Analysis of Influence Factors on Aquifer Thermal Energy Storage Performance

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Thermal energy storage efficiency, influence factors, temperature field, double-well system, numerical simulation

ABSTRACT

In the aquifer thermal energy storage system, the thermal energy storage performances of the system are related to many factors such as the distance between the wells, injection/extraction rate and the porosity of the aquifer. In this paper, the temperature of the underground in different working conditions and geological parameters is simulated using COMSOL software, and then the energy storage efficiency is analyzed. The results indicate that the energy storage efficiency increases with the increase of the well distance while it decreases as the extraction/injection rate rises. When the porosity of the aquifer increases, the energy storage efficiency increases first, then decreases and increases toward the end.

1. Introduction

It can be demonstrated that reinjection could effectively alleviate the land subsidence problem resulted from over-exploitation of groundwater [1]. It also promotes the development of the aquifer thermal energy storage technology (ATES). In the ATES system, temperature distribution plays an important role in the performance of the system, and it is highly influenced by the reinjection process and geological parameters [2, 3]. With the development of computer technology, more and more researchers used numerical simulation methods to study the heat transfer performance in the aquifer. Numerical experiments can extend the limitations of practical experiments and help design a hypothetical system under any working conditions. Many schemes can be discussed in advance, and it is easy to help engineers reach a scientific decision [4]. Numerical modeling of the system has been studied from 1970s [5]. An unified finite element was applied to dealing with transient heat transport in an aquifer based on the conduction-convection coupled theory on a one-dimensional model problem [6]. A two-dimensional transport model, Galerkin finite-element, was applied to study the feasibility of low temperature, heat pump coupled aquifer thermal energy storage in a confined sandstone aquifer in northeastern Ohio [7]. N. Tenma.et al. [8] estimated the parameters of a typical underground system using the two-well model. By changing the parameters of the system, six different heat extraction scenarios were studied and one was recommended because of its small energy loss. In order to study an ATES system more correctly, three-dimensional numerical models have been widely used. Kim et al. [9] used COMSOL software to set up a thermo-hydraulic model to identify the thermal interference by three parameters including the borehole distance, the hydraulic conductivity, and the pumping/injection rate and to estimate the system performance changed by the thermal interference. So as to determine the reasonable distribution of injection wells and extraction wells, Paksoy H.O. et al. [10] quantitatively simulated the migration characteristics of thermal fronts in the process of energy extraction in aquifer by CONFLOW procedures. A numerical simulation, based on the finite difference method, was carried out for velocity and temperature distributions as well as the heat transfer in the aquifer. It got the effect of parameters such as groundwater velocity, porosity, operational parameters, and aquifer parameters on recovery factor and coefficient of performance (COP) of the ATES system [11].

In the ATES system, the thermal energy storage performances of the system are related to many factors, such as the distance between the wells, injection/extraction rate and the porosity of the aquifer. In this paper, the temperature of the subsurface in different working conditions and geological parameters is simulated using COMSOL software, and then the energy storage efficiency is analyzed.

2. Numerical Model

2.1 Physical Model

The simulated aquifer is a cube and the dimension is 200m×200m×40m in the x, y and z directions, as shown in Fig.1. In the domain, there are two wells, one is an injection well and the other an extraction well. The depth of each well is 40m and the radius of the well is 0.1m.

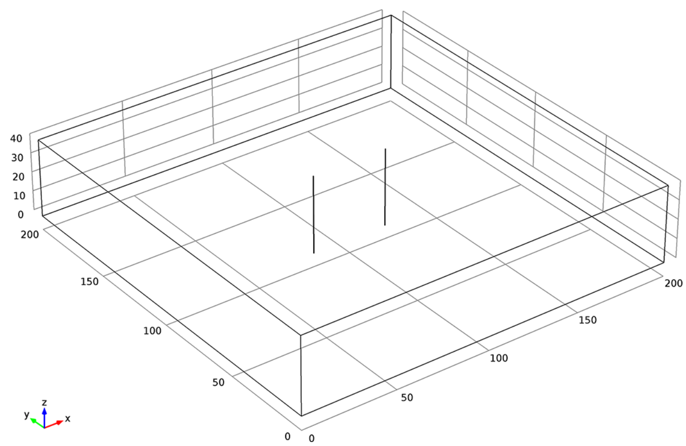

Figure 1. The three-dimensional model for aquifer.

2.2 Governing Equations

In the simulation, the following assumptions were made to simplify the model:

1) The confined aquifer is homogeneous and isotropic and saturated with water;

2) The aquifer and water are always in the state of thermal equilibrium;

3) Physical and thermal-physics properties of aquifer and water are constant;

4) There is only one kind of fluid;

5) The heat radiation effect is ignored.

Energy conservation equation is as follows:

$$\left(\rho c_p\right)_{eq}\frac{\partial T}{\partial t}+\rho c_p u\cdot\nabla T=\nabla\cdot\left(k_{eq}\nabla T\right)+Q \tag{1}$$

$$\left(\rho c_p\right)_{eq}=\theta_p\rho_p c_{p,p}+\left(1-\theta_p\right)\rho c_p \tag{2}$$

$$k_{eq}=\theta_p k_p+\left(1-\theta_p\right)k \tag{3}$$

In the equation, subscript eq represents the whole aquifer. And subscript p donates solid matrix. Q is heat source, while c_p, k, u and θ are heat capacity at constant pressure, thermal conductivity, the Darcy velocity and dimensionless number, respectively.

Darcy's law states that the velocity is determined by the pressure gradient, the fluid viscosity, and the structure of the porous medium:

$$\frac{\partial}{\partial \mathrm{t}}\left(\rho\varepsilon_p\right)+\nabla\cdot\left(\rho u\right)=Q_m \tag{4}$$

In the above equation, ρ is the density of the fluid, ε (dimensionless) is the porosity, and Q_m is a mass source term. Porosity is defined as the fraction of the control volume that is occupied by pores.

$$\mathrm{u}=-\frac{k}{\mu}\nabla p \tag{5}$$

In this equation, k denotes the permeability of the porous medium, μ is the dynamic viscosity of the fluid, while p is the pressure.

2.3 Boundary and Initial Conditions

The initial temperature of the model domain is 17.5°C. Based on the assumption, there is no flow and heat transfer at the top and bottom sides. Then the temperature and the hydraulic head of four lateral boundaries are constant. In winter, cold water at 7°C is injected into the aquifer. After that, there is no injecting and extracting for three months. In the summer, warm water at 30°C is reinjected into the aquifer from warm well, at the same time the cold water, which was injected into the aquifer in winter, is pumped, for use, from the aquifer.

In the simulation, thermo-physical properties of the aquifer and fluid are shown in Table 1.

2.4 Meshing

Considering the degree of accuracy and simulation time comprehensively, adaptive arid extra fine mesh was used, and the domain near wells was refined partially for extremely fine grid. Fig. 2 gives the mesh of the simulation region in COMSOL.

Table 1. Thermo-physical properties of the aquifer and fluid.

Property	Value
Density of water	1000 kg/m^3
Specific heat of water	4180 J/kg K
Thermal conductivity of water	0.64 W/m K
Compressibility of water	4.4e-10 Pa^{-1}
Density of aquifer	2000 kg/m^3
Specific heat of aquifer	1000 J/kg K
Thermal conductivity of aquifer	2 W/m K
Compressibility of aquifer	6.9e-7 Pa^{-1}
Permeability	1.0×10^{-12} m^2

3. Simulation Results

3.1 Effect of the Injection Rate

In the simulation, the time of cold injection and heat injection both are 120 days. During the time of cold injection, water at 7℃ is injected into the aquifer, and in the time of heat injection, water temperature is 30℃. The well distance is 40m and the porosity of the aquifer is 0.4, the temperature variation of the extraction well with the injection rate is simulated, and the results are shown in Fig. 3. In the cold injection period, the extraction well water temperature decreases as the cold injection proceeds and with the increasing of injection rate the temperature decrease is enhanced, as shown in Fig. 3 (a). This is because with the increasing injection rate the pressure gradient between two wells will rise. When porosity is constant, the seepage velocity will rise. Due to the rise of the seepage velocity, the injected cold water will more easily flow into the extraction well, and the heat transfer between the aquifer and the injected water is improved. The area influenced by the cold water is enlarged and the extraction well water temperature decreased. As the cold injection rate is 40m^3/h, 60m^3/h, 80m^3/h and 100m^3/h, the temperature of the extraction well begins to decrease on the 8th day, 6th day, 4th day, 4th day respectively. At the end of cold injection, the temperature decrease to 7℃.

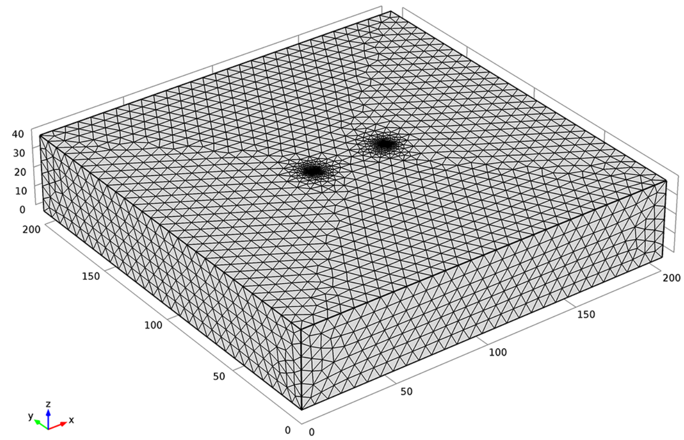

Figure 2. Model mesh.

During the period of the heat injection, the extraction well temperature variation with the injection rate increasing has the same tendencies as the cold injection process. Fig. 3 (b) gives the temperature variation of the extraction well in the period of the heat injection. The extraction well water temperature increases with heat injection, and with the increasing

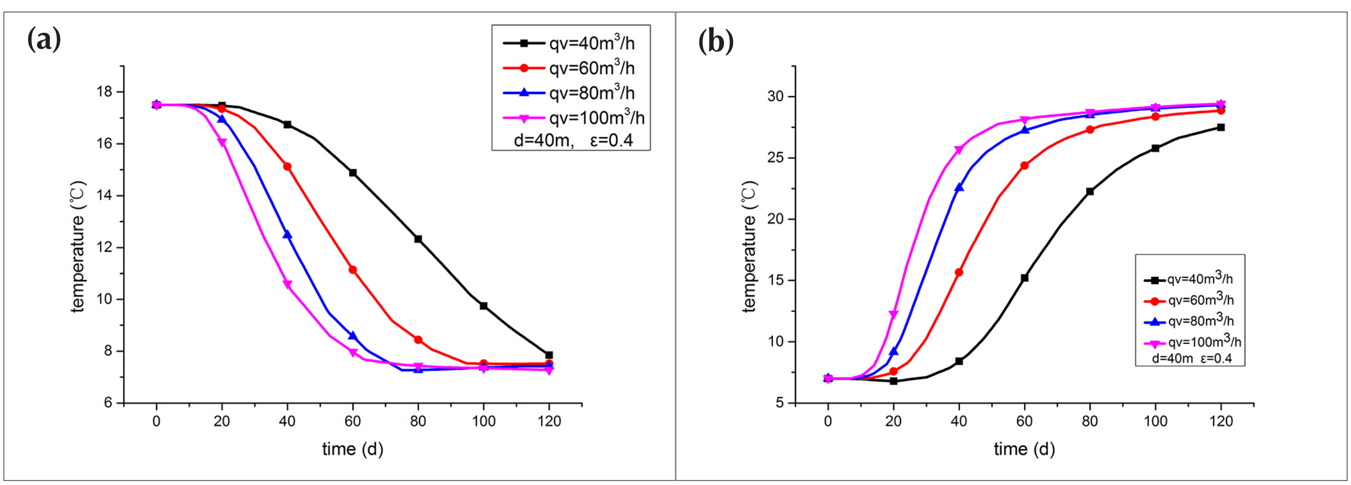

Figure 3. Temperature variation of the aquifer in different injection/extraction rates (a) cold injection and (b) heat injection.

of injection rate, the rate of temperature increase is higher. As the injection rate is 40m^3/h, 60m^3/h, 80m^3/h and 100m^3/h, the temperature of the extraction well begin to increase on the 8th day, 10th day, 13th day, 20th day respectively.

3.2 Effect of Porosity

When the well distance is 40m and injection rate is 40m^3/h, the temperature variation of the extraction well with the porosity is simulated. In the simulation, the cold injection and heat injection both are 120 days, and the cold injection water temperature is 7℃ and the heat injection water temperature is 30℃. Fig. 4 gives the temperature variation of the aquifer in different porosity. Fig. 4 (a) is the result in the condition of cold injection and Fig. 4 (b) is the result of the heat injection. From Fig. 4, it can be seen that the porosity is larger, the temperature decreasing is slower. The reason is that as the porosity increases, there is much more water in the pores, and the mean heat capacity of the aquifer increases. The heat capacity is larger, the thermal diffusivity is smaller, which means the heat will diffuse more slowly through the aquifer. So, the temperature decreases slowly as the porosity is larger in the cold injection condition, while the temperature increases slowly as the porosity is larger in the heat injection process.

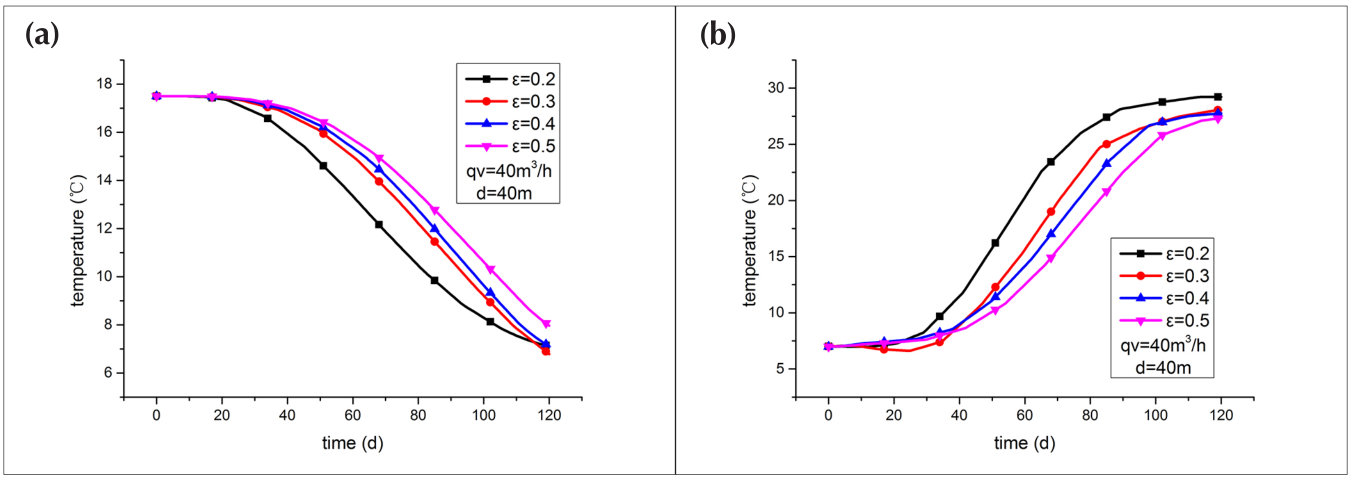

Figure 4. Temperature variation of the aquifer in different porosity (a) cold injection and (b) heat injection.

3.3 Effect of Distance Between Wells

When the injection rate is 40m^3/h and the porosity of the aquifer is 0.4, the temperature variation of the extraction well with the well distance is simulated. In the simulation, the cold injection and heat injection both are 120 days, and the cold injection water temperature is 7°C and the heat injection water temperature is 30°C. Fig. 5 gives the temperature variation with the well distance. Fig. 5(a) is the result in the condition of cold injection and Fig. 5(b) is the result of the heat injection. The further the distance between wells, the smaller the temperature changes. This is because, as the well distance increases, the time of the injected cold water flowing into the extraction well will slower. With the well distance

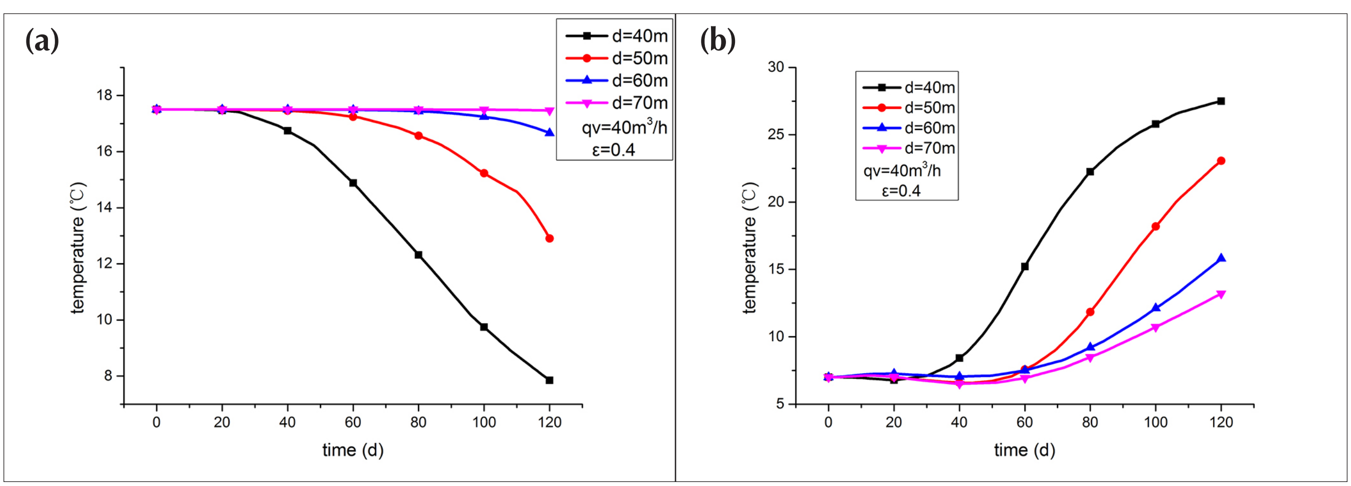

Figure 5. Temperature variation of the aquifer in different well distance (a) cold injection (b) heat injection.

increasing the effect of the injected water on the extraction well is less over the same period of time. It can be seen from Fig. 5(a) that the extraction well water temperature begins to decrease more quickly from the 26th day when the well distance is 40m. While the water temperature is hardly decreasing when the well distance is 70m in the cold injection period, it means the interference between injection well and extraction well is small, which is beneficial to thermal energy storage. At the end of the cold injection, the extraction well water temperature is decreased to 7.8°C，12.9°C，16.6°C and 17.4°C when the well distance is 40m, 50m, 60m, 70m, respectively.

During the period of the heat injection, the extraction well temperature variation with increasing injection rate has the same tendencies as with cold injection. Fig. 5(b) gives the temperature variation of the extraction well in the period of the heat injection. As the well distance is 40m, 50m, 60m, 70m, the temperature of the extraction well begins to increase quickly since the 20th day, 40th day, 50th day, and 50th day respectively. After that, the temperature increased quickly. At the end of heat injection, the temperature of the extraction well is 27.5°C，23.1°C，15.8°C and 13.2°C, respectively and at the well distance of 40m becomes flat.

4. Thermal Energy Storage Efficiency

There are two kinds of methods to evaluate the performance of thermal energy storage system in the reported studies, thermal energy recovery factor [11] and thermal energy storage efficiency [12-14].

When the specific heat capacity of water is assumed to be constant and the rate of withdraw is equal to injection rate, the thermal energy recovery factor is given by H.Ghaebi as:

$$\eta = \frac{\sum_0^m \left| T_{W,S} - T_{I,S} \right|}{\sum_0^n \left| T_{W,W} - T_{I,W} \right|} \tag{6}$$

Where $T_{W,W}$ and $T_{I,W}$ are average temperatures of withdraw water and injection water during injection time. $T_{W,S}$ and $T_{I,S}$ are average temperatures of withdraw water and injection water during withdraw time. Superscript m and n represent the days of withdraw and injection, respectively.

Thermal energy storage efficiency η' is given by Xueling Liu and Liwei Liu as:

$$\eta' = \frac{\sum_0^m \left| T_0 - T_{I,S} \right|}{\sum_0^n \left| T_{W,W} - T_{I,W} \right|} \tag{7}$$

In the equation, $T_{I,S}$ is average temperature of withdraw water during energy stored period and T_0 is the temperature of the aquifer. $T_{W,W}$ and $T_{I,W}$ are average temperatures of withdraw water and injection water during energy pumped period. Superscript m and n represent the days that the temperature of withdraw water is lower than the initial temperature of aquifer during cold withdraw time or the temperature of withdraw water is higher than the initial temperature of aquifer during heat withdraw time, respectively.

In the two evaluation methods, thermal energy recovery factor calculates the ratio of thermal energy extracted and injected in the aquifer. Thermal energy storage efficiency calculates the ratio of that the energy really stored in the aquifer by aquifer thermal energy storage system and the injected total energy. The thermal energy storage efficiency is used to analyze the performance of the aquifer thermal energy storage system.

The thermal energy storage efficiency at different injection rate, well distance and the porosity are calculated, and are presented in Table 2, Table 3 and Table 4. As shown in Table 2, the energy storage efficiency η' decreases when the injection/extraction rate increases. If injection/extraction rate increases, water flows more quickly and heat transfer is enhanced and heat loss increased. From Table 3, it can be seen that η' rises when porosity rises at first, then decreases and increases at the end. It is because the heat capacity and thermal conductivity both increase. The heat capacity is larger, the thermal diffusivity is smaller, which means the slower heat will diffuse through the aquifer. Thermal conductivity helps conductive

Table 2. Variations of energy storage efficiency with various injection/extraction rates.

injection/extraction rate(m^3/h) (d=40m, ε=0.4)	40	60	80	100
η'	0.650	0.579	0.563	0.519

Table 3. Variations of energy storage efficiency with various porosities.

Porosity (qv=40m^3/h, d=40m)	0.2	0.3	0.4	0.5
η'	0.597	0.651	0.631	0.652

Table 4. Variations of energy storage efficiency with various distances between wells.

distance between wells(m) (qv=40m^3/h, ε=0.4)	40	50	60	70
η'	0.650	0.735	0.813	0.878

heat transfer. From Table 4, it can be concluded that η' increased dramatically with the well distance decrease. At the well distance of 70m, in the condition of 40 m^3/h injection rate and porosity of 0.4, the energy storage efficiency reaches 0.878. A good thermal energy storage performance can be achieved in this situation.

5. Conclusions

In this paper, a three dimensional numerical model is used to simulate the temperature field of the aquifer. Based on the simulated temperature, the influences of the injection rate, porosity and the well distance on the extraction water temperature and the thermal energy storage efficiency are studied. From the analysis, we present the following conclusions:

1) The extraction well water temperature decreases/increases with cold/heat injection. The degree of the temperature variation is increased with the decreasing of well distance, porosity and increasing injection rate.

2) The effects of the injection rate, well distance and the porosity on the thermal energy storage efficiency are studied. Results indicate that the thermal energy storage efficiency increases with the injection/extraction rate decrease, and well separation increase. The reasons are that water flows more slowly and heat transfer is weakened, heat capacity increases and the heat loss reduces and extraction well has a less effect on injection well. When porosity rises, the thermal energy storage efficiency increases first, then decreases and increases at the end, because the heat capacity and thermal conductivity both increase.

Acknowledgments

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