Optimization of well field configurations for Aquifer Thermal Energy Storage

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Abstract

For a given location and a given set of energy figures, such as injection temperatures and amount of energy to be stored, there are still many degrees of freedom to design an ATES (Aquifer Thermal Energy Storage). The most important degrees of freedom are: (1) aquifer choice; (2) section to screen; (3) distance between the warm and cold wells; (4) angle of the line connecting the wells with the direction of the regional flow; (5) positioning of multiple cold and warm wells with respect to each other. These design parameters can be used to optimize an ATES for the following goals: (1) to reduce costs; (2) to improve the thermal efficiency and exergy and (3) to reduce the environmental impact. This paper presents some practical guidelines and examples to optimize a well field configuration for ATES based on our experiences with Dutch ATES projects.

Introduction

Aquifer Thermal Energy Storage (ATES) has been applied for more than 15 years in The Netherlands. More than 100 ATES systems have presently been realized or are under construction (SNIJDERS; this conference). In many cases it was desirable or necessary to optimize the well field configuration: e.g. to increase the cost effectiveness, to improve the thermal efficiency and/or to reduce the environmental impact. From these projects much knowledge has been gained to optimize a well field configuration. Some design aspects of these ATES systems have already been discussed by JENNE et al. (1992), and WILLEMSEN and GROENEVELD (1989). This paper describes some practical guidelines to optimize a well field configuration for ATES systems based on experiences collected with Dutch ATES projects. The guidelines are given for four general cases in which the design of a well field is strongly related to limitations in (1) induced hydraulic changes, (2) induced changes of the water quality, (3) storage space and (4) induced thermal changes.

ATES systems in The Netherlands

ATES systems in The Netherlands mainly comprise cold storage, (low-temperature) heat storage and combined cold and (low-temperature) heat storage. Most systems have injection temperatures between 6 and 9 °C in the winter and 15 to 25 °C in the summer. Generally, ATES systems are single doublet systems (one cold and one warm well) with an average yield between 10 and 250 m^3/h per well, and the amount of pumped/reinjected water ranges between 10 000 to 500 000 m^3 per well per season (i.e. summer or winter). More recently, larger ATES systems have been designed and constructed. These systems comprise multiple well systems with yields of 300 to 3 000 m^3/h, and approx. 0.5 to 5 million m^3 water is pumped/reinjected per season. The discussion in this paper is limited to seasonal storage doublet systems, since 90% of the Dutch ATES systems comprise this type of ATES systems.

Good hydrogeological conditions have contributed to the rapid growth of the number of ATES systems in The Netherlands. In nearly the entire country unconsolidated sandy aquifers are available for ATES. The depth of the aquifers used for ATES systems ranges between 20 and 200 m and the thickness of the aquifers is generally between 10 and 100 m. The aquifers in the western part of The Netherlands are frequently semi-confined, whereas the upper aquifers in the centre and eastern parts of the country are phreatic. As a result of the absence of altitude differences the velocity of the groundwater flow is normally limited to 5 to 50 m per year. The temperature of groundwater in aquifers up to a depth of 150 m ranges between 10 and 13 °C. Since the injection temperatures for most ATES systems differ not more than 7 °C from the natural groundwater temperature, buoyancy forced flow is often negligible.

Optimization objectives and parameters

The overall objective of the optimization procedure is to design a well field configuration of an ATES which results in (1) minimum initial and running costs, (2) maximum thermal efficiency and exergy and (3) minimum environmental impact. There are many degrees of freedom (i.e. parameters) to optimize the well field configuration. The most important parameters are: (1) aquifer choice, (2) section to screen, (3) distance between cold and warm wells, (4) positions of wells with respect to the direction of regional flow and (5) positions of multiple cold and warm wells respect to each other. Table 1 shows how the optimization parameters may be related to costs, thermal efficiency and environmental impact. From Table 1 can be concluded that:

- Initial costs are mainly determined by the number (and diameter) of wells, the depth of the wells and the distances between the wells. Preventing clogging of wells and cracking of the soil near the wells require a minimum number of wells. Therefore, the number of wells is related to the required maximum flow rate, the total amount of reinjected water, the transmissivity of the aquifer and the permissible injection pressure (see e.g. OLTSHOORN, 1982; DRISCOLL, 1989). The distance between a cold and a warm well must be sufficient to avoid thermal break-through of the wells. Lowest costs are gained with a minimum number of (shallow) wells and a minimum distance between the wells. In general, the number of wells is the main factor determining the costs, so it will mostly be cheaper to have less wells in a deeper aquifer than to have many shallow wells. If the injection pressure determines the number of wells, it is generally cheaper to intersperse cold and warm wells than to cluster cold and warm wells.
- Highest thermal efficiency is gained in aquifers with the lowest regional groundwater flow velocities, sufficient spacing between warm and cold wells in order to prevent thermal break-through, large thermal volume and an optimal ratio between thermal radius and the thickness of the storage (see DOUGHTY et al., 1982). From a thermal point of view, it is better to concentrate all the cold wells in a cluster and the warm wells in a different cluster instead of interspersing cold and warm wells.
- Lowest environmental impact will generally be caused by a storage in deep aquifers and short distances between cold and warm wells. Alternating positions of warm and cold wells will result in the lowest hydraulic and thermal impact.
- Optimizing one objective may deteriorate one of the other objectives. It is recommended that the optimization procedure is started with a well field configuration with the lowest costs and the highest thermal efficiency. If the environmental impact is not acceptable, alternative configurations must be considered. These configurations will probably have higher costs and a lower thermal efficiency.

Table 1: Relationships between costs, thermal efficiency, environmental impact and optimization parameters.

	Choice of aquifer **(shallow vs. deep)**	**Section to screen (within an aquifer)** **(shallow vs. deep or short vs. long)**	**Distance between cold and warm wells** **(short vs. long)**	**Position of wells with respect to direction of regional flow**	**Positioning of multiple cold and warm wells (clustered vs. interspersed)**
Costs	depends mainly on required number of wells for each aquifer; shallow wells are cheaper, but have a smaller permissible injection pressure	shallow: cheaper, but with smaller permissible injection pressure long: higher flow per well possible	short: cheaper and injection pressure decreases	-	If no. of wells is determined by flow injection velocity, clustering of wells is cheaper than interspersing of cold and warm wells due to less length of connecting pipes between wells. If no. of wells is determined by injection presssure: interspersed cold and warm wells are cheaper.
Thermal efficiency and exergy	depends on regional flow velocity; a larger flow velocity results in lower thermal efficiency and exergy	longer screens lead to a smaller radius of stored water around the wells, which in turn results in a smaller minimally required distance between a cold and warm well in order to prevent thermal break-through; there may be more thermal losses due to regional flow	short: possibly more thermal interaction between cold and warm wells	In case heat or cold is the most important energy stored: place the most important wells upstream. In case both are equally important: an angle of 90° between the position of wells with respect to direction of regional flow. This results in less risk of thermal break-through of the wells.	clustered: higher thermal efficiency
Environ-mental impact	shallow: larger impact near ground level (thermal, hydraulic and soil consolidation)	shallow: larger environmental impact; short: larger horizontal thermal impact and higher hydraulic impact	short: smaller hydraulic impact	Parameter to minimize interaction with pollution or other ATES system. Water balance on an annual basis is important.	clustered: higher environmental impact (thermal and hydraulic)

General cases

Possibilities of optimizing ATES well field configurations are shown for different cases. In each case the well field design has to be optimized with respect to one of the following limitations: (1) induced pressure changes (= hydraulic limitations), (2) induced changes in water quality, (3) storage space and (4) induced thermal changes. Each case shows how optimization parameters can be used to optimize a well field design.

1. Hydraulically limited systems

Hydraulic limitations may occur due to different causes, e.g: cracking (as a result of an excessive injection pressure), a large drawdown, consolidation and land subsidence, crop growth reduction due to draught and/or wetness and reduced stability in civil works (tunnels, cellars, etc.).

In all cases it is desirable to reduce the hydraulic impact of the ATES system. There are several possibilities to reduce the hydraulic impact of the system, e.g. by: (1) longer well screens; (2) a larger number of wells; (3) a larger well diameter; (4) a smaller distance between cold and warm wells; and for multiple well fields: (5) a larger intermediate distance between the cold (or warm) wells and (6) interspersing cold and warm wells. The effectiveness of the proposed changes can be illustrated with the simple equation to calculate the pressure changes for a single and a double doublet:

$$\Delta h(x,y) = \frac{Q}{2\pi T}\ln\frac{r_{i1}\cdot r_{i2}}{r_{p1}\cdot r_{p2}} \tag{1}$$

Where: Δh = Pressure change [m]
Q = Amount of pumped/reinjected water [m^3/d]
T = Transmissivity of the aquifer [m^2/d]
r_{i1}, r_{i2} = Distance from observed point (x,y) to infiltration wells i1 and i2 [m]
r_{p1},r_{p2} = Distance from observed point (x,y) to production wells p1 and p2 [m]

For a single doublet the values of r_{i2} and r_{p2} can be omitted. From this equation can be deduced that T and Q are linearly related to the pressure change in the aquifer. The well configuration is, however, not linear. To illustrate the effect of the well configuration an example is presented. In this example the maximum pressure changes for an ATES system are calculated with 2 and 4 wells (with T = 1 000 m^2/d and well radius = 0.5 m). The results are presented in Table 2.

Table 2: Maximum pressure changes for different well configurations

			20 m	100 m	100 m
			◄──►	◄──►	◄──►
100 m ↕	• I1 • P1	• I1 • P1	I1• • I2 P1• • P2	I1• • I2 P1• • P2	I1• • P2 P1• • I2
Q per well (m^3/h)	100	200	100	100	100
Q total prod. (m^3/h)	100	200	200	200	200
Max Δh (m)	**2.03**	**4.06**	**2.65**	**2.16**	**1.89**

The results show that due to alternating positions of the injection and the production wells in a multiple well configuration smaller pressure changes are induced than with the original single doublet. This example illustrates that multiple doublet systems can offer very good possibilities to reduce the pressure changes and that an extension of an existing system does not necessarily lead to an increased impact.

2. Water quality limited systems

Water quality limited systems may be divided into three categories:

1. High dissolved gas content in groundwater

   If groundwater contains high concentrations of dissolved gas, there is a risk of degassing which can rapidly lead to clogging of the infiltration well. Maintaining sufficient overpressure may prevent this type of well clogging. This is only possible if the gas pressure is not close to the hydrostatic pressure in the aquifer. In case the gas pressure is close to the hydrostatic pressure in the aquifer, a different aquifer should preferably be chosen.

2. Vertical water quality interface (e.g. salt/fresh, iron/oxygen)

   In these cases, it is important to avoid vertical displacement of groundwater near the water quality interface. This may be realized by:

   - Screening of the ATES in an aquifer or part of an aquifer so that there is a high hydraulic resistance between the interface and the well screens;

- Balancing the amounts of water that are pumped/reinjected in summer and winter;
- Reducing the hydraulic impact of the ATES (see previous case).

3. Horizontal water quality interface (e.g. polluted groundwater)

   Extra displacement of polluted groundwater is mostly not allowed in The Netherlands. The extra costs that are involved with the cleaning of the site must be paid by the one who caused the extra costs. Because of the fact that natural attenuation is becoming the most popular technology to deal with polluted plumes in groundwater, a small extra displacement is often acceptable. Horizontal displacement can be minimized by the above mentioned parameters and in addition by the positioning of the wells with respect to the flow directions. It should be noted that an ATES system may also have positive contributions to the natural attenuation of contaminants. Positioning of the warm wells near the polluted plume may increase the rate of decomposition of contaminants.

3. Storage space limited systems

Storage space limited systems may be caused by the presence of a thin aquifer and a limited property area without the possibility to place the wells outside the property area. This may cause thermal break-through between cold and warm wells. For thermal balanced systems, a minimum distance between a warm and a cold well of 3 times the thermal radius of the stored cold or heat is sufficient to prevent thermal break-through between wells. The thermal radius r_{th} can be calculated from:

$$r_{th} = \sqrt{\frac{c_w Q}{c_a H \pi}} \qquad (2)$$

Where: r_{th} = Thermal radius of the stored cold or heat [m]

c_w, c_a = Heat capacity of water and aquifer material [J/(m^{3}K)]

Q = Amount of pumped/reinjected water per season [m^3]

H = Length of the screens [m]

If the actual distance between the cold and warm well is less than $3r_{th}$, a thermal calculation should be carried out in order to determine the interflow component. Storage space limited systems may be optimized as follows:

1. Reduction of the hydraulic radius of the stored energy.

   From Formula 2 it can be deduced that the thermal radius can be reduced by decreasing the amount of stored cold and warm water or by increasing the length of the screens. The amount of pumped/reinjected water reduces for a certain amount of energy when the temperature of the infiltrated water is decreased in the winter and increased in the summer. Alternatively, clustering of the cold and warm wells will lead to a smaller r_{th} than alternating positions of cold and warm wells , since r_{th} is as a square-root related to Q.

2. Allowing thermal short-circuiting

   In case there is not enough space for an optimal distance between the wells, thermal short circuiting between the warm and cold wells will occur. This will decrease the energetic and exergetic efficiency of the system, but it might still be acceptable. When short circuiting happens, it may be necessary to store more heat (and cold) than required for a certain amount of heat production (and cold production) than in case of a proper distance between the wells. If a significant regional groundwater flow exists, this flow may be used to reduce short-circuiting of the upstream well and will in turn increase short-circuiting of the downstream well (see below).

4. Temperature limited systems

Examples of temperature limited systems are: (1) system with presence of high regional flows (discussed below) and (2) system in the vicinity of an existing ATES system or a pumping station for drinking water (not discussed).

High regional flow may result in significant losses of the stored energy. The positions of the wells with respect to the flow direction will be important for the performance of the ATES. The thermal efficiency of the ATES may be improved by:

1. Positioning the favourable type of wells (cold or warm) upstream from the less favourable type of wells. This reduces the risk that the favourable type of energy is affected by energy losses of the other (type of) wells.
2. Positioning the cold and warm wells in the direction of the regional flow for single cold and heat storage. As mentioned above, the favourable energy is stored upstream and the other type of energy is stored downstream. Consequently, upstream energy losses will be recovered at the downstream well. This improves the thermal efficiency of the single cold or heat ATES system. For a combined cold and heat storage system, it is better to position the wells perpendicular to the direction of flow in order to minimize the risk of thermal break-through of the wells.

Conclusions

Optimizing the well field configuration may result in lower costs, higher thermal efficiency and/or lower environmental impact. Optimizing one objective may, however, deteriorate one of the other objectives.

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