Investigating the heat transfer phenomena of CO₂-EGS in the reservoir by experiment verification

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Abstract. The purpose of this study is to find the heat transfer phenomena of CO₂-EGS in the reservoir. The heat transfer model conjugated with the Brinkman model is used. This numerical model is validated by the experiment of supercritical CO₂. The heat transfer coefficient of experiment is derived from the thermal resistance method of comparison between numerical model and experiment. Further, the heat transfer coefficients with different operating conditions are build in this study. This study will provide the better combination of operating conditions for the improved heat extraction.

1 Introduction

Recently, the geothermal exploration obtains more efficiency for the technological breakthroughs, especial in the enhanced geothermal system. The geothermal temperature of deepest stratum reaches 6000 °C but power generation only need the depth of 1 km to 10 km, where geothermal temperature is 300°C. In earlier, the technology of exploitation is restricted in the extracting hot underground water directly for generating electricity. It is the reason for the few regions are feasible to develop the geothermal system. International Energy Agency indicates the geothermal projects can improve the exploration technique and decrease the cost of geothermal system. The geothermal system will be a larger utilization in future.

Nowadays, the deep geothermal power generation technology common with enhanced geothermal system (EGS) and complex energy extraction geothermal system (CEEG) are proposed for the higher efficiency of geothermal system. Water is first applied on the EGS as the working fluid because of the high latent heat, the specific enthalpy and the cheap cost. However, a number of disadvantages have to overcome, the main ones are mineralization. These will bring the pipeline fouling. Moreover, CO₂ may be the practicable working fluid for the heat extraction of EGS. The researches of EGS proliferate recently from CO₂-EGS is first proposed by Brown from 2000[1]. There are many benefits in the

CO₂-EGS, such as reducing the pumping power for the thermal siphon phenomena, hardly combining with minerals in the surface of the pipes, reducing CO₂ emissions for the geological storage, reducing cost of the maintenance and improving the efficiency of the heat extraction. In order to obtain more fully understand the CO₂-EGS, Zhang et al. compare with the heat transfer performance between CO₂-EGS and water-EGS systems [2]. Fouillac et al. discuss the sequestration benefits of CO₂ [3]. The deep-saline aquifers the advance of CO₂ sequestration [4] is presented by Rosenbauer et al.. Ueda et al. [5] and Wan et al. [6] propose the interaction of fluid and rock. A series of studies of CO₂-EGS, such as heat transmission [7], sequestration of CO₂ [8], and production behavior [9] are proposed by Pruess et al. from 2006. In addition, the chemical changes of the granite and sandstone in CO₂ injection [10], the thermosiphon of CO₂ [11], the thermal convection of CO₂ in the vertical tube [12] and miniature tube [13] are presented, respectively.

However, the above researches have some limits. We difficult to know actual circumstances of the heat transfer phenomena for few comparative studies for the heat extraction. Therefore, the purpose of this study proposes an integrated method which combines the experiment. The results can prove reliability of numerical model whereby also can observe the heat transfer phenomena of CO₂-EGS in the horizontal tube.

2 Methods

2.1 Experiment

This study investigates the efficiency of the heat extraction of supercritical CO₂ at different pressure, mass flow rate. The efficiency of the heat extraction depends on the pressure and mass flow rate. Therefore, the pressure of experimental system is assumed as 7.5, 9, 10, 11 and 12.5 MPa, and the mass flow rate is 0.00082 and 0.00109 kg/s.

To simulate the reservoir temperature, the wall of test section is heated to 200 °C as the circumstance of the reservoir. The reservoir assumes as filling the silica-base particles, the average size of particle is 1.54 mm. The schematic diagram of the experimental system is shown in figure 1. It contains of a CO₂ cylinder, high pressure pump, pre-heated bath, cooling bath, test section, differential pressure gage, flow meter, and data logger. The photograph of experimental system is shown in figure 2. The beginning of the experimental procedure injects CO₂ into the pre-heater bath and reaches the supercritical status. Then the supercritical CO₂ flows into the test section until the experimental steady. The test section is composed of the stainless steel, ten calibrated thermocouples (T-type) and the differential pressure gage, are inserted into the test section to record experimental data. The inside, outside diameter and length of the test section are 29.9, 55.0 mm, and 235.0 mm, respectively. The temperature, pressure, and mass flow rate are measured and analysis to obtain the heat extraction.

Figure 1. The schematic diagram of experimental apparatus.

Figure 2. The photograph of experimental apparatus.

2.2 Simulation

A simulated model is assumed as the part of reservoir of EGS. This model is simulated based on the experimental test section as shown in figure 3. In this model, a 3D porous media flow model combines with heat transfer model established by finite element method – COMSOL multiphysics package. The Brinkman model is presented as the porous media. The material of test section is made of stainless steel. The properties of supercritical CO₂ are interpolate function based on the National Institute of Standards and Technology (NIST) standard reference database 69.

Figure 3. The schematic diagram of test tube.

The governing equations of non-porous medium are described as follows:

Continuity equation is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad (1)$$

Momentum equation is:

$$\rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = \nabla \cdot \left[-pI + \mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla \cdot u)I \right] + F \quad (2)$$

here, μ is viscosity; u is velocity; ρ is fluid density; p is pressure and F is forced term.

The governing equations of the Brinkman model are described as follows:

Continuity equation is:

$$\frac{\partial}{\partial t}(\varepsilon \rho_f) + \nabla \cdot (u \rho_f) = Q_{br} \quad (3)$$

Momentum equation is:

$$\frac{\rho_f}{\varepsilon_p} \left(\frac{\partial u}{\partial t} + (u \cdot \nabla) \frac{u}{\varepsilon_p} \right) = -\nabla P_f + \nabla \cdot \left[\frac{1}{\varepsilon} \left\{ \mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla \cdot u)I \right\} - \left(\frac{\mu}{\kappa} + \frac{Q_{br}}{\varepsilon^2} \right) u + F \right] \quad (4)$$

here, ε is porosity; κ is permeability; Q_{br} is mass force and the subscript label f means fluid and p is media.

The Fourier's law of porous medium are described as follows:

$$\frac{\partial}{\partial t}[(1 - \varepsilon)\rho_p C_{p,p} T_p] - (1 - \varepsilon)\nabla \cdot (k_p \nabla T_p) = 0 \quad (5)$$

Energy balance equation is:

$$\frac{\partial}{\partial t}[\varepsilon \rho_f C_{p,f} T_f] + \nabla \cdot (\rho_f C_{p,f} D T_f) - \varepsilon \nabla \cdot (k_f \nabla T_f) = 0 \quad (6)$$

here, T is temperature; C_p is specific heat; k is thermal conductivity and D is Darcy flow.

The relationship between heat extraction, temperature difference and thermal resistance is defined as follows:

$$Q = \frac{\Delta T}{R_{th}} \quad (7)$$

$$R_{th} = \frac{1}{hA} \quad (8)$$

here, Q is the heat extraction, ΔT is the temperature difference between the inlet and outlet of test tube, R_{th} is the thermal resistance of test tube, and A is the surface area of the heat exchange in the test section.

The heat transfer coefficient of numerical model can be obtained from the thermal resistance. Therefore, the heat transfer coefficient can be derived from the validation between experiment and numerical model.

3 Results and Discussion

This study processes the experimental verification of the heat extraction under the various pressure and mass flow rate. The comparison of the heat extraction between simulation and experiment with the different pressure (7.5, 9, 10, 11 and 12.5 MPa) and mass flow rate (0.00082 and 0.00109 kg/s) is presented.

Through figure 4 & 5, the heat extraction increases as the mass flow rate increases. We can find that the maximum heat extraction is 39.22 W occurred at 9 MPa. It is better than that of 7.5 and 12.5 MPa, and reaches the highest value at 0.00109 kg/s. We observe that the heat extraction at 7.5 to 9 MPa increases 44.93 %, at 9 to 10 MPa decreases 8.08 %, then decreases 15.64 % from 10 to 11 MPa, final decreases 4.42 % from 11 to 12.5 MPa. The nonlinear variation of heat extraction is shown as the pressure variation. The major reason is that the pressure depends on the thermal properties of the supercritical CO₂. The error of heat extraction are less than $\pm 1.9\%$. It can proof that the simulation is reliable.

Through figure 6 & 7, the outlet temperature increases as the mass flow rate decreases. We can find that the maximum outlet temperature is 50.90 °C occurred at 7.5 MPa, which is better than other pressures, and reached the highest value at 0.00082 kg/s. We observe that the outlet temperature at 7.5 to 9 MPa decreases 9.52 %, at 9 to 10 MPa increases 3.21 %, then increases 2.09 % from 10 to 11 MPa, final increases 2.7 % from 11 to 12.5 MPa. The analysis show that the error outlet temperature are less than $\pm 1.7\%$. It can proof that the simulation is very reliable under the variable pressure and mass flow rate.

Figure 4. The comparison of heat extraction between experiment and simulation (mass flow rate is 0.00082 kg/s).

Figure 5. The comparison of heat extraction between experiment and simulation (mass flow rate is 0.00109 kg/s).

Figure 6. The comparison of outlet temperature between experiment and simulation (mass flow rate is 0.00082 kg/s).

Figure 7. The comparison of outlet temperature between experiment and simulation (mass flow rate is 0.00109 kg/s).

Figure 8. The profiles of heat transfer coefficient with different pressure and mass flow rate (mass flow rate is 0.00082 kg/s).

Figure 9. The profiles of heat transfer coefficient with different pressure and mass flow rate (mass flow rate is 0.00109 kg/s).

Figure 8 & 9 shows the heat transfer coefficient of simulation. It derives from the definition of thermal resistance. Through the validation results of numerical model, the heat transfer coefficient can be applied as the actual circumstances of experimental system. We also observe that the heat transfer coefficient increases as the

mass flow rate increases. We can find that the maximum heat transfer coefficient is $1174.1 \text{ W/m}^2 \cdot \text{k}$ occurred at 9 MPa, which is better than that of at 7.5 and 12.5 MPa, and reaches the highest value in 0.00109 kg/s . We observe that the heat transfer coefficient at 7.5 to 9 MPa significantly increases to 311.4 %, at 9 to 10 MPa decreases 41.14 %, then decreases 32.02 % from 10 to 11 MPa, final decreases 23.95 % from 11 to 12.5 MPa. In addition, it figures out the complex phenomena of porous flow of supercritical CO_2 to study the actual circumstances of the heat extraction.

4 Conclusion

This study is to investigate the actual circumstances of the heat transfer phenomena of CO_2 -EGS. The results show that the error of the heat extraction between simulation and experiment is very small. The heat transfer coefficient of this experimental system can derives from the comparison between the experiment and simulation. It observe that the best heat extraction close to 9 MPa. In addition, the complex phenomena of the porous flow of supercritical CO_2 is shown in the numerical model and proof the nonlinear tendency of the heat extraction with various pressure and mass flow rate. These results can validate that the experimental system is very reliable and reduces the cost of actual test of CO_2 -EGS. This study will provide the better combination of operating conditions for the improved heat extraction.

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References

1. D. Brown, Geothermal Reservoir Engineering **25**, 233 (2000)
2. F.Z. Zhang, P.X. Jiang, R.N. Xu, Applied Thermal Engineering **61**, 236 (2013)
3. C. Fouillac, B. Sanjuan, S. Gentier, C.L Isabelle, Carbon Capture and Sequestration **3**, 3 (2004)
4. R.J. Rosenbauer, K. Tamer, J.L. Palandri, Fuel Processing Technology **86**, 1581 (2005)
5. A. Ueda, K. Kato, T. Ohsumi, T. Yajima, H. Ito, H. Kaieda, R. Meycalf, H. Takase, Geochemical Journal **39**, 417 (2005)
6. Y. Wan, T. Xu, K. Pruess, Geothermal Reservoir Engineering **36**, SGP-TR-191 (2011)
7. K. Pruess, M. Azaroual, Geothermal Reservoir Engineering **31**, 386 (2006)
8. K. Pruess, Geothermics **35**, 351 (2006)
9. K. Pruess, Energy Conversion and Management **49**, 1446 (2008)
10. L. Lihui, S. Yuko, B. Greg, Y. Nakamichi, H. Energy Conversion and Management **44**, 1399 (2003)

11. A.D. Atrens, G. Hal, R. Victor, *Geothermics* **39**, 161 (2010)
12. P.X. Jiang, Y.J. Xu, R.F. Shi., S. He, J.D. Jackson, *Applied Thermal Engineering* **24**, 1255 (2004)
13. S.M. Liao, T.S. Zhao, *International Journal of Heat and Mass Transfer* **45**, 5025 (2002)