Energy 112 (2016) 443–456

Contents lists available at ScienceDirect

Energy

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

Numerical simulation of a high-temperature aquifer thermal energy storage system coupled with heating and cooling of a thermal plant in a cold region, China

Xiao Xiao [a], Zhenjiao Jiang [a,*], Daniel Owen [b], Christoph Schrank [b,c]

[a] Key Laboratory of Groundwater Resources and Environment, Ministry of Education, College of Environment and Resources, Jilin University, Changchun 130021, China
[b] School of Earth, Environmental & Biological Sciences, Queensland University of Technology, Brisbane, QLD 4001, Australia
[c] School of Earth and Environment, The University of Western Australia, Crawley, WA 6009, Australia

ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form
3 June 2016
Accepted 23 June 2016

Keywords:
Thermal water
Cooling tower
Cold region
Unconfined aquifer

ABSTRACT

This study investigates the performance of an aquifer thermal energy storage system (ATES) that is coupled with the cooling tower of a seasonally-running thermal plant. The ATES supplies cool water and stores heated water for the cooling tower during the runtimes of the thermal plant. Moreover, it supplies warm water for bathing or irrigation during downtimes of the thermal plant. The performance of ATES is evaluated numerically for a full year, and well placement is optimized. Findings indicate that the ATES system could be optimized by locating the cool water supply well upstream of the storage well. In the optimized ATES, the outflow temperature from the cool water supply well can be maintained below 15 °C, which satisfies the temperature requirement for the cooling tower. The injection of heated water (with temperature of 70 °C) at 8400 m^3/d for six months leads to over 140,000 m^3 of warm water (with temperature ≥ 40 °C) stored in the aquifer. This warm water can supply at least 12,000 m^3/d of warm water for six months. The recovery efficiency is estimated at 60.9%, and the energy loss is attributed to rainfall infiltration, thermal diffusion into underlying low-permeability layer and advection downstream.

1. Introduction

In China electric power is mainly generated by burning fossil fuels in thermal plants, which often releases significant amount of waste energy [1]. In order to save the energy, most thermal plants in cold regions of China are only allowed to run in winter, and thus a portion of the thermal energy taken by water can be used to supply heat to cities. However, the heated water in the cooling tower of a thermal plant is commonly cooled under natural aeration, which involves both water and energy losses via evaporation. Aquifers as the heat source or sink can be used to store the heat energy and buffer the heat loss [2,3]. Here, we propose to couple an aquifer thermal energy storage system (ATES) with the cooling tower of a thermal plant, to conserve the energy and also maintain the normal running of thermal plant.

ATES developed rapidly in recent decades [4,5], and is well accepted in regions with a cold-warm seasonal period to balance cooling and heating supply and demand in such as greenhouses, hospitals and business centers [6–10]. In summer, water is extracted from the aquifer to cool the buildings, and the heated water is injected into the aquifer for the sequential use in winter to warm the buildings. ATES also succeeded in buffering the variation of solar energy from the daily period to monthly period [11,12].

However, the energy recovery from the extraction well in the ATES is lower than the injected thermal energy, attributed to the hydraulic-thermal processes such as advection, diffusion and dispersion in the storage aquifer [13,14]. The diffusion of heat depends on the thermal conductivity of both fluid and solid phases in the aquifer, while the advection and dispersion of heat relate to groundwater flow under either natural conditions or artificial interferences [15,16]. In addition, the recovery efficiency of energy also relates to well placement [15–17], aquifer heterogeneity [18,19], and the geological structure of storage rocks [20].

Due to the complex geometry of geological heat and water reservoirs, one has to resort to numerical modeling of heat and groundwater transport to investigate the thermal responses in the

* Corresponding author.
E-mail address: jiangzhenjiao@hotmail.com (Z. Jiang).

http://dx.doi.org/10.1016/j.energy.2016.06.124
0360-5442/

Nomenclature

α	Thermal dispersivity, m
β	Thermal expansion coefficient, 1/°C
$\rho_f c_f$	Heat capacity of fluid, J/m^3 °C
$\rho_s c_s$	Heat capacity of solid, J/m^3 °C
d	Distance between cool water supply wells, m
f_μ	Constitutive viscosity relation function
e_i	Extent, $e_1 = 0$, $e_2 = 0$, but $e_3 = 1$ which is the gravitational unit vector
E	The retrieved energy, J
h	Hydraulic head, m
i	Principal direction index, $i = 1$, 2 and 3, indicate x, y, z direction, respectively
K	Hydraulic conductivity, m/d
λ_b	Bulk thermal conductivity, W/m °C
λ_f	Thermal conductivity for fluid, W/m °C
λ_s	Thermal conductivity for solid, W/m °C
ϕ	Porosity
q	Darcy flux, m/d
q_v	Extraction rate of warm water, m^3/d
Q_f	Sink/source of water, 1/d
Q_T	Sink/source of heat, 1/d
r	Distance between cool water supply well and storage wells, m
ρ_{f_0}	Reference fluid density at 4 °C, kg/m^3
ρ_f	Fluid density, kg/m^3
ρ_s	Solid density, kg/m^3
S	Specific storage, 1/m
θ	Angle between cool water supply well and storage wells, degree
t	Time, day
T	Temperature, °C
T_0	Reference temperature, 4 °C
T_b	Background water temperature, °C
x	Coordinate
ε	Infiltration coefficient

aquifer and to predict the performance of an ATES. For example, Sommer et al. [18] concluded that thermal recovery decreases with increasing heterogeneity, as groundwater flow and heat disperse strongly in a heterogeneous aquifer. Zhou et al. [15] investigated the influences of the natural groundwater flow and the artificial perturbation on the thermal fluxes in the aquifer, and indicated that the injection and extraction should not induce a large hydraulic gradient, as this can enhance the heat advection and lead to the additional energy loss.

This study evaluates the feasibility of constructing a high temperature ATES (HT-ATES) near a thermal plant numerically. The aim is to store the surplus heat from the cooling tower by injecting hot water (70 °C) into the aquifer during the runtime of the thermal plant, which in turn can be used as a supply of warm water (≥30 °C) during the downtime of the plant. In addition, low-temperature water (≤25 °C) is extracted from the aquifer to supplement the water for the cooling tower during the runtime of the thermal plant. The placement of water supply wells and storage wells is optimized for both the long-term supply of warm water and normal running of the cooling tower.

The operation of high temperature ATES (HT-ATES) presents challenges, such as the mineral scaling and corrosion, and the low recovery efficiency due to thermal advection under high buoyancy forces induced by density contrasts [21]. To date, the former problem can be solved through the advances in water treatment technologies [22]. To improve the performance of the HT-ATES by reducing the effects of density-driven flow, it was suggested to store the thermal energy in low-permeability aquifers, which can reduce the convectional heat losses [23]. Moreover, Van Lopik (2016) proposed to compensate the density contrast related to the high temperature difference by increasing the salinity contrast via brackish water injection [24].

We here focus on a specific site in the northeastern China, where a thermal plant has run for 15 years and the hydrogeological structure is well known from the lithological logs. Our goal is to optimize the placement of wells in the HT-ATES and evaluate the performance of the system, regarding the influence of (1) the thickness of clay cover, (2) background groundwater flow, (3) the density driven flow, and (4) the rainfall and snow melting infiltration. 3D thermo-hydraulic modeling is conducted to simulate the dynamics of groundwater flow and heat distribution in the aquifer under both natural (for parameter validation) and artificial scenarios (for well placement optimization and performance evaluation). The results may provide a procedural template for the decision makers to achieve sustainable utilization of waste energy generated from thermal plants in the study area and elsewhere.

2. Research area description

2.1. Location and climate

Huadian is a city located in the Northeast China (Fig. 1) with an area of 6624 km^2. Climatic conditions are mid-temperate and controlled by the continental monsoon [25]. The temperatures range from −36.3 °C to 25 °C. The average yearly precipitation is 771.2 mm, 70% of which occurs in summer from June to September. In winter, snow cover lasts for 120–150 days from November to March. The soil beneath the snow cover can be frozen up to a maximum depth of 1.97 m. Snow thaws in March and April, releasing cold water into the shallow aquifer [26]. The daily maximum and minimum air temperature measured in Huadian City in 2014 are shown in Fig. 2a, and the monthly average precipitation over the same period is shown in Fig. 3a.

2.2. Geohydrology

Huadian is one of the most famous oil shale production fields in China [27,28]. Explorations of oil shale in the 1970s–1990s provided lithological logs in 64 drillholes (Fig. 1) (data from Bureau of Geology and Mineral Resources in Jilin Province, China) [29]. According to these logs, the shallow part of subsurface zone in Huadian city is divided into four layers, which from top to bottom are composed of clay (0–4.3 m), silt (0–1.5 m), coarse gravel (2–15 m) and claystone interbedded with minor sandstone (>150 m), respectively (Fig. 4). The layer of coarse gravel forms the major unconfined aquifer in Huadian.

The hydrogeological investigation conducted by China Northeast Municipal Engineering Design & Research Institute Co. Ltd (MEDRI) in 1993 suggested that groundwater in the unconfined aquifer generally flows in the southeast and east directions (Fig. 1). The unconfined aquifer is mainly recharged by precipitation, and discharged to Huifa River. In addition, groundwater level