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Research Article

AQUIFER THERMAL ENERGY STORAGE SYSTEMS: BASIC CONCEPTS AND GENERAL DESIGN METHODS

Nihan Aydın Ertuğrul *[1], Zübeyde Hatipoğlu Bağcı [2] and Özgür Lütfi Ertuğrul [3]

[1] Mersin University, Directorate of Construction and Technical Works, Mersin, Turkey
ORCID ID 0000 – 0002 – 2850 – 1275
(nihanertugrul@mersin.edu.tr)

[2] Mersin University, Engineering Faculty, Department of Geological Engineering, Mersin, Turkey
ORCID ID 0000 – 0002 – 7935 – 5028
(zubeyde@mersin.edu.tr)

[3] Mersin University, Engineering Faculty, Department of Civil Engineering, Mersin, Turkey
ORCID ID 0000 – 0002 – 1270 – 3649
(ozgurertugrul@hotmail.com)

* Corresponding Author
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ABSTRACT
Renewable energy plays an important role in meeting the ever increasing energy demand of the modern world. At this point, underground thermal energy storage has been suggested as a clean and efficient alternative of energy extraction for the sustainable future as one of the renewable energy varieties. Thermal energy storage systems in the aquifers have preluded the energy market with great success in many countries. Hot and cold natural energy sources are stored in the aquifer by using underground water to store the heat in this system. Efficiency of the system depends on several factors including groundwater temperatures and flow characteristics. Among the different underground thermal energy storage options, one of the most promising and commercial option is known as aquifer thermal energy storage (ATES). Based on the recent developments reported in the literature, general design procedures and construction techniques as well as relationships related with the efficiency of ATES systems are reviewed within the scope of this paper. The applications from the world and Turkey were discussed in a comparative approach.

Keywords: *Aquifer Thermal Energy Storage, Groundwater Flow, Heat Transfer, Underground Thermal Energy Storage*

1. INTRODUCTION

The concept of energy and the sustainability of energy resources have been one of the most important issues coming from the past. Energy plays an important role in the economic prosperity and the technological competitiveness of a nation. In conjunction with the rapidly increasing world population and industrial production rates, overall energy demand is reaching to record high values in the current decade. One of the main problems of ever increasing energy demand is related with heavy consumption of fossil fuels which is leading to significant environmental impact. Fossil fuels, at the forefront of energy reserves consumed today, have tended to run out on one hand, and become one of the most important factors of environmental pollution on the other. Several energy conservation strategies become more feasible as fossil fuel resources such as oil, natural gas, and coal are reaching to their limits. Since global warming is also becoming one of the most critical problems in the world, more efficient and economical ways to utilize clean and renewable energies are heavily needed. The demand for the utilization is not only in the field of energy production and consumption, but also in the area of energy storage.

The search for alternative energy sources, such as solar, wind and thermal energy has been initiated and problems of climate change and global warming caused by the harmful gases released to the atmosphere due to the use of fossil fuels will seriously be reduced. Increasing attention has been paid to thermal energy storage (TES) system applications since they offer environmentally friendly solutions to afore mentioned energy problems and make it possible to more effectively utilize waste heat/cold recovery for space heating and cooling. With a storage medium of various types and sizes, TES systems contribute to improving energy efficiency to contribute for building self-sustainable cities.

Thermal energy storage at shallow soils and rocks has recently been developed as an innovative approach for keeping excess energy and use it when needed. Thermal energy storage systems in the aquifers, one of the underground storage alternatives for thermal energy applications, have penetrated the energy market with a great success in many countries including Europe, United States and Canada. Aquifer thermal energy storage (ATES) is a cost-effective technology that enables the reduction of energy use and CO_2 emissions associated with the heating and cooling of buildings by storage and recovery of large quantities of thermal energy in the subsurface. In these systems, thermal energy is stored in the aquifers by injecting heat energy into groundwater by means of injection wells. Energy storage capacity depends on several factors including, groundwater temperatures, flow characteristics and volume of the aquifer. Stored energy is extracted as a reversible process to meet heating or cooling demands of buildings when required.

ATES systems provide significant energy saving rates which ensures efficient use of other energy sources. Even more important issue is the use of local and natural resources to increase energy security while reducing environmental hazards. There is a significant reduction in the emission of greenhouse gases by means of the energy savings provided by thermal energy storage methods. This technique provides serious reductions in CO_2 emissions. Thirteen OECD countries have been conducting research and development activities of thermal energy storage techniques within the framework of the Energy Saving Implementation Agreement (IEA ECES-IA) since 1970.

There are several hundreds of aquifer thermal energy storage systems in operation, with the Netherlands and Sweden as dominating countries of implementation. Particularly the Netherlands is the world leader in terms of utilization of this method. Thermal energy storage systems using groundwater have become a standard technique in public buildings and facilities in the Netherlands. The number of ATES system in the Netherlands in the utility sector is depicted in Figure 1 (Sommer *et al.*, 2014).

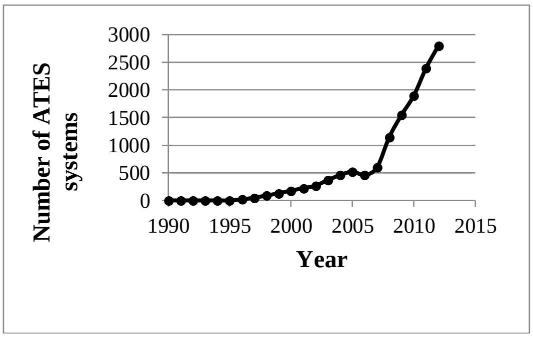


Fig. 1. The number of ATES systems in the utility sector of the Netherlands (Sommer *et al.*, 2014)

As one of the leading countries utilizing ATES systems, Germany's long-term goal is to reduce the use of fossil fuels by 50% by the year of 2050. There are currently eight large-scale, residential buildings built using solar energy supported TES systems in Germany. The German Federal Parliament Building Reichstag is heated and cooled by the storage of waste heat energy from the building within the aquifer. In addition, Canada has the world's largest underground heat pump application. The system located at the University of Ontario Institute of Technology contains 370 wells reaching at a depth of 200 meters.

Based on the field applications and design techniques reported in the current literature, this study presents an up-to-date review of underground thermal energy storage methods while aiming to introduce general design procedures and construction techniques related with aquifer thermal energy storage applications.

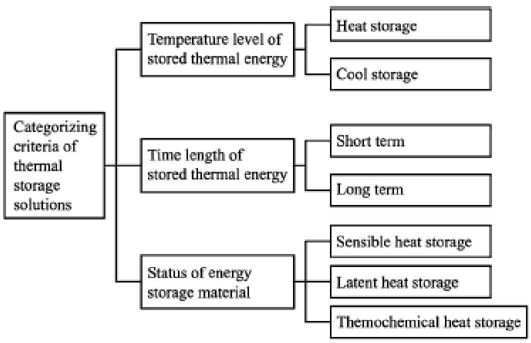
2. THERMAL ENERGY STORAGE CONCEPT

Thermal energy is a form of energy that is the sum of the potential and kinetic energies of a substance in the environment or in a specific system. Thermal energy storage (TES) refers to the technology that allows the storage and transfer of energy in terms of heat. The basic idea behind thermal storage is to provide a buffer to balance fluctuations in supply and demand of energy (Nielsen, 2003) and to compensate the time difference between periods of energy input and those of power demand. Thermal energy storage systems generally involve a temporary buffer storage of high- or low-temperature thermal energy for later use. According to Rosen *et al.* (2003), utilization of thermal energy storage systems often provides significant benefits as the following which is outlined as follows:

• reduced energy costs and consumption;
• improved indoor air quality;
• increased flexibility of operation;
• decreased initial and maintenance costs;
• reduced equipment size;
• more efficient and effective utilization of equipment;
• conservation of fossil fuels (by facilitating more efficient energy use);
• reduced pollutant gas emissions.

There are various thermal energy storage systems, storing the energy as sensible heat. These systems include designed containers, underground aquifers, shallow soils and rocks as well as surface waters such as ponds and lakes. Alternatively, thermal energy can be stored in the latent heat of melting in such materials as salts or paraffin based chemicals. TES technologies can be categorized according to criteria based on different chemicals given in Table 1 (Cao, 2010). If the criterion is based on the temperature level, the thermal storage solutions can be divided into ‘‘heat and cold storage’’. If based on the time length of stored thermal heat, it can be divided into ‘‘short and long term’’. If based on the state of energy storage material, it can be divided into ‘‘sensible, latent and thermochemical heat storage’’.

Table 1. Classification of thermal energy storage solutions (Cao, 2010).



2.1. Underground Thermal Energy Storage (UTES)

The shallow subsurface is increasingly being used as a storage medium for thermal energy, generally referred to as underground thermal energy storage. Shallow soil and rock provides buffer storage systems between the seasons since thermal energy is passively stored into the soil and groundwater by the seasonal climate changes. Average temperature of the ground is higher than that of surface air temperature during the winter and lower during the summer. As a result, the ground and groundwater are suitable media or source for heat extraction during the winter and cold extraction during the summer. The low thermal diffusivity of the Earth's subsurface relative to river and air at Elverum, Norway is shown in Figure 2 (Banks., 2012). Measurement results indicate that the groundwater temperature remains relatively constant throughout the year starting from 10 meters below ground surface while increasing very slowly due to the geothermal gradient coming from earth core (Sanner *et al.*, 2003). Temperature profile of the geological units within a certain depth indicating the seasonal zone of fluctuation in temperature and the nearly constant temperature zone is given in Figure 3 (Florides and Kalogirou, 2007). This figure illustrates the actual ground temperatures as measured in a borehole drilled in Nicosia, Cyprus. The temperature rises from 1°C to 3°C as the depth increases due to the heat flux (Banks, 2012) which is shown in Figure 4.

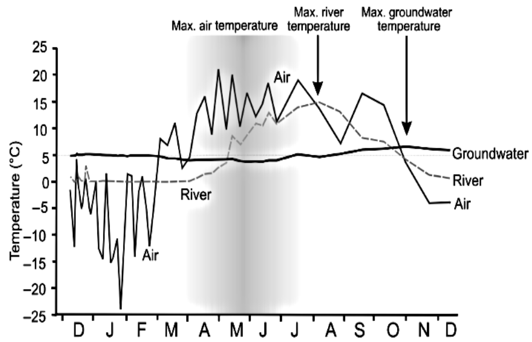


Fig. 2. Fluctuation of temperature of the air, the river and shallow groundwater, at Elverum, Norway (Banks, 2012).

Since the ambient climatic conditions affect the temperature profile below the ground surface, it needs to be considered when designing a thermal energy storage system. The Earth's average annual surface temperature is determined by the balance between solar radiation energy since the Earth's surface acts as a huge solar collector, geothermal heat flux derived from the Earth's interior and the variables of these factors which is illustrated in Figure 5 (Florides and Kalogirou, 2007) and accepted to be approximately 14°C. The temperature of the shallow subsurface is affected by the physical properties of the ground, as well as the climate interaction determined by air temperature, wind, solar radiation, air humidity and rainfall.

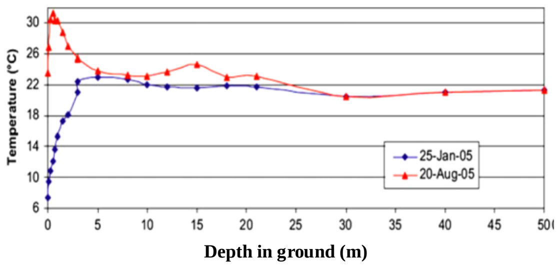


Fig. 3. Zone of fluctuation in temperature due to the seasonal changes (Florides and Kalogirou, 2007).

2.1.1. Basic concepts and applications

Underground storage for thermal energy is mostly used for heat storage on a seasonal basis. In winter period, while heating demand is high, heat can be extracted from underground energy storage, whereas in summer term, while cooling is needed, a reverse process can be facilitated which can also mean storage of additional heat in the subsurface storage. There is not any standard design procedure for conventional UTES installations. Each facility is unique even though the basic principles are similar and components like fluid circulation pumps, pipes and heat exchangers etc. are industrial products. To choose the right system for a specific installation, several factors such as geological and hydrogeological conditions, area and utilization on the surface, existence of potential heat sources like mines, and the heating and cooling characteristics of the infrastructures have to be considered. In the design phase, more accurate data of the key parameters are necessary for the chosen technology so as to achieve the optimum performance with minimum cost. There are several concepts regarding the underground medium thermal energy storage alternatives (Novo *et al.*, 2010). The main concepts can be listed as;

- Aquifer thermal energy storage (ATES),
- Borehole thermal energy storage (BTES),
- Cavern thermal energy storage (CTES)
- Ducts in soil
- Pit storage

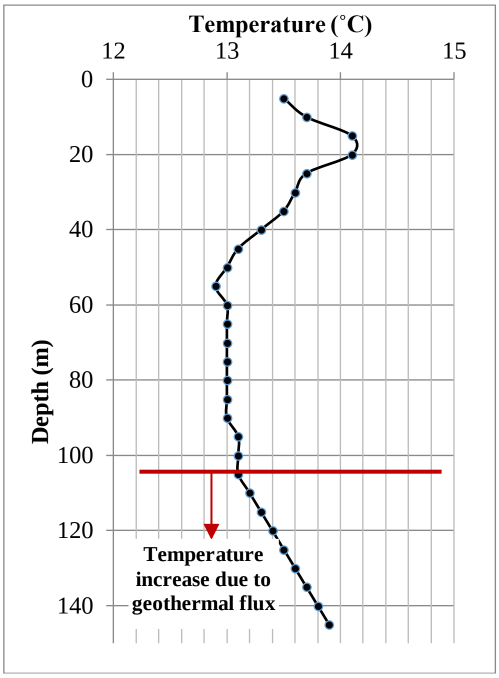


Fig. 4. Downward increase in temperature beginning approximately from 100 m depth depending upon geothermal heat flux (Banks, 2012)

Aquifer Thermal Energy Storage (ATES) uses natural ground water in a saturated and permeable subsoil layer as the storage medium. Thermal energy is transferred by extracting groundwater from the aquifer and by re-injecting it at an altered temperature to a separate well nearby.

Borehole thermal energy storage (BTES) applications are operated in closed loop heat exchanger systems in which there is no contact between the natural groundwater and the heat exchange fluid. This system includes one or more boreholes equipped with borehole heat exchangers through which waste heat or cold energy is circulated and transferred to underground for storage.

Cavern Thermal Energy Storage (CTES) utilize large groundwater reservoirs existing in the subsoil to serve as a thermal energy storage system. These storage technologies are technically feasible, but the actual application is still limited due to the relatively high initial investment cost.

The duct type storage in soils is best suited for circulating fluids with low temperature around 25-30˚C, and needs heat pump supported systems to raise the temperature of the space heating and tap water to a suitable level. This type of storage has found extensive use in connection with ground coupled heat pumps (GCHP) where the duct can be placed in horizontal relatively shallow trenches, or in vertical boreholes. (Nielsen, 2003)

Pit storage systems are artificial structures, also called man-made aquifers, built below ground like buried tanks or close to the surface to reduce high investment cost. These systems seem to be a viable option when environmental restrictions about natural ground water are involved.

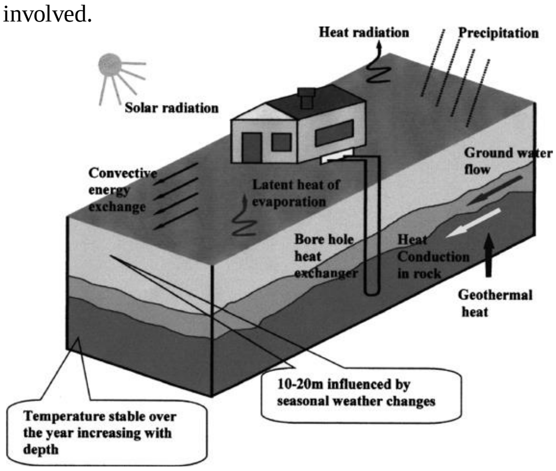


Fig. 5. Thermal energy flow diagram in the ground (Florides and Kalogirou, 2007).

Considering the well documented field applications in the world, heat storage in aquifers may be achieved by open systems such as ATES and closed loop heat exchange systems such as BTES systems (Furbo, 2014). Basic working principal scheme of aquifer and borehole thermal energy storage systems is depicted in Figure 6. These concepts have already been introduced as commercial systems on the energy market in several countries. Thermo-hydraulic and hydrogeological criteria for the optimum thermal energy storage technique choice are shown in Figure 7 by Sanner (2001).

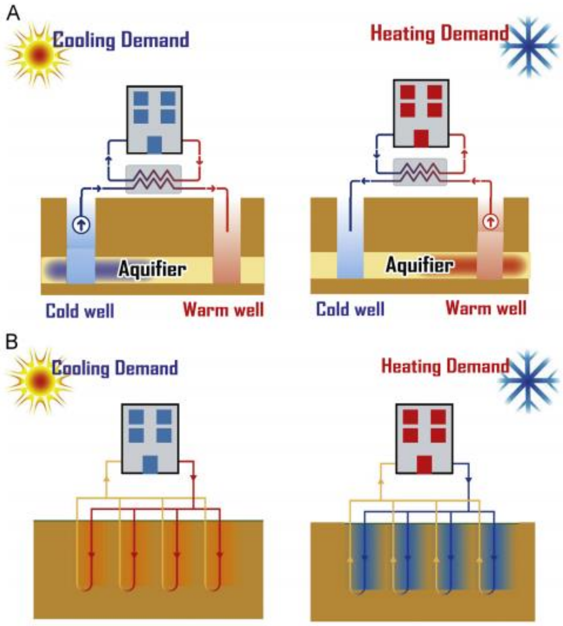


Fig. 6. Principle schemes of (a) aquifer and (b) borehole thermal energy storage systems (Bloemendal *et al.*, 2014).

In aquifer thermal energy storage systems, groundwater is utilized as heat carrier whereas in closed loop borehole thermal energy storage applications, heat carrier fluid is cycled in boreholes independent from the groundwater occurrence and are operated in closed loop as explained in Figure 7. Porosity of the subsurface formation is another significant factor for the selection of the most suitable thermal energy storage system.

Aquifer thermal energy storage technique is particularly suitable among the different system types to store large amounts of thermal energy (Sommer *et al.*, 2014). The system has developed into a cost-effective technology for heating and cooling of utility buildings such as offices, hospitals, universities and greenhouses, and to reduce greenhouse gas emissions by replacing fossil fuel dependent heating and cooling systems. Although ATES systems are limited to aquifers and have more geographical limitations, they have lower initial drilling and equipment expenditures with high maintenance cost whereas closed loop systems have lower manufacturing and maintenance costs (Lee, 2013) compared to aquifer thermal energy storage systems. BTES systems are generally easier to construct and operate and have proven long term durability. Yet, their payback times are relatively long compared to ATES systems, normally 6–10 years due to expensive borehole investments and the fact that BTES systems normally need some other sources to cover the peak load situations (Lanahan and Tabares-Velasco, 2017). Within the scope of this paper, Aquifer Thermal Energy Storage technique is primarily investigated and the principles of heat transfer, general design steps and some expressions related with the efficiency of the Aquifer Thermal Energy Storage technique is discussed.

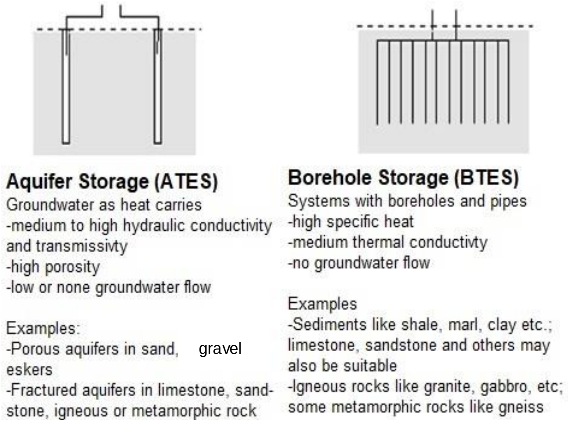
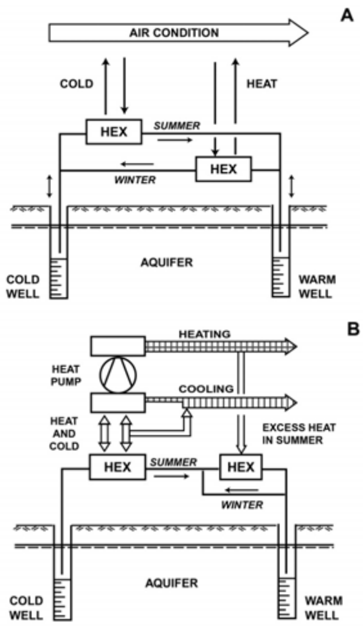


Fig. 7. Hydrogeological and thermolic parameters for ATES and BTES preferences (Sanner, 2001)

The installed ATES systems utilized in Sweden can be divided into four basic groups as to whether heat pump supported or not, as depicted in Figure 8 (Andersson *et al.*, 2003). Groundwater is directly used for preheating of ventilation air during the winter by means of heat exchanger fluid at a temperature level of approximately +5 ˚C and for cooling during the summer season at a temperature level of approximately +15 ˚C in the simplest system (Figure 8a). The system (Figure 8b), having the same working principle as (Figure 8a), is more frequently implemented as the heat production in which the temperature change is somewhat greater. System (Figure 8c) stands for an early type of ATES utilization where surface water is used as a source of energy for the heat pump. The fourth system (Figure 8d) has a similar working principle with the system (Figure 8c); however, in this case already cooled reservoir during winter season is used for district cooling. In the same study, it is shown that the energy savings can reach up to 90–95% for direct heating and cooling, 80–87% for heat pump assisted heating and cooling, 60–75% for heat pump assisted heating systems and 90–97% for district cooling.



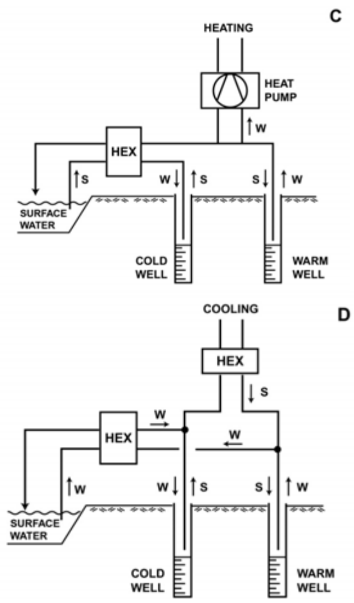


Fig. 8. Graphical representation of four basic ATES system configurations currently being used in Sweden. (a) Direct heating and cooling without heat pump (b) Heat pump supported heating and cooling (c) Heat pump supported heating only and (d) Storage of natural cold for cooling only (Andersson *et al.*, 2003).

When it comes to Turkey, although heat pump technology is well known, the number of applied underground thermal energy applications is limited. Ground source heat pump applications are summarized in a study performed by Çetin and Paksoy (2013). The first applications of shallow geothermal systems were encountered in early 2000 (Babur, 1986; Kara, 1999). The recent projects in Turkey indicate that the people's trust and awareness in these systems are increasing (Çetin and Paksoy, 2013). Moreover, Paksoy (1999) mapped the suitable areas for underground thermal energy storage applications in Turkey (Figure 9). It is observed that probable application areas for underground thermal energy storage are very broad considering the housing and industrial sectors, which share the first two orders of energy consumption in Turkey.

In addition to energy concerns, a study related to the mitigation of CO_2 emissions has been performed by utilizing different TES concepts in Turkey; one is for the heating and cooling of a supermarket utilizing aquifer thermal energy storage in Mersin and the other one for a greenhouse in Adana (Paksoy *et al.*, 2009). It is concluded that the yearly CO_2 emission has been reduced by 113 tons/year in the first project, performed in Mersin for a supermarket, and by 26 tons/year in the second project while providing energy conservation rates up to 60% and 68%, respectively.

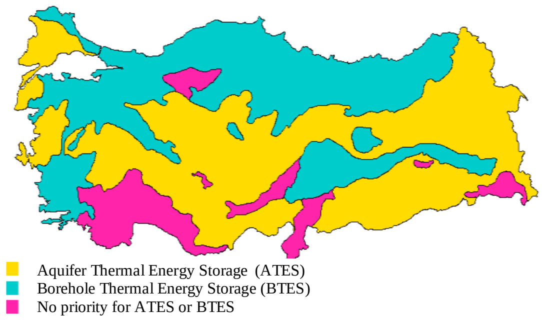


Fig. 9. Map showing potential areas of underground thermal energy storage application in Turkey (Paksoy, 1999).

2.2. The Design of Groundwater Based Open Loop Systems

Aquifer thermal energy storage (ATES) system generally consists of one or more pairs of tube wells that extract and simultaneously infiltrate groundwater to extract or store thermal energy in or from the subsurface by altering the temperature of the ground and groundwater. The thermodynamic transfer and storage is governed by advection, conduction or diffusion and dispersion as illustrated in Figure 10 (Courtois *et al.*, 2007). In the shallow subsurface environment, conduction through minerals or pore fluids and convection via groundwater are the two most important mechanisms of heat flow. In some cases, radiation may also be significant.

Diffusion or heat conduction describes the process by which heat transfers through a solid, liquid or gas by processes of molecular interaction. This process, formulized by Fourier's law, depends on the thermal conductivity and heat capacity of the aquifer. In a composite medium such as an aquifer, the thermal properties of both the fluid and the solid play essential role in heat transport. Advection describes the movement of thermal energy directly due to the linear flow of groundwater through the porous medium. The process represents the movement of the thermal stock due to the natural flow of the aquifer. Movement adds a spreading out of the thermal stock due to spatial heterogeneity of the velocity field, which is called as dispersion. This phenomenon leads to an increase of the global aquifer thermal conductivity. The physical processes of conduction (diffusion) and convection govern the transport and storage of heat in an aquifer. Thermal conductivity and volumetric heat capacity of some common TES materials are given in Table 2.

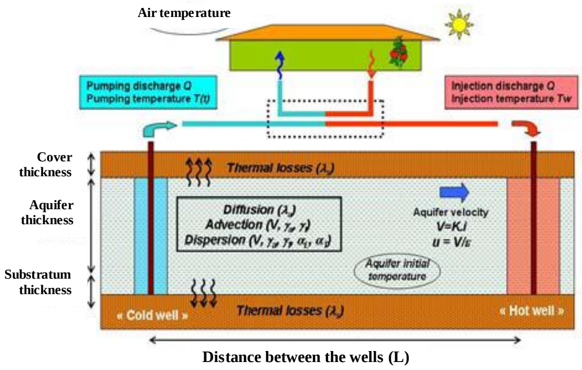


Fig. 10. Basic principle of thermal energy transfer in the subsurface (Courtois *et al*., 2007).

Researches on analytical methods for heat transfer have been conducted by Sauty *et al.* (1982), Uffink (1983), Voigt and Haefner (1987), Krarti and Claridge (1990), Yang and Yeh (2002), and Stopa and Wojnarowski (2006). It is pointed out that analytical solution is only applicable to the qualitative estimations or to the simple cases (Kangas and Lund, 1994). For this reason, it would be more realistic to simulate the heat transfer by performing the numerical modeling of complex geological and hydrological characteristics (Tsang, 1983). Nowadays numerical modeling studies are carried out to predict recovery temperature by heat loss (Lee, 2008; Molson *et al.*, 1992), injection depth (Lee, 2008; Tenma *et al.*, 2003), injection time (Tenma *et al.*, 2003) and regional groundwater flow (Kangas and Lund, 1994).

As it can be seen in Figure 10, the wells are separated by a critical distance to ensure that the warm and cold storage remain separate. This interval, called critical distance (L), prevents the occurrence of thermal breakthrough within one season. The critical distance is primarily a function of operational and thermo-hydraulic parameters involving the well production rates, the aquifer thickness, and the hydraulic and thermal properties that control the storage volume. Clyde and Madabhushi (1983) have proven that the critical distance (L) preventing hydraulic breakthrough is explained by the following equation;

$$L < 2Z/\pi Ti \qquad (1)$$

where Z is the groundwater discharge, i is the natural hydraulic gradient and T is the aquifer transmissivity, multiplication of the depth of the aquifer with hydraulic conductivity K, which is a measure of the rate at which water moves through a unit width of the aquifer under a unit hydraulic gradient. The diagrams of the hydraulic breakthrough and the location of the extraction and injection well doublet system placed greater and less than the critical distance are illustrated in Figs. 11(a) and 11(b).

Table 2. Thermal properties of selected rocks and minerals (Banks, 2012).

	Thermal conductivity ($W m^{-1} K^{-1}$)	Volumetric heat capacity ($MJ m^{-3} K^{-1}$)
Rocks		
Coal	*0.3*	*1.8*
Limestone	1.5–3.0 (*2.8, massive limestone*)	1.9–2.4 (*2.3*)
Shale	1.5–3.5 (*2.1*)	*2.3*
Basalt	1.3–2.3 (*1.7*)	*2.4–2.6*
Diorite	1.7–3.0 (*2.6*)	*2.9–3.3*
Sandstone	2.0–6.5 (*2.3*)	*2.0–2.1*
Gneiss	2.5–4.5 (*2.9*)	2.1–2.6 (*2.1*)
Arkose	2.3–3.7 (*2.9*)	*2.0*
Granite	3.0–4.0 (*3.4*)	1.6–3.1 (*2.4*)
Quartzite	5.5–7.5 (*6.0*)	1.9–2.7 (*2.1*)
Minerals		
Plagioclase	1.5–2.3	1.64–2.21
Mica	2.0–2.3	2.2–2.3
K-feldspar	2.3–2.5	1.6–1.8
Olivine	3.1–5.1	2.0–3.6
Quartz	7.7-7.8	1.9–2.0
Calcite	3.4-3.6	2.24
Pyrite	19.2–23.2	2.58
Galena	2.3–2.8	1.59
Haematite	11.3–12.4	3.19
Diamond	545	–
Halite	5.9–6.5	1.98
Other		
Air	0.024	1.29×10^{-3} at 1 atm
Glass	0.8–1.3	1.6–1.9
Concrete	0.8–1.7 (*1.6*)	*1.8*
Ice	1.7–2.0 (*2.2*)	*1.9*
Water	*0.6*	4.18
Copper	390	3.5
Freon-12[a] at 7°C (liquid)	0.073	1.3
Oak	0.1–0.4	1.4
Polypropene	0.17–0.20	1.7
Expanded polystyrene	0.035	–

In order to determine the optimum well distance, besides thermal breakthrough, thermal interference for open loop doublet systems should be taken into consideration in terms of thermal radius which is described as the maximum distance of the thermal front from the injection well in a homogeneous medium, neglecting vertical flow, advection by regional flow, thermal conduction and dispersion (Bloemendal *et al.*, 2014). Previous studies have shown that the thermal radius (R_{th}) of an ATES can be calculated by setting the injected energy ($c_w.V.\Delta T$) equal to the energy stored in a cylinder, centered around the injecting well ($c_a.H.\pi.R_{th}^2$), yielding the Eq. (2). This serves as a first order approximation of the thermally affected area around an ATES well, where c_w and c_a are the volumetric heat capacity of water and the aquifer, respectively, V is the volume of water that is injected in one storage cycle and H is the length of the well screen (Sommer *et al.*, 2013). It should be noted that the actual affected area may be different from this approximation caused by thermal conduction, dispersion, heterogeneities and the presence of flow components other than radial type flow.

$$R_{ty} = (c_w V / c_a \pi H)^{0.5} \qquad (2)$$

In a numerical modeling study performed by Kim *et al.* (2010), it is reported that the thermal interference, influencing the performance of an aquifer thermal energy system, depends primarily on the hydraulic conductivity of an aquifer, the distance between two boreholes and the production/injection rate of the wells. They suggest that the thermal interference increases as the hydraulic conductivity increases, as the distance between two boreholes decreases and as the pumping/injection rate increases.

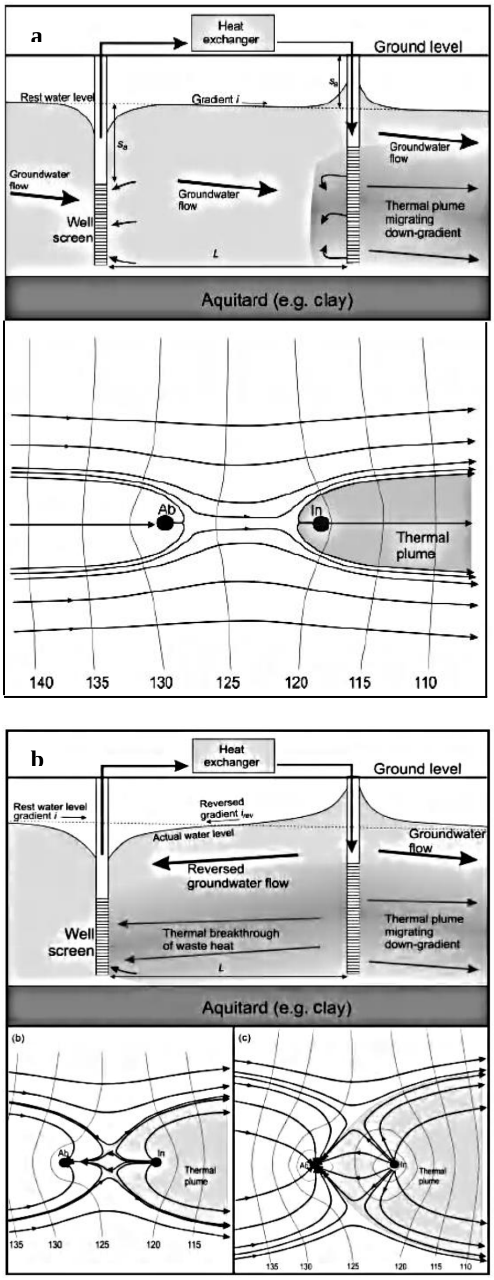


Fig. 11. An open well doublet system having a well to well distance of a) greater than the critical distance (L), b) significantly less than the critical distance, and the lower diagrams show the plan view. Black arrows show groundwater flow lines for both systems where there is a hydraulic feedback in system "b" (Banks, 2012).

The amount of energy that is recovered from the aquifer is generally lower than the amount that is stored because part of the energy is lost due to dissipation of heat to the surroundings of the storage and advection with regional groundwater flow. This energy loss is expressed as thermal recovery (η_{rec}) of a well (Bakr *et al.*, 2013; McDaniel and Kosanovic, 2016),

$$\eta_{rec}=E_{extracted}/E_{injected} \quad (3)$$

Additionally, Kim *et al.* (2010) report that the recovery of thermal energy is not considerably affected when the wells are located by more than one thermal radius, while Kowalczyk and Havinga (1991) report that there should be a well-to-well distance between one and two thermal radii. Sommer *et al.* (2013) explain that there should be a well distance of at least two thermal radii to avoid thermal interference in both homogeneous and heterogeneous aquifers. The Dutch Society for Subsurface Heat Storage (NVOE, 2006) advises that the thermal recovery decreases for well distances less than three thermal radii. Moreover, a detailed numerical simulation study was performed by Lee (2010) showing the effect of interwell distance on the normalized thermal storage. Although there are uncertainties related to the available aquifer thickness, aquifer heterogeneity, and uncertainty and variability in future energy demands, above mentioned interwell distance assumptions might be a preliminary design step.

Selection of a suitable aquifer in terms of the groundwater flow velocity is another significant criterion in the design of an ATES system. Numerical modeling study of a doublet open loop thermal energy storage system pointed out that thermal recovery in a stagnant aquifer can be higher than 75% and drop to 40% with a regional groundwater flow velocity of 150 m/year (Sommer *et al.*, 2013) whilst field studies report thermal recovery values range between 65% and 82% (Molz *et al.*, 1981). To reduce the dissipative heat loss due to the groundwater flow as depicted in Figure 12 (Groot, 2014), the aquifer should have a low hydraulic gradient. In general, suitable aquifers should readily yield water and have a low hydraulic gradient to prevent the stored energy to be transported outside the capture zone of the well (Hamada *et al.*, 2002). Care should also be taken to select appropriate materials according the chemical composition of the soil and groundwater to prevent well clogging. According to Andersson (2007), three main clogging processes are reported as clogging by fines, hydrochemical clogging and biochemical clogging. Injection wells require specialist design and construction since they are more susceptible to clogging and degradation of performance than abstraction wells. The re-injected water must be particle free to prevent clogging of the well screen or aquifer. The maximum allowed velocity limiting the well-clogging on the walls of borehole is given by the equation below (NVOE, 2006),

$$v_{inject} = 1000(K_s/150)^{0.6}\left[(v_{cl}/2MFI_{mem}u_{eq})^{0.5}\right] \quad (4)$$

Where v_{inject} is the design injection Darcy velocity on the walls of the borehole (m/h), v_{cl} is the specific clogging speed (m/year), MFI_{mem} is the measured membrane filter index (s/l^2) (Olsthoorn, 1982) and u_{eq} is the number of equivalent full load hours the well pumps per year (Buik and Snijders, 2006).

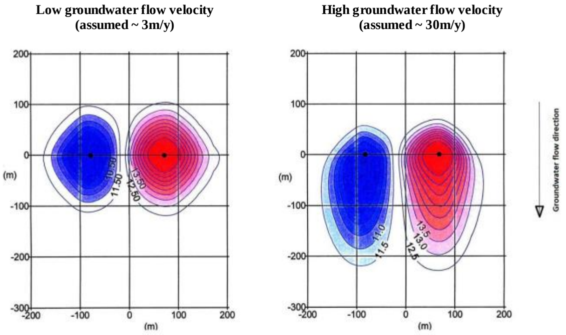


Fig. 12. Influence of groundwater flow velocity and direction on the stored heat of ATES systems (Groot, 2014).

3. CONCLUSION

Thermal energy storage in aquifers has a long history while achieving broad acceptance for heating and cooling in the energy market in many countries, with the Netherlands and Sweden as dominating countries of implementation. A brief summary related to the history of the thermal energy storage applications have been presented in this study. In addition, general design procedures and construction techniques as well as relationships related with the efficiency of ATES systems present in the most up-to-date literature are reviewed within the scope of this paper. The applications from the world and Turkey were discussed in a comparative approach.

The temperatures below ground surface at shallow depths are always higher than outside air temperatures in winter and are lower in summer. The temperature differences make shallow-depth soils and aquifers an efficient media for heat storage. Energy storage can be achieved by pre-heating operation in winter and pre-cooling operation in summer by means of ground heat exchangers. Aquifer thermal energy storage (ATES) systems take advantage of natural groundwater in a saturated and permeable layer as the storage medium. The transfer of thermal energy is carried out by extracting groundwater from the aquifer and by reinjecting it at a modified temperature into a separate well nearby. In the present work, a brief review is presented on the concepts and applications of ATES systems.

Any ATES project involves a complex procedure depending on many parameters and has to follow a standardized approach for design and field application. The heat transfer and storage in an aquifer can be modeled with analytical or numerical approaches. As the analytical solutions are limited with the simple cases, numerical modeling studies to simulate complex heat transfer processes within the aquifer thermal energy storage involving multiple injection/extraction systems should be performed. When it comes to the general design procedure of an ATES system, to avoid occurrence of thermal breakthrough within a season, the wells should be separated by a critical distance to ensure that the warm and cold storage remain separate. This distance is a function of operational and thermo-hydraulic parameters. Some of the previous studies show that there should be a well distance of at least one thermal radius to avoid thermal interference while other studies suggest at least two thermal radii whereas the Dutch Society for Subsurface Heat Storage advises at least three thermal radii for this purpose.

Selection of a suitable aquifer in terms of the groundwater flow velocity is another significant criterion in the design of an ATES system. The aquifer should have a low hydraulic gradient so as to reduce the dissipative heat loss due to the groundwater flow. Moreover, care should also be taken to select appropriate materials in terms of the chemical composition of the soil and groundwater to prevent well clogging. Injection wells require specialist design and construction since they are more susceptible to clogging and degradation of performance than abstraction wells. The re-injected water must be particle free to prevent clogging of the well screen or aquifer**.**

ATES applications in Turkey are still emerging. Hence, more effort should be performed to carry research to put forth the aquifer energy storage potential of Turkey. These studies should basically concentrate on the proper determination of aquifer parameters such as volume, seepage velocity and temperatures as well as the thermal conductivity and specific heat values of shallow soils and rocks around Turkey.

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