Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Investigation of the Potential and Thermal Performance of a Proposed Aquifer Thermal Energy Storage System at Ropar, India

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Keywords: Shallow geothermal; Aquifer thermal energy storage; Thermal performance; Energy conservation; Numerical modeling; Thermal-front.

ABSTRACT

The storage of excess thermal energy in subsurface has become a very popular application of shallow geothermal energy in many countries. Aquifer thermal energy storage (ATES) is an open system which uses subsurface porous media to store seasonal thermal energy for long-term. As an economical, environment friendly, easy to operate and maintain system, ATES has gained huge popularity in recent times. A three-dimensional coupled thermo-hydrogeological model of a potential ATES system in Ropar, India is presented in the present study. Thermal and hydrogeological data of the aquifer planned to be used for the ATES system, is used for modeling of thermal performance of the system here. The model includes the heat transport processes of advection, conduction and heat-loss to the adjacent layers. Layered heterogeneity and anisotropy of the aquifer is also taken into account in the model. Based on the thermal modeling, recovery efficiency and thermal performance in terms of energy output from the ATES system are estimated. The thermal modeling of the aquifer thermal energy storage system presented here gives a preliminary idea for the proposed experimental ATES system at Ropar.

1. INTRODUCTION

As the demand for power across the world is rapidly rising due to industrialization, increase in population and improve in living standards, catering to the heavy demand has become one of the major challenges of this century. Given the reserve of fossil fuels is depleting and pollution problems increasing with the use of them, the world is looking forward to a future powered by renewable and sustainable energy sources. Energy conservation simultaneously has become a very important topic in recent years which targets to store energy available in excess and use it in time of demand. Among different ways to store thermal energy, aquifer thermal energy storage (ATES) has become very popular in recent years (Kim et al. 2010; Ganguly et al. 2017; Ganguly and Mohan Kumar, 2015; Sommer et al. 2013) which uses shallow subsurface porous media as reservoirs to inject and store thermal energy for long term. As an environment friendly, economical and easy to operate and maintain system, ATES is being used in many countries and number of such systems increasing rapidly (Schout et al .2014; Fleuchaus et al. 2018). This eventually leads to huge savings of energy, and reduction of fossil fuels leading to reduction of emission on greenhouse gas emission. According to Fleuchaus et al. (2018) as compared to other conventional technologies, using ATES systems can result in energy savings between 40% and 70% and reduction in CO_2 emission up to several thousand tons per year. According to Schout et al. (2014) energy savings up to 80% in heating buildings and about 30% in cooling buildings can be achieved by underground energy storage systems. The basic operation principle of an ATES system is to collect thermal energy and inject the same to shallow aquifer, use groundwater to store thermal energy and harvest the energy in the time of demand. Seasonal thermal energy or the waste heat collected from power plants or other industries and solar collectors can thus be injected and stored and later can be extracted and used for heating/cooling of buildings/districts or other purposes. In case of seasonal thermal energy storage, during winter the ambient water at cold temperature outside can be injected and stored till the next summer. In summer the stored cold energy can be extracted for building cooling purposes. The extracted water which gains heat during the cooling process is reinjected into the aquifer and stored till the next winter when the heat is extracted for heating buildings/districts.

Although an ATES system can be set-up practically anywhere, establishing an ATES project at a specific site requires extensive investigation on many things like the local geology, availability of land, energy demand, investigation the repercussions related to the thermal injection into subsurface environment etc. It is important to pursue thermal modeling of the proposed site subsurface to investigate the extent of possible changes in subsurface temperature and the possible recovery efficiency of the system. The motive of the modeling is to ensure the maximum possible energy can be stored and recovered in the time of need efficiently.

The present paper is a study on the numerical modeling of thermal performance of a potential experimental ATES system at the Indian Institute of Technology (IIT) Ropar campus, Punjab, India. Some of the data for properties of different soil layers was collected by sampling while drilling the experimental site. The different soil layers along with the ATES injection well are shown in Fig. 1. The injection of water is proposed in the coarse sand and gravel layer which is the second layer from the top. Since the concerned layer is of significant hydraulic conductivity, is overlain and underlain by clay layers, hydraulic conductivities of which are considerably smaller than the sand and gravel layer, it seems ideal to use the layer as a reservoir to inject and store thermal energy for long term. Atmospheric temperature data of the site was collected from an automatic weather station (AWS) installed near the experimental site. Transient temperature distribution in the aquifer due to thermal injection is modelled and the thermal output from the ATES system is estimated. The numerical modeling results have to be further validated with the experiments planned ahead.

2. GEOLOGY OF THE EXPERIMENT SITE

The field experimental site at the soil-water plant laboratory at IIT Ropar was drilled to set-up a couple of piezometers. The piezometers tap two confined/semi-confined aquifers to measure their piezometric heads. The respective layers are marked as (2) and (4) in Fig.1 which are situated at 8.5 and 28.5 meters below ground level (mbgl) and of thickness 7.5 m and 8.5 m, respectively. The soil samples were collected during drilling from different depths which were analyzed in the laboratory. The monthly average daily temperature data of Ropar during three months of peak summer (Jun-Aug) is collected from the AWS installed at the IIT Ropar campus and found to be around 28.5°C.

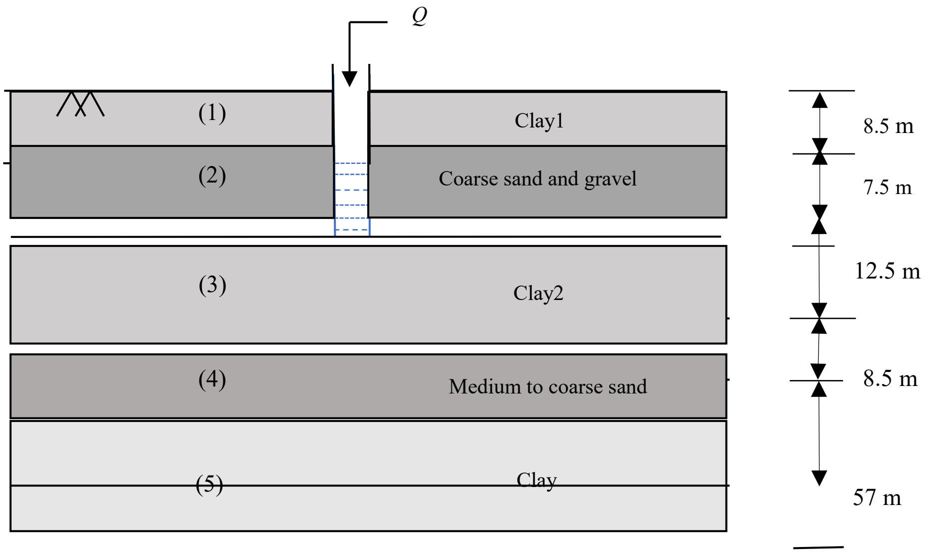

Figure 1: Schematic of the experimental ATES system showing different soil layers beneath IIT Ropar campus and the injection well.

3 MATHEMATICAL AND NUMERICAL MODELING

3.1. Mathematical Model

Three-dimensional fluid flow and heat transport equations are modelled in this study to predict transient temperature distribution in the subsurface. The flow equation in the porous media is given by

$$S\frac{\partial h}{\partial t} - \nabla \cdot \{K \cdot \nabla h\} = q_f \tag{1}$$

where K is the hydraulic conductivity of the aquifer (in m/s), h is the hydraulic head (in m), S is the specific storage (in m^{-1}) and q_f is source term (in sec^{-1}). The heat transport equation in porous media is given by

$$\frac{\partial}{\partial t}\{(1-\phi)\rho_r c_r T(x,y,z,t) + \phi\rho_w c_w T(x,y,z,t)\} + \nabla \cdot \{u_w \rho_w c_w T(x,y,z,t)\} + q_1 - q_2 = \nabla \cdot \{(\boldsymbol{\lambda} \cdot \nabla) T(x,y,z,t)\} \tag{2}$$

Where ϕ is the porosity of the aquifer; ρ_r and ρ_w are the densities of the rock and water, respectively (in kg/m^3); c_r and c_w are the specific heat capacities of rock and water, respectively (in J/Kg·K); T is the temperature (in K); u_w is the 3D velocity of groundwater (in m/s); $\boldsymbol{\lambda}$ is the equivalent thermal conductivity tensor of the aquifer (in W/m·K); t is injection time (in seconds); x, y, z are the distances in longitudinal, lateral and vertical directions, respectively (in m) and q_1 and q_2 are the heat loss terms which quantify the heat transfer fluxes from the aquifer to the overlying and underlying rocks (in W/m^3). These are modelled by the Fourier's law of heat transfer given by

$$q_{1,2} = -\lambda_{1,2} \left.\frac{\partial T_{1,2}}{\partial z}\right|_{\text{interfaces}} \tag{3}$$

where $T_{1,2}$ are the temperatures of the overlying and underlying layers, respectively. At the surface the initial temperature prior to the thermal injection is assumed to be the monthly average temperature of Ropar during the three months of injection. The boundaries of the computational domain are fixed at far field and assumed to be at constant temperature which is not affected by the injection activities.

The coupled equations (1) and (2) above are solved using finite element technique. COMSOL Multiphysics software®, a finite element-based commercial package is used for the implementation of finite element technique. This helps to map the transients of hot water plume, which is injected through the injection well, at the center of the domain, which represents the study area located at Indian Institute of Technology Ropar, India.

3.2 Computational Domain

The permeable coarse sand-gravel layer and the two adjacent clay layers are considered for the computational purposes here. In view of the soil stratum observed during the drilling of borewells, the depth of the domain is considered as 28.5 meters. Layer-1 extends to a depth of 8.5 meters and the dominant lithology is observed to be clay. This layer is underlain by a pervious layer, which is a mixture of coarse sand and gravel, extending up to a depth of 7.5 m from layer 1. Subsequent to this layer, again clay layer of 12.5 m is encountered. Since, the intent of this study is to observe the transient of hot water plume, an injection well of 0.3 meters diameter is assumed to be located in the center of domain. The schematic representation of the problem is shown in Fig.1. An injection rate of 432 m^3/day is considered for this study, which is in line with the literature. The thermo-hydro-geological properties of the domain are also shown in Figure 2.

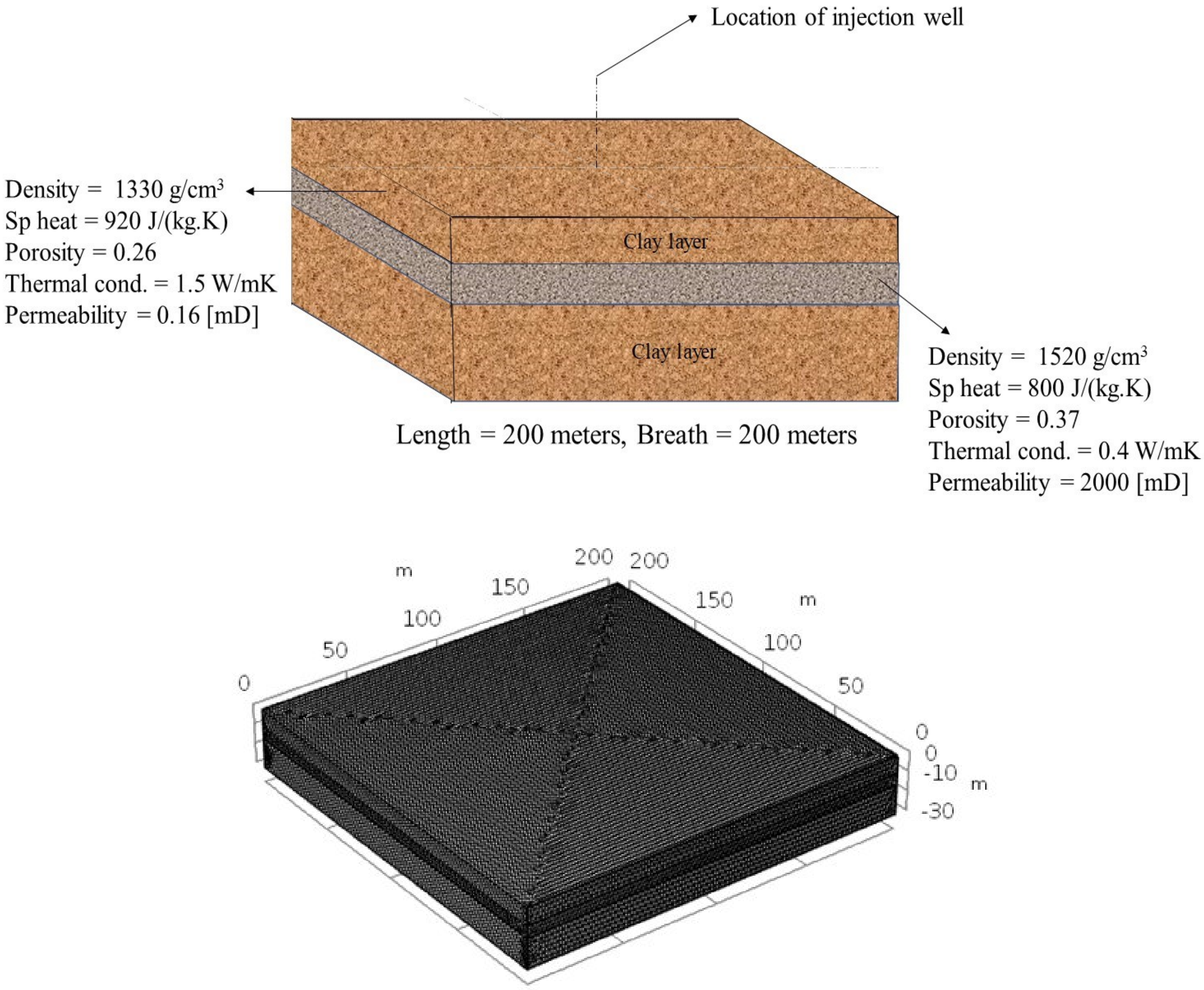

Figure 2: Schematic representation of the computational domain and the finite element mesh.

3.3 Initial values and boundary conditions:

Any existing regional groundwater is neglected for the thermal modeling here. A constant injection rate is given as a boundary condition for the well. The aquifer region which is highlighted in Figure 2 is modelled as the storage region. Typically, at a location, the subsurface temperature rises with depth. Since the considered depth of domain is relatively less, it assumed that the temperature is constant for the entire domain with depth, which is considered as 17°C. Further the temperature of hot water which is injected is at 28.5°C, which is the monthly average daily temperature of Ropar, India during summer. To account the losses that would occur from medium to the surrounding, the boundary walls of the 3D domain are considered as open boundaries. Subsequent to assigning the boundary conditions, the computational domain is divided into 864051 elements which include tetrahedral elements, triangular elements, edge elements and vertex elements, which enabled to maintain a minimum element quality of 0.1573 and an average element quality is 0.665. Considering the aforementioned aspects, coupled equations i.e. Eq 1 and 2 are solved using COMSOL Multiphysics software®, to examine the transients of hot water plume for a span of 3 months with an intermittent time step of 1 hour. The transient temperature distributions for different injection times are shown in Figure 3.

4 RESULTS AND DISCUSSION

The transient temperature distribution in the aquifer (layer 2) due to thermal injection is presented in Fig. 3 for thermal injection into the aquifer for three months of summer (Jun-Aug). Due to constant injection a hot reservoir is formed around the injection well which grows in size with injection time. The temperature of the aquifer thus rises gradually as the thermal front propagates through the porous media. After summer the warm water is stored for three months of autumn (Sep-Nov) when there is no demand for heating/cooling. The warm water is withdrawn during the winter months (Dec-Feb) for building/district heating purposes. The aquifer loses some amount of heat during its long-term storage in the aquifer and thus the amount of heat extracted from the aquifer will not be equal to the amount of heat injected into it. This effect is discussed in the next section

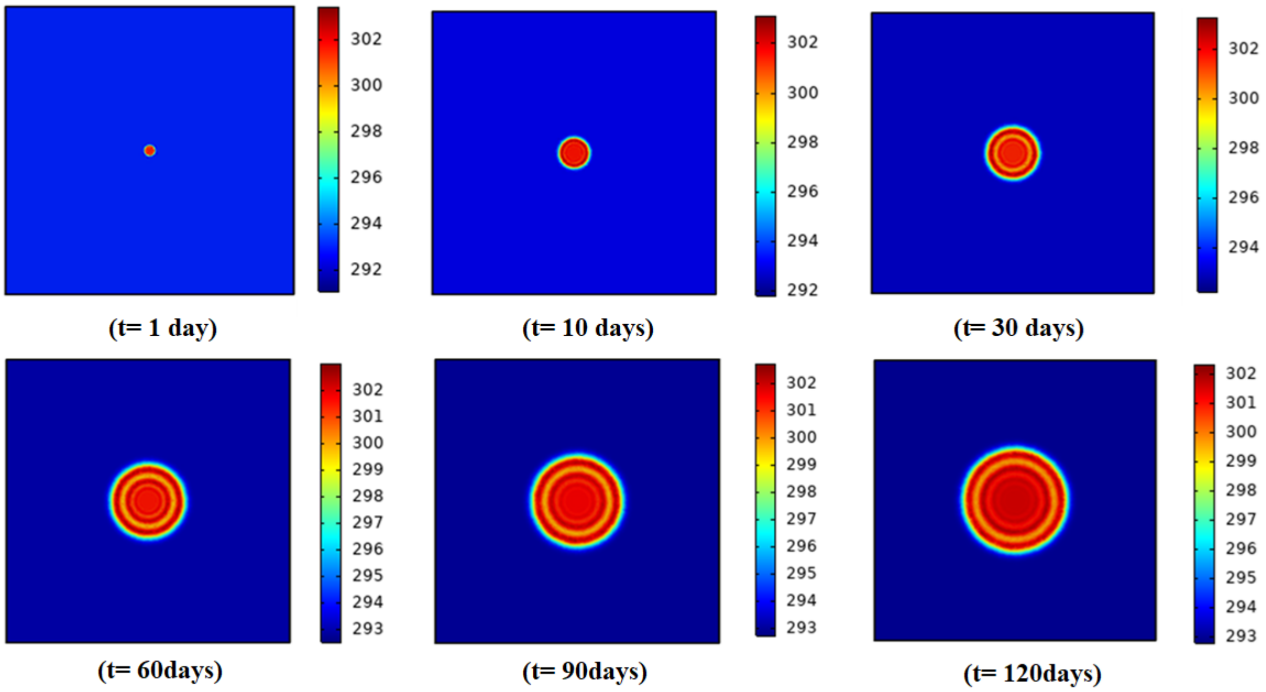

Figure 3: Transient temperature plots in the aquifer during three months of heated water injection.

4.1 Recovery efficiency

The recovery efficiency is one of the most important parameters which defines the feasibility of an ATES system for effective long-term storage capability of it. The recovery efficiency is defined as the ratio of the amount of heat extracted from an ATES system to the amount of heat injected into it. Mathematically the ratio is given as

$$\eta = \frac{V_p \cdot c_w \cdot \left(T_p - T_a\right)}{V_i \cdot c_w \cdot \left(T_i - T_a\right)} \tag{4}$$

Here V_i and V_p are the injected and produced amounts of water (m^3), c_w is the volumetric heat capacity of water (J/(m^3·K), T_p is the average temperature of the produced water (K), T_a is the ambient temperature and T_i i the injection temperature. For several reasons the recovery efficiency of an ATES system cannot be equal to 100%. This involves the heat loss from the aquifer to its adjacent confining layers, the regional groundwater flow and the thermal interference between the hot and cold zones created due to thermal injection during summer and winter, respectively (Ganguly et al. 2017). Here the recovery efficiency is estimated assuming the volume of the warm water injected during summer (Jun-Aug) is equal to the volume of that withdrawn during winter (Dec-Feb) for heating. Which reduces equation (4) to

$$\eta = \frac{\left(T_p - T_a\right)}{\left(T_i - T_a\right)} \tag{5}$$

The monthly average ambient temperature of Ropar during the winter months estimated from AWS data is around 16°C. The recovery efficiency for heat extraction thus calculated from the simulations equals to around 0.68.

4.2 Thermal Energy Discharge

The thermal energy discharge is the most important parameter which is to be estimated while proposing an ATES system for long-term thermal energy storage. The thermal energy which can be extracted from an ATES system during the time of demand depends on the long-term storage capability of the system and thus such systems are designed to maximize it. The thermal-energy discharge can be mathematically presented as (Ganguly et al. 2017).

$$W = \eta \cdot Q \cdot \rho_w \cdot c_w \cdot \Delta T \quad (6)$$

Here where W is the rate of thermal energy discharged by the ATES system (in Watts), ΔT is the difference between the injected water and ambient groundwater (in K), c_w is the heat capacity (J/kg·K) and ρ_w is the density (kg/m^3) of the discharged water. For the present system given that the rate of extraction is 432 m^3/day, the thermal-energy discharge is estimated to be 175 kW. The thermal energy discharge can be enhanced by increasing the extraction rate Q (m^3/s). However, this might lead to loss of quality of heat after a certain time. Meaning heat which is extracted from the system will be at a lower temperature than expected, limiting its applicability. Normally in ATES projects multiple injection-production wells are deployed to enhance the thermal performance of a system (Ganguly et al. 2015). Such an ATES system should be designed properly by thermal modeling keeping sufficient spacing between injection-production wells, which otherwise might result in thermal interference and deterioration of recovery efficiency a thermal performance of such systems (Sommer et al 2014; Fleuchaus et al .2019).

5 SUMARY AND CONCLUSIONS

A numerical study on the thermal modeling of a potential ATES system at Ropar, India has been presented in this study, which stores seasonal thermal energy in a shallow permeable sandy-gravel aquifer. The transient temperature distribution in the ATES system due to the thermal injection of water at seasonal temperature during summer is modelled. The monthly average temperature data at Ropar is collected from an AWS in the IIT Ropar campus, while some of the input data has been estimated from soil samples collected during drilling the experimental site. The preliminary numerical investigation shows promising results for the long-term storage capacity of the aquifer. The numerical investigation is planned to be further extended for more complex three-dimensional thermal modeling as more field data becomes available. Field experiments of thermal injection are also envisaged for further exploration for possibility of such a system.

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