

A Numerical Study of Factors Affecting the Efficiency of Closed-Loop Geothermal Wells

Sai Liu, and Arash Dahi Taleghani

John and Willie Leone Family Department of Energy and Mineral Engineering, The Pennsylvania State University, University Park, PA 16802, United States

Keywords

Geothermal energy; Closed-loop geothermal well; Heat transfer; Production efficiency

ABSTRACT

Geothermal energy has a promising prospect of becoming a feasible source of clean energy. However, conventional open-loop geothermal systems need continuous water circulation, which limits their application in dry areas. On the other hand, long-term fluid injection into the reservoir may cause issues such as induced seismicity. To overcome these drawbacks, closed-loop geothermal systems (CLGS) are proposed as they are not requiring any water withdrawal. However, the mechanisms controlling the efficiency of closed-loop systems are not well-analyzed. Therefore, a coupled three-dimensional model is established using finite element methods to explore factors affecting production efficiency in a closed-loop geothermal well (CLGW). The model is validated against the experimental results available in the literature. Using this model, the effect of several factors on the harvested heat are investigated. These factors include thermal conductivity of cement, circulation velocity of the fluid, and the heat capacity of the circulating fluid. The results indicate that increasing the cement thermal conductivity enhances produced fluid temperature as well as the thermal power. As the circulation velocity of the working fluid increases, the temperature of produced fluid decreases but thermal power increases asymptotically. Using circulating fluid with high heat capacity would result in a higher thermal power up to a limit. Results and conclusions obtained in this paper may provide an insight to design closed-loop systems.

1. Introduction

Emissions and pollution due to consumption of fossil fuels have become a serious problem in terms of greenhouse effects that has encourage countries to pursue renewable source of energies with no such issues. Geothermal energy is one of those resources that might be available independent of time or weather conditions. To extract thermal energy from the underground, the

typical approach is drilling a well and producing hot water from underground reservoirs. Extracting hot water from the subsurface is the so-called open-loop geothermal system. However, there should always exist enough amount of water to extract heat from the subsurface. Due to the limitation of underground waters, Enhanced Geothermal Systems (EGS) has been evolved over the years. The EGS concept is to extract heat by creating a fracture system in the subsurface to which water can be circulated through injection wells. Injected water is pushing existing water and also heated by contact with the rock as it returns to the surface through production wells, as in naturally occurring hydrothermal systems. Creating an enhanced or engineered geothermal system requires high enough permeability of the rock which can often be achieved artificially by hydroshearing or hydraulic fracturing the wells allow large volume of water to be circulated in the system for energy extraction at economic rates (Kazemi et al., 2019; Pollack and Mukerji, 2019; Zhang and Zhao, 2020). Seismicity due to fault activations is another issue that limits the operation of these systems (Knoblauch and Trutnevyte, 2018; Andrés et al., 2019; Rathnaweera et al., 2020). Induced seismicity is often driven by significant pore pressure changes due to fluid injection or extraction.

The open-loop systems exhibit few advantages due to the characteristics of fluid circulation. First, the reservoir works as a part of the fluid circulation channel (heat exchanger), thus eliminating the need for drilling a horizontal well, which cuts back additional drilling costs. Second, the heat extraction rate is significantly high in these systems as heat transfer rate is dominated by the forced convection which is often enhanced by fractures in EGS. Many studies have been devoted to the development of open systems over the years. For example, Vaganova and Filimonov (2017) built a three-dimensional time-dependent numerical model to simulate open-loop systems, which considered the temperature distribution and fluid filtration in the subsurface. They solved the equations of the model by combining a finite difference method and implicit central-difference algorithm. Di Dato et al. (2022) studied the effect of reservoir heterogeneity on thermal breakthrough time and fluid recirculation ratio, which describe the heat production of shallow open-loop systems. Adopting a new configuration of a coaxial open-loop geothermal system, Dai et al. (2019) performed an in-situ experiment on geothermal energy exploitation to evaluate the heat extraction rate from the subsurface. Tilley and Baumann (2012) proposed a mathematical solution to characterize the stationary temperature distribution inside staged open-loop wells, based on which the thermal energy loss in the wells was analyzed quantitatively.

Regardless of the advantages, there are also shortcomings in open-loop systems. In the traditional open-loop geothermal system, water as the circulation fluid needs to be supplemented continuously during the whole heat extraction process (Dahi Taleghani, 2013). This prevents it from being used in dry areas and induces environmental problems like seismicity. To surmount this issue, the closed-loop geothermal well (CLGW), which does not need a constant source of water, was proposed in recent years. In the meantime, some research has been done to investigate the efficiency of CLGW. For instance, Bu et al. (2012) put forward a numerical model to quantify the thermal power of CLGW which was established based on abandoned oil and gas wells. By introducing hydraulic fractures with high thermal conductivity, Ahmadi and Dahi Taleghani (2016) conducted a comprehensive numerical study to assess the feasibility of exploiting thermal energy from a closed-loop fractured reservoir. Song et al. (2018) established a time-dependent numerical model which accounts for variable heat transfer coefficients and carried out numerical simulations to investigate heat extraction from closed-loop systems.

Beckers et al. (2022) performed a series of numerical simulations to evaluate the technical and economic limitations of a CLGW for heat extraction and consequently power generation.

However, research on the production of CLGW is far from enough, the mechanisms that affect the production efficiency of CLGW are not completely ascertained. To further address the problem, in this paper, a coupled three-dimensional CLGW model is built with Finite Element Methods. Using this model, a series of numerical simulations were performed to explore the effects of a few factors on the efficiency of a CLGW.

2. Modelling of CLGW

The longitudinal section and boundary conditions of the closed-loop geothermal well (CLGW) model are demonstrated in Figure 1. The geometric model is a vertical cylinder that consists of various components, including rock formation, cement, casing, and tubing. The ring-shaped space between casing and tubing is used as the injection channel, while space inside the tubing is adopted as the output channel. Fluid with a constant temperature is injected from the injection channel and flows out from the output channel after being heated by the high-temperature geothermal reservoir.

Based on this three-dimensional model, numerical simulations are performed using the finite element method. The intended results are the production temperature, i.e., the temperature of fluid flowing out through the output channel; and the thermal power, which is the produced heat from the well per unit time. The effects of some critical factors on the simulation results will be explored.

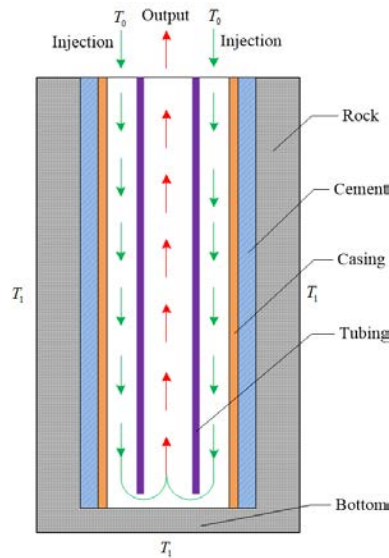


Figure 1: Diagram of a closed-loop geothermal well.

3. Governing equations

The main physics governing the problem is the heat transfer between different components of the well system in the subsurface. The heat transfer occurs through the reservoir, cement, casing, tubing, and finally a working fluid circulating inside the well. Additionally, if the reservoir is

considered composed of porous media, fluid flow in the porous media needs to be taken into consideration. In this case, Darcy's flow model is employed to calculate fluid flow in the porous media. The corresponding governing equations involved in this study are the partial differential equations listed below.

3.1 Heat transfer

Heat transfer in the numerical model can be characterized by the corresponding energy conservation equations. For the solids, the energy conservation equation is formulated as

$$\rho_s C_{p,s} \frac{\partial T}{\partial t} - \nabla(k_s \nabla T) = 0 \quad , \quad (1)$$

where T is temperature; t is time; ρ_s is the density of solids; $C_{p,s}$ is the heat capacity of solids under constant pressure; k_s is the thermal conductivity of solids. For the circulation fluid in the well, the energy conservation equation is expressed as

$$\rho_f C_{p,f} \frac{\partial T}{\partial t} - \nabla(k_f \nabla T) + \rho_f C_{p,f} \mathbf{u} \nabla T = 0 \quad , \quad (2)$$

where ρ_f is the density of the circulation fluid in the well; $C_{p,f}$ is the heat capacity of the circulation fluid; k_f is the thermal conductivity of the circulation fluid; \mathbf{u} is the flow velocity of the circulation fluid. For the heat transfer in the geothermal reservoir, if we consider the reservoir to be composed of porous media, it is assumed that the porous media are saturated. The energy conservation equation for the porous media is formulated as

$$\left(\rho C_p\right)_{eff} \frac{\partial T}{\partial t} - \nabla(k_{eff} \nabla T) + \rho_w C_{p,w} \mathbf{v} \nabla T = 0 \quad , \quad (3)$$

where ρ_w is the density of the fluid in the reservoir; $C_{p,w}$ is the heat capacity of fluid in the reservoir; \mathbf{v} is the flow velocity of the fluid in the reservoir; $\left(\rho C_p\right)_{eff}$ is the effective heat capacity of the porous media, which is calculated as

$$\left(\rho C_p\right)_{eff} = (1 - \varepsilon) \rho_s C_{p,s} + \varepsilon \rho_w C_{p,w} \quad , \quad (4)$$

where ε is the porosity of the porous media; k_{eff} is the effective thermal conductivity of the porous media, expressed as

$$k_{eff} = \varepsilon k_w + (1 - \varepsilon) k_s \quad , \quad (5)$$

where k_w is the thermal conductivity of fluid in the reservoir; The thermal power obtained at the outlet of the output channel can be calculated using the following equation.

$$P = q \rho_f C_{p,f} (T_{out} - T_{in}) \quad , \quad (6)$$

where q is the fluid circulation rate in the well; T_{in} is the temperature of the fluid at the inlet; T_{out} is the temperature of the fluid at the outlet.

3.2 Fluid flow in the reservoir

Apart from heat transfer through conductivity, fluid flow in the reservoir and its potential impact on heat transfer through convection are also incorporated into our model. To account for this aspect, Darcy's flow is assumed in the rock and coupled with the mass balance for the fluid, i.e.

$$\frac{\partial(\epsilon\rho_w)}{\partial t} - \nabla(\rho_w \mathbf{v}) = 0 , \quad (7)$$

where \mathbf{v} , the flow velocity of the fluid in the reservoir, is calculated as

$$\mathbf{v} = \frac{k}{\mu_w} (-\nabla P + \rho_w \mathbf{g}) , \quad (8)$$

where k is the permeability of the reservoir; μ_w is the viscosity of the fluid in the reservoir; P is the fluid pressure in the reservoir; \mathbf{g} is a vector of the gravitational acceleration. Some previous research, e.g. (Ahmadi and Dahi Taleghani, 2016), considered the variation of the reservoir fluid density induced by temperature changes (convection in the reservoir). However, the magnitude of the natural convection is much smaller than that of the forced convection. This effect can be included in the simulation using Eq. (7) mentioned above.

The governing equations, listed above, are discretized using the shape functions of the finite element method. Then these equations are furthermore discretized over the time domain. Finally, the discretized equations are solved by iteration using the Newton-Raphson method.

4. Validation Case

To validate the reliability of our numerical model, we simulate the experimental test by Bu et. al (2019). The Casing profile of the geothermal well for this experiment is shown in Figure 2, and the results of this experiment are presented in Figure 3. The basic parameters of geometry and boundary conditions are listed in Table 1. Material parameters are given in Table 2. The simulation results of the validation case are given in Figure 4, from which we can see that the production temperature and thermal power obtained by our model show an acceptable agreement with those obtained in the experiment.

Table 1: Parameters of geometry and boundary conditions used for validation

Parameter (Unit)	Value	Parameter (Unit)	Value
<i>Tubing outer diameter</i> (mm)	110	<i>Tubing thickness</i> (mm)	10
<i>Casing outer diameter</i> (mm)	177.8	<i>Casing thickness</i> (mm)	6.91
<i>Well depth</i> (m)	2600	<i>Cement thickness</i> (mm)	19.05
<i>Injection temperature</i> T_0 (°C)	5	<i>Injection velocity</i> (m/s)	0.7174

Table 2: Material parameters used for validation

Parameter (Unit)	Rock	Tubing	Casing	Cement	water
<i>Density</i> (kg/m ³)	2800	900	7850	2400	1000
<i>Thermal conductivity</i> (W/(m · K))	3.49	0.21	45	0.73	0.598
<i>Heat capacity</i> (J/(kg · K))	920	1800	490	920	4184

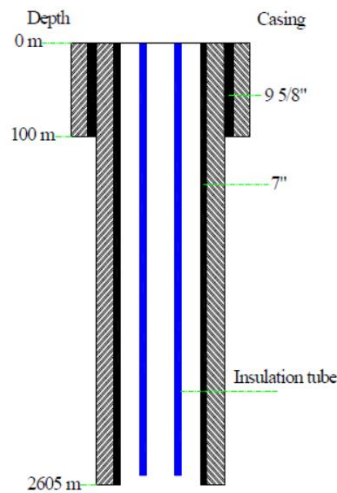


Figure 2: Casing profile of a geothermal well in Qingdao, China that is used for validating our model. (See Bu et. al, 2019)

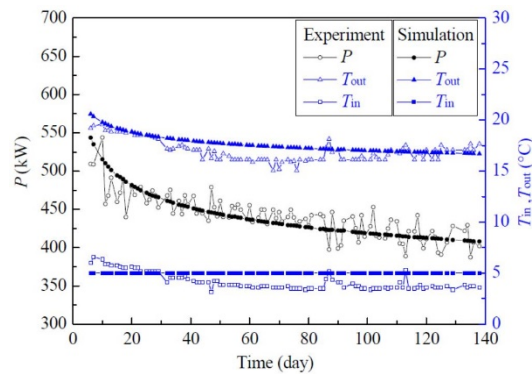


Figure 3: We validated our numerical model against the experimental results reported by Bu et. al (2019).

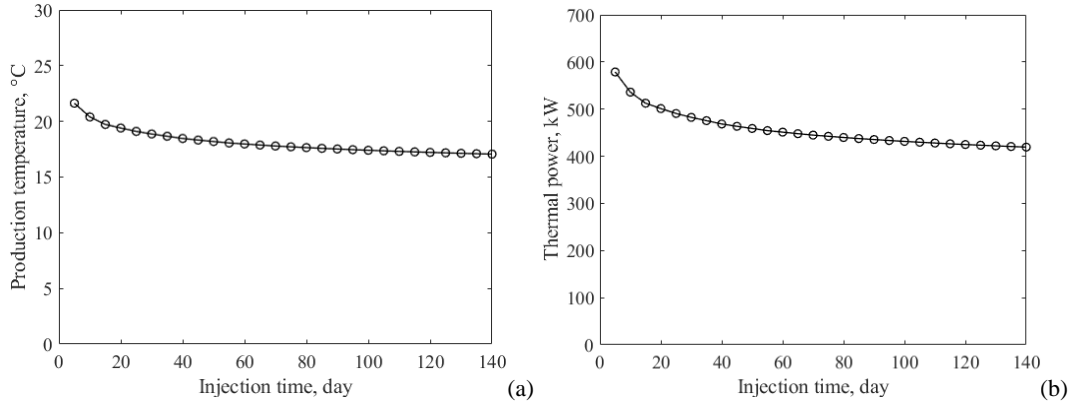


Figure 4: Simulation results of a validation case: (a) production temperature versus time; (b) thermal power versus time.

5. Effects of Critical Factors

There are several critical factors that can impact the efficiency of the closed-loop geothermal well (CLGW). To investigate the effects of some factors, an example model is established, and a series of numerical simulations are conducted. The basic parameters for the geometry and boundary conditions of the simulation model are listed in Table 3, and the corresponding material parameters are given in Table 4.

Table 3: Parameters of geometry and boundary conditions used for the modeling

Parameter (Unit)	Value	Parameter (Unit)	Value
<i>Reservoir radius</i> (m)	600	<i>Reservoir height</i> (m)	1200
<i>Tubing outer diameter</i> (mm)	150	<i>Tubing thickness</i> (mm)	10
<i>Casing outer diameter</i> (mm)	250	<i>Casing thickness</i> (mm)	10
<i>Cement thickness</i> (mm)	20	<i>Heat exchanger height</i> (m)	1000
<i>Injection velocity</i> (m/s)	0.1	<i>Injection temperature T_0</i> (°C)	35
<i>Reservoir temperature T_1</i> (°C)	175		

Table 4: Material parameters used in simulations

Parameter (Unit)	Rock	Tubing	Casing	Cement	water
<i>Density</i> (kg/m ³)	2800	900	7850	2400	1000
<i>Thermal conductivity</i> (W/(m·K))	4	0.1	45	0.8	0.598
<i>Heat capacity</i> (J/(kg·K))	920	1800	490	920	4184

5.1 Cement Thermal Conductivity

To explore the effect of the cement thermal conductivity (CTC) on the efficiency of a CLGW, several cases with different thermal conductivity values are simulated. To make a consistent comparison, the thickness of cement is set fixed as 64.8mm. The CTC values considered are

presumed to vary from $0.2 \text{ W}/(\text{m}\cdot\text{K})$ to $8.0 \text{ W}/(\text{m}\cdot\text{K})$. The simulation results of these cases are shown in Figures 5-6. In Figure 5, we can see that the production temperature and thermal power decrease with respect to time, ultimately approaching a steady state. One may notice that CTC has a significant impact on heat extraction, especially when CTC is increased from $0.2 \text{ W}/(\text{m}\cdot\text{K})$ to $0.4 \text{ W}/(\text{m}\cdot\text{K})$. As CTC increases, both produced fluid temperature and thermal power increase but at a diminishing rate. In other words, the production efficiency of the well increases in an asymptotic way as CTC increases. Figure 6 gives the relationship between the results after 70 days and cement thermal conductivity, which reflects the asymptotic characteristic of an increase in well production power. When CTC increases from $0.2 \text{ W}/(\text{m}\cdot\text{K})$ to $8.0 \text{ W}/(\text{m}\cdot\text{K})$, the production temperature and thermal power are enhanced by $40.42 \text{ }^\circ\text{C}$ and 400.27 kW , respectively. From the above results, we can observe that high-thermal-conductivity cement is significant for enhancing the efficiency of CLGW but this improvement would be limited. In general, cement with low thermal conductivity may act as a bottleneck against the heat flow but a significant improvement of the thermal conductivity cannot further accelerate heat flow to the wellbore. Maybe a larger wellbore radius and to some extent larger cement thickness would further increase the heat extraction rate.

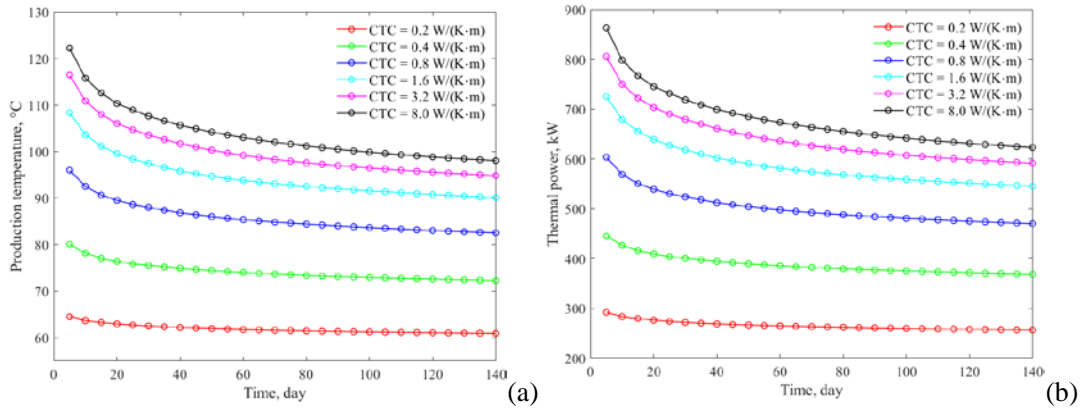


Figure 5: The effect of cement thermal conductivity: (a) production temperature versus time; (b) thermal power versus time.

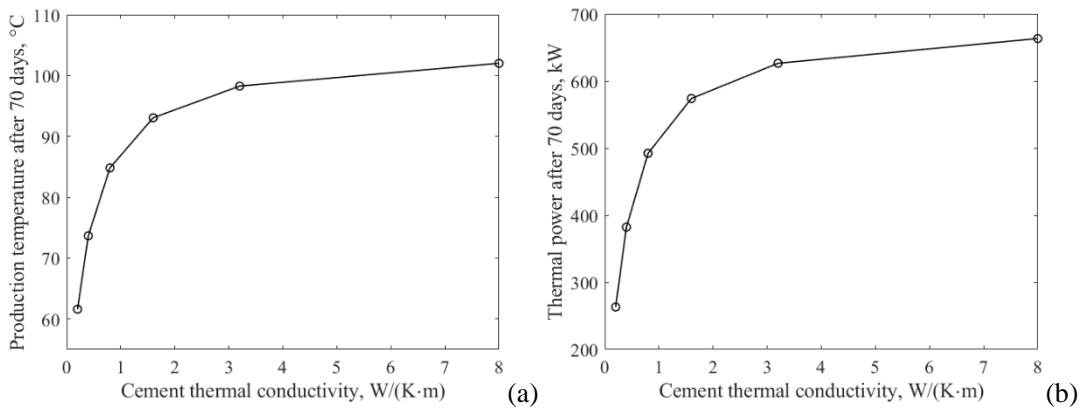


Figure 6: Results after 70 days versus cement thermal conductivity: (a) production temperature versus time; (b) thermal power versus time.

5.2 Circulation Rate of the Working Fluid

To explore the impact of fluid circulation velocity on the efficiency of a CLGW, cases with different flow velocities inside the wellbore are simulated for comparison. In these cases, the cement thermal conductivity is set to be $0.8 \text{ W}/(\text{m}\cdot\text{K})$ and the thickness of cement is 20 mm. The velocity is varied from 0.1 m/s to 0.35 m/s in an arithmetic progression, and the corresponding simulation results are presented in Figures 7-8.

It can be observed from Figure 7 that the flow velocity has significant effects on both the thermal power and temperature of the produced fluid, especially when the circulation rate varies between 0.1 m/s and 0.15 m/s. In general, as the velocity increases, the temperature of produced fluid decreases although the thermal power keeps increasing to a certain point. In other words, the fluid velocity is inversely proportional to the production temperature but directly proportional to the thermal power. From Figure 8, we can see that results after 70 days vary in an asymptotic pattern as the fluid circulation rate changes. The production temperature decreases asymptotically as injection velocity increases, while the thermal power increases asymptotically. When the velocity increases from 0.1 m/s to 0.35 m/s, the production temperature is reduced by $35.91 \text{ }^\circ\text{C}$, while thermal power is enhanced by 151.30 kW . In conclusion, a high fluid circulation rate is needed if we seek high thermal power instead of high production temperature from the CLGW, but the enhancement is limited as the fluid circulation rate keeps increasing. In contrast, if a high production temperature is preferred, then adopting a low fluid circulation rate should be our choice. For another, if one tries to get both good production temperature and thermal power, then an intermediate fluid circulation rate should be adopted.

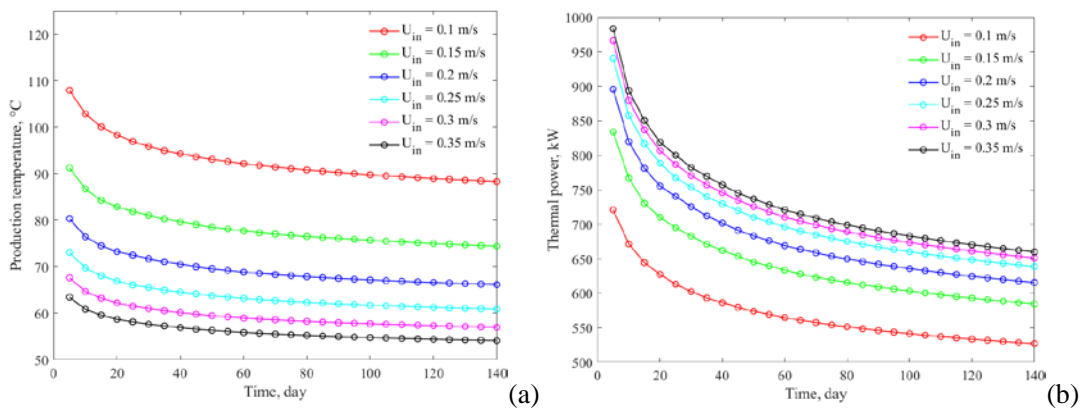


Figure 7: The effect of the working fluid circulation rate: (a) production temperature versus time; (b) thermal power versus time.

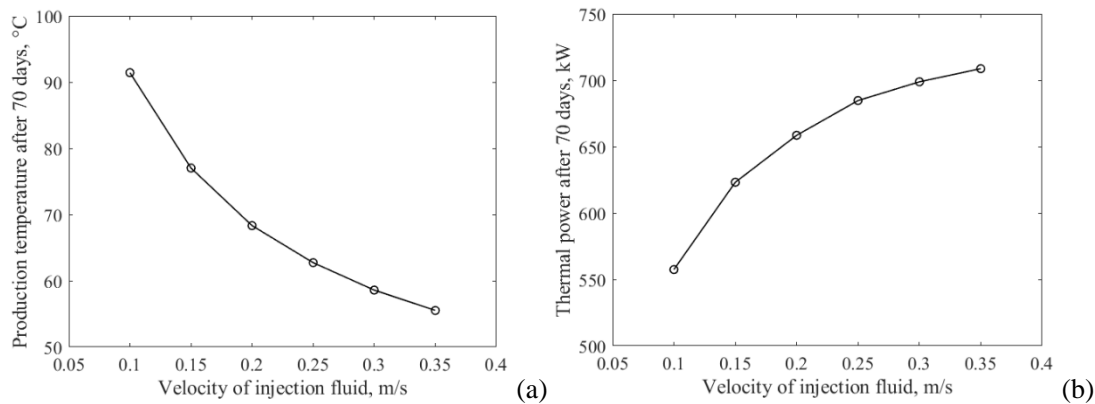


Figure 8: Results after 70 days versus velocity of injection fluid: (a) production temperature; (b) thermal power.

5.3 Circulating Fluid Heat Capacity

During the process of extracting heat from geothermal reservoirs using CLGW, the thermal properties of circulating fluid, like heat capacity, might also affect the heat extraction process. To analyze how the circulating fluid heat capacity impacts the efficiency of the CLGW, a group of cases with different circulating fluid heat capacities are simulated. The heat capacity is varied from $3184\text{J}/(\text{K}\cdot\text{kg})$ to $5684\text{J}/(\text{K}\cdot\text{kg})$ in an arithmetic progression, and Figures 9-10 show corresponding simulation results. Based on Figure 9, it can be noticed that with higher heat capacity, the production temperature is generally lower while the thermal power is higher. From Figure 10, we can see that the results after 70 days vary nearly in an asymptotic manner as the heat capacity increases. The production temperature decreases almost asymptotically whereas the thermal power increases asymptotically as the heat capacity increases. When the heat capacity increases from $3184\text{J}/(\text{K}\cdot\text{kg})$ to $5684\text{J}/(\text{K}\cdot\text{kg})$, the production temperature is reduced by $21.27\text{ }^\circ\text{C}$, while thermal power is enhanced by 107.34 kW . In summary, the effect of circulating fluid heat capacity is similar to that of the fluid circulation rate, although they are not the same. Compared with the impact of the fluid circulation rate, both the production temperature and thermal power vary relatively more linearly with respect to the fluid heat capacity. In other words, the increase in thermal power with increasing fluid heat capacity shows less limitation. Circulating fluid with high heat capacity is required if we prefer high thermal power from the CLGW. Conversely, if we want to obtain a high production temperature, then we are supposed to utilize fluid with low heat capacity. Besides, if both good production temperature and thermal power are intended, choosing a circulating fluid with intermediate heat capacity should be the case. To some extent, adjusting the fluid heat capacity could be a substitute for changing the fluid circulation rate, and it might be more economical than the latter in terms of the costs.

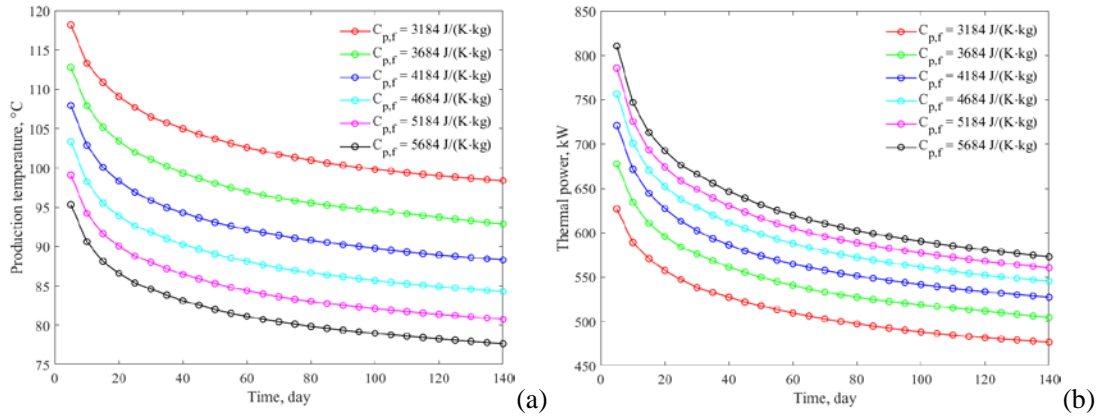


Figure 9: Effect of circulating fluid heat capacity: (a) production temperature versus time; (b) thermal power versus time.

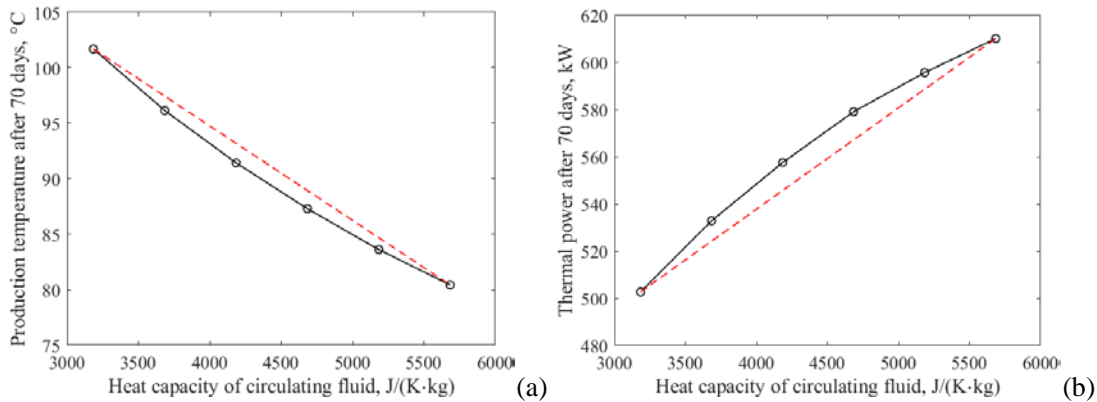


Figure 10: Results after 70 days versus circulating fluid heat capacity: (a) production temperature; (b) thermal power.

6. Conclusions

In this paper, a coupled three-dimensional model is proposed to simulate the performance of a closed-loop geothermal well (CLGW). The presented finite element model has been validated by available experimental data in the literature. Then, several simulations are carried out to evaluate the effects of some critical factors on the efficiency of CLGW. Based on the simulation results of these cases, some regularities have been identified.

First, it is found that increasing the cement thermal conductivity (CTC) would enhance both production temperature and thermal power extracted from the system, but the values increase asymptotically as CTC increases. As the circulation velocity of the fluid increases, the temperature of the produced fluid decreases, while thermal power increases asymptotically. The heat capacity of circulating fluid is also an important factor. Using circulating fluid with high heat capacity would result in low production temperature but higher thermal power. The effect of high heat capacity is similar to that of having large circulation velocities. The results and conclusions obtained in this paper can provide a reference to design closed-loop systems in the future.

REFERENCES

- Ahmadi, M., and Dahi Taleghani, A. "Feasibility Study of Heat Extraction from a Closed-Loop Fractured Geothermal Reservoir; A Multiphysics Problem." *Paper presented at the 50th U.S. Rock Mechanics/Geomechanics Symposium*, Houston, TX (2016).
- Andrés, S., Santillán, D., Mosquera, J.C., and Cueto-Felgueroso, L. "Thermo-Poroelastic Analysis of Induced Seismicity at the Basel Enhanced Geothermal System." *Sustainability*, 11, (2019), 6904.
- Beckers, K.F., Rangel-Jurado, N., Chandrasekar, H., Hawkins, A.J., Fulton, P.M., and Tester, J.W. "Techno-Economic Performance of Closed-Loop Geothermal Systems for Heat Production and Electricity Generation." *Geothermics*, 100, (2022), 102318.
- Bu, X., Ma, W., and Li, H. "Geothermal Energy Production Utilizing Abandoned Oil and Gas Wells." *Renewable Energy*, 41, (2012), 80-85.
- Bu, X., Ran, Y., and Zhang, D. "Experimental and Simulation Studies of Geothermal Single Well for Building Heating." *Renewable Energy*, 143, (2019), 1902-1909.
- Dahi Taleghani, A. "An Improved Closed-Loop Heat Extraction Method from Geothermal Resources." *Journal of Energy Resources Technology*, 135, (2013), 042904.
- Dai, C., Li, J., Shi, Y., Zeng, L., and Lei, H. "An Experiment on Heat Extraction from a Deep Geothermal Well Using a Downhole Coaxial Open Loop Design." *Applied Energy*, 252, (2019), 113447.
- Di Dato, M., D'Angelo, C., Casasso, A., and Zarlenga, A. "The Impact of Porous Medium Heterogeneity on the Thermal Feedback of Open-loop Shallow Geothermal Systems." *Journal of Hydrology*, 604, (2022), 127205.
- Kazemi, A.R., Mahbaz, S.B., Dehghani-Sanij, A.R., Dusseault, M.B., and Fraser, R. "Performance Evaluation of an Enhanced Geothermal System in the Western Canada Sedimentary Basin." *Renewable and Sustainable Energy Reviews*, 113, (2019), 109278.
- Knoblauch, T.A.K., and Trutnevyte, E. "Siting enhanced geothermal systems (EGS): Heat benefits versus induced seismicity risks from an investor and societal perspective." *Energy*, 164, (2018), 1311-1325.
- Pollack, A., and Mukerji, T. "Accounting for subsurface uncertainty in enhanced geothermal systems to make more robust techno-economic decisions." *Applied Energy*, 254, (2019), 113666.
- Rathnaweera, T.D., Wu, W., Ji, Y., and Gamage, R.P. "Understanding injection-induced seismicity in enhanced geothermal systems: From the coupled thermo-hydro-mechanical-chemical process to anthropogenic earthquake prediction." *Earth-Science Reviews*, 205, (2020), 103182.
- Song, X., Shi, Y., Li, G., Shen, Z., Hu, X., Lyu, Z., Zheng, R., and Wang, G. "Numerical Analysis of the Heat Production Performance of a Closed Loop Geothermal System." *Renewable Energy*, 120, (2018), 365-378.
- Tilley, B.S., and Baumann, T. "On temperature attenuation in staged open-loop wells." *Renewable Energy*, 48, (2012), 416-423.

- Vaganova, N.A., and Yu Filimonov, M. “A General Model of an Open Geothermal System.” *Journal of Physics: Conference Series*, 820, (2017), 012010.
- Zhang, Y., and Zhao, G.F. “A global review of deep geothermal energy exploration: from a view of rock mechanics and engineering.” *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*. 6, (2020), 4.