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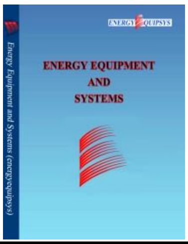

Energy efficiency in a building complex through seasonal storage of thermal energy in a confined aquifer

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ABSTRACT

Confined aquifers are formations surrounded by impermeable layers called cap rocks and bed rocks. These aquifers are suitable for the seasonal storage of thermal energy.
A confined aquifer was designed to meet the cooling and heating energy needs of a residential building complex located in Tehran, Iran. The annual cooling and heating energy needs of the buildings were estimated to be 8.7 TJ and 1.9 TJ, respectively. Two different alternatives were analyzed for an aquifer thermal energy storage (ATES) system. These alternatives were: 1) using ATES for cooling alone, and 2) coupling ATES with a heat pump for both cooling and heating. The thermal annual energy recovery factor and the annual coefficient of performance (COP) of the system were determined. A COP of 10 was obtained when ATES was employed for cooling alone. When ATES was employed for cooling and heating (using a heat pump), a COP of 17 was obtained for the cooling mode, and 5 for the heating mode.

Keywords: Aquifer, Energy Recovery, Heat Pump, Thermal Energy Storage.

1. Introduction

In relation to energy and buildings, sustainable engineering requires: 1) reduction of the heating and cooling energy needs of buildings to their minimum possible values; and 2) reduction of the 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.

The seasonal storage of thermal energy in aquifers and the utilization of heat pumps can be considered as innovative approaches to reduce the primary sources of energy for the heating and cooling of buildings.

Underground thermal energy storage (TES) for the cooling and heating of buildings has been employed since the 1970s in the United States [1–4], European nations [5–10], and other countries [11–14]. Recently, it has gained in popularity worldwide due to the problems resulting from the depletion of fossil fuels and the increase of global warming [15]. Aquifer thermal energy storage (ATES) systems are generally considered economically viable for the seasonal storage of thermal energy. In ATES, the contamination and depletion of groundwater are minimal, since the water is withdrawn from an aquifer, circulated through a

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heat exchanger, and immediately injected back to the aquifer through injection well(s) [12]. The use of aquifers for TES for the reduction of the primary energy needs of buildings related to heating and cooling has been investigated by the authors [16–18].

We designed a confined aquifer to store thermal energy to meet the cooling and heating energy needs of a residential building complex located in Tehran. The size of the aquifer to meet both the annual cooling and heating energy needs of the complex was determined.

Nomenclature

A	area, cross-section (m^2), aquifer
α	diffusivity $(m^2 s^{-1})$
b	aquifer thickness (m)
COP	coefficient of performance
C_f	volumetric heat capacity of fluid $(J\,m^3\,K^{-1})$
C_S	volumetric heat capacity of aquifer $(J\,m^3\,K^{-1})$
E_{req}	required energy (J)
η	efficiency
h	hydraulic head (m)
K_f	hydraulic conductivity $(m\,s^{-1})$
K_S	aquifer thermal conductivity $(W\,m^{-1}K^{-1})$
Q_f	source/sink mass flux (s^{-1})
$Q_{injection}$	injected heat (J)
Q_S	source/sink heat $(W\,m^{-3})$
$Q_{withdraw}$	withdrawn heat (J)
R	wells distance (m)
S	specific storage coefficient (m^{-1})
t	time (s)
T	temperature (K)
u	fluid velocity $(m\,s^{-1})$
$V_{storage}$	volume (m^3)
W	work (J)

2. Description of the residential building complex

The residential building complex considered in this study consisted of 10 separate buildings with a total floor area of 12,800 m^2.

The hourly cooling and heating energy needs of the buildings were estimated [16]. The buildings needed heating for four months of the year, beginning from November 21. They also needed cooling for four months, beginning from 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 energy requirements of the complex were estimated to be 1.9 TJ and 8.7 TJ, respectively [16]. At present, the heating and cooling needs of the buildings are met through gas-fired boilers and a vapor-compression refrigeration system, respectively.

3. Design of an ATES for cooling and heating of the building complex

In an ATES system, two or more well pairs are employed. Half of these wells are for the injection of water and the other half for the withdrawal of water. The removed water goes through a heat exchanger to meet the energy needs of the building. It is then injected back into the aquifer through the injection well(s). During the cold months, warm water, and during the hot months, cold water is withdrawn from the aquifer.

- Cooling through ATES alone

In this alternative, water is withdrawn from the aquifer in winter, cooled by one or more cooling towers, and injected back into the aquifer, thus allowing the aquifer to store cold water for summer use. In summer, cooled water is withdrawn from the aquifer and sent through one or more heat exchangers, thus meeting the cooling needs of the residential complex. Fig. 1 shows the system operation in this alternative.

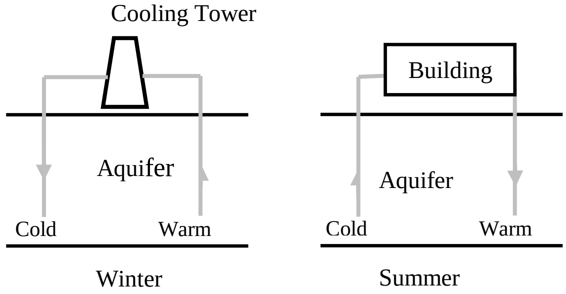

Fig. 1. Cooling through ATES alone

- Coupling of ATES with a heat pump for both cooling and heating

Another alternative for ATES to meet the heating needs of buildings is its combination with a heat pump. The summer application of this alternative is the same as the summer operation mode for the cooling-alone alternative.

Warm water from the aquifer acts as a low-temperature heat source for the heat pump (see Fig. 2). Since in this study (for the buildings located in Tehran) the heating energy needs are much less than the cooling needs, only a portion of the withdrawn water needed to pass through the heat pump to provide the low-temperature heat source for it. The other part of the withdrawn water passes through the cooling tower. These two parts of withdrawn water are combined and then injected back into the aquifer for summer cooling.

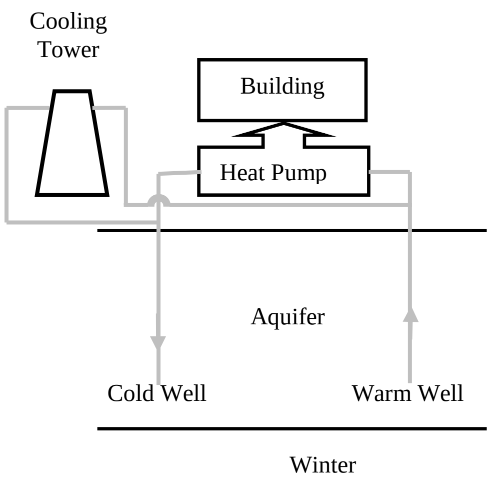

Fig. 2. Combination of ATES with a heat pump for heating and cooling of the buildings

4. Mathematical formulation

- Governing equations

Two governing equations—the fluid flow and heat transfer equations—are used for the thermo-hydraulic modeling of the ATES system. Fluid flow in a porous medium is described by Darcy's law as:

$$S\left(\frac{\partial h}{\partial t}\right)+\vec{\nabla}.\left[-K_f\vec{\nabla}h\right]=Q_f \quad (1)$$

The heat transfer equation, which includes conduction and convection, can be expressed as:

$$C_s\frac{\partial T}{\partial t}+\nabla.\left[-K_S\nabla T+C_f uT\right]=\mathrm{Q}_H \quad (2)$$

The thermo-physical properties of water and aquifer are listed in Table 1. We assume that these properties are constant.

The heat transfer phenomena within the upper and lower surrounding layers of the aquifer are mainly conduction. Therefore, we have:

$$\frac{\partial T}{\partial t}=\alpha\nabla^2\mathrm{T} \quad (3)$$

Table 1. Thermo-physical properties of the aquifer

Property	Value
Aquifer permeability	$0.0017\,\frac{\mathrm{m}}{\mathrm{s}}$
Porosity	0.3
Density of water	$1{,}000\,\frac{\mathrm{Kg}}{\mathrm{m}^3}$
Density of pebbles	$1{,}800\,\frac{\mathrm{Kg}}{\mathrm{m}^3}$
Specific heat of water	$4{,}200\,\frac{\mathrm{J}}{\mathrm{kgK}}$
Specific heat of pebbles	$1{,}292\,\frac{\mathrm{J}}{\mathrm{kgK}}$
Thermal conductivity of water	$0.63\,\frac{\mathrm{W}}{\mathrm{mK}}$
Thermal conductivity of pebbles	$1.3\,\frac{\mathrm{W}}{\mathrm{mK}}$

- Energy recovery factor and the COP of the designed aquifer

After determining the temperature field within the aquifer at different time steps [16], the amount of energy recovered from the aquifer was determined. The most important factor of an ATES is the amount of energy recovery. It determines the amount of energy which can be recovered from the stored water. The thermal energy recovery factor of an aquifer, η_A, is defined as:

$$\eta_A=\frac{Q_{Withdraw}}{Q_{Injection}} \quad (4)$$

In an air-conditioning system (heating or cooling), the coefficient of performance is defined as:

$$COP_{system}=\frac{Q_{Required}}{W} \quad (5)$$

In this equation, $Q_{Required}$ is the annually required energy for the cooling or heating of the building, and W is the total annual electrical energy required to run circulation pumps, cooling-tower fans, and the heat pump.

5. Steps for the design of an energy storage system in a given aquifer

After determining the aquifer characteristics and the heating/cooling requirement of the building, the storage system can be designed according to the following procedure [19].

1. The specific heat capacity of the aquifer is determined.
2. The recovery factor of the aquifer (ηA) is determined.

This factor is calculated via a numerical simulation. Since the numerical model gets the aquifer dimensions as input, the approximate typical value must first be typical for the recovery factor of the aquifer. At the end of the design procedure and after determining the wells' distance, it can be precisely calculated by applying the developed code for real dimensions and iterating the design procedure until the two successive values of the recovery factor of the aquifer are equal.

3. The required storage volume is calculated:

$$V_{Storage} = \frac{E_{req}}{C_S \Delta T \eta_A} \quad (6)$$

By dividing the storage volume by the storage/removal period, the amount of injection/withdrawal flow rate is obtained.

4. The horizontal area required for an aquifer with a height b is determined by:

$$A = \frac{V_{Storage}}{b} \quad (7)$$

5. The distance needed between pairs of wells is set by:

$$R = \sqrt{A/1.05} \quad (8)$$

6. With the known distance between wells and the injection/withdrawal flow rates, the developed codes will be run to obtain the recovery factor of the aquifer.
7. Steps 3 to 6 will be repeated until the difference between two consecutive amounts of the recovery factor of the aquifer is less than a certain amount.

6. Estimation of the aquifer dimensions

According to the previous section and assuming one injection well and one withdrawal well, the dimensions of the ATES suitable for meeting the cooling and heating energy needs of the buildings were estimated. Fig. 3 shows the computational domain and Table 2 presents the results of the aquifer design.

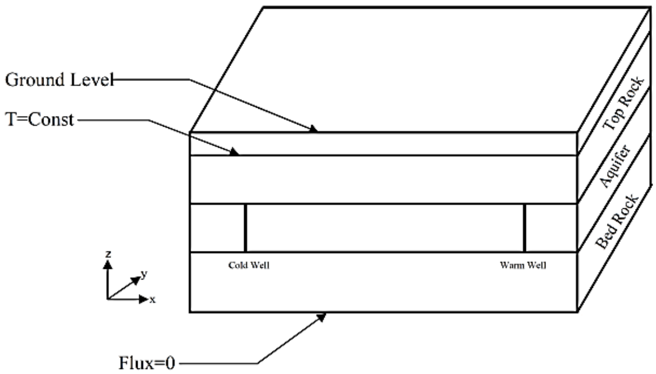

Fig. 3. Three Dimensional Computational Domain

Table 2. Results of the ATES design

Parameter	Value
The recovery factor of the aquifer (%)	73
Aquifer length (m)	182
Aquifer width (m)	116
Injection/withdrawal rate (L/s)	32.5
Aquifer volume (m^3)	337,080
The area of the horizontal surface of the aquifer (m^2)	21,067
Distance of the wells (m)	142
Coordination of cold well in horizontal surface of aquifer	x = 20 m y = 58 m
Coordination of warm well in horizontal surface of aquifer	x = 162 m y = 58m

7. Numerical modeling

In this study, FLUENT® software—a commercial finite-volume program—was used to simulate the ATES system. The computational domain is shown in Fig. 4. In this, an unstructured 3D mesh of 259,346 cells was built. The chosen element was Tet/Hybrid and the type was TGrid.

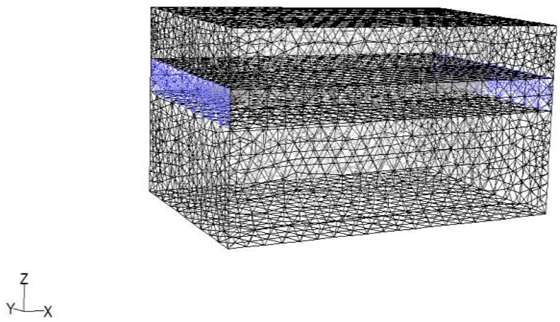

Fig. 4. Model mesh in FLUENT

- Boundary and initial conditions

The boundary condition at the upper layer of the cap rock is constant temperature and the depth of the ground where the temperature remains constant throughout the year. At the lower layer of the bed rock, the boundary condition is thermally insulated. The sides are assumed to be thermally insulated. The initial temperature in the model domain linearly increases from the top to the bottom to express the thermal equilibrium state prior to the thermal injection.

According to the requirement, a value for the flow rate of injection/withdrawal wells is considered. These values are considered as the source terms in Equation 1. By considering the groundwater velocity, a pressure gradient in the direction of x is added as obtained from the Darcy equation. The initial head in the model domain is equal to the model elevation. The boundary condition on the lateral and the upper and lower sides is no flow.

8. Discussion and results

Here are the results of numerical modeling. The most important factor at the ATES is the injection and withdrawal temperatures. Figure 5 shows the hourly variations in the temperature of the cold well (injection well during the cold season and withdrawal well in the hot season) and the warm well (injection well during the hot season and withdrawal well during the cold season) for 10 years of operation of the ATES. In winter, groundwater is withdrawn at a temperature of 12°C, cooled by cooling towers, and injected back into the aquifer through cold the well at 3°C . Therefore, the cold well temperature during this period is constant at 3°C. In spring (March 21 May 21), when the system is idle and there are no injections or withdrawals, the temperature of the cold well increases because of the heat transfer. In summer (May 21 to September 21), warm water is injected to the aquifer through the warm well at a temperature of 14°C. During this period, the warm well temperature is constant and the cold well temperature increases. Finally, in fall (September 21 to November 21) the temperatures of the cold well and the warm well are increased and decreased, respectively. In the following years, this trend in temperature variation is repeated.

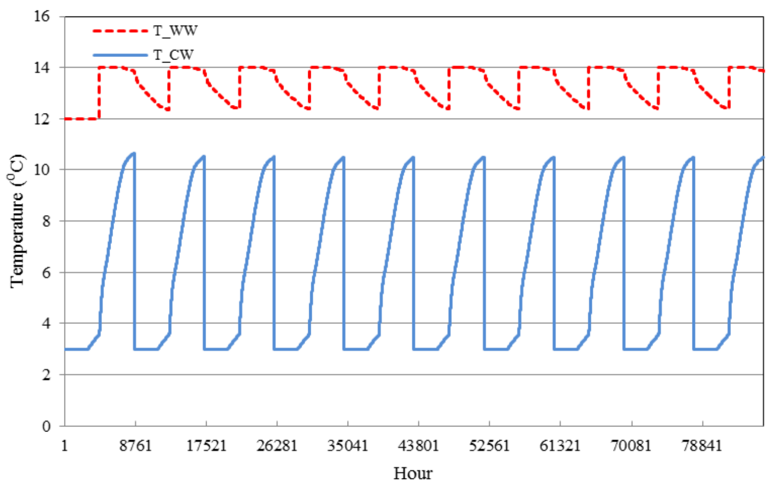

Fig. 5. Temperature variation of cold and warm wells at ten years operation

The recovery factor of the aquifer and the COP of the HVAC system are important in ATES. These parameters are shown in Fig. 6 for a period of 10 years. As seen, η_A and COP are both higher during the first year than in the other years. This is rational because, during the first year, the temperature of water removed from the aquifer is equal to the groundwater temperature, which is lower than that of water in the aquifer in the following years. For direct cooling or the cooling-alone operation, the $Q_{Required}$ in Equation 5 is the annual cooling requirement of the building, which is equal to 8.7 TJ. In this equation, W is the sum of all the energy consumed by the circulation pump and the cooling tower fans for cooling of the water in winter. Because water temperature removed from the warm well (to be chilled in winter) is lower during the first year than in other years, the cooling tower energy consumption is lower during this year. Consequently, the COP of the system will be higher during the first year of operation than in the other years.

The hourly temperature variations of the cold and warm wells of the coupled ATES with a heat pump are the same as in the direct-cooling option because of the similar injection/withdrawal temperatures.

Figure 7 shows the variations in η_A and COP when ATES is combined with a heat pump for the cooling and heating of the buildings.

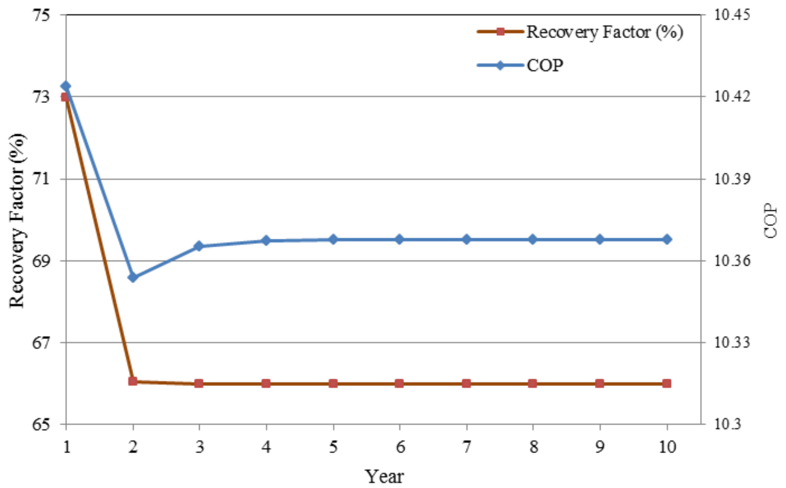

Fig.6. The recovery factor of the aquifer and COP at the period of ten years

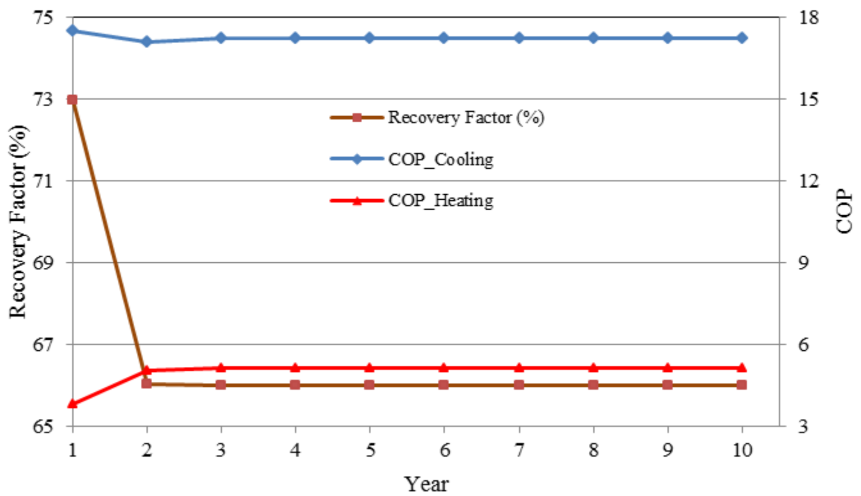

Fig.7. The Recovery Factor of the Aquifer and COP in the ATES Coupled with a Heat Pump, for Ten Years of Operation

In this alternative, η_A is the same as in the cooling-alone operation.

For this alternative, $COP_{Heating}$ and $COP_{Cooling}$ are considered. $Q_{Required,Heating}$ and $Q_{Required,Cooling}$ in Equation 5 are the annual heating and cooling requirements of the buildings, respectively. W in Equation 5 is the sum of the energy needs of the heat pump and the circulation pumps for $COP_{Heating}$, and the sum of the circulation pumps and the cooling tower fan(s) for $COP_{Cooling}$. The energy consumption of these components is calculated by considering the hours of the cooling and heating requirements of the building complex.

$COP_{Heating}$ of the designed ATES is less during the first year of operation than in the other years. During the first year, water supplied to the heat pump as the low-temperature heat source is at a lower temperature than in other years (water temperature is equal to the groundwater temperature at 12℃); therefore, the energy consumption of the heat pump is more in order to satisfy the heating requirements of the buildings. But $COP_{Cooling}$ in the first year of operation is more than in the other years. That is because, in the first year, the power consumption of the cooling tower is less than in the other years. As time goes on, with the heating and cooling energy needs remaining the same, $COP_{Heating}$ and $COP_{Cooling}$ remain nearly constant.

9. Conclusion

An ATES system was designed to meet the thermal energy needs of a residential complex located in Tehran, Iran. The objective was the storage of 8.7 TJ of thermal energy in the form of chilled water for summer cooling and 1.9 TJ of thermal energy in the form of hot water for winter heating. Two different alternatives were considered.

The following conclusions may be drawn from this investigation:

When ATES is employed for thermal energy storage for cooling alone, a COP of 10.36 is obtained.

When ATES is employed for cooling and is coupled with a heat pump for TES for heating of the buildings, a COP of 17.2 is obtained for the cooling process and a COP of 5 is obtained for the heating process.

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