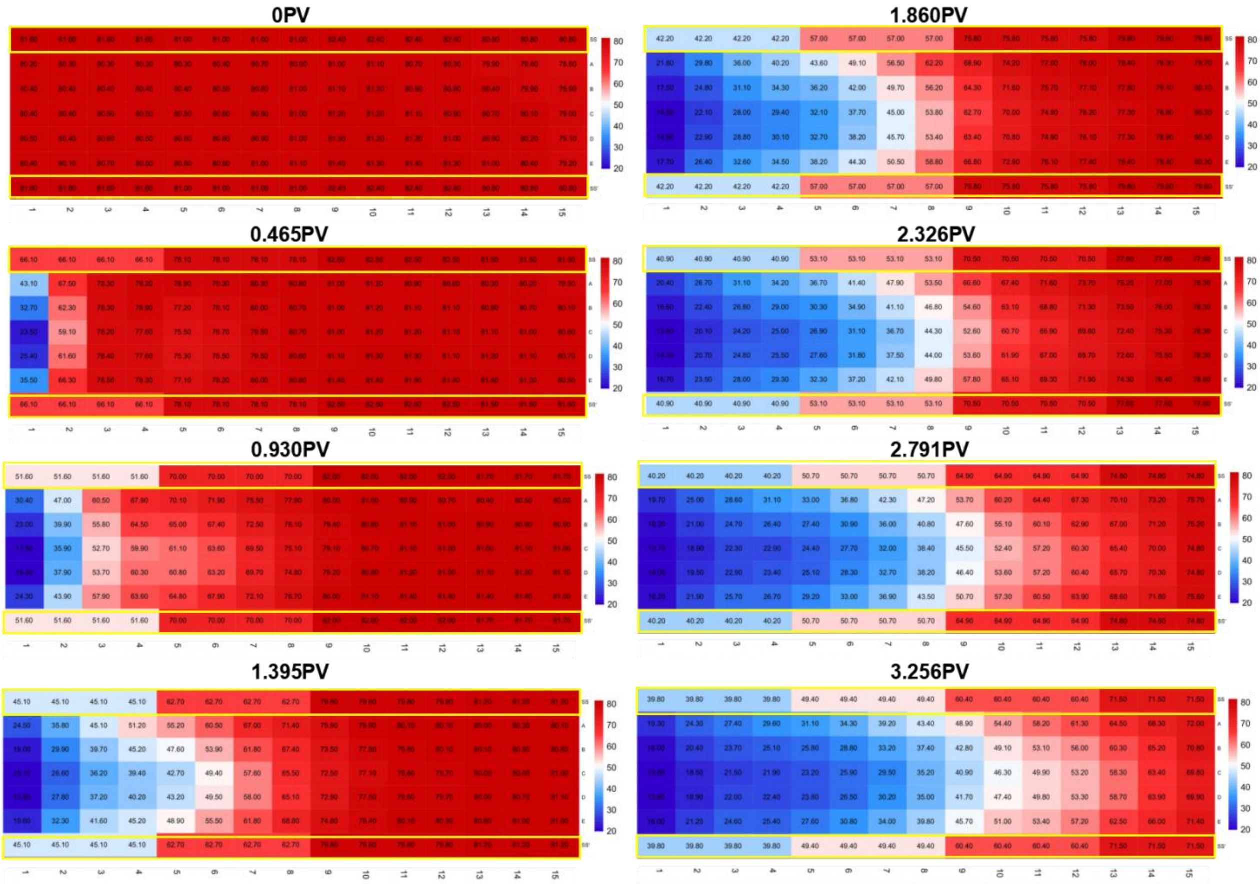


**Figure 10 The heat map of water heat mining under 120bar, 80℃ and 100ml/min flow rate condition**

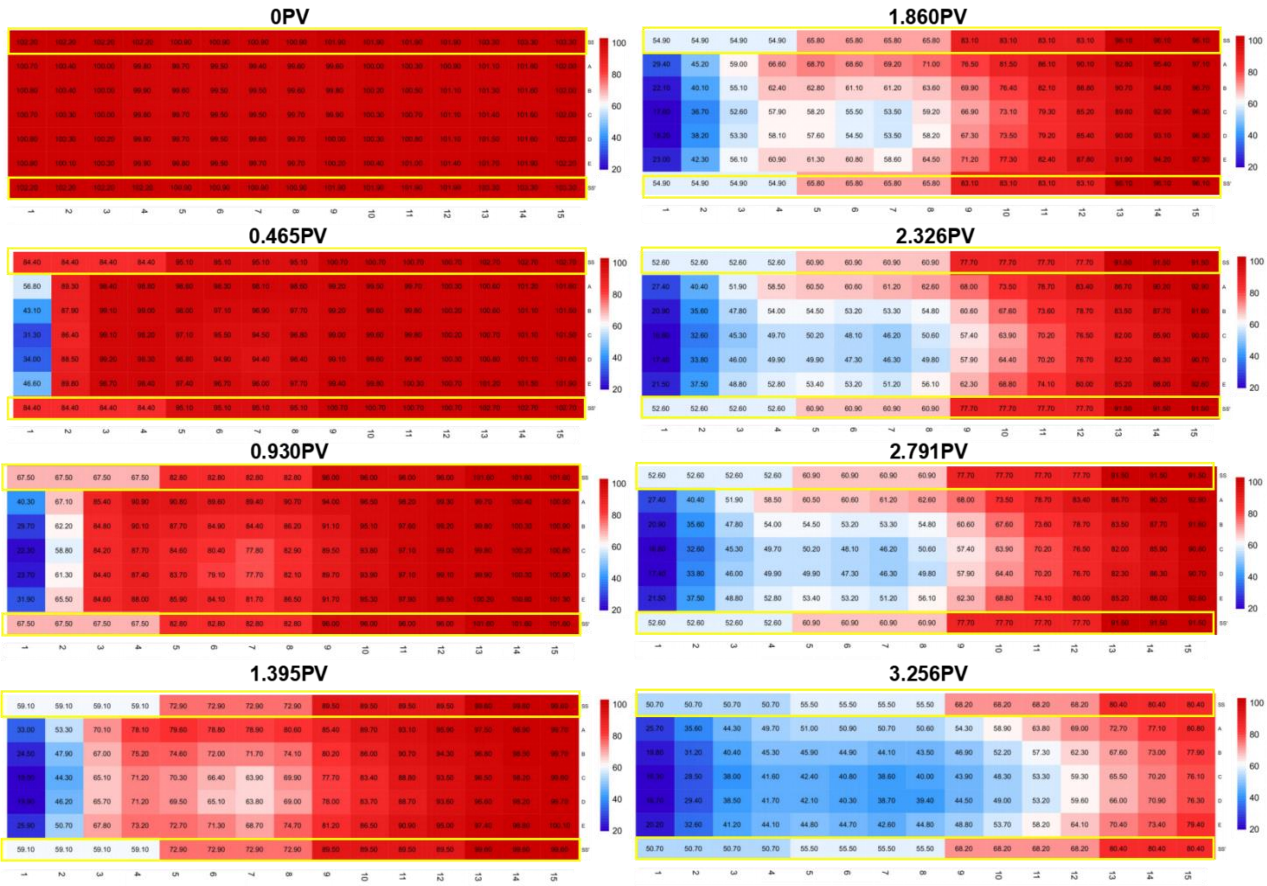


**Figure 20 The heat map of water heat mining under 120bar, 100℃ and 100ml/min flow rate condition**

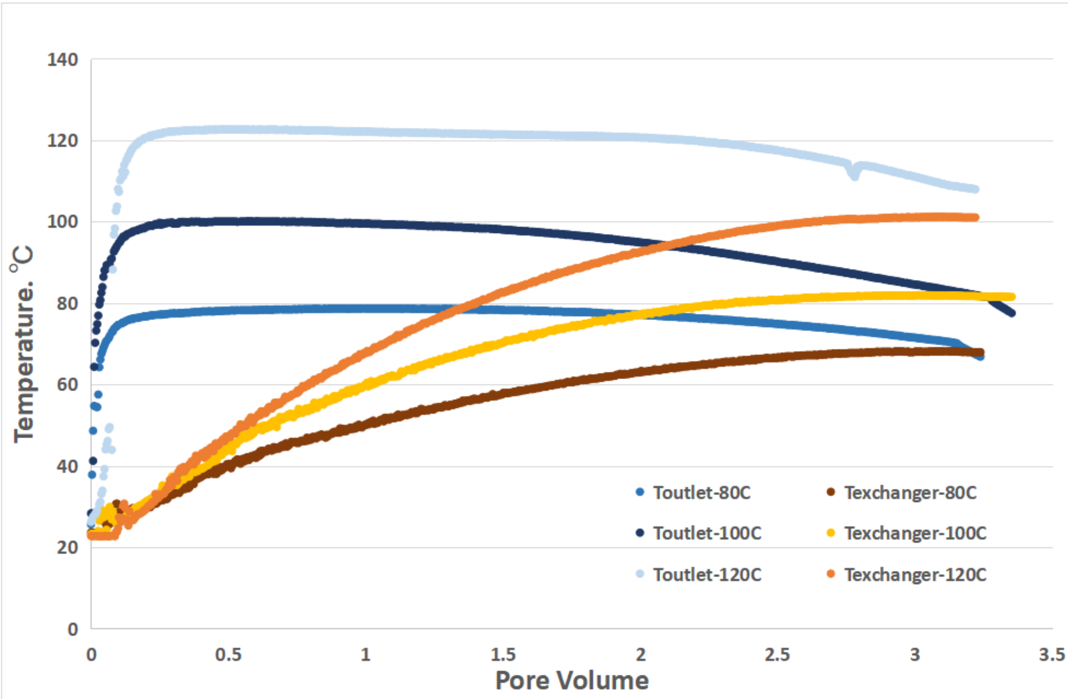


**Figure 21 The temperature of outlet and heat exchanger versus injection pore volume for water case (different temperature cases under 120bar and 100ml/min flow rate condition)**

### 4.3 Comparison of geothermal heating mining performance between supercritical CO2 and water

In this part, a comparison of heat mining performance between water and CO2 cases were discussed. For the same flow rate (100ml/min) scenario at120bar and 100℃. The results are plotted in Figure 22. Due to the high heat capacity, water case has high heat exchanger temperature at any pore volume and at the end of injection the temperature is 10℃ higher than CO2 case, showing better performance on heat mining.

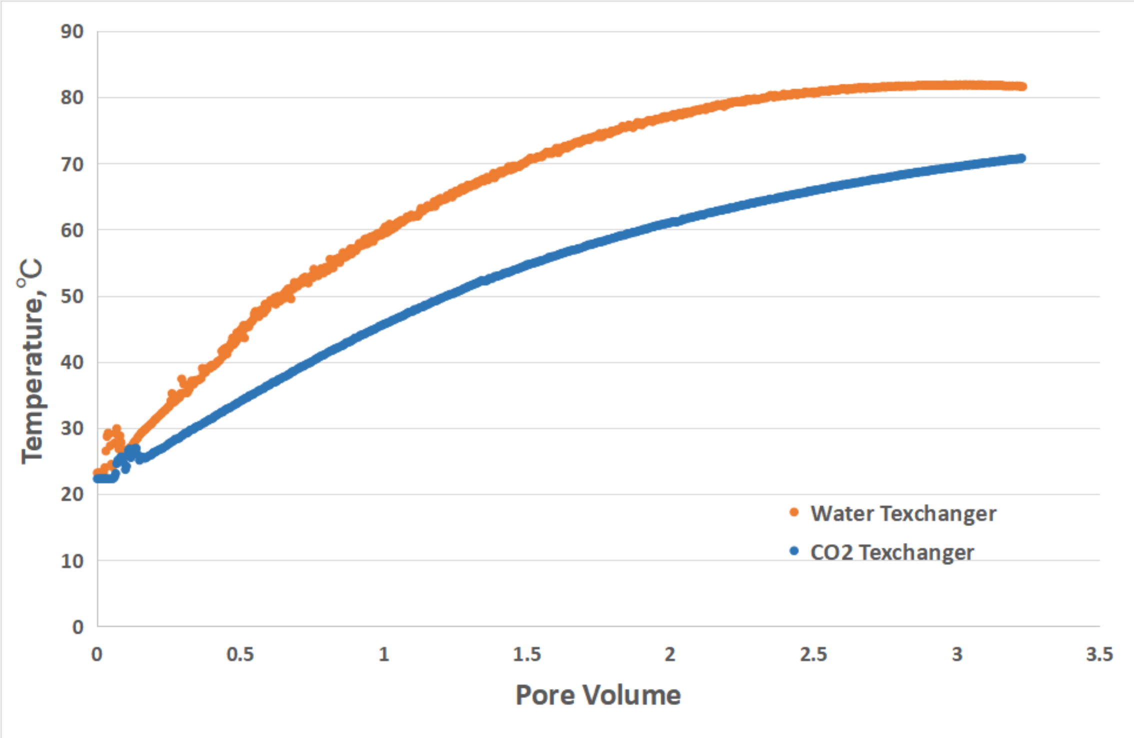


**Figure 11 Comparison between water and cases on heat exchanger temperature under the same flow rate**

For a field pilot, one of the biggest challenges of geothermal heat mining project is reinjection of heat carrying fluid, due to higher viscosity of water, it may cost more energy to reject water with lower flow rate. While, supercritical $CO_2$ has a lower viscosity than water and can be rejected with higher flow rate under the same injection pressure. So in this experiments, we kept the constant injection pressure for water case and $CO_2$ case, and the results are compared and shown in Figure 23. Since $CO_2$ was injected with higher flow rate, hence the heat exchanger temperature of $CO_2$ case is always higher than water case and at the end of injection the temperature of $CO_2$ case is 17℃ higher than water case. $CO_2$ shows a better heat mining performance than water under the constant injection pressure.

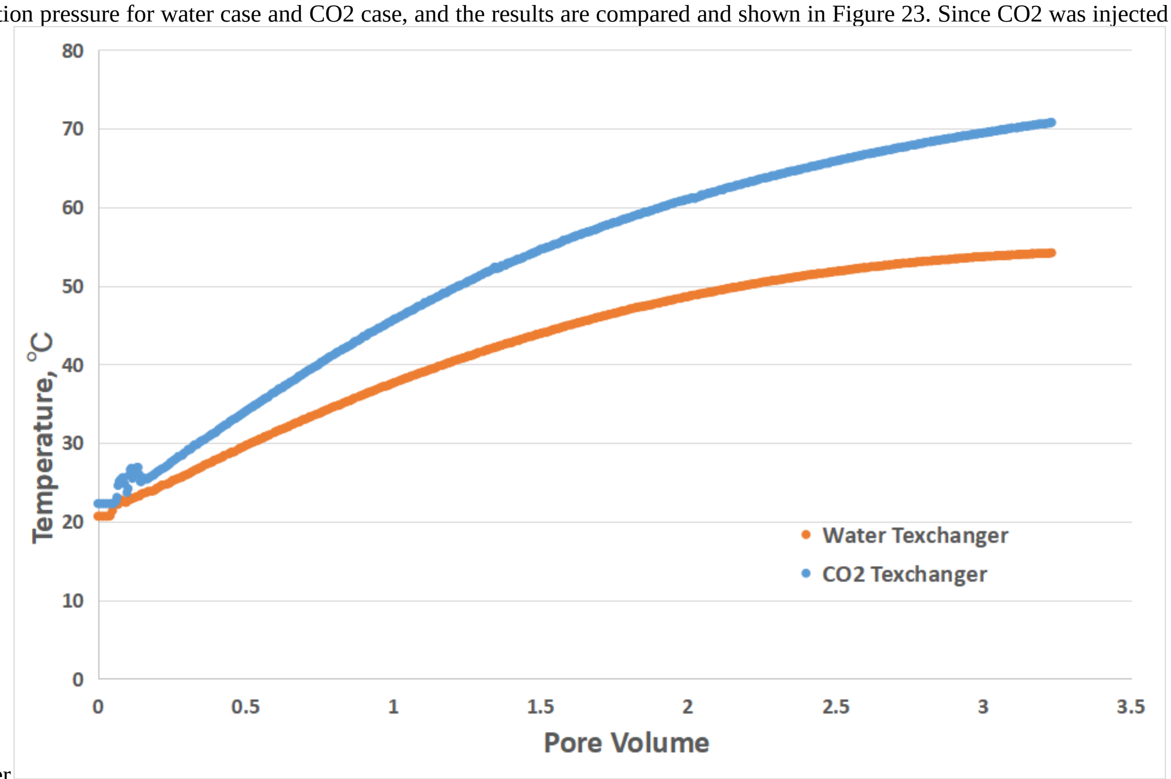


**Figure 12 Comparison between water and cases on heat exchanger temperature under the same injection pressure**

## 5 CONCLUSIONS

In this experimental study, we investigated the effect of some factors on heat mining efficiency of water and supercritical CO2 and compared the heat mining performance between water case and supercritical CO2 case by building an integrated large-scale geothermal heat mining sandpack with multiple thermocouples. The following conclusions can be obtained.

1. It is possible to develop a HPHT sandpack with multipoints thermocouples to measure the inside temperature and get an overall temperature distribution.

2. Flow rate, temperature and pressure can affect heat mining performance of supercritical CO2 and water, under different injection scenario, an economic flow rate can obtained.

3. Under the constant flow rate, water has better heat mining performance than CO2, due to its higher heat capacity.

4. Under the constant injection pressure, supercritical CO2 has higher heat mining efficiency than water, since CO2 has less viscosity and can be injected with higher flow rate.

## REFERENCES

Brown DW. A hot dry rock geothermal energy concept utilizing supercritical CO2 instead of water. Twenty-Fifth Workshop onGeothermal Reservoir Engineering 2000.

Pruess K, Azaroual M. On the feasibility of using supercritical CO2 as heat transmission fluid in an engineered hot dry rockgeothermal system. In: Proceedings of the Thirty-First Workshop on Geothermal Reservoir Engineering 2006:386–393.

Pruess K. Enhanced geothermal systems (EGS) using CO2 as working fluid - a novel approach for generating renewable energywith simultaneous sequestration of carbon. Geothermics 2006; 35:351-367.

Pruess K. On production behavior of enhanced geothermal systems with CO2 as working fluid. Energ Convers Manage 2008;49:1446-1454.

Cui, Guodong, Zhang, Liang, Tan, Chunyang, et al., 2017. Injection of supercritical CO2 for geothermal exploitation from sandstone and carbonate reservoirs: CO2–water–rock interactions and their effects. J. CO2 Util. 20, 113–128.

Cui, G., Ren, S., Rui, Z., 2017. The influence of complicated fluid-rock interactions on the geothermal exploitation in the CO2 plume geothermal system. Appl. Energy.