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EFFECTS OF INJECTION ON THERMAL PERFORMANCE OF BRINE AQUIFERS CONTAINING MONTMORILLONITE

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ABSTRACT

Aquifer thermal energy storage (ATES) has been proved to be an efficient way to achieve seasonal thermal energy storage and can improve the efficiency of heat pump systems greatly. But for ATES systems using brine aquifer as thermal energy storage medium, there is large reduction in permeability of the aquifer due to the difference of salinity and temperature between the injected water and aquifer, then heat transfer process could be influenced. In present work, effects of injection salinity and injection temperature on the underground temperature and performance of the ATES system are studied. Results indicate that reducing injection salinity slows down the heat transport in the brine aquifer, and improve the thermal energy storage of the brine aquifer thermal energy storage system due to the decrease of hydraulic conductivity of brine aquifer. Decreasing injected cold water temperature or increasing injected hot water temperature is helpful to improve the thermal energy storage, which is the comprehensive influence of the reduction of hydraulic conductivity and the increase of temperature difference.

Keywords: brine aquifer, injection salinity, injection temperature, underground temperature

1. INTRODUCTION

As an efficient way to improve the efficiency of heat pump systems, seasonal aquifer thermal energy storage (ATES) has been widely used and primary energy consumption of heating or cooling has been reduced greatly [1-2]. The performance of the ATES system and thermal energy storage efficiency are much related with the process of flow, heat transfer and solute transport in the aquifer [3-11].

Some researchers pointed out that the performance of ATES systems is mainly dependent on thermal interference between warm and cold water in aquifers, and thermal interference led to poor thermal performance [3-4]. But for multiple ATES systems or ATES systems with multi-wells, thermal interference may have positive impact [5-6]. Yapparova [7] got the conclusion that thermal energy storage efficiency increased with reducing the well distance and increasing injection temperature. Gilian [8] took the density-driven flow into account to investigate the prime factors influencing the recovery efficiency. Sommer [9] showed that thermal recovery efficiency decreased as heterogeneity increased. Drijver [10] pointed that aquifers with low permeability were preferred for energy storage.

All in all, low flow rate and opposite to the injected water were beneficial to ATES system due to small heat loss and little fluctuation in extracted thermal energy [11].

When using brine aquifers as the thermal energy storage medium, there was releasing and migration of colloidal particles as the injection salinity and consequently affected the relative permeability [12-13]. Konikow [14] quantified the relations between permeability, clay mineralogy, clay content, and initial water salinity. Rosenbrand [15] observed permeability reduced with the injection temperature increasing and injection salinity reducing. The permeability reduction was due to mobilization and migration of detached colloidal or suspended fines that were strained in thin pore throats [16-17].

So far, due to over-exploitation, underground freshwater is less and less. Because of the brine and existence of clay minerals in brackish aquifer, permeability characteristics and heat transfer process in brackish aquifers are significantly different from those in fresh aquifers. Especially, when the salinity and temperature of injection fluid are different from those of the reservoir, which could result in release, migration and sedimentation of clay particles and great change in permeability. At present, the development and utilization of brine aquifer are still in preliminary stage at home and abroad. It is of great significance to study the heat transfer characteristics and thermal energy storage performance after the changes of seepage characteristics in reservoirs under different injection conditions for the development of the brine aquifer, solving the heating and air conditioning problems of the building, and storing the heat energy of industrial waste heat. In present work, effects of injection salinity and injection temperature on the underground temperature and performance of the ATES system are studied.

2. NUMERICAL PROCESS

2.1 Physical model

Typical doublet wells ATES system is chosen in present numerical simulation as shown in Fig 1. Well distance is 40 m, computational aquifer domain is 200 m×160 m in x and y directions.

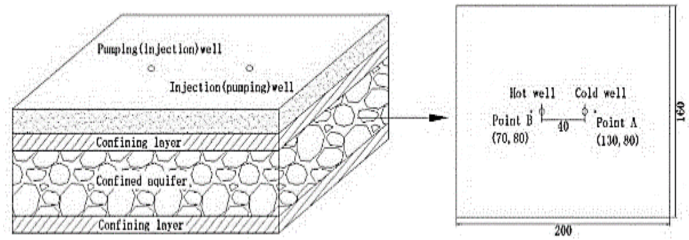


Fig 1 Schematic of the ATES system

2.2 mathematical model

Continuity equation for porous medium is as follows,

$$\frac{\partial}{\partial \tau}(\rho_{\mathrm{f}} \varepsilon)+\nabla \cdot\left(\rho_{\mathrm{f}} \frac{k_f}{\mu_f}(\nabla P+\rho g)\right)=Q_{\mathrm{m}} \tag{1}$$

Energy conservation equation in the aquifer is,

$$\frac{\partial\left[\rho_{\mathrm{f}} c_{\mathrm{f}} \varepsilon+\rho_{\mathrm{s}} c_{\mathrm{s}}(1-\varepsilon)\right] T}{\partial \tau}+\nabla \cdot\left(\rho_{\mathrm{f}} c_{\mathrm{f}} T \mathbf{u}\right)=\nabla \cdot\left(\mathbf{k}_{\mathbf{t}} \nabla T\right)+Q_{\mathrm{H}} \tag{2}$$

$$\mathbf{k}_{\mathbf{t}}=\mathbf{k}_{\mathbf{c}}+\mathbf{k}_{\mathbf{d}} \tag{3}$$

$$\mathbf{k}_{\mathbf{c}}=\left[\varepsilon k_{\mathrm{f}}+(1-\varepsilon) k_{\mathrm{s}}\right] \mathbf{I} \boldsymbol{\delta}_{\mathbf{ij}} \tag{4}$$

$$\mathbf{k}_{\mathbf{d}}=\varepsilon \rho_{\mathrm{f}} c_{\mathrm{f}}\left(\alpha_{\mathrm{T}}|\mathbf{u}| \mathbf{I} \boldsymbol{\delta}_{\mathbf{ij}}+\left(\alpha_{\mathrm{L}}-\alpha_{\mathrm{T}}\right) \frac{\mathbf{u u}}{|\mathbf{u}|}\right) \tag{5}$$

Solute transport governing equation is,

$$\frac{\partial\left(\rho_{\mathrm{f}} \varepsilon C\right)}{\partial t}+\nabla \cdot\left(\rho_{\mathrm{f}} \varepsilon C \mathbf{u}\right)=\nabla \cdot\left(\rho_{\mathrm{f}} \varepsilon \mathbf{D} \cdot \nabla C\right)+Q_{\mathrm{C}} \tag{8}$$

$$\mathbf{D}=D_{\mathrm{m}} \mathbf{I}+\left(\beta_{\mathrm{L}}-\beta_{\mathrm{T}}\right) \frac{\mathbf{u u}}{|\mathbf{u}|}+\beta_{\mathrm{T}}|\mathbf{u}| \mathbf{I} \tag{9}$$

2.3 Initial and boundary conditions

The injection well in summer will be used as pumping well in winter, while the pumping well in summer will be used as injection well of cold water in winter. The initial temperature of aquifer is 14.5 °C. During hot water storage period, 35 °C water is injected into the aquifer from June 1 to August 31. While in the time of the cold water injection, 5 °C water is injected into the aquifer and the injecting time is from December 1 to February 28 next year. The volumetric flow rate of hot water and cold water injected are both 10 m^3/h. The temperature of four lateral boundaries is constant. Hydraulic head difference between left and right boundaries is specified as 0.5 m. The expression of density and viscosity with temperature and salt concentration would be considered [18]. Thermalphysical properties of the aquifer and fluid are listed in Table 1.

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

Property	Value
Specific heat of fluid (c_f)	4186 J/ (kg K)
Thermal conductivity of fluid (k_f)	0.65 W/(m K)
Density of aquifer (ρ_s)	2562 kg/m^3
Specific heat of aquifer (c_s)	1400 J/(kg K)
Thermal conductivity of aquifer (k_s)	1.8 W/(m K)
Effective porosity (ε)	0.35
Longitudinal mechanical dispersivity (α_L)	1.2 m
Molecular diffusivity (D_0)	1.35×10^{-9} m^2/s
Fluid density difference ratio (α)	1.23×10^{-2}
Longitudinal thermal dispersivity (β_L)	1.2 m

2.4 Verification of numerical method

The comparison of the pumping temperature at the end of the period of heat storage derived by present numerical simulation and available experiment is shown Fig 2. The maximum temperature error is 0.8 °C, which indicates that the present result has high accuracy.

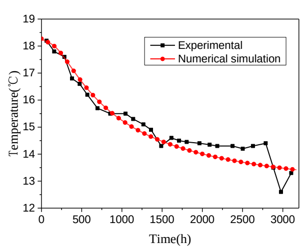


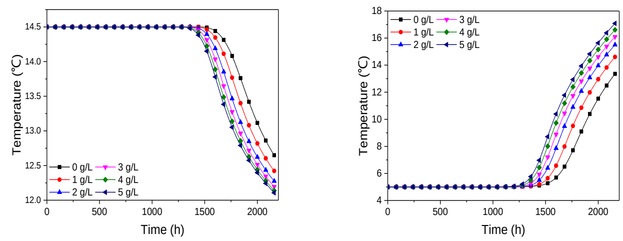
Fig 2 Comparison of the pumping temperature at the end of the period of heat storage

3. RESULT AND DISCUSSION

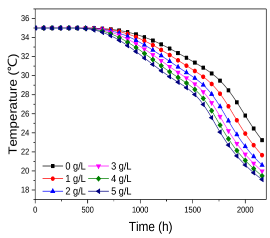
3.1 Effect of injection salinity

As the injection salinity varies from 0 g/L to 5 g/L, the temperature variation of pumping well during the period of cold injection and heat injection are shown in Fig. 3. The temperature change of pumping water is the smallest when injection salinity is 0 g/L whenever in cold or warm water injection time. That is, decreasing injection salinity reduces the temperature change of the aquifer, which is helpful to store thermal energy in the aquifer. At the end of the first period of cold water injection, as the injection salinity varies from 0 g/L to 5 g/L, the pumping temperature decreases to 12.64 °C, and 12.11 °C, respectively (Fig 3a). During the second cold injection time (Fig 3c), when injection finished, the pumping water temperature is 23.23 °C at 0 g/L, while it is 19.10 °C at 5 g/L. So decreasing injection salinity reduces the temperature change in the aquifer, is helpful for thermal energy storage. For the end of hot water injection, when the injection salinity reduces from 5 g/L to 0 g/L, the pumping water temperature decreases from 17.09 °C to 13.36 °C. Decreasing injection salinity reduces the temperature change of pumping water. Then, it can be concluded that, whenever during the time of hot water injection or cold water injection, decreasing injection salinity could reduce the heat transfer in the aquifer. Because decreasing injection salinity could result in the reduction of permeability of brine aquifer. Lower seepage velocity causes poor heat transfer performance between the injected water and aquifer matrix, thermal migration in the brine aquifer slows down.

The temperature distribution in different injection salinity at the end of hot water injection time and at the end of the second cold water injection time are shown in Fig 4 and Fig 5, respectively. It can be found that underground water temperature increases with the increasing of injection salinity (Fig 4), also the area influenced by injection water is enlarged. During the hot water injection, the temperature of the point A (Fig 4), which is near the hot well, are 7.36 °C, 7.45 °C, 8.28 °C and 10.13 °C from injection salinity 0 g/L to 5 g/L, respectively. That means as injection salinity increases, more thermal energy is transferred to the aquifer matrix, heat loss is larger. Similarly, during the period of cold water injection, the underground temperature decreases with the increasing of injection salinity (Fig 5). The temperature of the point B (Fig 5), which is near cold well, are 15.51 °C, 14.78 °C, 14.54 °C and 14.50 °C, at injection salinity 0 g/L, 1 g/L, 3 g/L and 5 g/L, respectively. It indicates the injected cold energy is more easy to transferred to the around aquifer matrix at large injection salinity and heat loss is larger. So decreasing injection salinity is helpful for the thermal/cold energy storage.

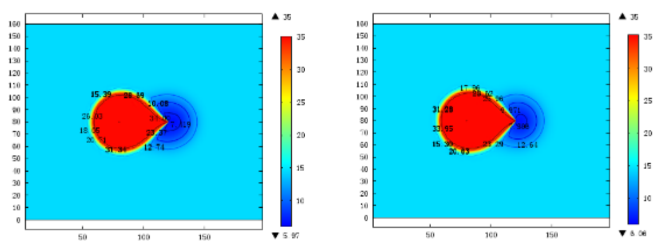


(a) the first period of cold storage (b) the period of heat storage

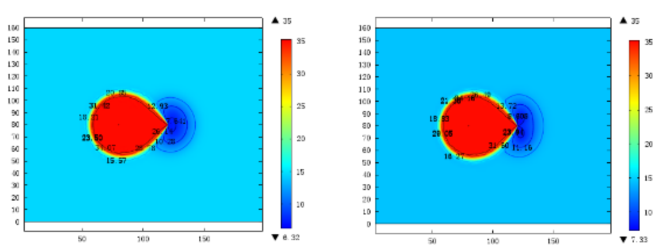


(c) the second period of cold storage.

Fig 3 Pumping temperature

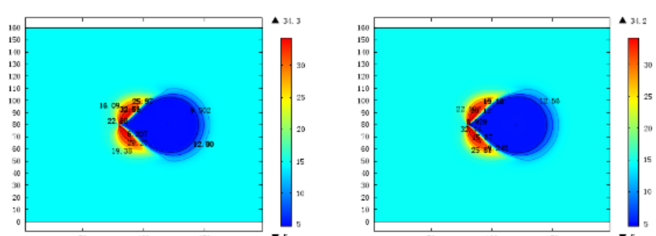


(a) 0 g/L (b) 1 g/L

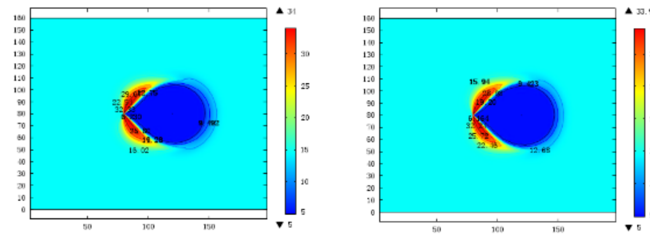


(c) 3 g/L (d) 5 g/L.

Fig 4 Temperature distribution at the end of the period of heat storage



(a) 0 g/L (b) 1 g/L



(c) 3 g/L (d) 5 g/L

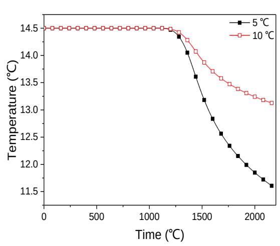
Fig 5 Temperature distribution at the end of the second period of cold storage

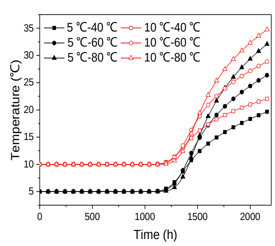
3.2 Effect of injection temperature

In the simulation, underground temperature is obtained in different injection temperature. Injected water temperature is 5 °C and 10 °C in cold injection, and that is 40 °C, 60 °C and 80 °C in hot water injection.

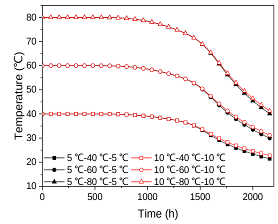
In Fig 6a, it can be found that the pumping water temperature begins to decline 1122 hours later after the cold water injected into the aquifer. When injection temperature is 5 °C and 10 °C, pumping temperature drops to 11.61 °C and 13.13 °C respectively. Lower injection temperature could cause the temperature decline of the underground and pumping water during the cold injection time. After cold injecting, hot water is injected into the underground, the pumping water temperature variation is shown in Fig 6b. During the period of hot water injection, pumping water temperature begins to increase a certain time later since injection started. Increasing injected hot water temperature causes large increasing of pumping temperature for the enhancement of the heat transfer in the aquifer due to the high temperature difference. If 5 °C cold water injected into the underground in the cold storage time, as the hot water of 40 °C, 60 °C and 80 °C injected into the underground, the pumping water temperature begins to increase about 1154 h, 1178 h and 1222 h later, respectively. However, for 10 °C water injection, the time of pumping water temperature begin to increase delays about 12 h, 8 h and 6 h. During the second period of cold injection (Fig 6c), the pumping water decreases to 21.43 °C, 29.94 °C and 40.09 °C. when injection mode is 5 °C-40°C-5 °C, 5 °C-60°C-5 °C and 5 °C-80 °C-5°C. while, as 10°C water is injected into the underground, it decreases to 22.74 °C, 31.20 °C and 41.26 °C. The simulation results indicate that decreasing injection temperature accelerates the velocity of heat transport, during the cold injection time. But for the hot water injection time, increasing the injected water temperature has little influence on the heat transport velocity, but the amplitude of temperature variation is high, which is derived from the combined effect of temperature difference and hydraulic conductivity. Increasing temperature enlarges the thermal migration in the aquifer, while the reduction of hydraulic conductivity reduces with the increasing of temperature, which will slow down the thermal migration during the hot water injection time. However, there is little reduction in the hydraulic conductivity during the cold injection time for the small temperature variation, then the influence of the hydraulic conductivity reduction on the heat transfer is less. With the injection temperature decline, high temperature difference between the injected water and the underground matrix accelerates the heat transport.

Fig 7 shows the underground temperature distribution at the end of the second period of cold storage in different injection conditions. The temperature variation in the direction to pumping well is larger than that in other directions, which is due to the pressure gradient between the pumping well and injection well is larger than that of other directions. The underground temperature near the cold well is lower than the initial temperature of the aquifer 14.5 °C for the injected cold energy stored around the injection well. At the end of the second period of cold storage, the temperature of the hot well is 21.43 °C and 22.74 °C (Fig 7a and Fig 7d), 29.94 °C and 31.20 °C (Fig 7b and Fig 7e), 40.09 °C and 41.26 °C (Fig 7c and Fig 7f), respectively. Obviously, when injection water temperature is 5 °C, the temperature of the hot well is lower than that when the injection water temperature is 10 °C.



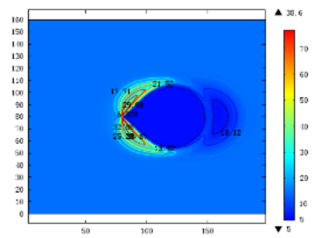


(a) the first period of cold storage (b) the period of heat storage

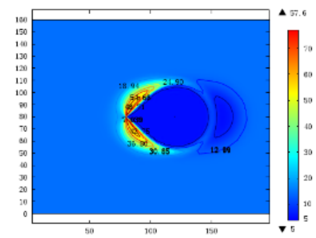


(c) second period of cold storage.

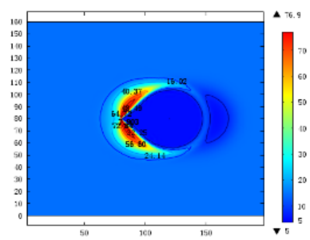
Fig 6 Pumping temperature



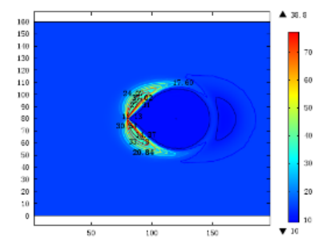
(a) 5 °C-40 °C-5 °C



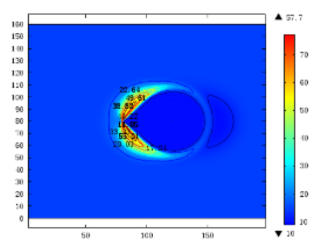
(b) 5 °C-60 °C-5 °C



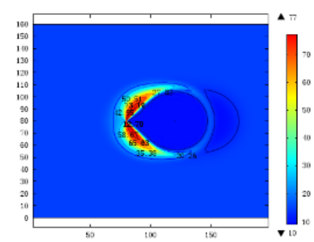
(c) 5 °C-80 °C-5 °C



(d) 10 °C-40 °C-10 °C



(e) 10 °C-60 °C-10 °C



(f) 10 °C-80 °C-10 °C.

Fig 7 Underground temperature distribution at the end of the second period of cold storage

4. CONCLUSION

Effects of injection salinity and injection temperature on temperature distribution and thermal energy storage of the brine aquifer are studied in present work.

(1) Variation of the underground temperature and pumping water temperature decrease as injection salinity decreases. That is reducing injection salinity slows down the heat transport in the brine aquifer due to the reduction of the hydraulic conductivity. Thus thermal energy storage could be improved as the injection salinity decreases.

(2) During cold injection period, decrease of the injection temperature accelerates the velocity of heat transport and the time of the pumping water temperature begin to decline occurred early. Increasing injection temperature makes the time of pumping water started to change later during the hot water injection period, but there is high amplitude of the temperature rise because of the combined effect of temperature difference and hydraulic conductivity.

(3) Whenever in cold injection or hot water injection, thermal energy storage efficiency can be improved when the temperature difference between the injected water and the aquifer increase.

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REFERENCE

[1] Vanhoudt D, Desmedt J, Bael J V, et al. An aquifer thermal storage system in a Belgian hospital: Long-term experimental evaluation of energy and cost savings. Energy and Buildings 2011;43(12):3657-3665.

[2] Dickinson J S, Buik N, Matthews M C, et al. Aquifer thermal energy storage: theoretical and operational analysis. Geotechnique 2009;59(3):249-260.

[3] Jongchan K, Youngmin L, Woonsang Y, et al. Numerical modeling of aquifer thermal energy storage system. Energy, 2010;35(12):4955-4965.

[4] Ganguly S, Kumar M S M, Date A, et al. Numerical investigation of temperature distribution and thermal performance while charging-discharging thermal energy in aquifer. Applied Thermal Engineering 2017;115:756-773.

[5] Sommer W, Valstar J, Leusbrock I, et al. Optimization and spatial pattern of large-scale aquifer thermal energy storage. Applied Energy 2015;137:322-337.

[6] Bakr M, Oostrom N, Sommer W. Efficiency of and interference among multiple aquifer thermal energy storage systems: A Dutch case study. Renewable Energy 2013;60:53-62.

[7] Yapparova A, Matthai S, Driesner T. Realistic simulation of an aquifer thermal energy storage: Effects of injection temperature, well placement and groundwater flow. Energy 2014;76:1011-1018.

[8] Schout G, Drijver B, Gutierrez-Neri M, et al. Analysis of recovery efficiency in high-temperature aquifer thermal energy storage: a Rayleigh-based method. Hydrogeology Journal 2014;22(1):281-291.

[9] Sommer W, Valstar J, Gaans P V, et al. The impact of aquifer heterogeneity on the performance of aquifer thermal energy storage. Water Resources Research 2013;49(12):8128–8138.

[10] Drijver B, Aarssen V M, Zwart D B. High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable. The 12th International Conference on Energy Storage, 2012.

[11] Lee K S. Effects of regional groundwater flow on the performance of an aquifer thermal energy storage system under continuous operation. Hydrogeology Journal, 2014;22(1):251-262.

[12] Zeinijahromi A, Farajzadeh R, Bruining J, et al. Effect of fines migration on oil–water relative permeability during two-phase flow in porous media. Fuel 2016;176:222-236.

[13] Russell T, Pham D, Neishaboor M T, et al. Effects of kaolinite in rocks on fines migration. Journal of Natural Gas Science and Engineering 2017;45:243-255.

[14] Konikow L F, August L L, Voss C I. Effects of clay dispersion on aquifer storage and recovery in Coastal Aquifers. Transport in Porous Media 2001;43(1):45-64.

[15] Rosenbrand E, Kjoller C, Riis J F, et al. Different effects of temperature and salinity on permeability reduction by fines migration in Berea sandstone. Geothermics 2015;53:225-235.

[16] Yang Y, Siqueira F D, Vaz A S L, et al. Slow migration of detached fine particles over rock surface in porous media. Journal of Natural Gas Science and Engineering 2016;34:1159-1173.

[17] You Z, Bedrikovetsky P, Badalyan A, et al. Particle mobilization in porous media: Temperature effects on competing electrostatic and drag forces. Geophysical Research Letters 2015;42(8):2852-2860

[18] Ma J, Zhao J. The research on the coupled model of water-heat-salt in brackish aquifers underground and it's application of storage. Renewable Energy Resources 2011;29(5):113-119.