The experimental study of heat extraction of supercritical CO₂ in the geothermal reservoir

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Abstract. The heat transfer phenomena of supercritical CO₂ are experimentally investigated in a horizontal tube for improving the efficiency of CO₂-EGS. This study discusses the experimental verification of the numerical simulations. The experiment is conducted for the pressure, the flow rate, and particle size 1.54mm. In addition, the experiment and simulation that the maximum heat extraction is occurred at the 9MPa pressure and mass flow rate of 0.00109 kg/s. The maximum specific heat extraction at 9MPa and flow rate of 0.00082 kg/s. The results show that the numerical model has been experimentally verified for the feasibility. Furthermore, the pseudo-critical point had a significant influence on the heat extraction, temperature difference and specific heat extraction.

1 Introduction

The global warming of the earth becomes more and more serious. The use of green energy is a good choice. Geothermal energy is a renewable energy, it can be sustainable developed the new type energy [1]. Many researchers have rated it highly.

The geothermal system is divided into traditional geothermal system and non-traditional geothermal system. Non-traditional geothermal systems are normally called enhanced geothermal system (EGS). The operated process of EGS exists two stages. First, the injection well shall be at least drilled three kilometers deep and the temperature shall be more than 250°C. Second, the high pressure working fluid composed of chemical component (depend on geologic condition) is used to create the fracture in the reservoir though the injection well. The high pressure water is used to absorb the heat from the fracture of the reservoir and then flow out from the production well. Finally, the extracted heat from the working fluid can be used to generate power. In the past, water is used as working fluids, but previous studies have suggested that CO₂ can be the possible EGS working fluid for its chemistry property and density. It is a new breakthrough in the geothermal development. Brown first proposes CO₂-EGS in 2000 [2].

In recent years, there are many researchers to conduct the study of CO₂. The CO₂ exists unique feature, in areas with scarce water resources using CO₂ as an alternative to water as a working fluid [3]. The thermal siphon power generation and analysis between water and carbon dioxide is presented by Atrens et al. [3]. In 2014, Xu et al. investigated fluid and rock chemical interaction in CO₂-EGS [4]. Hsieh et al. [5] discussed the heat transfer phenomena of supercritical CO₂ are experimentally investigated upward flow vertical tube with silica-based porous media. For the availability of CO₂-EGS, researchers have discussed several topics, including CO₂ mineralization by injecting CO₂ into granite and sandstone [6], carbon capture utilization and sequestration [7], geothermal production and CO₂ sequestration in CO₂-EGS [8].

Researchers have investigated heat transfer phenomena related to CO₂-EGS, determine that buoyancy effects are significant for all flow orientations [9, 10, 11]. Most of these studies show that the flow rate and pressure are the most important parameters in the EGS. However, all of these studies have been limited by the absence of an experimental system for investigating the performance of supercritical CO₂ in a reservoir.

This study is to determine the efficiency of EGS by using the supercritical CO₂ to perform the heat extraction of the silica-based porous media in the experimental scale.

2 Experiment

2.1. Experimental apparatus

The schematic diagram of the experimental system is shown in figure 1. The experimental system consists of a CO₂ pressure vessel, high pressure pump, preheated water
bath, cooling water bath, heating unit, test section, differential pressure gage, flow meter, and data logger. The photograph of experimental system is shown in figure 2. Here, CO₂ pumped into the preheated water bath and reaches the supercritical status. Then, the supercritical CO₂ flows into the test section and extracts the heat to simulate the geothermal reservoir. The temperature profile, pressure, and mass flow rate are measured and recorded. The test section consists of stainless tube, and ten calibrated T-type thermocouples and differential pressure gage inserted into the test section to record experimental data. The inside, outside diameter and length of test sections is 29.9, 55, and 235 mm, respectively. The test section is filled with silica-base particles. To determine the behavior of supercritical CO₂, various experimental parameters are applied during the experiment including the system pressure (7.5 MPa, 9 MPa, 10 MPa, 11 MPa, and 12.5 MPa), mass flow rate (0.00082 and 0.00109 kg/s), and the particle size 1.54 mm.

In addition, the initial test section temperature is pre-set at 200°C by a constant heat flux to simulate the actual reservoir temperature.

The heat transfer rate from the tube wall to CO₂ is calculated in a steady state as follows:

\[ \dot{Q} = \dot{m}(h_{out} - h_{in}) \]  
\[ q = \frac{\dot{Q}}{\dot{m}} \]

where \( \dot{m} \) indicates the mass flow rate, \( h_{in} \) is the inlet enthalpy, \( h_{out} \) is the outlet enthalpy of supercritical CO₂.

\[ Q_{in}(W) = \dot{Q}(W) + Q_{loss}(W) \]

where \( \dot{Q} \) indicates the heat extraction rate of supercritical carbon dioxide, \( Q_{loss} \) is heat loss.

3 Experimental results and discussion

In the present study, the experiments are carried out with various supercritical pressures from 7.5 to 12.5 MPa, and various mass flow rates (0.00082 and 0.00109 kg/s) at the initial wall temperature 200°C. As the initial wall temperature reached a steady state, the supercritical CO₂ is poured into the test section. All the experimental data reported in this study is preprocessed based on the physical properties of CO₂ provided by the NIST Refrigerants Database [12]. Figure 3 shows the relationship of specific heat with temperature in the critical region under different pressure by using the NIST Refrigerants Database. As shown in this figure, the pseudo critical temperatures are 31.7°C (7.5 MPa), 40°C (9 MPa), 45.02°C (10 MPa), 49.7°C (11 MPa) and 55.95°C (12.5 MPa) for CO₂ at these pressures.

The profiles of temperature difference are shown in figure 4. The temperature difference with different pressure (7.5, 9, 10, 11, and 12.5 MPa), mass flow rate (0.00082 and 0.00109 kg/s) are presented. Through figure 4, we can observe that the temperature difference decreases as the mass flow rate increases. The reason is that the lower velocity of supercritical CO₂ is beneficial to heat extraction. In addition, the temperature difference is nonlinear with the pressure variation. It is dependent on the complex supercritical thermal properties of CO₂. We observe that the maximum temperature difference is happened at 7.5 MPa pressure. The minimum temperature difference is happened at 9 MPa pressure. It corresponding the maximum specific heat is occurred at the same pressure, i.e., pseudo critical temperatures are 31.7°C and 1 MPa pressure. The temperature difference in heat extraction is one of the important factors. The larger temperature difference is, the better heat extraction is.

For saving the experimental cost, the simulated model is built to fit the experimental system. The optimization of simulated model can provide the range of the operated parameters. Then, the best operated parameters can be found based on the experiment. First, the comparison of heat extraction between experiment and simulation with different pressure (7.5, 9, 10, 11, and 12.5 MPa), mass flow rate (0.00082 and 0.00109 kg/s) are shown in figure 5.
Through figure 5, we can observe that the heat extraction increases as the mass flow rate. The results show that the maximum heat extraction is occurred at the 9MPa pressure and 0.00109 kg/s. The error of heat extraction between the numerical model and experiment is 0.61%. In addition, simulation model has been experimentally verified. It proofs that the numerical model is suitable for simulating the supercritical CO₂ porous flow to study the complex phenomena. Therefore, it find the combination of pressure, flow rate, and particle size for the optimal heat extraction.

Second, the heat extraction of numerical model are shown in figure 6. The heat extraction of numerical model with different pressure (7.5, 9, 10, 11 and 12.5 MPa) and mass flow rate (0.00082 and 0.00109 kg/s) at particle size 1.54mm is presented. Through figure 6, we can observe that the maximum heat extraction is occurred at the 9MPa pressure. Finally, the optimal heat extraction profiles of experiment are shown in figure 7. The optimal heat extraction with different pressure (8.9, 8.95, 9, 9.05 and 9.1 MPa), mass flow rate 0.00109 kg/s is presented. Through figure 7, we can observe that the maximum heat extraction is happened on 9 MPa.

For the consideration of cost of realistic practice, the heat extraction of working fluid per kilogram is necessary to study. The specific heat extraction is defined as the heat extraction per kilogram supercritical CO₂. The specific heat extraction profiles are shown in figure 8. The specific heat extraction with different pressure (7.5, 9, 10, 11 and 12.5 MPa), mass flow rate (0.00082 and 0.00109 kg/s) at particle size 1.54mm is presented. Through figure 8, we can observe that the specific heat extraction increases as the mass flow rate decrease. The results show the maximum specific heat extraction is occurred at the 9MPa pressure and 0.00082 kg/s. Moreover, the specific heat extraction at 9MPa of 0.00082 kg/s is approximately 13.2% higher than that of 0.00109 kg/s. The specific heat extraction can point out what kind of pressure and flow rate to approach economic efficiency better. Better the specific heat extraction, the economic efficiency is.
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