Investigation on the influence of thermophysical properties of working fluid on heat extraction from hot dry rock

Yuanming Wang¹,², Jinxu Zhang¹,², Xueling Liu¹,²* and Jiansheng Wang¹,²

¹ Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, Tianjin, 300354, China
² Geothermal Research & Training Center, Tianjin University, Tianjin, 300354, China
* lxling@tju.edu.cn

Abstract. High pressure hydraulic fracturing is a safe and environment-friendly method for the utilization of hot dry rock. In present work, the heat transfer characteristics of water and helium in hot dry rock are probed with numerical simulation. The results show that reducing the injection temperature, increasing the pressure difference between the injection well and producing well, can increase the heat extraction rate and the total heat extraction. Furthermore, under the condition of same pressure difference and injection temperature, the heat extraction rate of helium is greater than that of water, which indicates that helium is more suitable for hot dry rock heat extraction.

1. Introduction

The utilization of geothermal energy can be divided into direct thermal utilization and indirect utilization through power generation [1]. Hot dry rock (HDR), also known as enhanced geothermal system (EGS), refers to the high-temperature rock mass with temperature higher than 200 °C, buried thousands of meters underground, without fluid or only a small amount of underground fluid [2] [3]. The study of hot dry rocks began in the United States in the 1970s [4]. The heat transfer characteristics of hot dry rock reservoirs are affected by working fluid characteristics, thermal storage structure and operating parameters. Zhao et al. [5] found that large fracture cross-section area and high fluid velocity can enhance the heat transfer effect. Zhou et al. [6] found that reducing the injection temperature, flow rate, and the fracture permeability can improve the heat recovery per unit working fluid and the heat supplement rate of surrounding rock. Bai et al. [7] studied the thermal properties of rock specimens under different confining pressure fluid flow rates, and proposed an analytical model for the experimental results. Chapman [8] proposed a thermal boundary layer model to obtain the average heat transfer coefficient (HTC) of laminar flow in a flat plate at a constant temperature. Zhao [9] combined the previous experimental results with the analytical solution of a rectangular model embedded in a single line, the results showed that HTC was positively correlated with fluid flow. Chen [10] [11] proposed a transient solution to describe the local heat transfer process by dynamic heat transfer coefficient, which was extended to the reservoir scale heat transfer simulation. Hadgu et al. [12] studied the influence of horizontal and vertical fracture direction on reservoir thermal extraction performance. The results showed that the influence of horizontal well was small, while for vertical well, the fracture direction with the best thermal extraction performance was high dip angle and low or high tendency. Wang [13] studied the effects of reservoir heterogeneity and anisotropy on CO2 based EGS sequestration and thermal recovery. Cao [14] compared the EGS with water as the medium and the EGS with supercritical...
CO₂ as the medium. The results showed that the thermal extraction speed of supercritical CO₂ was fast, but the service life was short. Shi [15] found that increasing the thermal expansion coefficient and reducing the injection temperature can accelerate the thermal penetration of the system, increasing the number of fractures and the complexity of fractures had a good impact on the enhanced geothermal system running.

2. Physical and mathematical models

2.1. Physical model
In present work, the fracture is randomly generated in porous media as shown in figure 1. The computational domain is set as 800 m × 800 m rock mass within 3000 m to 3800 m underground. As shown in figure 2, the reservoir with 500 m × 500 m × 500 m in the center of the rock mass is permeable reservoir, and the rest part is impermeable rock mass. The heat extraction system is consist of a injection well and a producing well. The diameter of both wells is 0.3 m and the well depth is 500 m. The well spacing between the injection well and producing well is 300 m.

2.2. Mathematical model
In present numerical process, some assumptions are made. The rock in the reservoir is assumed to be isotropic porous material, and the permeability is lower than that of fracture. The flow of working fluid in reservoir meets to Darcy’s law, and the loss of working fluid is ignored. The influence of thermal stress caused by temperature change on permeability can be ignored as well. In addition, the chemical reaction between working fluid and rock is neglected. The continuity equation of working fluid in rock is described as following

\[ S \rho_f \frac{\partial P}{\partial \tau} + \nabla \cdot (\rho_f \mathbf{u}_s) = -Q \]  

Where \( S \) is the water storage coefficient of rock (1 / Pa), \( \mathbf{u}_s \) is the seepage velocity in rock (m/s), and \( Q \) is the weight source (kg / (m³ / s)).

The velocity of working fluid in rock meets Darcy’s law

\[ \mathbf{u}_s = -\frac{k_s}{\mu_f} \nabla P + \rho_f g \mathbf{z} \]  

Where \( k_s \) is rock permeability (m²), \( \mathbf{z} \) is reservoir height (m).

The continuity equation of working fluid flow in fracture is as follows

\[ d_f S_f \rho_f \frac{\partial P}{\partial \tau} + \nabla \cdot (d_f \rho_f \mathbf{u}_j) = d_f Q \]  

Where \( S_f \) is the fracture water storage coefficient (1 / Pa); \( d_f \) is the fracture thickness (m).

The velocity of working fluid in fracture accords with Darcy’s law
\[ \tilde{u}_f = -\frac{k_f}{\mu_f} (\nabla \cdot P + \rho_g g \nabla \tau z) \] (4)

Where \( k_f \) is fracture permeability (m²).

Because the seepage velocity in the rock matrix is much smaller than that in the fracture, it can be approximately considered that the temperature of the rock matrix and the fluid is synergetic

\[ (\rho c)_\text{eff} \frac{\partial T}{\partial \tau} + (\rho c)_\text{eff} \tilde{u}_s \cdot \nabla T_s = \nabla (\lambda_{\text{eff}} \nabla T_s) \] (5)

\[ (\rho c)_\text{eff} = (1 - \varphi_s) \rho_s c_s + \varphi_s \rho_f c_f \] (6)

\[ \lambda_{\text{eff}} = (1 - \varphi_s) \lambda_s + \varphi_s \lambda_f \] (7)

Where \((\rho c)_\text{eff}\) is equivalent specific heat capacity of rock matrix (J/ (m³·K)), \(\lambda_{\text{eff}}\) is equivalent heat transfer coefficient of rock matrix (W / (m·K)), \(\varphi_s\) is porosity of rock matrix.

Because of the high seepage velocity of working fluid in fracture, it is necessary to consider the effects of convection heat transfer between the working fluid and the wall, and the heat transferred in such way is equivalent to an internal heat source, which can be defined as following

\[ \frac{d}{\partial \tau} (d_f \rho_f c_f \tilde{u}_f \cdot \nabla T_f) + d_f \rho_f c_f \tilde{u}_f \cdot \nabla T_f = \nabla (d_f \lambda_f \nabla T_f) + h(T_s - T_f) \] (8)

3. Thermal extraction performance of water

In present work, the temperature of injection well is set to be 70 °C, the heat extraction capacity of water in hot dry rock is investigated under three pressure difference (injection well and producing well) of 22MPa, 30MPa and 34MPa. Furthermore, the heat recovery rate is mainly used to characterize the heat extraction capacity of working fluid, and the heat extraction rate is defined as the heat extraction capacity of unit mass working fluid.

As shown in figure 3(a), the thermal extraction rate increases significantly with the increase of the pressure difference between the injection well and producing well. The higher the pressure difference between the injection well and producing well, the higher of the extraction rate. When the pressure difference between injection well and producing well increases from 22MPa to 34MPa, the thermal extraction rate increases by 57%.

The influence of injection temperature on heat removal capacity, under the condition of the same fluid flow rate, the pressure difference of 34MPa between injection well and producing well is investigated. As shown in figure 3(b), when the injection temperature increases, the thermal extraction rate decreases. When the injection temperature increases from 70 °C to 90 °C, the thermal extraction rate under stable state decreases from 788425W to 540978W, which increases nearly by 31%. Therefore, reducing the temperature of the injected working fluid will increase the heat extraction.

![Figure 3](image-url)

**Figure 3.** (a)Variation of heat extraction with various pressure differences (b)Variation of Heat extraction with various injection temperatures
4. Thermal extraction performance of helium

The heat extraction capacity of helium in hot dry rock reservoir under the conditions of injection well and producing well pressure difference of 22MPa, 30MPa, 34MPa and injection temperature of 70 °C are probed. As shown in figure 4(a), in the first 1000 days of the same operation, with the increase of the pressure difference between the injection well and producing well, the heat recovery rate also increases significantly. When the pressure difference between the injection well and producing well increases from 22MPa to 34MPa, the heat recovery rate increases by 227%.

![Figure 4.](image)

Figure 4. (a) Variation of helium heat extraction with various pressure differences (b) Variation of Heat extraction with various injection temperatures

As shown in figure 4(b), when the injection temperature of hot fluid decreases, the thermal extraction rate increases. When the injection temperature was reduced from 90 °C to 70 °C, the heat extraction rate increased by 30%. However, in the stable operation state, the heat extraction rate does not change obviously with the injection temperature. The reason is because in the stable state, the temperature of helium medium is very close to the temperature of the rock, which indicates that the influence of the injection temperature on the fluid temperature is no longer dominant after the intense heat transfer in the unstable state, so the change of the heat recovery rate and the injection temperature is not obvious.

5. Comparison of thermal extraction characteristics of water and helium

As shown in figure 5. The pressure difference between injection well and producing well of present two working fluid is 22MPa and the injection temperature is 70 °C. In the initial stage of heat extraction, the heat extraction rate of helium medium is an order of magnitude higher than that of water medium. However, due to the larger heat extraction capacity of helium, the temperature of rock decreases rapidly, and the temperature difference between work fluid and rock mass decreases. Therefore, the heat extraction rate of helium decays rapidly. It can be found that the heating effect of helium medium is much greater than that of water medium.

![Figure 5.](image)

Figure 5. Variation of water and helium heat extraction
6. Conclusion
The heat extraction feature in hot rock with two different working fluids is numerical investigated. The numerical results indicate that the injection temperature and the pressure difference between injection well and producing well have obvious effects on the seepage characteristics of water and helium. It can be found that reducing the injection temperature and increasing the pressure difference between injection well and producing well can effectively increase the heat recovery rate and the total heat extraction, and the heat energy inside hot dry rock can be utilized to the maximum extent. Furthermore, under the same working parameters, the heat recovery rate of helium medium is much higher than that of water medium.

Acknowledgments
The authors gratefully acknowledge the financial support provided by the Natural Science Foundation of Tianjin (No.18JCYBJC22100).

References
[1] Zhou Z., Liu S., Liu J. (2015) Study on the Characteristics and Development Strategies of Geothermal Resources in China. J. Natural Resources, 30:1210-1221.
[2] Brown D. (2015) The US Hot Dry Rock program-20 years of experience in reservoir testing. http://www.geothermalenergy.org/pdf/GAstandard/
[3] Brown D. (1995) Verification flow testing of the HDR reservoir at Fenton Hill, New Mexico. NM, USA: Los Alamos National Lab.
[4] Ma W. W., Wang Y.D., Wu X.T., et al. (2020) Hot dry rock (HDR) hydraulic fracturing propagation and impact factors assessment via sensitivity indicator. Renew. Energy, 146: 2716-2723.
[5] Zhao J. (1987) Experimental Studies of the Hydro-Thermo-Mechanical Behaviour of Joints in Granite PhD thesis. Imperial College, London.
[6] Zhou L., Zhang Y., Hua Z., et al. (2019) Analysis of influencing factors of the production performance of an enhanced geothermal system (EGS) with numerical simulation and artificial neural network (ANN). Energy Build., 200: 31–46.
[7] Bai B., He Y.Y., Li X.C., et al. (2017) Experimental and analytical study of the overall heat transfer coefficient of water flowing through a single fracture in a granite core. Appl. Therm. Eng., 116:79–90.
[8] Chapman A.J., (1984) Heat Transfer, fourth ed., Macmillan Publishing Company. New York.
[9] Zhang G.W., Zhu J.L., Li J., et al. (2015) The analytical solution of the water-rock heat transfer coefficient and sensitivity analyses of parameters, in: Proceedings World Geothermal Congress. Melbourne, Australia.
[10] Chen Y., Ma G. W., Wang H. D. (2018) Heat extraction mechanism in a geothermal reservoir with rough-walled fracture networks. Int. J. Heat Mass Transf.,126: 1083-1093.
[11] Catalan L., Araiz M., Gurutze, et al. (2019) New opportunities for electricity generation in shallow hot dry rock fields: A study of thermoelectric generators with different heat exchangers. Energy Conv. Manag., 200.
[12] Hadgu T, Kalinina E, Lowry T S. (2016) Modeling of heat extraction from variably fractured porous media in Enhanced Geothermal Systems. Geothermics, 61: 75-85.
[13] Wang C.L., Huang Z.J., LU Y.H., et al. (2019) Influences of Reservoir Heterogeneity and Anisotropy on CO_2 Sequestration and Heat Extraction for CO_2-Based Enhanced Geothermal System. J. Therm. Sci., 28(02):319-325.
[14] Cao W, Huang W, Jiang F. (2016) Numerical study on variable thermophysical properties of heat transfer fluid affecting EGS heat extraction. Int. J. Heat Mass Transf., 92: 1205-1217.
[15] Shi Y, Song X, Li J, et al. (2019) Numerical investigation on heat extraction performance of a multilateral-well enhanced geothermal system with a discrete fracture network. Fuel, 2019, 24.