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Research Paper

Numerical investigation of temperature distribution and thermal performance while charging-discharging thermal energy in aquifer

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HIGHLIGHTS

- A 3D coupled thermo-hydrogeological numerical model of an ATES system is presented.
- Importance of a few parameters involved in the study is determined.
- Thermal energy discharge by the ATES system for two seasons is estimated.
- A strategy and a safe well spacing are proposed to avoid thermal interference.
- The proposed model is applied to simulate a real life ATES field study.

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ABSTRACT

A three-dimensional (3D) coupled thermo-hydrogeological numerical model for a confined aquifer thermal energy storage (ATES) system underlain and overlain by rock media has been presented in this paper. The ATES system operates in cyclic mode. The model takes into account heat transport processes of advection, conduction and heat loss to confining rock media. The model also includes regional groundwater flow in the aquifer in the longitudinal and lateral directions, geothermal gradient and anisotropy in the aquifer. Results show that thermal injection into the aquifer results in the generation of a thermal-front which grows in size with time. The thermal interference caused by the premature thermal-breakthrough when the thermal-front reaches the production well results in the fall of system performance and hence should be avoided. This study models the transient temperature distribution in the aquifer for different flow and geological conditions which may be effectively used in designing an efficient ATES project by ensuring safety from thermal-breakthrough while catering to the energy demand. Parameter studies are also performed which reveals that permeability of the confining rocks; well spacing and injection temperature are important parameters which influence transient heat transport in the subsurface porous media. Based on the simulations here a safe well spacing is proposed. The thermal energy produced by the system in two seasons is estimated for four different cases and strategy to avoid the premature thermal-breakthrough in critical cases is also discussed. The present numerical model results are validated using an analytical model and also compared with results from an experimental field study performed at an ATES test site at Auburn University. The present model results agree with the analytical model very well and have been found to approximate the field results quite well.

1. Introduction

With the advancement of civilization and increasing population of the world, the demand for power is rising and coping with the increasing demand is one of the most important issues of the present century. The production of renewable and sustainable energy has been the focus of modern research for quite some time together now. Besides production, energy conservation and storage is becoming equally crucial to make use of the excess energy during times of future demand. Due to seasonal variations of temperature, an imbalance between the supply and demand of energy for heating/cooling always exists. For solving this imbalance and reduce the energy consumption from conventional sources, thermal energy storage is essential [5]. Aquifers provide a large volume for storage of thermal energy with low cost of implementation and

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maintenance and with almost no adverse environmental effects. Using low temperature geothermal resources in an aquifer by circulation of groundwater [36,35] i.e. storing the excess thermal energy in water by injecting it into an aquifer and extracting in time of demand is the main principle of an Aquifer Thermal Energy Storage (ATES) system. The extracted energy can be used for various applications like space heating, air conditioning, greenhouse heating, industrial processes and road de-icing etc. Direct use of groundwater with relatively high volumetric heat capacity makes ATES systems more efficient than other heat storage systems. Many ATES systems designed for heating purposes are linked to electricity driven heat pumps when they are not able to supply heat at required temperature. If the stored thermal energy in such system is of sufficiently high temperature then direct use of extracted groundwater is preferred.

An ATES system operates mainly in four stages in a complete cycle, 1. Injection of hot/cold-water into the aquifer, 2. Storage of the hot/cold-water, 3. Production and 4. Heating/cooling of buildings/districts. The waste heat generated from industrial processes of incinerators and thermal power plants [32], heat collected during periods of bright sunshine in a solar collector [17], surplus heat from a cogeneration plant (CHP) [26,38] or the excess heat produced by a biogas plant [50] can be injected into the aquifer for long term storage and extracted during winter for heating purposes. Similarly the ambient water at cold outside temperature during winter or water carrying cold thermal energy from any other sources can be injected, stored and extracted during summer for cooling of buildings/districts [5]. For instance in the ATES system used for cooling the German parliament (Reichstag) building the cold storage is cooled by dry cooling when ambient temperature is low [26]. Chillers and absorption heat pumps are also used [38] for cold energy storage.

As a practical, environment friendly and economical system of storage of renewable thermal energy, the popularity of ATES systems is growing rapidly. Moreover using ATES systems for energy conservation leads to energy savings and reduces the dependence on fossil fuels. This results in reduction of emission of greenhouse gases (thus possibility of global warming), considerable reduction in pollution and significant reduction of cost for heating/cooling of buildings and districts. Sommer et al. [44] reports the growth of ATES systems in the Netherlands for huge demand of sustainable energy in the country. The number of such systems has increased from five in 1990 to >1300 in 2010 [10]. According to Scout et al. [41] the usage of subsurface for energy conservation can lead to energy savings up to 80% for cooling and 30% for heating. Vanhoudt et al. [47] report a monitoring study for a period of three years in an ATES system used at a Belgian hospital in which the economic analysis shows that the cost for cooling is 85% lower than conventional cooling installation whereas cost saving for heating is 55% as compared to a gas-fired boiler installation. The authors also mention a total saving of 1280 tons of CO_2 emission after three years of operation.

Aquifer thermal energy storage systems generally operate in two modes, cyclic and continuous. In the cyclic mode, hot and cold-water are stored in different locations using two sets of wells, hot and cold. In this system, the wells for injection and production are switched seasonally. During winter ambient cold-water is injected into the aquifer through injection wells and hot groundwater which was stored in summer is extracted using production wells and used for room heating. During summer the pumping is reversed i.e. the production wells used in the winter to extract hot-water are used in the summer to inject the hot-water and injection wells used in winter for injecting cold-water is now used for extracting cold-water for district cooling. Hence hot and cold-water reservoirs are created around the wells in the process of injection or extraction. The cyclic mode of operation is more efficient than the continuous one due to the separate storage of the cold and hot energy. Since the efficiency of the system depends on the capacity of the system to retain heat, the system should be efficiently designed in order to minimize heat loss by avoiding thermal interference between the cold and hot well reservoirs.

In the continuous mode of operation the same sets of wells are used for injection and extraction throughout the year and are not seasonally switched. The hot and cold-water are not stored in different locations and thus the system efficiency is lesser than the cyclic one.

Thermal energy demand for heating and cooling is high in the urban areas where land availability is less. Hence the density of the ATES systems has to be high to cater to the energy demand and thus thermal interference between different systems is a major concern. It has been a challenge designing large scale systems by keeping safe distance between the wells while meeting the energy demand [43]. Ferguson and Woodbury [11] performed a numerical modeling study along with field observations to determine the thermal pollution in the area of 'Carbonate Rock Aquifer' beneath Winnipeg in Manitoba, Canada where they found the temperature at the production wells in three of the four ATES systems (which are meant to supply water for cooling purposes) have increased due to thermal-breakthrough of the injected hot-water. This breakthrough and consequent thermal interference was due to the insufficient spacing of the wells which was smaller than the optimum according to the authors. The authors concluded that there should be a limit to the density of development of ATES systems in an aquifer. Bridger and Allen [4] also noticed thermal short circuiting and premature thermal-breakthrough while studying the temperature logs in an ATES system in Agassiz, Canada. Application of multiple screens in the production wells also could not prevent thermal interference after 7 months of operation. Galgaro and Cultrera [13] suggested analytical solutions for thermal short circuit problems in ATES systems and proposed graphical solutions to check minimum spacing between injection-production wells. Stefansson [45] in his review paper discussed the thermal-breakthrough and cooling of production wells in geothermal reservoirs from different parts of the world. The fear of premature thermal-breakthrough has been against the application of the reinjection of cold-water in geothermal reservoir projects. The examples of reservoir cooling and thermal interference due to reinjection include 1. Ahuachapan, El Salvador where cooling by approximately 30 °C was observed in production well [48] 2. Palinpinon in the Philippines where cooling of approximately 50 °C was observed during a production time of three years after the arrival of the thermal-front [31]. 3. Svartsengi field in Iceland, where cooling of 8 °C was noticed [3]. 4. Hatchobaru field in Japan, where temperature of the production area dropped by 11 °C within the first two years [46] and so on.

In some previous studies [43,44] authors defined an analytical expression of a thermal-radius (R_{th}), which is the maximum distance from an injection well a thermal-front can penetrate in porous media. The thermal radius is given by

$$R_{th} = \sqrt{\frac{C_w \cdot V}{C_r \cdot \pi \cdot b}} \tag{1}$$

where C_w and C_r are volumetric heat capacities of water and aquifer respectively (in J/m^3 K); V is the volume of water injected in one storage cycle (in m^3) and b is the length of the well screen (in m). The assumptions involved in the above analytical expression are 1. The aquifer concerned is a homogeneous one, 2. Regional groundwater flow (referred as *RGF* hereafter) is neglected, 3. Thermal conduction and dispersion is not considered, 4. Heat flow interaction of the aquifer with surrounding rocks is neglected and 5. Effect of injection/production temperatures is not taken into account.