Aquifer thermal energy storage: theoretical and operational analysis

J. DICKINSON*, N. BUIK†, M. MATTHEWS‡ and A. SNIJDERS†

Aquifer thermal energy storage (ATES) systems provide a method of improving the performance of more commonly installed mono-directional groundwater heating and cooling systems. Rather than using the prevailing temperature of the abstracted groundwater, ATES systems are bidirectional, therefore allowing for the interseasonal storage of low- and higher-temperature energy. This paper provides a theoretical base for ATES and an empirical review of the performance of a typical system installed in an office building in the Netherlands. This research was carried out by engineering consultancies in the UK and the Netherlands, and a UK University. The geology and hydrogeological conditions under focus can be briefly described as a confined saturated medium sand aquifer covered by horizons of clay and fine sand. A design simulation using HSTWin, a modified version of the software package HST3D, is compared against operational data collected over a 12-month period. These data were collected following 5 years of operation. The main conclusion from the case study is that there is good agreement between the HSTWin simulation and operational findings. Furthermore, it can be inferred that active ground thermal storage strategies can offer improvements OVER conventional ground source energy systems.

KEYWORDS: groundwater; temperature effects; numerical modelling and analysis; design; monitoring; environmental engineering; sands

INTRODUCTION

The use of the ground to aid the heating and cooling of buildings is not a new technique. However, the recent drive towards a low-carbon economy and higher energy prices has increased attention on the most efficient and sustainable methods to utilise and accurately simulate these systems. In parallel, changes in building legislation have led to a move away from traditional forms of heating and cooling commercial buildings. For example, in the UK, Building Regulations (ODPM, 2006) have been revised in line with the European Performance in Buildings Directive (EPBD, 2002).

Aquifer thermal energy storage (ATES) is an approach used to enhance the efficiency in comparison with other ground energy systems. ATES installations actively store cooled and heated groundwater in the ground from respective heating and cooling mode cycles. For reference purposes, Fig. 1 illustrates the various systems more commonly used in practice, and highlights the position of ATES under open loop approaches.

It is useful to make an important distinction between higher-enthalpy systems, which take advantage of higher-temperature geothermal resource generated from a heat flux originating from the deeper geology of the earth (i.e. from decaying isotopes of uranium, potassium and thorium in the earth's crust; Dickson, 2003), and lower-enthalpy systems, which take advantage of the net solar energy absorbed and stored in the subsurface (VDI, 2000). With the latter systems, the groundwater temperature nearer the surface is inherently linked to the above-ground temperatures throughout the year. Within the first few metres below ground level there are seasonal fluctuations in temperatures (Brandl, 2006). With greater depth this effect is reduced, so the prevailing temperature is the average annual air temperature with an additional temperature gradient relating to the thermal flux (Rawlings, 1999).

Open-loop systems abstract and discharge groundwater either from an aquifer of suitable permeability or from a surface water body. Energy is then typically transferred to and from the building’s heating and cooling system via a heat exchanger located within the main plant room. Conversely, closed-loop systems exchange energy directly in the ground using ground heat exchangers, which are commonly installed in bespoke trenches at relatively shallow depth or in vertical boreholes (VDI, 2001a). Other variations allow for the transfer of energy through heat exchanger pipework installed in foundation structures (Brandl, 2006).
In the case of aquifer open-loop systems there are two main techniques: monodirectional and bidirectional (VDI, 2001b). Monodirectional systems simply abstract and discharge groundwater in one direction, whereas bidirectional systems, otherwise known as ATES systems, generally consist of two or more wells, where the flow can be reversed to actively store heated and cooled water (Fig. 2). In summer, groundwater is abstracted from a previously designated ‘cold’ well or wells, and is typically passed through a heat exchanger, whereby it is possible to reject heat from the building. The heated water is then discharged to one or more ‘warm’ wells. In winter the process is reversed, and hence it is possible to establish a thermodynamic advantage by storing heated groundwater from the cooling summer operation and cooled groundwater from the winter or heating operation. The thermodynamic advantage is particularly prevalent in the cooling operation, where undisturbed groundwater temperatures are generally not suited to direct cooling systems in buildings that require flow temperatures of less than 10°C (CIBSE, 2004). ATES systems can eliminate the need to run conventional cooling plant, thereby significantly reducing running costs and the effective carbon emissions from the operation of the building. In the heating mode, heat pumps are still typically used to upgrade the energy gained from the ground, although the performance is now improved. The common application of ATES remains in the lower-enthalpy field although there is an ongoing potential to expand the theory to higher-temperature and -enthalpy systems (Sanner, 1999).

The particular problems associated with linking the ground to the building are inherent in the geological and hydrogeological properties of the ground beneath the site, and the dynamic and cyclic nature of the energy loads. First, there is a need to analyse the instantaneous heating and cooling capacity (kW) and the cumulative required energy transfer over a 12 month cycle (kW h). It is important at this stage, also, to consider how the capacity and cyclic energy transfer may change over the lifetime of the building operation. Second, owing to the variable nature of geological thermal attributes, simulation techniques are required that allow the subsurface energy fluxes to be modelled according to site-specific ground parameters. Third, it is important that a multidiscipline approach links together the respective thermal attributes, to ensure that the system is both sustainable for the building operation and generates the desired optimisation of the ground resource.

What is common in all low-enthalpy systems is that there is a clear thermodynamic advantage in using residual solar heat stored in the ground to aid heating and cooling systems in buildings, provided the system is designed satisfactorily to ensure long-term performance (Vinsome, 1980; Brandl, 2006; Banks, 2008). Analytical techniques to model the ground and size closed-loop systems are well developed (Eskilon, 1987; Hellstrom, 1991). These techniques cannot be directly applied to open-loop systems owing to the more complex and dynamic ground model.

This paper first reviews the theoretical basis for aquifer thermal storage, and also the numerical solution preferred in this case. A case study is then presented of an office building located in the south-west of the Netherlands, which has a two-well ATES system that has been operational for 5 years. More recently, the office building has been extensively

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**Fig. 1. Organisation of ground energy systems**

**Fig. 2. Aquifer thermal energy storage system**
monitored to allow for optimisation, and also to provide data for ongoing reporting to the Netherlands Environmental Assessment Agency (MNP). Permits issued by the MNP for ATES systems in the Netherlands generally require that there be a near energy balance of heat abstracted and discharged over a 12-month period. Twelve months of data have been collated from 2007 to enable validation against the simulation model. This model has been updated from the initial model, completed before project installation, to include the 2007 starting condition in the wells and the observed heating and cooling loads in the building during this year. A modified version of the software package HST3D has been used to simulate the groundwater flow and thermal plume migration at each well (Kipp, 1986).

BACKGROUND TO AQUIFER THERMAL ENERGY STORAGE

Fundamental ATES theory

Sanner (1999) reported that the first ATES modelling research was conducted by Kazman and Rabbimov in the early 1970s (Kazmann, 1971; Rabbimov et al., 1971). However, there are records of operational ATES systems in Shanghai, China, in the 1960s (Luxiang & Manfang, 1984). Perhaps the first condensed publication was by Schaetzle et al. (1980), where the basic static and time step models were presented alongside possible applications and research activities. Since this time many systems have been successfully installed in North America and Europe.

Thermal energy is stored in both the groundwater and aquifer material, and hence the volumetric heat capacity is a function of the porosity and thermal properties of the respective fluid and solid materials.

The thermal capacity of an aquifer can be defined as

\[ Q = \left[ (\rho_w c_w)(1 - n) \right] + (\rho_w c_w) n \]  

(1)

As the heat rejection and abstraction is a dynamic process throughout the year, the problem suits a step response software package with a suitable time-step resolution for the analysis required. This must take into account the existing condition, the step energy flux, and the natural flow through the aquifer. The model is different from normal contaminated groundwater models owing to the thermal capacitance of the solid matter. As a result of energy storage in this solid fraction the thermal velocity is slower than the natural aquifer groundwater velocity. The thermal front velocity and time are given by (Schaetzle et al., 1980)

\[ v_t = \frac{\rho_w c_w n}{\rho_w c_w n + \rho_s c_s (1 - n)} \frac{v_w}{v_w} \]  

(2)

\[ t_t = \frac{\rho_w c_w n + \rho_s c_s (1 - n)}{\rho_w c_w n} \frac{t_w}{t_w} \]  

(3)

On reversal of the flow, the same theory can be adopted: that is, the thermal flow is equal to the injection flow without a variation in temperature. In practice it is accepted that some stratification may occur in the aquifer, and heat will be transferred by conductive processes to the confining impermeable layers above and below, and horizontally.

HSTWin software model

To calculate the thermal impact of ATES systems the computer model HSTWin can be used. This program has been derived from HST3D (Heat and Solute Transport), a program that was initially developed by the United States Geological Survey (Kipp, 1986). Since its conception the HST3D model has been modified a number of times to improve applicability of the software interface to ATES system design. The program can be used not only for simulating thermal transport through aquifers, but also for models with differing groundwater properties, such as fresh and salt water density. The simulation model is first validated against analytical solutions before comparing against measured data in the case study.

CASE STUDY: OFFICE IN DORDRECHT, THE NETHERLANDS

Building and ATES description

The office building is located in the south-west of The Netherlands, south of the town Dordrecht. The site plan for the building is shown in Fig. 3.

The building is fronted with a three-storey office block, with some packaging and manufacturing capability in a warehouse to the rear of the building. The total treated floor area is 4800 m², and the entire heating and cooling load is delivered from the ATES system. A cold well is located in the south-west of the site, and a warm well to the north-east at a distance of 119 m from the cold well, as shown in Fig. 3.

The schematic for the ATES system is shown in Fig. 4. A primary plate heat exchanger isolates the groundwater from the secondary side heating and cooling circuits. During
heating operation water is abstracted from the warm well at approximately 14°C and discharged to the cold well via the heat exchanger at approximately 6°C. In the cooling season the groundwater is abstracted from the cold well at approximately 7–9°C and discharged to the warm well again via the heat exchanger at 13–14°C. A submersible pump rated at 7 kW is installed in each well, and the maximum pump flow rate is 21 m³/h. A heat pump with a rated thermal capacity of 245 kW is used to generate elevated hot water at 45°C, whereas in cooling mode the prevailing flow temperatures on the secondary side of the heat exchanger can be used directly for cooling in the building.

Site geology, hydrogeology and well construction

The geology of the site comprises an alternating sequence of sands and clays of Holocene and Plio-Pleistocene age, creating a multiple aquifer system. The Holocene sediments comprise fluvial, tidal-flat and estuarine deposits, accumulated under the influence of a rising sea level behind a series of coastal barriers. These deposits reach a maximum thickness of about 25 m. In the Dordrecht area the Holocene sediments are dominated by river deposits, principally from the Rhine. The Plio-Pleistocene sediments are dominated by river deposits, principally from the Rhine. The Plio-Pleistocene sediments are not continuous, owing to the changes in the river system over this period.

The borehole logs for the cold and warm wells at the site are shown in Fig. 5. There is a reasonable correlation of strata between each well. However, not all the beds are continuous over the distance between the wells: this is typical of fluvial deposits such as these. Two distinct aquifers dominated by medium-grained sand can be identified, between approximately 5 and 15 mbgl, and between approximately 90 and 115 mbgl. In this case the lower aquifer horizon was considered the most suitable for the application. The mean nominal particle sizes (d₅₀) over the length of the well screens in the cold and warm wells are 339 μm and 328 μm respectively (see Fig. 5).

The groundwater flow pattern in the aquifer system is driven by rainfall-induced and topographically controlled potential energy (De Vries, 2007). The area around the site is relatively flat, between 0 and 5 m above sea level: hence the groundwater flow rates are likely to be very low. This means that the warm and cold water plumes developed around the wells will not be drawn out or significantly diluted by water at the undisturbed aquifer temperature.

The lowland areas of the Netherlands, such as that in which the site is located, suffer from problems with brackish and saline water. However, the water abstracted from the warm and cold wells has a chloride content of less than 20 mg/l, indicating the presence of fresh groundwater.

The well construction is shown in Fig. 6. The submersible pump is located in a pump chamber constructed of PVC to a depth of 18 m, and a smaller-diameter casing is installed to the screen at 100 m depth. The well screen is perforated with 0.6 mm diameter slots, and is situated between 100 and 115 m depth with the bottom of the well at 116 m below ground level. A separate piezometric level sensor is installed adjacent to each well. Bentonite grout is used to prevent the creation of pathways for brackish water, and to isolate other aquifer horizons throughout the depth of the borehole.

The undisturbed or far-field groundwater temperature can be estimated using equation (4) suggested by Eggen (1990), and presented by Rawlings (1999). This equation suggests a 0.02 deg C/m increase in the undisturbed temperature with increasing depth.

\[ T_w = T_m + 0.02d \]

By considering a mean air temperature of 10-5°C at the location, and a depth of 107.5 m at the midpoint of the well screen, the undisturbed temperature is calculated to be 12.7°C at this site.

Model validation

Advection is the primary method of heat transport through the aquifer. HSTWin has been compared with several analytical solutions for heat transport through intergranular aquifers (Gringarten & Sauty, 1975; Vinsome & Westerveld, 1980). One of the analytical solutions that is used for the validation has been derived by Lauwerier (1955). In this analysis the flow is considered to be Darcian. The solution describes the non-stationary heat transport through an aquifer that is situated between two impermeable (clay) layers. Only advective heat transfer is taken into account in the aquifer, and heat conduction through the confining layers. Fig. 7 illustrates the applied boundary conditions and system assumptions. If HSTWin can approximate the calculated values of the analytical solution, then it follows that it can also simulate the thermal impact of an ATES system.

The input parameters to compare the analytical solution with the HSTWin model are given in Table 1.

Equations (5) and (6) have been derived by Lauwerier (1955)

\[ T(t, \theta) = \text{erfc} \left( \frac{\psi(t - \theta)}{2\sqrt{2\pi}\beta} \right) \]

\[ \beta = \frac{\rho g c_s}{\rho c_l} \frac{(b_1)^2}{\lambda_l/\rho c_l} \]

Figure 8 presents the comparison between the results of the analytical solution and HSTWin. The graph shows the ratio between the injection temperature and the normalised temperature at increasing distance from the aquifer. This is assuming planar flow through the aquifer after a 20-year period.

In the HSTWin model the thermal dispersion is approximated to be 1/10th of the radius of the thermal store, in line with field observations by Sauty et al. (1982). The thermal dispersion correction is to account for hydrodynamic dispersion caused by unknown heterogeneities in the aquifer.

A good correlation is shown through the aquifer to a distance of 200 m, where the temperature equates to the natural undisturbed temperature in the aquifer. The agreement shown between the analytical solution and the HSTWin provides a degree of confidence in the software model’s ability to simulate heat transport in the aquifer. This is prior to comparing the software simulation with the operational data from the case study.

Case study modelling methodology and results

The comparison of the HSTWin with the case study was completed using the observed starting temperatures for 2007. The hydraulic conductivity was set to be 20 m/day using the equation for channel and immature sediments suggested by Sheppard (1989).

\[ K = 3500d_50^{1.65} \]

Cold well average d₅₀ = 328 μm from Fig. 5: therefore

\[ K = 2.6 \times 10^{-4} \text{ m/s or 22.8 m/day} \]

Warm well average d₅₀ =
339 μm from Fig. 5: therefore $K = 2.8 \times 10^{-4}$ m/s or 24.1 m/day. The conductivity of 20 m/day used in the model is at the lower end of the published range for this aquifer (de Vries, 2007) in order to provide a lower-bound prediction.

Figure 9 shows the respective computed monthly well temperatures during heating and cooling modes. During the heating season the abstraction temperature is between 13.5°C and 14°C. During the period from January to April the...
temperature drops slightly as the thermal store is depleted.

During the cooling season, from March to November, the abstraction temperature is calculated to be 6.5°C, rising to 8°C by October. The heating and cooling seasons overlap, leading to a partial recharge of the cold well from heating operations during October and November. Figure 10 and 11 present the data in plan view for the start of the heating and cooling seasons respectively. The shape is to some extent a function of the grid resolution used in the model. In Fig. 10 the cold well has been partially depleted, with the temperature at the well screen approaching 8°C, as also indicated by Fig. 9. At the start of the cooling season, as shown in Fig. 11, the isothermal plot shows the abstraction temperature to be near 6.5°C. There is a more pronounced thermal gradient from the cold well, as the difference between the far-field temperature and the injection temperature during the heating mode is greater.

Both isothermal contour plots suggest that there is no thermal short-circuiting during the year. The far-field tem-

Table 1. Input parameters for HSTWin in analytical model validation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of HSTWin model, x: m</td>
<td>800</td>
</tr>
<tr>
<td>Temperature difference between injection and initial (aquifer) temperature, ΔT: K</td>
<td>4</td>
</tr>
<tr>
<td>Node distance; Δx: m</td>
<td>1</td>
</tr>
<tr>
<td>Volumetric heat capacity, solid material: ρc_s: MJ/(m³ K)</td>
<td>1.5</td>
</tr>
<tr>
<td>Volumetric heat capacity, (fresh) water: ρ_w c_w: MJ/(m³ K)</td>
<td>4.2</td>
</tr>
<tr>
<td>Volumetric heat capacity, over-/underlying layer (water saturated), ρc_o: MJ/(m³ K)</td>
<td>2.5</td>
</tr>
<tr>
<td>Heat conduction, aquifer, λ_a: W/(m K)</td>
<td>2.5</td>
</tr>
<tr>
<td>Heat conduction, over-/underlying layer: λ_l: W/(m K)</td>
<td>1.7</td>
</tr>
<tr>
<td>Porosity, n</td>
<td>0.35</td>
</tr>
<tr>
<td>Thickness of aquifer, b_a: m</td>
<td>20</td>
</tr>
<tr>
<td>Hydraulic gradient, K: m/day</td>
<td>20</td>
</tr>
<tr>
<td>Gradient, i</td>
<td>1</td>
</tr>
<tr>
<td>Maximum time step, Δt: h</td>
<td>0.5</td>
</tr>
</tbody>
</table>
perature has been calculated to be 12.7°C. If short-circuiting was demonstrated, the contour plot for either well would start to overlap the adjacent well. For example, part-way into the heating season the abstraction temperature from the warm well would fall significantly, not only below the injection temperature from the cooling season but also below the far-field temperature of 12.7°C. This would suggest that the thermal plume from the cold well had migrated to the warm well.

Operational data summary

Various measurements were taken in the building at 8 min intervals throughout the year and recorded via a building management system software package. The data were then imported into a spreadsheet to allow further analysis and interpretation. A summary of the data points used in the analysis is shown in Table 2.

The prevailing ambient air temperatures for the site were measured via a temperature sensor externally located to the north of the building to avoid adverse measurements due to direct sunlight. The average monthly daily recorded temperatures are presented in Fig. 12, alongside the average minimum and maximum daily temperatures. During 2007 the maximum recorded absolute temperature was 41.1°C and the minimum was –5.6°C.

The observed energy and volumetric abstraction during the heating mode and the energy rejection during the cooling mode are shown in Figs 13 and 14 respectively. The energy flows were calculated on the primary side of the heat exchanger using an obtrusive flow meter, and temperature probes located in the pipe flow on each side. The energy flow is calculated using the equation

\[ \dot{Q} = \dot{m}_w c_w \Delta T \]  

(8)

It can be deduced that the heating and cooling operations overlap during March to April and September to November. During these mid-season periods the building occupier manually changes the direction of flow between the two wells according to the building demands. The cumulative heat energy abstracted was 86.4 MW h, and the total cooling energy was 64.4 MW h: hence there was a net heat energy abstraction from the aquifer of 22 MW h observed during 2007. In comparison the cumulative volume of groundwater abstracted from the cold well was 10,930 m³ compared with 9760 m³ abstracted from the warm well, a difference of 1170 m³.

The variable-speed submersible pump abstracts groundwater from the respective well according to the relative demands of the building. Figs 15 and 16 illustrate the typical pumping regime, flow rates and well levels during heating-mode operation on 2 January 2007. After a short time the temperatures monitored before the primary side heat exchanger reach steady state during pumping, that is, equate to the actual groundwater temperature. When the well pump is turned off, the temperature tends towards the ambient air temperature in the plant room. Unfortunately, no measurements were taken of the ambient plant room temperature. During steady-state operation the temperature differential is approximately 8°C. The flow rate fluctuates continuously.

Table 2. Summary of measurements taking during monitoring of ATES system at Dordrecht

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sensor location</th>
</tr>
</thead>
<tbody>
<tr>
<td>External air temperature</td>
<td>External wall to north of building</td>
</tr>
<tr>
<td>Cold well abstraction</td>
<td>Plant room: adjacent to plate heat exchanger</td>
</tr>
<tr>
<td>volume</td>
<td>Plant room: adjacent to plate heat exchanger</td>
</tr>
<tr>
<td>Warm well abstraction</td>
<td>Plant room: adjacent to plate heat exchanger</td>
</tr>
<tr>
<td>volume</td>
<td>Plant room: adjacent to plate heat exchanger</td>
</tr>
<tr>
<td>Temperature, warm well</td>
<td>Adjacent to well</td>
</tr>
<tr>
<td>Temperature, cold well</td>
<td>Adjacent to well</td>
</tr>
<tr>
<td>Warm well level</td>
<td>Adjacent to well</td>
</tr>
<tr>
<td>Cold well level</td>
<td>Adjacent to well</td>
</tr>
</tbody>
</table>
throughout the day to match the operation of the heat pump, which in turn modulates to charge an in-series thermal buffer vessel. The maximum recorded flow from the warm well was 19.1 m$^3$/h.

During pumping the respective well levels were measured. Fig. 16 shows that the typical drawdown in the well for pumping at a flow rate of 15 m$^3$/h is 1 m from a resting water level of 3.1 mbgl. During 2007 the lowest recorded level in the warm well was 4.7 mbgl, corresponding to a drawdown of 1.6 m.

It can be seen from Figs 17 and 18 that in the cooling mode the flow rate fluctuates less during the day as there is
no buffer vessel installed for the passive cooling operation. The steady-state temperature differential is approximately 6°C. The recorded flow from the cold well was 16.5 m³/h. By way of comparison with the warm well operation at 15 m³/h, the drawdown was recorded at 0.7–0.9 m, although this was realised only for relatively short isolated periods of 8 and 16 min. The maximum drawdown observed throughout the year in the warm well was 1.4 m, and 1.3 m in the cold well.

Figure 19 shows the measured average abstraction and discharge temperatures for the warm and cold wells. Towards the end of the heating season in March and April there is a slight drop in the steady-state abstraction temperature as the groundwater thermal store is depleted. The abstraction temperature from the warm well is nearer 14°C following the cooling season. The depletion of the cooling energy storage is more pronounced towards the end of the cooling operation. This is reflected by the rising abstraction temperature from March to October. The abstraction temperature is again reduced in November following a period of heating and cold water discharge.

DISCUSSION
Comparison of computed and measured data
The predicted and measured data for the cooling and heating modes are shown in Figs 9 and 19 respectively. In the cooling mode the predicted temperature is higher than that predicted by the model. In the heating mode the difference is less pronounced. The temperature was measured in the plant room, whereas the model predicts the temperature at the well screen. The positioning of the temperature sensors was initially chosen by the building designers to monitor the groundwater temperature adjacent to the heat exchangers. This is ultimately of greater interest than the well screen temperature when implementing a control strategy for heating and cooling plant.

In the cooling mode the abstraction temperature is lower than the bulk temperature of the ground around the well shaft, and also along the horizontal trench between the well head and the inlet to the building. Therefore, as the groundwater flows from the base of the well to the plant room, the temperature is likely to increase. The pipework is only insulated within the building.

To investigate this further, the temperature uplift can be approximated using the equations (de Paepe, 2003)

\[ T_{w,\text{out}} = T_{w,\text{wall}} + (T_{w,\text{source}} - T_{w,\text{wall}})e^{-\left(h/(Nu_c_w)\right)} \]  
(9)

\[ h = \frac{Nu_c_w}{D} \]  
(10)

For the purposes of this investigation the mean temperature at the pipe wall \( T_{\text{wall}} \) for the length of the well shaft has been approximated using equation (4) and a depth of 58 m. This reflects the midpoint of the well depth. Along the length of the horizontal trench the temperature, \( T_{\text{wall}} \), can be approximated using the equation (Carslaw & Jaeger, 1959)

\[ T_{\text{wall}}(s, t) = T_m - T_{\text{amp}} e^{-s(\pi/365\alpha)^{1/2}} \times \cos\left\{2\pi/365\left[t - t_0 - s/(365/\pi\alpha)^{1/2}\right]\right\} \]  
(11)

Equation (11) has been used to calculate the temperature at 1.5 mbgl for a period of 12 months using the corresponding average monthly air temperatures for 2007 shown in Fig. 12. The calculated pipe wall temperatures for the well shaft and at 1.5 mbgl are shown in Fig. 20.

Using these estimated pipe wall temperatures the predicted abstraction temperatures from HSTWin have been calculated using (9) and (10). The parameters used in this approximation are shown in Table 3. The corrected HSTWin temperatures can now be compared with the HSTWin model outputs and the measured values.

The comparisons are shown in Figs 21 and 22. There is now an improved correlation with the cold well abstraction temperature and the measured data from the plant room. There is also an improvement in the warm well abstraction predicted temperatures, although, admittedly, from January to April the improvement is marginal. To be more accurate the correction would require a more dynamic ground model to account for conductive heat abstraction from surrounding

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**Table 3. Parameters for source temperature correction**

<table>
<thead>
<tr>
<th>Cold well</th>
<th>Warm well</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of horizontal pipe = 65 m</td>
<td>Length of horizontal pipe = 55 m</td>
</tr>
<tr>
<td>( V = 8 \text{ m}^3/\text{hr} )</td>
<td>( V = 16 \text{ m}^3/\text{hr} )</td>
</tr>
<tr>
<td>( m = 2.22 \text{ kg/s} )</td>
<td>( m = 4.44 \text{ kg/s} )</td>
</tr>
<tr>
<td>( c_w = 4.2 \text{ kJ/(kg K)} )</td>
<td>( c_w = 0.59 \text{ W/(m K)} )</td>
</tr>
<tr>
<td>Groundwater pipe inner diameter = 0.15 m</td>
<td>Groundwater pipe inner diameter = 0.15 m</td>
</tr>
<tr>
<td>Depth to midpoint of well screen = 107.5 m</td>
<td>Depth to midpoint of well screen = 107.5 m</td>
</tr>
<tr>
<td>( Nu = 3.66 ) (laminar flow)</td>
<td>( Nu = 3.66 ) (laminar flow)</td>
</tr>
</tbody>
</table>
Significant limiting factors for model

The numerical solution presented is limited in its application to the simulation of saturated aquifers, either unconfined or confined. Difficulties are likely to arise in unsaturated aquifers owing to the inherent inconsistency in heat capacity throughout the store. Also, higher-temperature heat storage, possibly from waste heat from combined heat and power plants or solar thermal systems, may reduce the accuracy of the model and the recovery efficiency without careful consideration of the input parameters and the possibility of chemical precipitation at higher temperatures.

The type of analysis used in this instance is limited to intergranular aquifers where the flow is assumed to be Darcian. Also, the total porosity is assumed to be the same as the total porosity. A different approach is needed for fractured bedrock systems where the flow regime cannot be assumed to be homogeneous.

Site investigation

Site investigation techniques are available to assess the necessary ground parameters for modelling, including the hydraulic conductivity and groundwater chemistry. In circumstances where a significant hydraulic gradient is anticipated (i.e., from the completion of a desktop study), the equipotential surface can be deduced using piezometers at a minimum of three locations, as detailed, for example, by Freeze & Cherry (1979). In the case study the hydraulic gradient was considered to be negligible at the desktop study stage. The measured temperatures during 2007 did not contradict this assumption, although the incidence of a significant hydraulic gradient cannot be proved without carrying out more detailed studies of the transport of heat at the site. However, HSTWin does have the ability to use this information to assess the movement of thermal energy over distinct time periods linked to the heating and cooling strategy of a building.

There is also suitable literature to correlate near-homogeneous aquifer properties (Sheppard, 1989) from standard borehole logging techniques. However, in situ testing still offers the obvious potential to increase the accuracy of input data for the HSTWin model. In some countries, for example in the Netherlands and the UK, there is also an absolute requirement to carry out such testing before gaining an abstraction licence from the Environment Agency. For heterogeneous fractured bedrock systems the applicability of desk study data is severely limited due to the inherent randomness of fissured systems. In such circumstances testing data for each specific well will be paramount to calculate the abstraction and discharge parameters required for the HSTWin model.
therefore needed to understand the limits of operation, and
simulation remains a valid way to understand how variations
from the design case will affect the performance in the short
and long term.

ATES is a valid way to improve performance compared
with monodirectional systems. With cold groundwater stor-
age from the heating season, lower temperatures can be
realised that enable direct cooling. In the heating mode,
raised groundwater temperatures improve the performance
of the heat pump plant. There is also a benefit compared
with closed-loop systems, where underground thermal energy
storage is limited by the principal conductive process of
these systems.

Regulatory aspects are likely to lead to the stricter control
of closed- and open-loop systems in all countries where
there is a thermodynamic advantage of using such techni-
ques, that is, mainly temperate climates where there are
significant seasonal swings in temperature. In The Nether-
lands the environmental authorities currently specify that all
ATES systems must be thermally balanced. Building occu-
piers are required by law to inform the environmental
authorities each year of the respective volumetric and energy
abstraction and rejection. This methodology is justified to
ensure the long-term performance and prevent the short-
circuiting of individual systems, and also prevent possible
impacts on nearby installations utilising the same aquifer.
For the user the long-term performance can also be ensured,
assuming the building continues to operate within certain
limits. Following the Dutch example, it is likely that many
countries will specify numerical simulation as a requirement
prior to approval by the respective governing body.

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NOTATION

A cross-sectional area of pipe from base of well to plant
room
b aquifer thickness
c1 heat capacity, impermeable layer
c2 heat capacity, aquifer
c3 heat capacity, solid material
cw heat capacity, groundwater
D pipe diameter
d50 nominal particle diameter in μm for 50% of particles
smaller in particle size distribution curve
erfc complementary error function
H heat convection coefficient
m mass flow rate of groundwater
N porosity
Nu Nusselt number
K hydraulic conductivity
Q thermal energy
Q thermal energy rate
S depth below ground level
Sw drawdown
T time; temperature
Tamp annual amplitude of temperature fluctuation at ground
surface
Tinj initial injection temperature
Tm mean annual temperature at ground surface
Tm mean undisturbed groundwater temperature
Twall temperature at pipe wall
Tth time, thermal front in aquifer
Tw time, groundwater
Tg time phase lag
V volumetric flow
V specific volumetric flow rate
Vth velocity, thermal front in aquifer
Vw velocity, groundwater
α thermal diffusivity
β time constant
λ1 heat conduction, impermeable layer
λa thermal conductivity, aquifer
λw thermal conductivity of groundwater
ρ1 density, impermeable layer
ρa density, aquifer
ρs density, solid material
ρw density, groundwater

REFERENCES

logical section across The Netherlands. Verhandeling Konink-
ljik Nederlands Geologisch en Mijnbouwkundig Genootschap 29,
105–106.
Institute of Building Services Engineers.
earth-air heat exchangers. Energy and Buildings 35, No. 3,
389–397.
De Vries, J. J. (2007). Groundwater. In Geology of the Nether-
Amsterdam: Royal Netherlands Academy of Arts and Sciences.
Eggen, G. (1990). Lavgemperatur Varmingekilder. Program for anvendi-
delse av varmevarper. Temakurs for konsulenter. Oslo: Norges
Teknisk-Naturvitenskapelige Forskningsråd.
EPBD (2002). Directive on the energy performance of buildings,
PhD thesis, Department of Mathematical Physics, University of
Lund, Sweden.
Cliffs, NJ: Prentice Hall.
extraction from aquifers with uniform regional flow. J. Geophys.
Res. 80, No. 35, 4956–4962.
duct storage systems. PhD thesis, Department of Mathematical
age Div. ASCE 97, No. IR3, 515–522.
Kipp, K. L. (1986). HST3D: A computer code for simulation of
heat and solute transport in three-dimensional-ground-water
flow systems. US Geological Survey Water Resources Investiga-
Survey.
150.
China. In Guidebook to studies of land subsidence due to ground-
ODPM (2006). Building Regulations: Conservation of fuel and
of solar energy in sandy-gravel ground. Geliotekhnika 7, No. 5,
57–64.


