Applied Thermal Engineering 146 (2019) 495–504

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental study of influence factors on heat transfer characteristics of brine aquifer

Xueling Liu*, Wanyi Li, Jinsong Liu, Shuai Li, Jun Li

Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (MOE), Tianjin University, Tianjin 300354, People's Republic of China
Tianjin Geothermal Research & Center, Tianjin University, Tianjin 300354, People's Republic of China

HIGHLIGHTS

- Heat transfer characteristics were tested when sands with clay minerals.
- Heat transfer characteristics were tested in different injected water temperature.
- Then influence of clay mineral content on heat transfer characteristics was analyzed.

ARTICLE INFO

Keywords:
Brine aquifer
Thermal energy storage
Effective thermal diffusivity
Injected temperature
Clay minerals

ABSTRACT

In this paper, a one-dimensional sand column experiment system was set up to study the heat transfer characteristics of brine aquifer, and the effective thermal diffusivity was calculated. In the conditions of different injected water temperatures and water head differences when the sand samples contained different kind of clay minerals and different contents, the temperature in sand column were tested. Based on the temperature change with time, the effective thermal diffusivities were obtained, also the function relationship between thermal diffusivity and injected temperature was obtained. Results indicate that the composition and content of clay minerals have the largest effect on the heat transfer performance of brine aquifer, followed by the temperature of injected water and the injected water head difference. For the three tested clay minerals, montmorillonite has the greatest influence on the heat transfer characteristics and the effective thermal diffusivity in the aquifer.

1. Introduction

With the development of heat pump technology and deterioration of environment, as an energy saving and environment-friendly heating and air conditioning technology, heat pump coupled with underground ATES (Aquifer Thermal Energy Storage) has been widely used for space heating and cooling around the world [1–4]. Aquifer thermal energy storage (ATES) system takes underground aquifer as energy storage medium, as shown in Fig. 1. When heat/cold is surplus, hot/cold water is injected into underground and stored around the injection well, that will be extracted when heat/cold is needed [5,6]. As coupled with ATES, COP (Coefficient of Performance) of heat pump is improved, and the electricity consumption of heating and cooling is reduced. In Turkey, a heat pump with ATES system was used for cooling or heating for a hospital, which saved about 3000 MWh electricity in summer [2]. Ghaebi got conclusion that cooling and heating for buildings using heat pump system with ATES had great economic benefits [4]. Economic analysis of heat pump with ATES system and heat transfer process in aquifer has been the focus of research in a certain time. Based on actual operating conditions and simulation results, Liu evaluated the performance of heat pump coupled with ATES, results indicated that seasonal thermal energy storage could be achieved using ATES, seasonal energy storage efficiency of heat and cold were 10.97% and 7.98%, respectively [5]. The operating cost of space heating and cooling decreased largely [6]. Mahmoud Bakr studied the efficiency of multiple wells aquifer thermal energy storage systems and analyzed the effect of thermal interference on energy storage efficiency. Results inferred that thermal interference had a positive influence on thermal energy storage efficiency [7]. However, it was reported in other literature that thermal interference reduced energy storage efficiency, because thermal breakthrough happened [8]. For high temperature aquifer thermal energy storage system (HT-ATES), natural convection could lead to heat recovery coefficient reduction, but that could be compensated by salinity difference, then saline water was recommended to be injected to

* Corresponding author.
E-mail address: lxling@tju.edu.cn (X. Liu).

https://doi.org/10.1016/j.applthermaleng.2018.10.018
Received 8 July 2018; Received in revised form 2 October 2018; Accepted 5 October 2018
Available online 09 October 2018

Nomenclature

Symbols

T	temperature, °C
τ	time, s
ρ	density, g/cm^3
c	mass specific heat, kJ/kg·K
q_1	volume flow intensity of source term, m^3/(m^2·s)
ε	porosity
α	thermal diffusivity, m^2/s
α^*	effective thermal diffusivity, m^2/s
ν	velocity of seepage solution, m/s
λ	thermal conductivity, W/(m·K)
ω	Frequency of oscillation, s^{-1}
z	depth of soil, m
S	salinity, g/L
φ	phase angle
A	amplitude of temperature oscillation
Q	heat, kJ
h	convective heat transfer coefficient, kJ/kg·K
l	characteristic length, m
η	dynamic viscosity of a fluid
x	distance from the entrance of sand column, m
R^2	correlation coefficient

Subscript

0	initial value
in	inlet value of sand column
f	fluid
s	matrix

improve energy storage efficiency [9].

Although utilization of ATES improved the efficiency of heat pump, long-term injection could result in the problem of blockage [10,11], which led to the permeability reduction in aquifer and the difficulty of recharging [12,13]. Especially for brine aquifer, as the injected water salinity is lower than that of the underground, there is the permeability reduction in aquifer [14,15]. That is due to the release, mobilization and disposition of the colloidal particles, micro and minimum particles [16–19]. When hot water was injected into underground, thermal expansion of particles and aquifer matrix could lead to the pores blockage [13]. McKay found that increasing injected water temperature could result in the clogging in pore throat, which was caused by the expansion of clay minerals and migration of small particles [20]. Rosenbrand found that permeability reduced as injected fluid heated from 20 °C to 80 °C, but it was reversible as cooled [15,21]. Ma studied the effect of solution temperature increase rate on permeability change through sand column experiment, results showed that the greater the temperature and the faster the temperature increase, and the greater of permeability reduced [22]. Permeability reduction of the aquifer will affect underground heat transfer characteristics, and then change the thermal energy storage performance.

Heat transfer in aquifer includes conductive heat transfer, advective heat transfer, and heat dispersion. Conductive heat transfer occurs in fluid and in solid matrix. Advective heat transfer includes heat transfer due to bulk fluid motion, and natural convection induced by temperature difference between fluid and matrix. Heat dispersion is because of the heterogeneity in local velocity [23–25]. Local fluid temperature and aquifer temperature are usually considered to be same in the local equilibrium calculation model, convective heat transfer usually is negligible [22]. For the simulation of heat transfer in ATES, heat

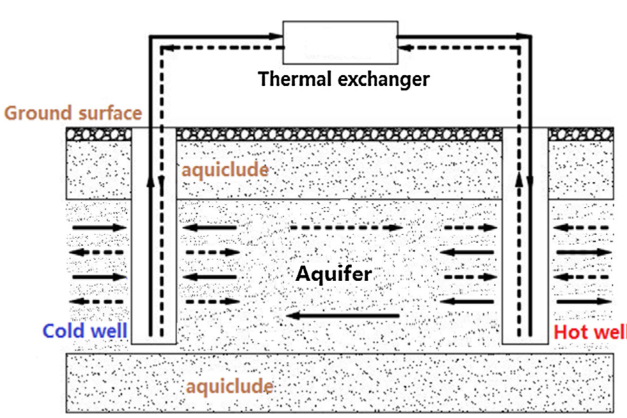

Fig. 1. Schematic diagram of ATES.

conduction model is usually used. Thermal dispersion is considered as equivalent heat conduction. All influencing factors, that affect heat transfer, are attributed to effective thermal diffusivity. Some researchers built a coupling model of seepage and heat transfer to predict the flow field and temperature field in aquifer [26–28]. Yang built a mathematical model to predict transient and steady temperature distribution in aquifer, when hot water was injected into confined aquifer. Also the influencing factors were evaluated, such as thermal properties of aquifer, reservoir thickness, injected water flux and operation time [29]. Thermal diffusivity was an important parameter that affected heat transfer characteristics and thermal energy storage performance of aquifer [30,31]. Giambastiani carried out experiment in a large sand tank and concluded that heat transfer in underground aquifer was dominated by thermal diffusion [32]. Yang verified that influencing radius of temperature was affected by many factors, including thermal diffusivity, physical and thermodynamic properties of aquifer, velocity and injected water temperature. Increased thermal diffusivity and injected solution velocity enlarged the influencing radius of temperature [33]. Higher thermal diffusivity caused rapid loss of heat [34]. When brine aquifer was used as thermal energy storage medium, blockage, caused by colloid particles, could result in the reduction of thermal diffusivity [35,36]. Therefore, effective thermal diffusivity is a significant parameter that affects heat transfer and energy storage performance of the aquifer.

Although there are lots of researches carried out on permeability and clogging problem of brine aquifer, effect of injection on heat transfer and thermal diffusivity are seldom reported. In order to use brine aquifer as thermal energy storage medium, it is necessary to study the influence of injection parameters and sand properties on the heat transfer characteristics and effective thermal diffusivity. When clay minerals were mixed in the sand, temperature variation in these sand samples were tested in different injecting conditions. Based on the experimental results, the effective thermal diffusivities of that sand samples were calculated, also the function relation between the effective thermal diffusivity and injected solution temperature were achieved. Influence of injected water temperature, water head difference between inlet and outlet, composition and content of clay minerals on heat transfer characteristics and effective thermal diffusivities were analyzed.

2. Mathematical model of underground heat transfer and thermal diffusivity

Mechanism of heat transfer in aquifer is very complicated. It contains not only heat conduction and convection, but also heat dispersion. Heat transfer characteristics in aquifer are also related to the physical properties of aquifer matrix, the physical properties and flow state of