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Numerical Simulation on the Continuous Operation of Aquifer Thermal Energy Storage System

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1. Introduction

As the demand for energy increases, any work to enhance energy conservation becomes crucial. Thermal energy storage (TES) system applications around the world have been known to provide economical and environmental solutions to the energy problems (Paksoy et al., 2004). TES systems contribute significantly to improving energy efficiency by helping match energy supply and demand. TES also makes it possible to more effectively utilize new renewable energy sources (solar, geothermal, ambient, etc.) and waste heat/cold recovery for space heating and cooling. With a storage medium of various types and sizes, TES systems therefore contribute to enhancing energy efficiency.

The storage medium can be located in containers of various types and sizes. Underground thermal energy storage (UTES) is mostly used for large quantities of seasonal heat/cold storage (Nielsen, 2003). There are several concepts as to how the underground can be used for underground thermal energy storage depending on geological, hydrogeological, and other site conditions. The two most promising options are storage in aquifers (aquifer thermal energy storage, ATES) and storage through borehole heat exchangers (borehole thermal energy storage, BTES) (Sanner[b], 2001; Andersson, 2007). In borehole thermal energy storage systems, also called "closed" systems, a fluid (water in most cases) is pumped through heat exchangers in the ground. In aquifer thermal energy storage or "open" systems, groundwater is pumped out of the ground and injected into the ground by using wells to carry the thermal energy into and out of an aquifer (Novo et al., 2010).

Aquifer thermal energy storage (ATES) system utilizes low-temperature geothermal resource in the aquifer (Sanner[a], 2001; Rafferty, 2003). Aquifer thermal energy storage, which is similar to the groundwater geothermal system under direct uses, involves storage and provides for both heating and cooling on a seasonal basis. An advantage of open systems is generally higher heat transfer capacity of a well compared to a borehole. This makes ATES usually the cheapest alternative if the subsurface is hydrogeologically and hydrochemically suited for the system. Such aquifers offer a potential and economical way of storing thermal energy for long periods of time. ATES systems have been used successfully around the world for the seasonal storage of heat and cold energy for the purpose of heating and cooling buildings (Probert et al., 1994; Paksoy et al., 2000; Allen et al., 2000; Schmidt, 2003; Paksoy et al., 2004).

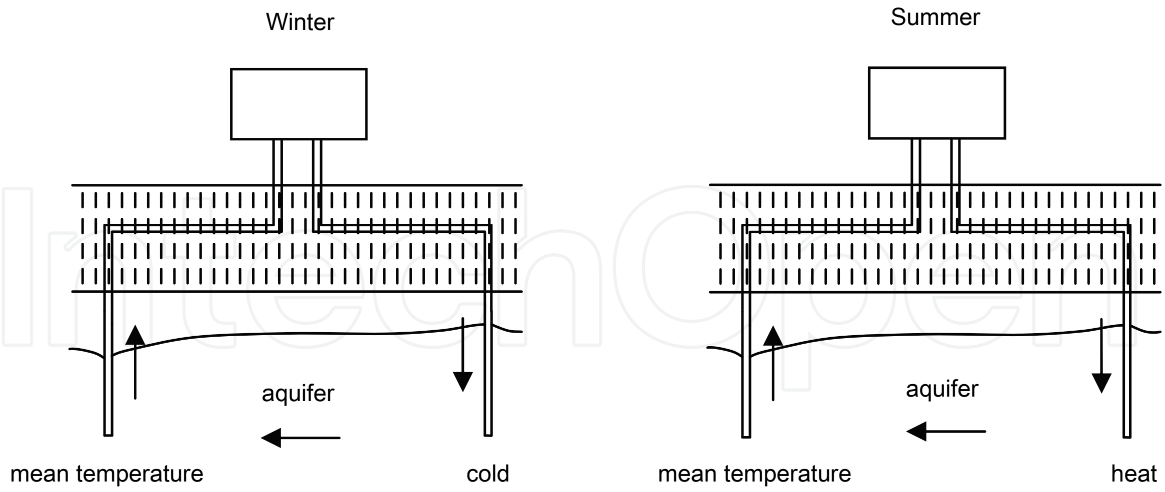
Recently, the use of computer modeling has become standard practice in the prediction and evaluation of geothermal performance (Breger et al., 1996; O'Sullivan et al., 2001). In carrying out ATES development projects, a numerical modeling based on coupled mass and energy transport theory has to be conducted on the behavior of local subsurface geothermal system to evaluate and optimize a project design.

A number of researchers have highlighted the important role of numerical modeling in the analysis of ATES systems. Probert et al. (1994) presented the thermodynamic evaluations of ATES projects and listed key aquifer properties and design parameters. Based on an elementary ATES model, Rosen (1999) performed second-law analysis to thermal energy storage systems to assess overall system performance. Chevalier and Banton (1999) applied the random walk method of resolution to the study of energy transfer phenomena in ATES using a single injection well. Tenma et al. (2003) carried out a more realistic two-well model study to examine an underground design of TES system. To provide basic data for design, they evaluated the sensitivity of parameters affecting on the long-time performance of ATES. Their study, however, derived conclusions based on the simulation results for ATES systems under simple operation scenarios. From the preliminary simulations, the location of screen, which was extensively examined in the Tenma et al. (2003)'s model, is shown to have a relatively limited impact on the predicted temperature profiles of produced water. To overcome a limited applicability of previous researches, more comprehensive study should be established for the evaluation of the ATES systems. The present work extends previously reported researches to ATES systems under various operation parameters which are key factors influencing long-time performance of ATES systems. The main design considerations involve loading conditions including injection/production schedules and temperature, heat losses, and configuration of well-aquifer system simulating various design and operation scenarios.

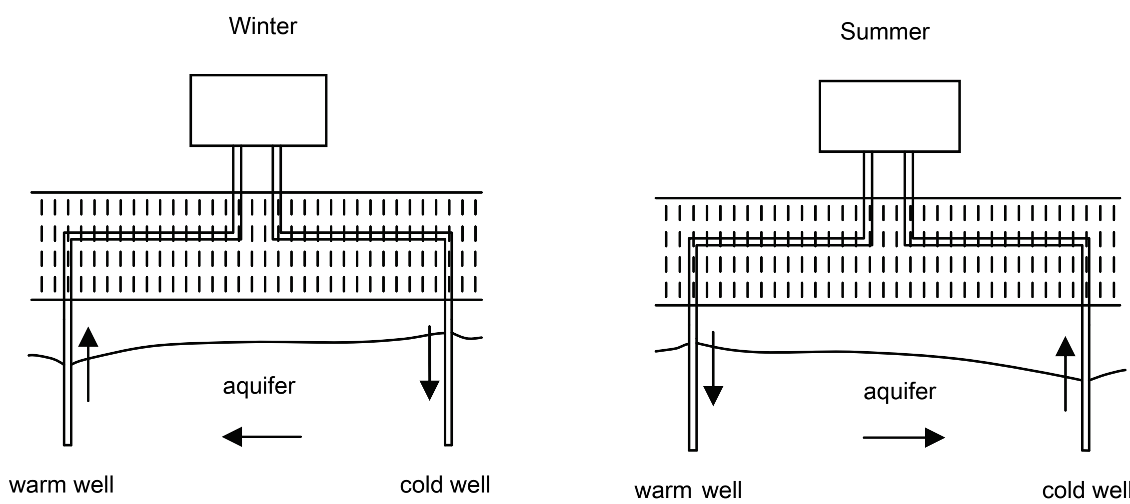
Coupled hydrogeological-thermal simulations were undertaken in order to predict thermal behavior of aquifer and recovery temperatures from the aquifer. Analyses for a two-well system in a confined aquifer were performed in order to determine how operational parameters affect results of aquifer thermal energy storage simulations. The aim of the evaluation is to make reliable predictions about future recovery temperatures and temperature distributions in the aquifer given the planned injection/production temperatures and rates.

2. Basic concepts

Being similar to direct use of a groundwater-geothermal system, aquifer thermal energy storage involves drilling a few wells to an aquifer for circulation of water between the storage region and the energy system. Then it can store energy whilst providing heating and cooling on a seasonal basis. The wells are separated by a critical distance to ensure that the warm and cold storage remain separate and that thermal breakthrough does not occur within one season. This critical distance is primarily a function of operational and thermohydraulic parameters involving the well production rates, the aquifer thickness, and the hydraulic and thermal properties that control the storage volume. A plant can also be made with groups of wells instead of just two wells. Multiple-well configurations have been employed where large volumes of water are required and in systems where individual well yields are low. Single-well applications have also been employed using vertical separation of hot and cold groundwater where multiple aquifers exist.



(a) continuous regime



(b) cyclic regime

Fig. 1. Basic operational regimes for aquifer thermal energy storage (after Nielsen)

Usually, a pair of wells are pumped constantly in one direction or alternatively, from one well to the other, especially when both heating and cooling being provided. As presented in Figure 1, these two operation principles are called continuous regime and cyclic regime, respectively. The continuous regime only is feasible for plants where the load can be met with temperatures close to natural ground temperatures, and the storage part is more an enhanced recovery of natural ground temperatures. With a continuous flow, design and control of the system are much simpler and easier. Only one well or group of well needs to be equipped with pumps. Disadvantage is the limited temperature range. Cyclic flow will create a definite cold and heat reservoir around each well or group of wells. It is possible to maintain a ground volume above or below the natural ground temperature all the time. One disadvantage is a more complicated well design and control system with each well being able to both produce and inject groundwater.

3. Background of numerical simulation

3.1 Mathematical theory

The thermohydraulic analysis requires a calculation of groundwater flow and the temperature in the aquifer and the surrounding layers. In this section, theoretical principles of water flow and heat transfer phenomena for calculating temperatures of the aquifer at different locations were explained. The coupled groundwater and heat flow are governed by the partial differential equations describing mass and energy balance in the aquifer.
The conservation of mass for water in association with Darcy's law is expressed as continuity equation (Delshad et al., 1996; Clauser, 2003).

$$\frac{\partial}{\partial t}(n\rho_w) + \nabla \cdot (\rho_w \mathbf{u}) = R_w \tag{1}$$

where
n: porosity
ρ_w: density of water
$\mathbf{u}$: Darcy flux
R_w: source/sink term
Specific discharge or Darcy velocity of water in the aquifer is defined by Darcy equation.

$$\mathbf{u} = -\frac{\mathbf{k}}{\mu_w}(\nabla p - \gamma_w \nabla z) \tag{2}$$

where $\mathbf{k}$ is the intrinsic permeability tensor; μ_w the viscosity; p the pressure; z the vertical depth, and γ_w the specific gravity (= $\rho_w g$).
The energy balance equation is derived by assuming that energy is a function of temperature only and energy flux in the aquifer occurs by convection and conduction only. The resulting general heat balance equation can be formulated as follows;

$$\frac{\partial T}{\partial t}\left[(1-n)\rho_s C_{vr} + n\rho_w C_{vw}\right] + \nabla \cdot (\rho_w C_{vw} \mathbf{u} T - \lambda_T \nabla T) = q_H - Q_L \tag{3}$$

where
T: aquifer temperature
C_{vr}, C_{vw}: rock and water heat capacity at constant volume
λ_T: thermal conductivity of aquifer
q_H: enthalpy source per unit bulk volume
Q_L: heat loss to overburden and underburden formations
The aquifer is assumed to be continuous and its thermal conductivity and volumetric heat capacity are considered to be a function of porosity and the thermal characteristics of water and soil matrix (Nassar et al., 2006). Thermal dependence of density, viscosity, thermal conductivity, and heat capacity is not taken into consideration because these parameters vary little in the considered temperature range.
The heat transfer with over and underlying low-permeability layers, is assumed to be due solely to thermal diffusion. The heat loss is computed by using the Vinsome & Westerveld (1980)'s method.

$$Q_L = \nabla \cdot (\lambda_{Te} \nabla T) \tag{4}$$

where λ_{Te} is the thermal conductivity of overburden or underburden rock. The heat transfer equation (3), which results from the principle of energy conservation, is coupled with the flow equation from Darcy's law (2) and the continuity equation (1).

3.2 Simulation model

Groundwater flow and thermal energy transport in the porous media have been studied in detail in the discipline of hydrogeology. Numerical research into groundwater and heat transport has been continuing for more than a decade in North American and Europe. Numerous commercially available and public domain numerical software codes exist. Of these, focus is given to the simulation modeling both mass and heat transport in groundwater.

Many simulation codes available to simulate ATES systems have their own merit. Deng (2004) and Schmidt & Hellström (2005) give a summary of available numerical models for groundwater flow and energy or solute transport in groundwater. These models can all be used to simulate an ATES system.

Amongst the more sophisticated simulators, a general simulator named UTCHEM has proved to be particularly useful for modeling multiphase transport processes under non-isothermal condition (Center for Petroleum and Geosystems Engineering, 2000). The simulator was originally developed to simulate the enhanced recovery of oil using surfactant and polymer processes. UTCHEM has been verified by comparing its ability to predict the flow of fluids through the aquifer to analytical solutions and experimental measurements.

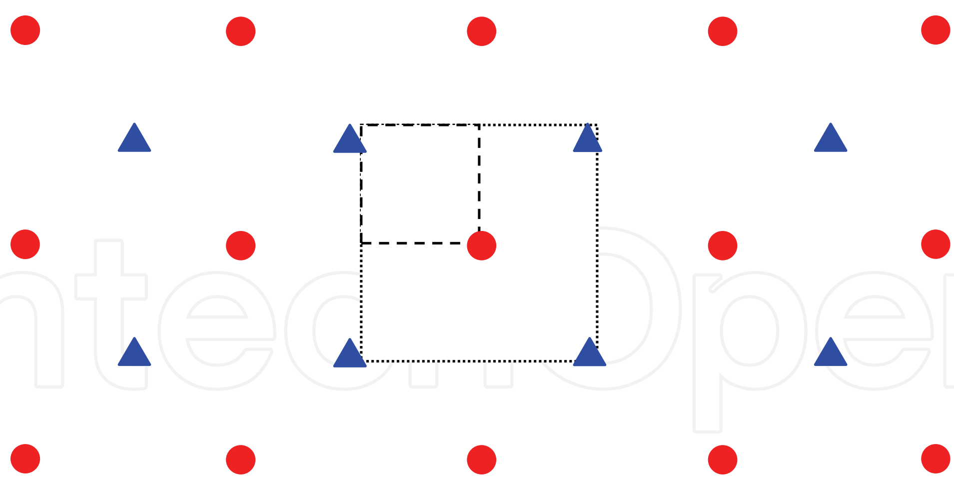
4. Numerical modeling

An understanding of the thermohydraulic processes in the aquifer is necessary for a proper design of an ATES system under given thermohydraulic conditions. The main design considerations concern the loading conditions (injection temperature and pumping rates), heat losses, thermal breakthrough, etc (Claesson et al., 1994). The model gives the temperature of the produced water and groundwater in the aquifer.

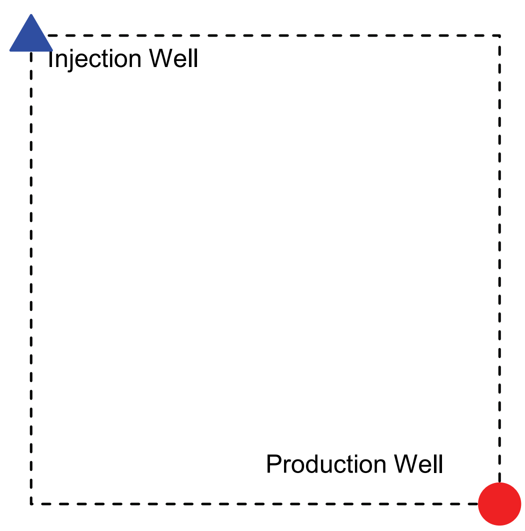
A multidimensional, finite-difference model for ground-water flow and heat transport is used to solve the complex thermohydraulic problems numerically. The numerical model includes the effects of hydraulic anisotropy, thermal convection and conduction, and heat loss to the adjacent confining strata. .In order to decide the sustainability of the aquifer for energy storage application, temperatures of producing water is estimated over a ten-year period.

In order to estimate the parameters of an underground system, a general ATES using the open system of 5-spot patterns is considered. As shown in Fig 2(a), four wells are situated at the corners of a square field. The fifth well is located at the center of square. Water is pumped into the injection well at a constant flow rate Q at a temperature Tinj, and the same flow rate of water is recovered from the neighboring four production wells or vice versa. In a large reservoir with repeated patterns, the flow is symmetric around each injection well with $0.25Q$ from each well confined to the pattern.

The 5-spot pattern can be further simplified to a two-well system because each quadrant is symmetric. A model of two-well on either corner with hydraulic coupling as shown in Fig. 2(b), has been developed to estimate the performance of symmetric array of wells in 5-spot pattern.



(a) 5-spot pattern



(b) two-well model for quadrant of a 5-spot pattern

Fig. 2. Array of wells in a 5-spot pattern

The outer boundary is represented as a noflow and adiabatic boundary to simulate symmetry in an array.

$$(\nabla T)\cdot \mathbf{n} = 0 \quad (5)$$

The model is similar to the model suggested by Tenma et al. (2003). This model is a unit of the system and composed of two wells partially-penetrating a confined aquifer. As the grid is divided into 13 grid blocks in horizontal directions, and 11 grid blocks in a vertical direction, there are total of 3,718 grid blocks. Well depth was set at the relatively shallow value of for the two-well system. Water level in the model was set at 6 m.

Determination of the potential of a specific confined aquifer as an effective thermal energy storage medium requires thorough knowledge of thermodynamic and hydraulic properties of the aquifer and its confining layers and fluid properties. Parameters include porosity and permeability of the storage aquifer and thermal conductivities and heat capacities of the aquifer matrix, native ground water, and confining layers. As presented in Table 1, the aquifer and water have constant thermal properties and assumed to be slightly compressible. The volumetric heat capacity and thermal conductivity were identical for the aquifer and the confining layers.

aquifer	porosity (n)	0.40
	permeability (k)	1,013 md
	compressibility of formation (β_r)	2.96×10^{-6} kPa^{-1}
	density of rock (ρ_r)	2.65 g/cm^3
	thermal conductivity of rock (λ_T)	249.2 kJ/day·m·°K
	thermal conductivity of overburden/underburden rock (λ_{Te})	249.2 kJ/day·m·°K
	heat capacity of rock (C_{vr})	0.8864 kJ/kg·°K
water	viscosity (μ_w)	1.1404 cp
	compressibility (β_w)	4.4×10^{-7} kPa^{-1}
	density (ρ_w)	1 g/cm^3
	heat capacity (C_{vw})	4.184 kJ/kg·°K

Table 1. Hydrogeological and thermal properties of aquifer and water

5. Results and discussion

To estimate the characteristics of the system, this two-well model was run for continuous flow regime. Heat transfer within the aquifer is simulated by specifying constant temperature T_{inj} at the injection well and with the aquifer temperature initialized at T_i. The initial temperature of the aquifer is assumed to be constant 17.5°C over the entire aquifer and confining layers. The model is run for 10 years to provide an adequate long-term assessment of thermal storage.

In the continuous flow regime, water is pumped from one well equipped with a pump and injected through a second well. A complete energy storage cycle is composed of four periods per year to simulate the seasonal conditions. Each cycle is symmetrical for identical injection ($Q > 0$) and production ($Q < 0$) rates and duration. The thermal field and the temperature of produced water, T_{prod}, are calculated from the numerical solutions of Equation (3) at constant time interval.

In order to evaluate and compare results obtained from ATES system simulations, a measure of performance is required. There is no generally valid basis for comparing the achieved performance of TES system under different conditions. In this study, the ratio of differential energy returned from aquifer to the energy originally in the aquifer, which is similar to dimensionless parameter adopted by Chavalier & Banton (1999) or Tenma et al. (2003), is used to measure TES performance.

$$\text{normalized thermal storage} = \frac{T_{\text{prod}} - T_i}{T_i} \tag{6}$$

A number of factors may influence the performance of the ATES. In this study, the following parameters were varied.

1. operation schedule: continuous and variations of cyclic regimes
2. heat loss to adjacent layers

3. temperature of injecting water
4. flow rate of water
5. distance between injection and production wells
6. aquifer thickness
7. screen length
8. anisotropy in vertical permeability

5.1 Operation schedule

The influence of a number of operation schedules on the performance of ATES was examined. The seasonal variations in the surface due to natural seasonal variations are involved in the operation schedules. Four cases of scenarios were considered in the present simulations, as list in Table 2.

	Injecting or Producing Flow Rate (m^3/day)				Temperature of Injecting Water(°C)			
Month / Case	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12
Case 1	50	50	50	50	5	15	25	15
Case 2	50	50	50	50	5	25	5	25
Case 3	50	50	50	50	5	5	25	25
Case 4	50	0	50	0	5	-	25	-

Table 2. Description of continuous operation scenarios for a year

Accounting for the seasonal changes in surface temperature, the injected water temperatures in Case 1 were taken as 5°C, 15°C, 25°C, and 15°C over a three-month period, respectively. Case 1 will be used as a base case for other simulations. Operation schedules of Cases 2 and 3 were scenarios presented by Tenma et al. (2003). In these cases, the inlet temperature was held constant at 5°C for a half year, then changed to a temperature of 25°C for the rest of the year. Case 4 is similar to Case 1, except rest periods of neither injection nor production between 5°C and 25°C water injection periods. During the rest periods in Case 4, temperature of a cell containing production well is considered as T_{prod}. The size of this two-well model is 39 m × 39 m × 22 m. The rates of injection or production of 50 m^3/day correspond to 0.45094 pore volume of the aquifer for three months.

The evaluation of a TES system was performed by the temperature of produced water shown in Fig. 3. Reflecting the changes in temperature of the injecting water, the recovery temperatures fluctuate with a quarterly year period. Balances between injecting and producing thermal energy and small variation in temperatures are the most desirable case, representing sustainable use of ground as an ATES system without a negative effect on the environment.

As the temperature of the circulated fluid changes by 25-5°C, the temperature eventually becomes 15°C, the average temperature of injected water. Due to energy imbalance between the initial temperature of 17.5°C and average injecting temperature of 15°C, the aquifer undergoes a gradual cooling process and negative value of balance of thermal energy. The temperatures at the producing well were constant within 2.6°C for Cases 2 and 4 and 7.8°C for Case 3 through the ten-year period.

The results of normalized thermal balance are shown in Fig. 4. A positive value means the energy produced is larger than the initial energy; a negative value means the initial energy

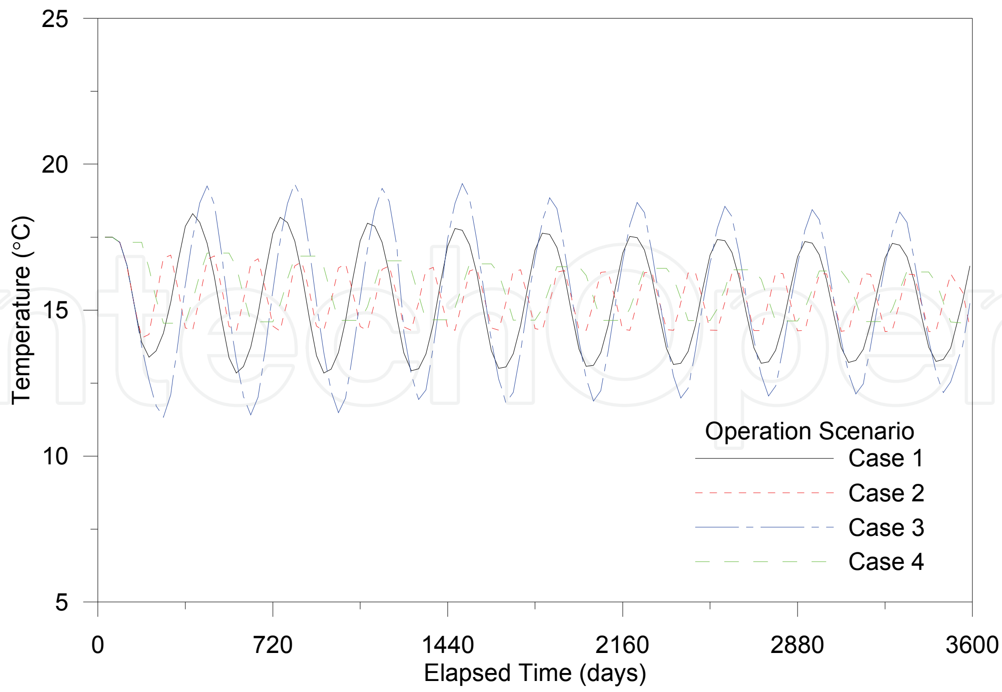


Fig. 3. History of recovery temperature obtained from simulations with different operation scenarios

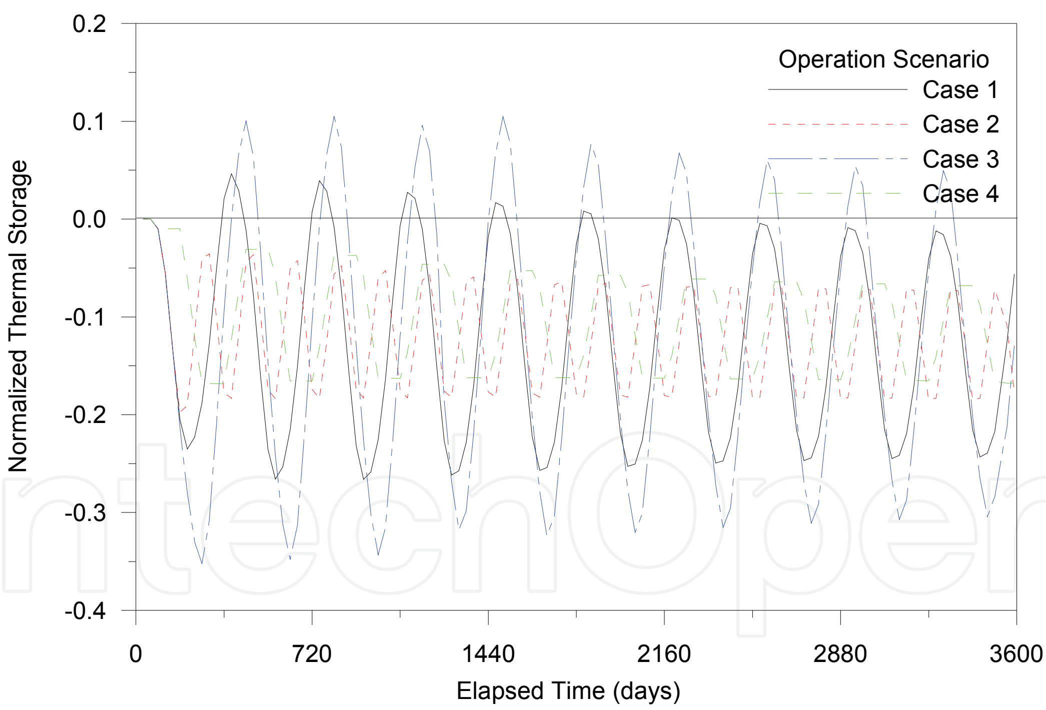


Fig. 4. History of balance of thermal energy obtained from simulations with different operation scenarios

is larger than the energy produced. Zero mean balance of thermal energy and small variation are the most desirable case, representing sustainable use of aquifer as a TES system. As shown in the Figure, the balance of thermal energy gradually decreases in all the cases. Reflecting the changes in temperature of the injecting water, the balance of thermal energy also fluctuates with a quarterly year period. The sum of normalized thermal storage values is smallest for Case 4 and largest for Case 3. Differences among cases are relatively small, less than 20%. However, the range of variation of Case 3 is the highest and 2.7 times higher than that of Case 4 which is the smallest. As the net change of thermal energy is small, the flow conditions of Cases 2 and 4 are promising.

One of objectives of numerical simulation is to visualize the groundwater flow and heat transfer in the aquifer and the movement of thermal front. With results from numerical simulations, one can provide graphical presentation of the groundwater flow and the motion of thermal fronts for given set of wells-aquifer configuration. The groundwater flow around the wells takes place mainly in the radial direction. The interface or thermal front is between the injected water and the water in the aquifer. The location of thermal front is determined by inspecting temperature distribution.

For the graphical representation of results, an illustrative example is taken from Case 1 for heat and cold storage. In Figs. 5(a) to (d), the simulated temperature distributions are presented with different colors for different temperatures. The temperatures are for the middle layer obtained from numerical calculations after 90, 180, 270, and 360 days of operation. These give direct pictures on the characteristics of energy flow fields and the location of thermal front. In the figures, there are clear evidences for energy storage. The area of relatively uniform temperature near the injection well represents the region influenced by water injected during each flow period. Clearly shown in the aquifer during winter and summer periods, the thermal fronts are from cold and warm water injected. They are located at a considerable distance from the production well. The pair of wells interacts slightly and the production well seems undisturbed by the injection well. Whilst the temperature of the injecting water changes by 25-5°C, the temperature of the produced water lies within much smaller range.

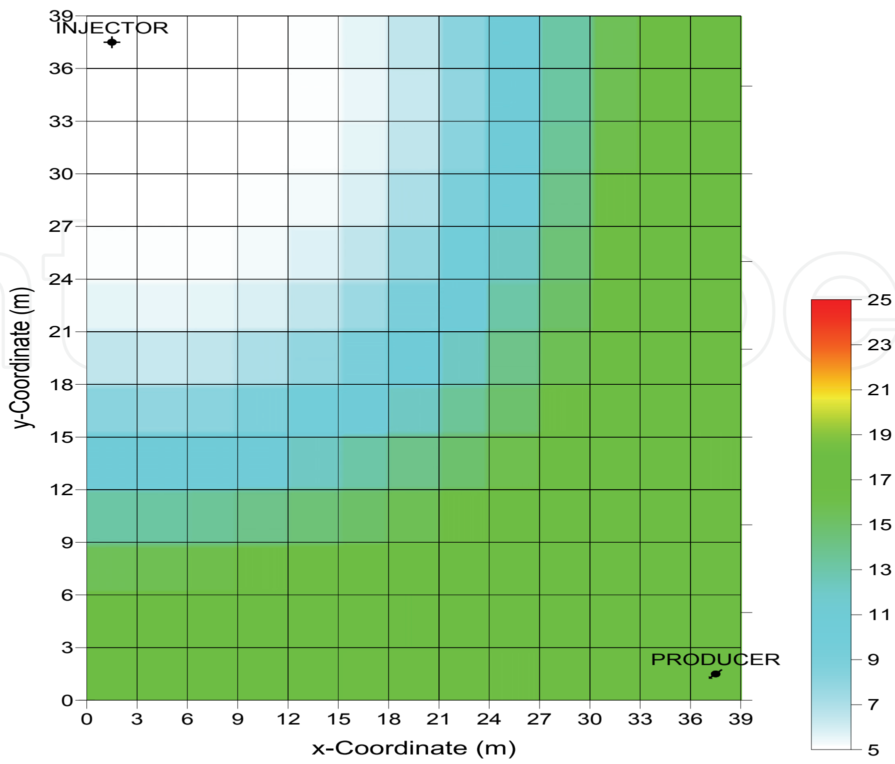
5.2 Heat loss

Heat transfer from/to overburden and underburden formations is considered as an important factor that may control the temperature of produced water. In the present work, results from the base case were compared with those from a case in which heat loss is not included. These formations are assumed to have the same thermal properties with aquifer, as stated earlier.

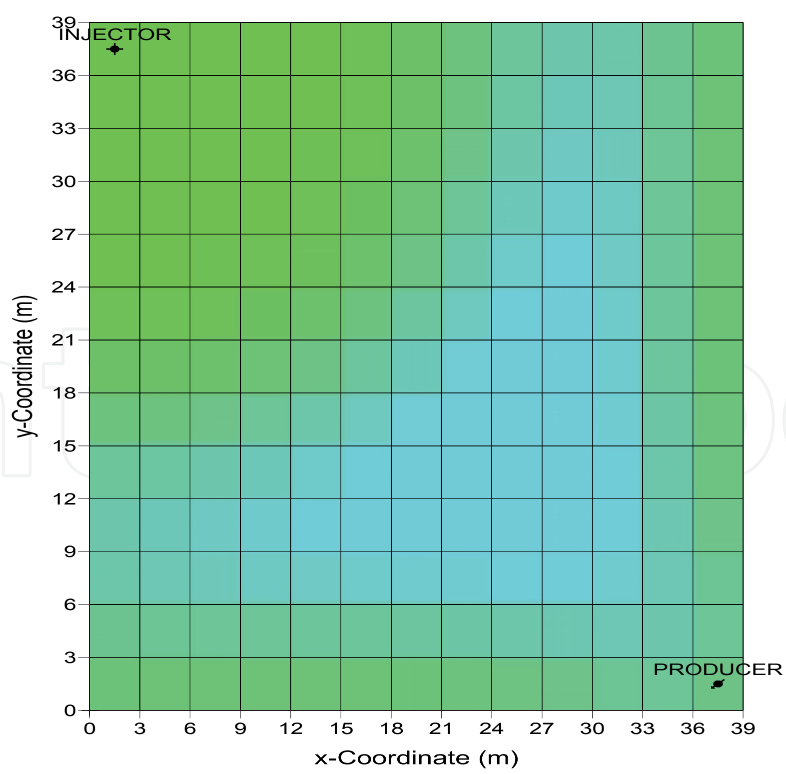
Figure 6 shows these results at different times. With heat loss, the average and range of thermal balance decreases gradually over time. Contrarily, the temperature at the production well fluctuates in the fixed range between 11.3°C and 19.6°C without heat loss. Therefore, the difference between results from two cases is gradually increasing. The range of thermal balance also remains constant at 0.53 which is higher than that obtained from the base case. The results indicate that conductive heat exchange with the surrounding rock is an important process causing different cycle of temperature variations in the production well.

5.3 Injection temperature

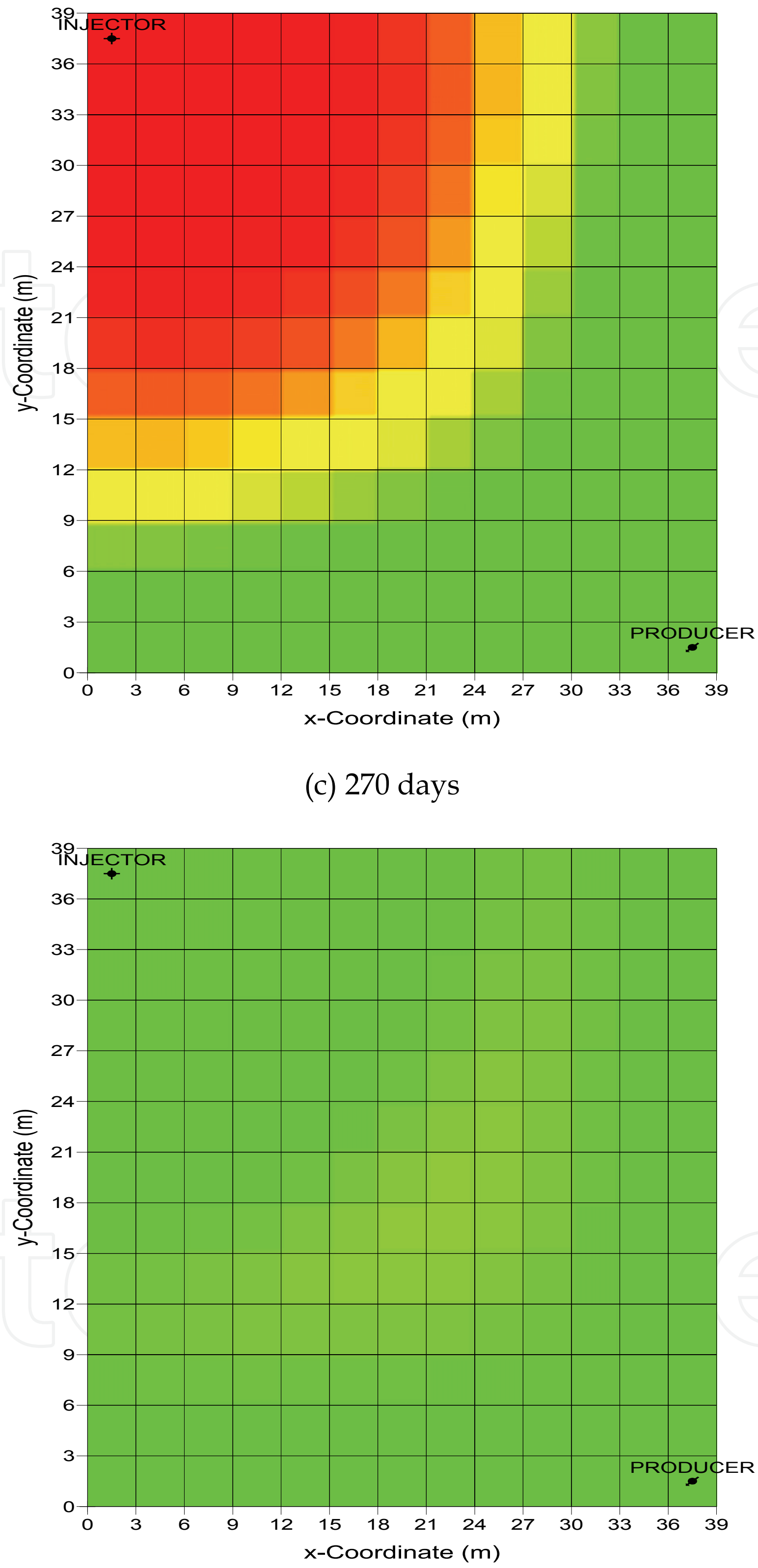
To demonstrate the effect of temperature difference on long-time thermal storage performance of the aquifer, additional simulations were performed using different combinations of water temperature at the injection side. Having average value of 15°C, the temperature of injecting water was constant during each three-month injection period and had values of 1°C/15°C/29°C/15°C and 9°C/15°C/21°C/15°C, respectively. Other conditions and parameters were not changed from the operation scenario of Case 1 with 5°C/15°C/25°C/15°C.



(a) 90 days



(b) 180 days



(c) 270 days

(d) 360 days

Fig. 5. Temperature distribution [°C] of the middle layer after cold/warm water injection during the first year

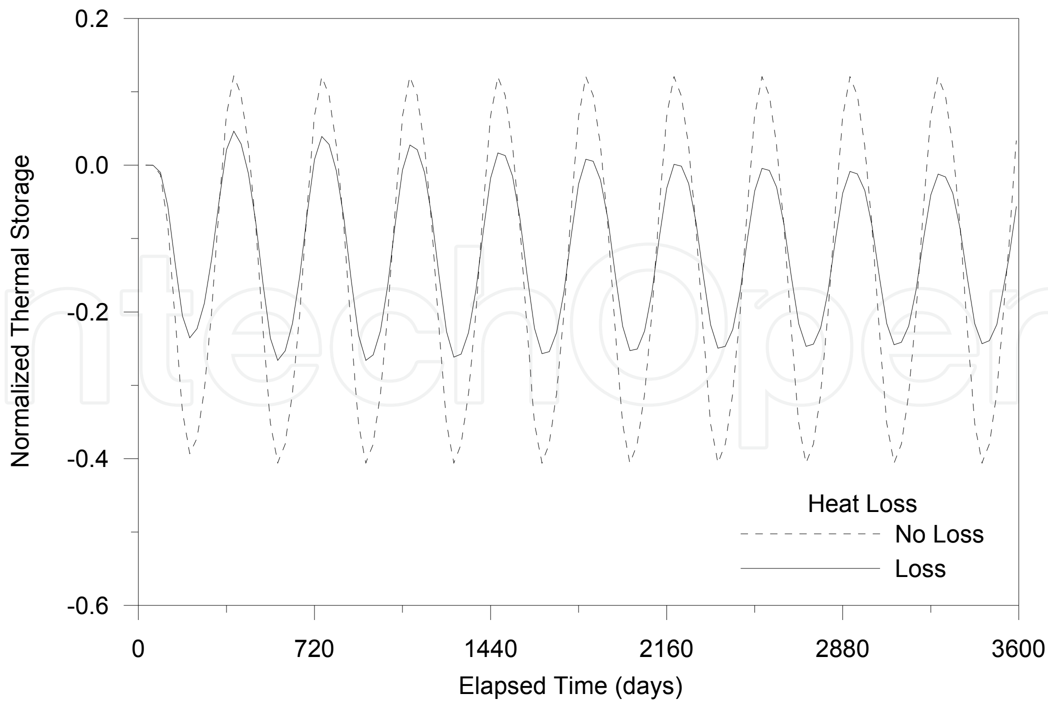


Fig. 6. History of balance of thermal energy obtained from simulations with different heat loss conditions

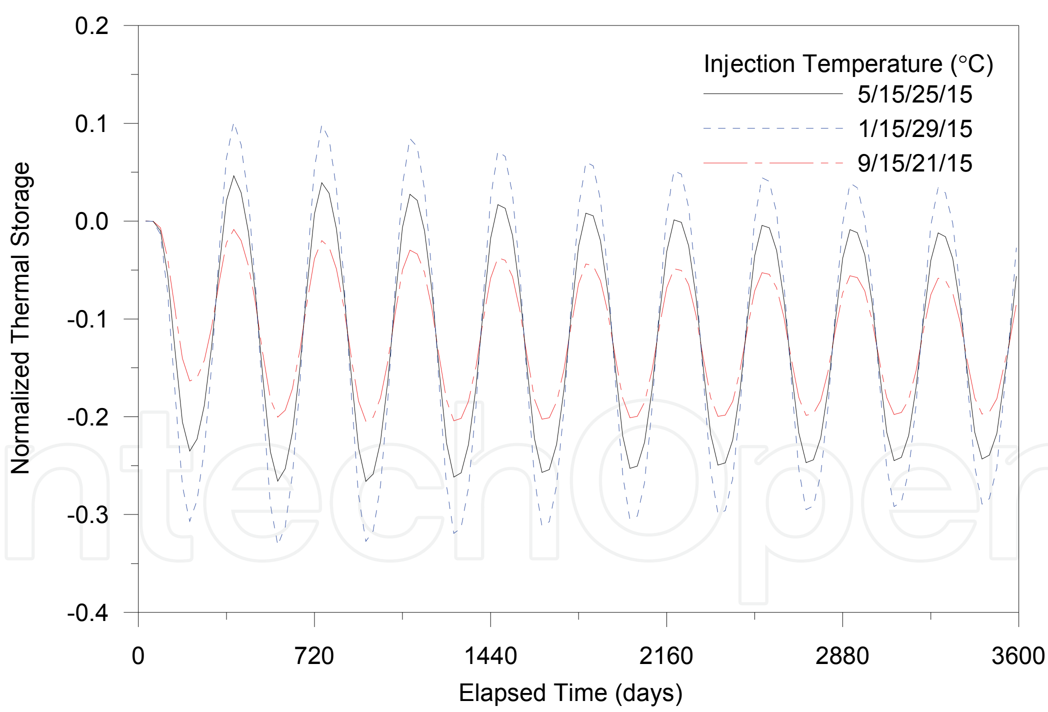


Fig. 7. History of balance of thermal energy obtained from simulations with different injection temperatures

The profiles in Fig. 7 shows increasing range in thermal balance with increasing differences in injection temperature, in accordance with the gradual drop over time. The range of variation of Case 1°C/15°C/29°C/15°C is the highest and 2.1 times higher than that of 9°C/15°C/21°C/15°C which is the smallest. By increasing the temperature difference around the year at the injection well from 12°C to 28°C, the normalized thermal storage is proportionally decreased. The sum of values is smallest for 9°C/15°C/21°C/15°C and largest for 1°C/15°C/29°C/15°C. Differences among summed values are relatively small, less than 20%.

5.4 Flow rate

The aim of this simulation is to evaluate the recovery of thermal energy from the aquifer given injection or production flow rates. The calculations were performed for well and aquifer configuration which is the same as the base case. However, in this simulation, the flow rates of injection and production are changed to 25, 50, and 75 m^3/day. These rates are equivalent to injecting 0.22547, 0.45094, and 0.67641 pore volumes for a three-month period, respectively.

Figure 8 presents a considerable drop in thermal storage and a significant increase in variation of the values with increasing flow rate. Tripling the flow rate results in increases in the sum of thermal storage values by 36% and ranges by 2.5 times. The result suggests that, everything else being the same, the use of less flow rate is a promising flow condition due to small net change in thermal energy. However, decreasing the flow rate considerably less than an appropriate value would not be effective because the resulting decrease in the amount of available thermal energy would be a problem.

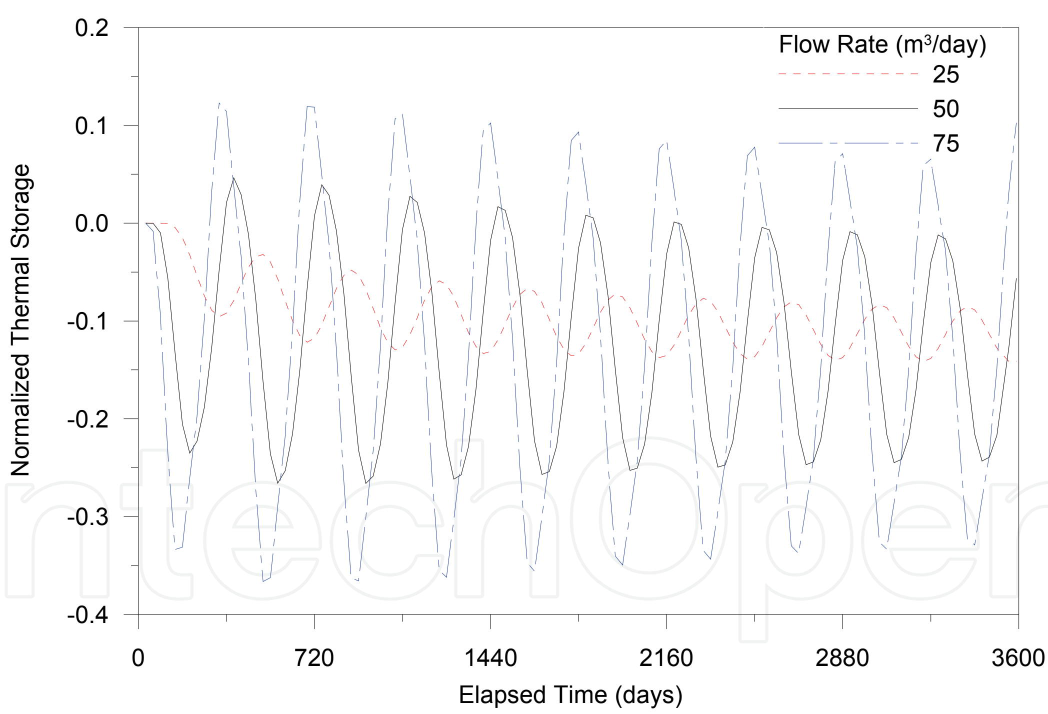


Fig. 8. History of balance of thermal energy obtained from simulations with different injection/production flow rates

5.5 Well distance

The distance between the injection and production wells influence the proportion of the aquifer that is effective in the heat transfer and thermal storage process. One objective with the numerical simulations is to find the well configuration to make the energy storage as dense as possible. In attempts to investigate effects of interwell distance, pumping and injection of groundwater were simulated for three cases where the sizes of computation domains are 32.5×32.5 m², 39.0×39.0 m², and 45.5×45.5 m². The injection and production wells are located 42.2 m, 50.9 m, and 59.4 m apart, respectively. These distances correspond to 0.64935, 0.45094, and 0.33130 pore volume of the aquifer for three months of injection or production at 50 m³/day.

Figure 9 illustrates the energy balance for different well distances. A longer well distance reduced the variations in thermal storage substantially. Although almost doubling the pore volume of the aquifer by increasing the well-to-well distance does not double the performance of ATES systems, it does improve the performance of ATES systems by decreasing the sum of thermal storage values by 14% and ranges by 55%. Larger variations for shorter well-to-well distance result from the fact that the thermal front of injected water approaches the production well within each operation period. Therefore, the region near a producing well is considerably affected by injected water. This observation emphasizes the importance of ensuring that adequate distance between wells is used, taking into account the thermal and hydraulic transport of injected water.

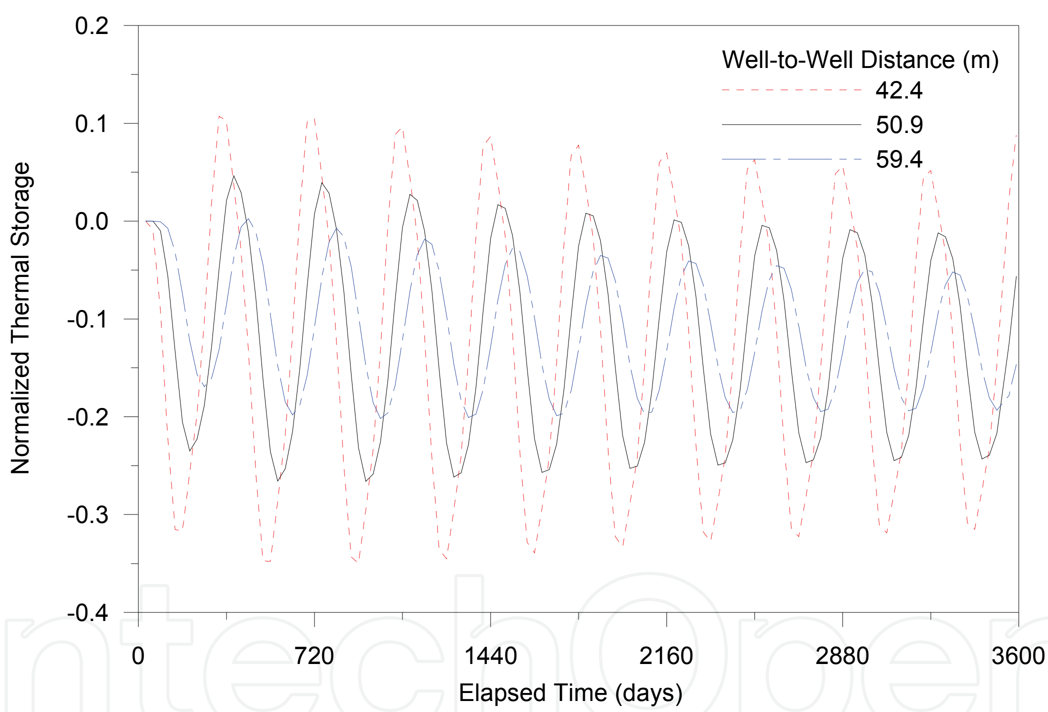


Fig. 9. History of balance of thermal energy obtained from simulations with different interwell distances

5.6 Aquifer thickness

To investigate the influence of the aquifer thickness in the performance of ATES system, two-well models with 22 m, 30 m, and 38 m thick aquifers were analyzed. The pore volumes of aquifers correspond to 0.45094, 0.33069, and 0.26107 for three months of injection or production at 50 m³/day. Screen is 6 m long and installed at the center of the aquifer for all cases.

Figure 10 shows that increasing the thickness of the aquifer from 22 m to 38 m decreases the range of thermal storage by 32%, but the sum of thermal storage only by 3%. Although the results demonstrate the importance of aquifer thickness, they also show that thick aquifers would not be so effective in thermal energy storage. Compared with results from the simulation with different interwell distance and similar pore volume, the resulting decrease of the net changes in thermal energy is limited.

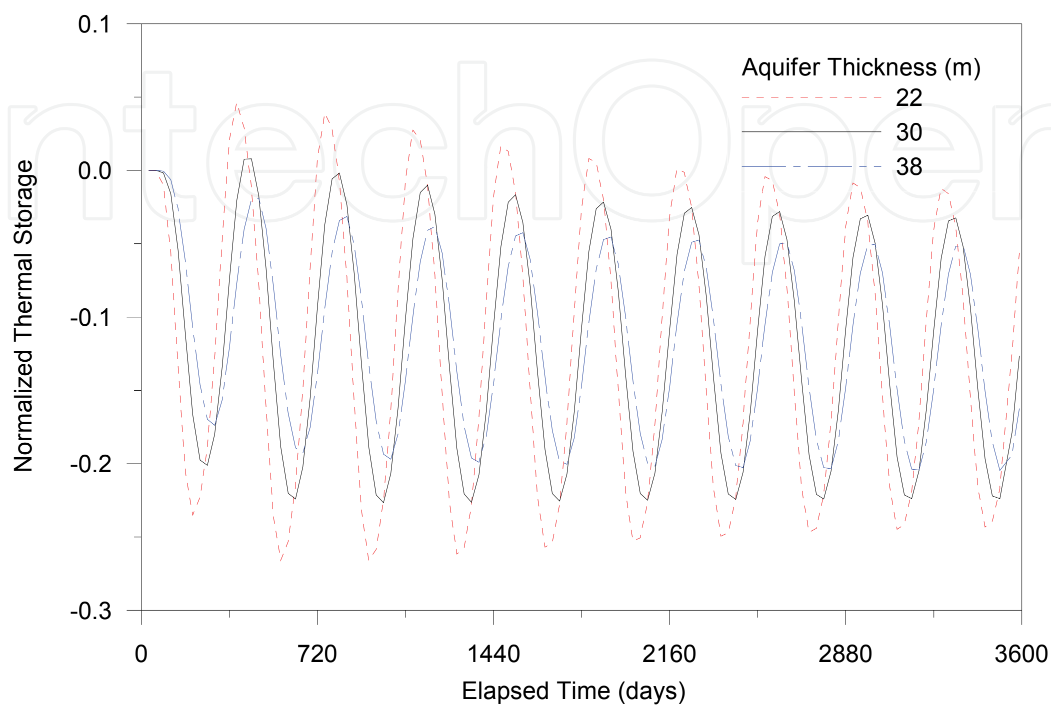


Fig. 10. History of balance of thermal energy obtained from simulations with different aquifer thicknesses

5.7 Screen length

To investigate how the screen length affects the performance of ATES system, two-well models is applied for aquifer of 39×39×22 m^3 with injection or production at 50 m^3/day. Screens for injection wells are 6 m long and installed at the center of the aquifer for all cases. For production wells, screens are 2m, 6 m, and 10 m long.

Figure 11 shows that increasing the length of the screen from 2 m to 10 m makes no differences in the range of thermal storage. The results show that long screen would not be so effective in thermal energy storage as long as vertical permeability is as high as horizontal permeability.

5.8 Vertical permeability

In this simulation, the effect of directional permeability on the performance of an ATES system was examined. All other conditions are similar to the base case except for considering anisotropy in permeability by replacing vertical permeability with different values. Permeabilities in x and y directions are kept constant. The ratios of vertical to horizontal permeability considered in this study are 1.0, 0.5, and 0.1.

Figure 12 presents the influence of vertical permeability on the performance of ATES systems in terms of values and variations of thermal storage. A weak dependence on the permeability anisotropy is obtained. The thermal storage values for k_z/k_x = 0.5 and

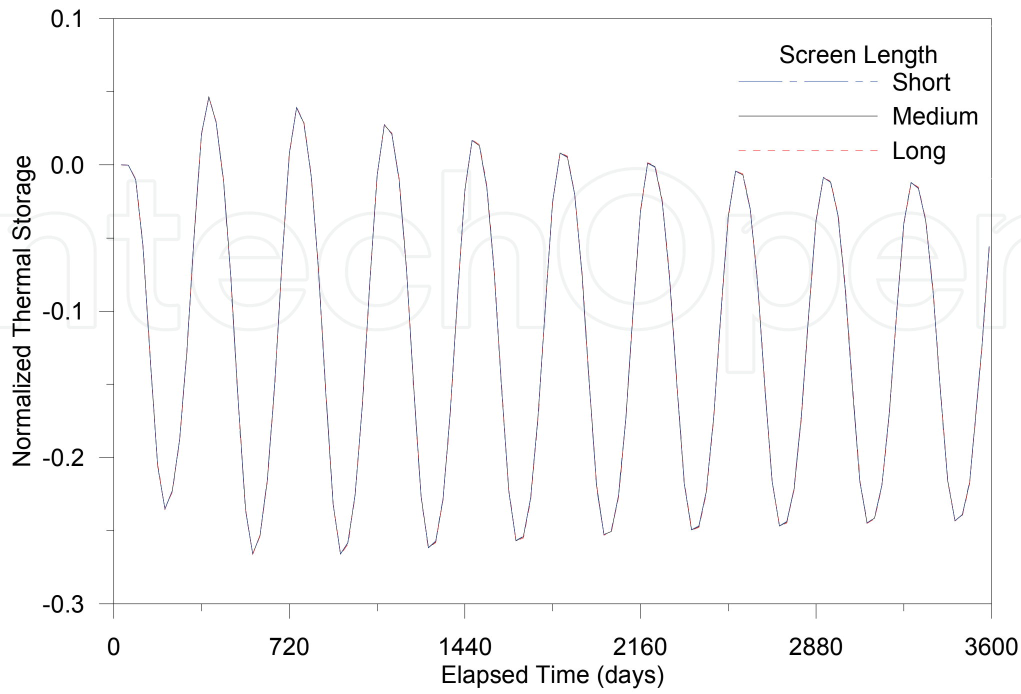


Fig. 11. History of balance of thermal energy obtained from simulations with different screen length

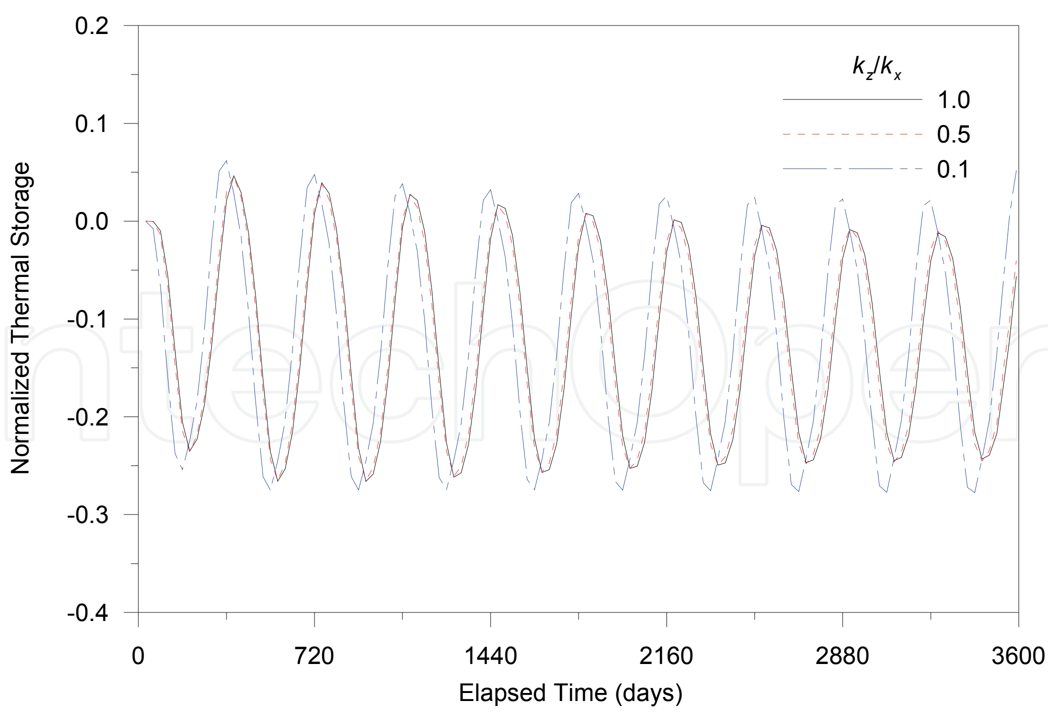


Fig. 12. History of balance of thermal energy obtained from simulations with different permeability anisotropy

k_z/k_x = 1.0 are almost identical, while those of k_z/k_x = 0.1 show a larger variations and less drop over time. However, the increase in the range of thermal storage is less than 9% and the sum of thermal storage only by 2%. The results suggest that, everything else being the same, the effects of permeability anisotropy would be only marginal.

6. Conclusion

A mathematical model describing the water flow and convective/conductive thermal energy transport in an ATES system is presented. The three-dimensional thermal process with combined groundwater and heat flow in the aquifer and heat conduction in surrounding layers is solved numerically. This paper presents the results of long-time thermal behavior of ATES system with two wells under continuous operation methods. The effects of various injection-withdrawal rates and durations on computed values of aquifer thermal behavior and final producing temperature were studied for a 10-year continuous injection and withdrawal. The hypothetical simulations indicate that the model of the two-well system will be a valuable tool in determining the most efficient system operation.

The thermal behavior of the storage system is shown to depend on the aquifer's volume relative to energy input and flow pattern of the water. Various operational and geometrical parameters including operation schedules, injection temperature, injection/production rates, and geometrical configuration of well and aquifer impact the predicted recovery water temperature. Small variations in injection temperatures, low flow rate, and large surface to volume ratio are recommended as an effective ATES because of small loss and little fluctuation in extracted thermal energy. However, aquifer thickness and hydraulic anisotropy have a minimal effect on the performance of ATES systems.

7. References

Allen D.M.; Ghomshei, M.M.; Sadler-Brown, T.L.; Dakin, A. & Holtz, D. (2000). The current status of geothermal exploration and development in Canada, *Proceedings of World Geothermal Congress 2000*, pp. 55-58, Kyushu-Tohoku, Japan, May 28-June 10 2000

Andersson, O. (2007). Aquifer thermal energy storage, In *Thermal Energy Storage for Sustainable Energy Consumption*, Paksoy, H.O. (Ed.), 155-176, Springer: Dordrecht, The Netherlands

Breger, D.B.; Hubbell, J.E.; Hasnaoui, H.E. & Sunderland, J.E. (1996). Thermal energy storage in the ground: comparative analysis of heat transfer modeling using U-tubes and boreholes, *Solar Energy*, Vol. 56, No. 6 (June 1996) 493-503

Center for Petroleum and Geosystems Engineering, (2000). *UTCHEM-9.0 A Three-Dimensional Chemical Flood Simulator*, University of Texas at Austin: Austin, TX, U.S.A.

Chavalier, S. & Banton, B. (1999). Modelling of heat transfer with the random walk method. Part 1. Application to thermal storage in porous aquifers, *Journal of Hydrology*, Vol. 222, No. 1-4 (September 1999) 129-139

Claesson, J.; Hellström, G. & Probert, T. (1994). Simulation models for ATES, *Proceedings of International Symposium on Aquifer Thermal Energy Storage*, pp. 131-137, Tuscaloosa, Alabama, U.S.A., November 14-15 1994

Clauser, C. (2003). *Numerical Simulation of Reactive Flow in Hot Aquifers*, Springer-Verlag: Berlin, Germany

Delshad, M.; Pope, G.A. & Sepehrnoori, K. (1996). A compositional simulator for modeling surfactant enhanced aquifer remediation, 1 fomulation, *Journal of Contaminant Hydrology*, Vol. 23, No. 4, (August 1996) 303-327

Deng, Z. (2004). *Modeling of Standing Column Wells in Ground Source Heat Pump Systems*, Ph.D. dissertation, Oklahoma State University: Stillwater, OK, U.S.A.

Nassar, Y.; ElNoaman, A.; Abutaima, A.; Yousif, S. & Salem, A. (2006). Evaluation of the underground soil thermal storage properties in Libya, *Renewable Energy*, Vol. 31, No. 5, (April 2006) 593-598

Nielsen, K. (2003). *Thermal Energy Storage, A State-of-the-Art*, Norwegian University of Science and Technology (NTNU): Trondheim, Norway

Novo, A.V.; Bayon, J.R.; Castro-Fresno, D. & Rodriguez-Hernandez, J. (2010) Review of seasonal heat storage in large basins: Water tanks and gravel-water pits, *Applied Energy*, Vol. 87, No. 2, (February 2010) 390-397

O'Sullivan, M.J.; K. Pruess & Lippmann, M.J. (2001). State of the art of geothermal reservoir simulation, *Geothermics*, Vol. 30, No. 4, (August 2001) 395-429

Paksoy, H.O.; Andersson, O.; Abaci, H.; Evliya, H. & Turgut, B. (2000). Heating and cooling of a hospital using solar energy coupled with seasonal thermal energy storage in aquifer, *Renewable Energy*, Vol. 19, No. 1-2, (January 2000) 177-122

Paksoy, H.O.; Gurbuz, Z.; Turgut, B.; Dikici, D. & Evliya, H. (2004). Aquifer thermal storage (ATES) for air-conditioning of supermarket in Turkey, *Renewable Energy*, Vol. 29, No. 12, (October 2004) 1991-1996

Probert T.; Hellsröm, G. & Glaesson, J. (1994). Thermohydraulic evaluation of two ATES projects in southern Sweden, *Proceedings of International Symposium on Aquifer Thermal Energy Storage*, pp. 73-81, Tuscaloosa, Alabama, U.S.A., November 14-15 1994

Rafferty, K. (2003). Ground water issues in geothermal heat pump systems, *Groundwater*, Vol. 41, No. 4, (July-August 2003) 408-410

Rosen, M.A. 1999. Second-law analysis of aquifer thermal energy storage systems, *Energy*, Vol. 24, No. 2, (February 1999) 167-182

Sanner[a], B. (2001). Shallow geothermal energy, *GHC Bulletin*, Vol. 22, No. 2, (June 2001) 19-25

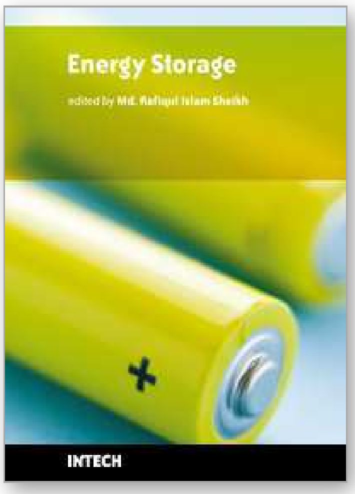
Sanner[b], B. (2001). A different approach to shallow geothermal energy–underground thermal energy storage (UTES). *International Summer School on Direct Application of Geothermal Energy (IGD2001)*, Giessen, Germany, September 17-22 2001

Schmidt, T.; Mangold, D. & Muller-Steinhagen, H. (2003). Seasonal thermal energy storage in Germany. *Proceedings of ISES Solar World Congress 2003*, pp. 1-7, Göteborg, Sweden, June 14-19 2003

Schmidt, T. & Hellström, G. (2005). *Ground Source Cooling - Working Paper on Usable Tools and Methods*

Tenma, N.; Yasukawa, K. & Zyvoloski, G. (2003). Model study of thermal storage system by FEHM code, *Geothermics*, Vol. 32, No. 4-6, (August-December 2003) 603-607

Vinsome, P.K. & Westerveld, J. (1980). A simple method for predicting cap and base rock heat losses in thermal reservoir simulators. *Journal of Canadian Petroleum Technology*, Vol. 19, No. 3, (July–September 1980) 87-90



Energy Storage
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Electricity is more versatile in use because it is a highly ordered form of energy that can be converted efficiently into other forms. However, the disadvantage of electricity is that it cannot be easily stored on a large scale. One of the distinctive characteristics of the electric power sector is that the amount of electricity that can be generated is relatively fixed over short periods of time, although demand for electricity fluctuates throughout the day. Almost all electrical energy used today is consumed as it is generated. This poses no hardship in conventional power plants, where the fuel consumption is varied with the load requirements. However, the photovoltaic and wind, being intermittent sources of power, cannot meet the load demand all of the time. Wherever intermittent power sources reach high levels of grid penetration, energy storage becomes one option to provide reliable energy supplies. These devices can help to make renewable energy more smooth and reliable, though the power output cannot be controlled by the grid operators. They can balance micro grids to achieve a good match between generation and load demand, which can further regulate the voltage and frequency. Also, it can significantly improve the load availability, a key requirement for any power system. The energy storage, therefore, is a desired feature to incorporate with renewable power systems, particularly in stand alone power plants. The purpose of this book is twofold. At first, for the interested researcher it shows the importance of different Energy Storage devices, but secondly, and more importantly, it forms a first attempt at dissemination of knowledge to the wider non-expert community who may wish to consider Energy Storage device for specific application. Thus this book will be helpful to provide an indication of the tools necessary for an assessment to be made Energy Storage device more powerful.

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