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Performance analysis and parametric study of thermal energy storage in an aquifer coupled with a heat pump and solar collectors, for a residential complex in Tehran, Iran

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HIGHLIGHTS

- Three ATES applications are considered.
- Numerical simulation of the ATES is carried out.
- Performance of the coupled ATES with heat pump and solar collectors are considered using numerical simulation.
- Parametric study of the ATEs is carried out.

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ABSTRACT

Aquifers are underground porous formations containing water. Confined aquifers are the formations surrounded by two impermeable layers, called cap rocks and bed rocks. These aquifers are suitable for seasonal thermal energy storage.

In the present study, a confined aquifer was considered to meet the cooling and heating energy needs of a residential complex located in Tehran, Iran. Three different alternatives were analyzed in this aquifer thermal energy storage (ATES), including: using ATES for cooling alone, for cooling and heating, as a heat pump, and for heating alone, employing flat plate solar energy collectors. A numerical simulation, based on the finite difference method, was carried out for velocity and temperature distributions as well as the heat transfer in the aquifer. The thermal energy recovery factor and the annual coefficient of performance of the system were determined under various schemes of operation, revealing that the combination of the ATES with the heat pump, to meet both cooling and heating needs of the complex, is the best. The study was repeated for different aquifer properties.

1. Introduction

In relation with energy and buildings, sustainable engineering requires: 1) reduction of the heating and cooling energy needs of buildings to their minimum possible values, 2) reduction of consumption of primary sources of energy to meet these minimum values through innovative designs of energy conversion systems and the employment of innovative methods to meet the energy demands.

Seasonal storage of thermal energy in aquifers, as well as the utilization of solar energy and heat pumps, are examples of innovative approaches to reduce primary energy demand for heating and cooling of buildings.

Thermal energy storage (TES) is considered one of the major advanced energy technologies and recently, increasing attention has been paid to its utilization for various thermal applications ranging from heating to cooling, particularly in buildings [1,2].

Employing large scale storage which exists in nature, such as using underground aquifers which already contain water is a very efficient and low cost investment [3].

The flow of groundwater and heat transfer has been carefully discussed in hydrology. Numerical simulations have been considered in Europe and North America for more than one decade, more and more of them focusing on heat and mass transfer [4]. The two-dimensional finite element method was employed by Sykes et al. for modeling of groundwater flow and heat transfer [5]. They compared their modeling results with the experimental results obtained at Auburn University in Alabama, USA. In their numerical model, factors such as hydraulic coefficients, thermal conductivity and thermal dissipation to surrounding layers were considered. A

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Nomenclature

A	area, cross section (m^2)
b	aquifer thickness (m)
c	specific heat (J kg^{-1} K^{-1})
COP	coefficient of performance
E	energy (J)
g	gravitational acceleration (m s^{-2})
h	hydraulic head (m)
K	permeability (m s^{-1})
k	specific permeability (m^2)
L	length (m)
p	specific heat capacity (J m^{-3} K^{-1})
q	specific velocity (m s^{-1})
Q	heat (J)
R	wells distance (m)
S	flow source term (kg s^{-1}) and heat source term (J m^{-3} K^{-1})
t	time
T	temperature
V	volume (m^3)
$\dot{V}$	flow rate (m^3 s^{-1})

Greek symbols

α	diffusivity (m^2 s^{-1})
η	efficiency
φ	porosity
λ	aquifer thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})

Subscripts

A	aquifer
f	fluid
gw	groundwater
imp	imposed
injection	injection
O	overall
Rock	rock or pebbles
S	specific, solid
V	void
water	water
withdraw	withdraw

general model for simulation of energy systems including thermal energy storage in an aquifer, along with subsystems such as boilers, heating load of a building and the energy sources was considered by Kangas and Lund [6,7]. Three-dimensional modeling of ATES has also been carried out [8,9]. Chevalier and Banton studied heat transfer in an aquifer, using the random walk method [10]. In this study, single-well system (for both injection and withdrawal) was employed. Tenma et al. used a two- well model for designing a TES [11]. They also performed a sensitivity analysis on the long-term operation of the ATES system. Lee investigated the effect of various operating parameters on the recovery of energy from the storage system [12]. These parameters included the operation of loading conditions and the timing and temperature of the injection/withdrawal of water under various operating conditions. Junhua and et al. employed the software Fluent to model the heat transfer in an aquifer located under the sea [13]. After this simulation, they carried a feasibility study to use their aquifer as a ground source for a heat pump.

Analytical solution of the temperature field inside an aquifer has been carried out by Yang et al., using mathematical modeling, and the numerical solution of inversion of the Laplace transform [14,15]. They employed the modified Crump method for numerical solution of the inverse Laplace transform. Long et al. [16] developed an unsteady-state mathematical model to handle the groundwater seepage and heat transfer caused by the single-well system in an aquifer. They deduced that heat storage improves the performance of the single well system in the next space heating or cooling season.

Kim et al. employed thermo-hydraulic modeling to investigate the effects of parameters, such as the distance between the wells, hydraulic conductivity, and the rate of injection/withdrawal on an ATES [17]. They used Comsol Software for numerical simulation. Paksoy et al. utilized an ATES for air-conditioning of a supermarket on the Mediterranean coast of Turkey [18]. They used the aquifer as a low temperature heat source for a heat pump. Dincer and Dost proposed a perspective for using the TES in solar applications [19]. Andersson et al. presented all of the underground thermal energy storage (UTES) projects in Sweden, divided by the type of operation and the amount of their heating and cooling capacity [20]. One major project in Europe is the German parliament building, which employs TES and solar energy for heating [21]. Caliskan et al. performed thermodynamic assessments of various thermal energy storage systems [22]. They also conducted energy, exergy and sustainability analyses for three various reference state conditions. An experimental investigation of an aquifer thermal energy storage system was conducted in Belgium [23], in which a low temperature ATES system was coupled with heat pumps for heating and cooling of a hospital over a three-year period. Gao et al. investigated the well position for improving the efficiency of thermal energy storage systems [24].

In the present investigation, we considered a suitable confined aquifer to meet the cooling and heating energy needs of a residential building complex located in Tehran. We determined the size of the aquifer to meet both annual cooling and heating energy needs of the complex. We developed a three-dimensional numerical model, employing the finite difference method, to determine the velocity and temperature distributions inside the aquifer, the thermal recovery factor, and the annual coefficient of performance of the ATES. For validation, the results of the developed code were compared with the results of the simulation using the software FLUENT. Thermodynamic performance of three different applications of ATES system were investigated and compared. We also investigated the effects of different aquifer and operational parameters on the operation of the ATES system considered.

2. Description of the residential building complex considered

2.1. Specification of the residential complex

A residential complex, consisting of ten four-story buildings, located in Pounak region of Tehran was considered. Each floor consisted of four small apartments. The total floor area of the residential complex was 12800 m^2.

2.2. Annual heating and cooling requirements of the residential complex

Hourly cooling and heating energy needs of the buildings were estimated using the software HAP 4.41(Carrier). The building needed heating four months of the year, beginning on Nov. 21, and needed cooling also for four months, beginning on May 21. The peak heating and cooling loads were estimated to be 0.504 MW and 1.13 MW, respectively. The annual heating and cooling