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Improving Aquifer Thermal Energy Storage Efficiency

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ABSTRACT

Aquifer thermal energy storage systems play an important role for the future energy supply systems. Such systems can decouple energy availability (e.g. fluctuating renewable energy, waste heat) and energy supply in times of demand. In order to fully contribute to the sustainability of energy supply, the essential requirements of energy storages are high energy efficiency, high reliability, cost effectiveness, as well as operational flexibility. Aquifer Thermal Energy Storage Systems (ATES) meet all these requirements and additionally offer a large potential. Various ATES projects have been realized, for example in the Netherlands or Sweden. Based on the comprehensive knowledge from R&D activities as well as operational experience it is known which factors generally affect storage efficiency and reliability: the hydrogeological conditions, the temperature level at which the storage is operated, and the amount of energy charged and discharged. In this paper the sensitivity of these factors on the storage efficiency is investigated by means of numerical simulations. Despite the experiences made, there are still significant potentials for improving their energy efficiency. It is shown how a significant increase in supply system efficiency and thus a wider application of ATES can be achieved at different site conditions by an optimized storage design.

1. INTRODUCTION

Aquifer Thermal Energy Storage (ATES) systems are a proven technology for reducing fuel consumption for heating and cooling purposes. Thermal energy storages are available at different temperature levels and a general classification is done accordingly. Low or moderate temperature ATES systems (LT-ATES) operate between 10-40°C whereas high temperature ATES (HT-ATES) operate at temperatures above 50°C (Lee, 2013). Many LT-ATES for heating and cooling were successfully realized in North America, China and Europe. In the Netherlands, more than one thousands of such systems are in operation. In contrast to that high number of systems only few HT-ATES were realized (Kabus, Hoffmann, & Möllmann, 2005). Reasons for the small number of HT-ATES are numerous. Due to the larger temperature changes chemical/geochemical/ microbiological reactions might be induced so that problems such as precipitation, well clogging and corrosion (Lerm et al., 2013) as well as closed systems (Drijver, 2011) can occur. Other reasons are (i) higher costs for the wells, since more advantageous conditions are found for higher natural aquifer temperatures in deeper aquifers, and (ii) lower energy efficiencies. The factors influencing the energy efficiency of HT-ATES are still subject of research and development (Schout, Drijver, Gutierrez-Neri, & Schotting, 2013) which are apart from geological parameters like aquifer thickness, thermal and hydraulic aquifer properties, also operating parameters such as well injections temperatures, circulated volume, the amount of surplus heat, and thermal energy demand of connected heating systems. One important issue is the optimal integration of the ATES in energy supply systems. The ATES system has to deal with the temperature level in the heating network (supply and return temperature). And, the larger the difference between natural aquifer temperature and the temperature of the heating network, the lower the possible energy efficiency is. The aim of optimal HT-ATES integration is to bring both temperature levels as close as possible together.

Typical heat sources are combined heat and power plants (CHP) or solar heating systems. The temperature of the surplus heat reaches 90°C or even higher. Connected building or district heating networks are operating on temperature levels between 30 and 90°C. The ATES system and the heating network have to be adjusted to each other for optimizing the energy efficiency.

Considering a common two well ATES system, one possibility is the choice of optimal well distance between cold and warm well depending on the storage operation conditions. The present article focuses on the improvement of the heat recovery factor (HRF) of HT-ATES systems at which the injection temperatures at both wells are higher than the natural, undisturbed aquifer temperatures.

The used Heat Recovery Factor is defined as follows:

$$HFR = \frac{heat\ output}{heat\ input} = \frac{\int_0^{t_{discharge}} cp_w\ \dot{m}_{discharge}(t)\ (T_{out,w}(t) - T_{in,c}\ (t))}{\int_0^{t_{charge}} cp_w\ \dot{m}_{charge}(t)\ (T_{in,w}(t) - T_{out,c}\ (t))}$$

cp_w Specific heat capacity of water [J/kg/K]

$\dot{m}$ Mass flow rate while charging and discharging [kg/s]

$T_{out,w}$ Production temperature at warm well [°C]

$T_{in,w}$ Injection temperature at warm well [°C]

$T_{out,c}$ Production temperature at cold well [°C]

$T_{in,c}$ Injections temperature at cold well [°C]

t Time [h]

A model based parameter study was performed in order to analyse the influence of the well distance on the ATES performance with consideration of relevant operating parameters such as mass flow rate and injection temperatures. The study is done exemplarily for an existing ATES in Germany.

2. METHODS

The ATES parameter study was done with a finite element model for subsurface flow and heat transport by using the Comsol Multiphysics modeling environment with the subsurface flow module. The model considers Darcy Flow for calculating the pressure and velocity field and heat transfer in porous media by conduction, convection and dispersion for calculating the temperature distribution.

2.1 Model description

The ATES Model consists of 3 layers and 2 wells (doublet). One layer represents the storage aquifer and one layer above and below the aquifer respectively. The adjacent layers are considered as low permeable layers. The models dimension is 600x600x300m. Bottom model is 400m below ground level and top model is 100 m below ground level. The hydraulic and thermal properties of the layers are summarized in the following table. The wells are implemented as cylinders with a diameter of 1m and a height similar to the ATES aquifer thickness which represents a well, screened in the whole aquifer layer. The hydraulic conductivity in the well cylinder is chosen much higher than in the aquifer.

Table 1: model design, hydrogeological and thermal properties

	Thermal conductivity [W/m/K] (bulk)	Specific heat capacity [J/m³/K] (bulk)	long. dispersivity/ trans. [m] dispersivity [m]	Porosity [%]	Hydraulic conductivity [m/s]	Temperature boundary conditions	Thickness [m] / length [m]
Layer 1	3	2500	1/0.5	0.3	0,001	Geothermal gradient 0.3 K/m	270 / 262
Layer 2 (Aquifer)	3	2500	1/0.5	0.3	0,31	~ 17°C (undisturbed)	17 / 25
Layer 3	3	2500	1/0.5	0.3	0,001	Geothermal gradient 0.3 K/m	113
Wells	0.6	4180	-	1	1000		17 / 25

2.2 Simulation Study

The ATES model was used for simulation studies in order to investigate the influence of well distance on the ATES energy performance. The operation mode of the ATES is seasonal and each simulation represents an operation time of 5 years amounting to 5 charging periods and 5 discharging periods in total. Each charging/discharging period lasts 5 months with a break of 1 month in between. During charging/discharging a constant flow rate is assumed. The volume circulated while charging and discharging in one storage period is balanced and the injection temperatures at both wells were kept constant during charging and discharging. The well distance was varied between 25 and 150 m. The influence of the well distance was analysed for different operating conditions. The operating conditions considered are as follows:

Table 2: Considered cases in the simulation study

	Injection temperature at warm well $T_{in,w}$ [°C]	Injection temperature at cold well $T_{in,c}$ [°C]	Mass flow rate [kg/s]	Aquifer thickness [m]
Base case	70	30	8	17
Case _T90	90	30	8	17
Case_T40	70	40	8	17
Case_T20	70	20	8	17
Case_m4	70	30	4	17

The definition of the cases investigated are based on the operating conditions of the HT-ATES incorporated in the energy supply system of the German Parliament Buildings in Berlin (Kranz & Bartels, 2009) and based on possible conditions considering similar applications with direct use of the stored heat without interconnected heat pumps.

3. RESULTS AND DISCUSSION

In the following, the results of the simulation study are presented. The HRF is presented as average value over 5 years of operation and for the 5th year of operation. The HRF in the 5th year of operation can approximately be considered as the average HRF for a 10 year operation. In addition, the temperature profile at the warm and the cold well for 5 years of operation are presented in order to illustrate how the temperature at each well are affected by different well distances.

3.1. Temperatures at the Wells

While charging and discharging the temperatures at each well are influenced by the respective injection temperature, the heat conduction and convection within the aquifer and conduction to the adjacent layers. The closer the wells are situated together, the more the temperature field at one well is influenced by the temperature field of the other well. The following two figures illustrate the temperature evolution at both wells for large well distance with negligible thermal interference and for closer situated wells where thermal interference is significant.

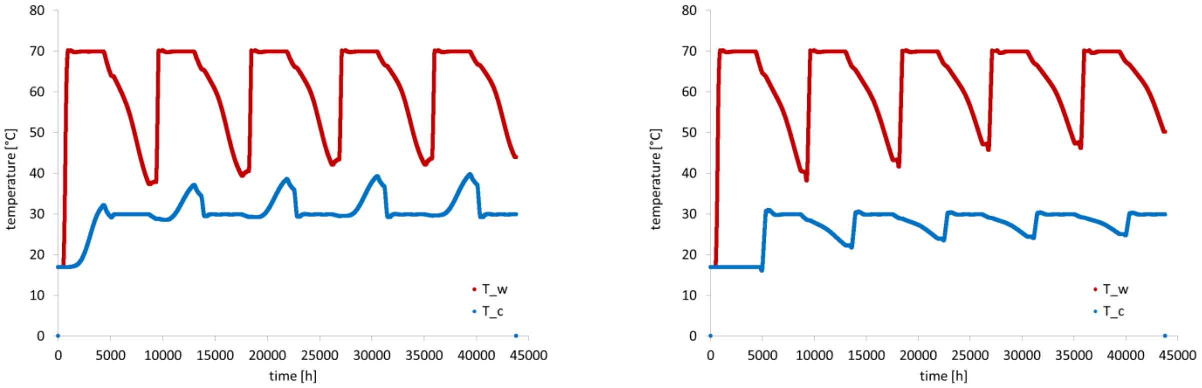

Figure 1: temperature at the warm and cold well for well distance 50m (left) and 300m (right), T_in_w=70°C, T_in_c=30°C, mass flow=8 kg/s

Thermal interference can be seen at the curve of the temperature at the cold well T_c. The cold well temperature for 300m well distance reaches maximum values in the range of the injection temperature at this well. Whereas the temperature for the 50m well distance arrangement is highly influenced by the warm well and reaches values up to 40°C.

3.2 Effect of Well Distance on Heat Recovery Factor

Figure 2 and Figure 3 show the results of the well distance analysis for the different operating conditions. In each graph the HRF curve is given for the 5th storage period and as average over the whole 5 years of operation. Figure 2 (left) represents the base case. For both curves the HRF increases with a decreasing well distance and reaches a maximum at approximately 60 m. If the well distance is reduced further the HRF decreases again. The HRF can be enhanced by ca. 2 percentage points. The right graph of Figure 2 shows the HRF trend for case_T40 with an injection temperature at the cold well of 40°C. In general the energy efficiency of this operation mode is lower in comparison to the base case but the HRF increase at optimized well distance reaches 6-7 percentage points compared to the case with a large well distance. The optimal well distance is at 45 m.

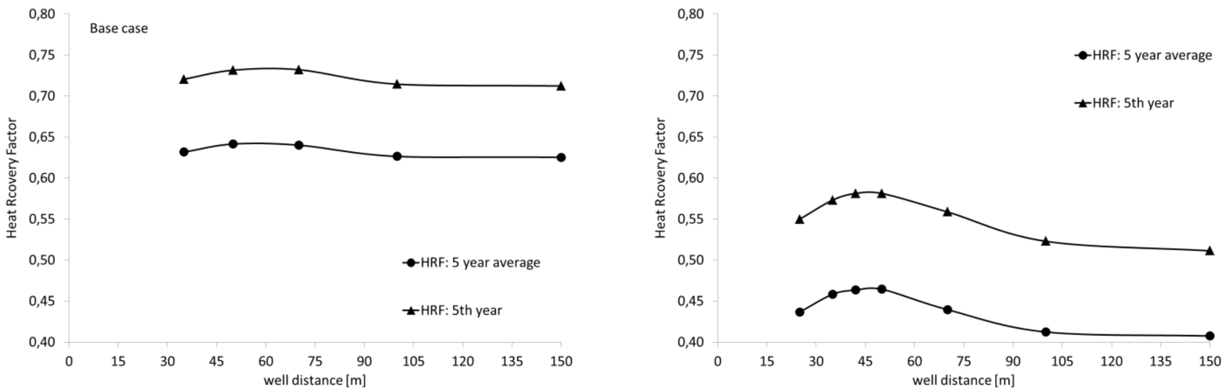

Figure 2: Effect of well distance on the HRF for the base case (left) and for case_T40 (right)

Considering a higher injection temperature at the warm well (90°C) leads to the curves shown left in Figure 3. Here also with decreasing well distance the HRF shows a distinctive maximum at approx. 50 m with a difference of ca 4.5 percentage points compared to the far distance well configuration. In case of a lower amount of thermal energy, considered through a lower mass flow rate of 4kg/s, the HRF can also be improved by 4-5 percentage points with choosing the optimal well distance. In this case the optimal well distance is at 40 m.

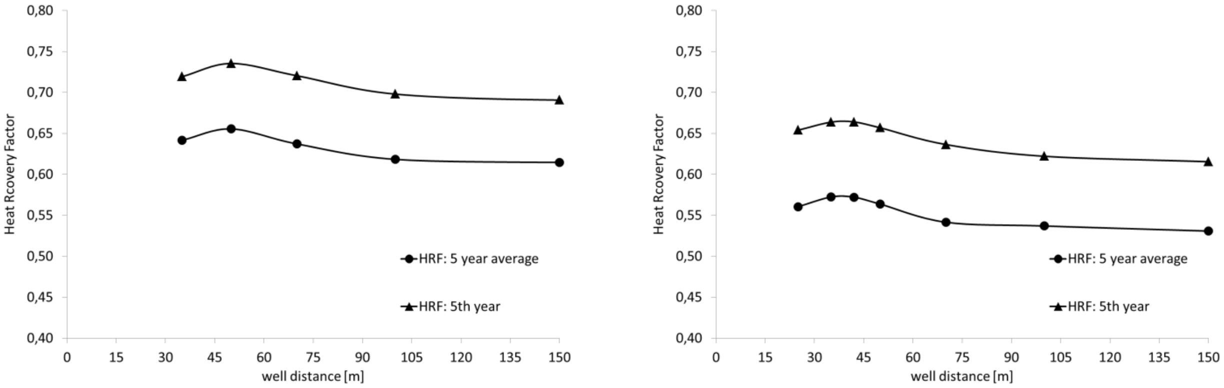

Figure 3: Effect of well distance on the HRF for case_T90 (left) and for case_m4 (right)

Reasons for the increasing HRF with lower well distances compared to large distances that avoid thermal interference is the increased temperature in between both wells, which reduces heat losses to the surrounding aquifer in this area. If both wells are too close together the groundwater with lower temperature from the cold well reaches the warm well and cools the hot plume.

Considering real applications with time depending surplus heat and heat demand the flow rate is not constant since it is determined by the amount of heat that can be transferred. For example, a constant flow rate for charging and discharging neglects the fact that changing temperatures at both wells also cause changes in charged and discharged amount of thermal energy comparing one storage period to another period. Furthermore the constant mass flow rate does not consider the case that after discharging heat, a useful temperature level might still be in the aquifer. In practice, if there is demand of heat, the ATES can be discharged as long as the temperature level allows heat transfer to the heating network.

5. CONCLUSION AND OUTLOOK

A model based parameter study was performed in order to analyse the effect of the well distance on the Heat Recovery Factor of High temperature ATES systems. The results show an optimal well distance for each operating condition analysed. Depending on these conditions the HRF can be increased in the range of 2 – 7 percentage points in comparison to well configuration that avoid thermal interference. The larger the temperature difference between natural aquifer temperature and the injection temperature at both wells, the more important is the choice of the optimal well distance.

In contrast to older studies, it might be advantageous to have thermal and hydraulic interference between both wells. However, each ATES system can be considered as unique and a comprehensive numerical study is necessary, not only for studying the hydrogeological influence and energy efficiency estimation, but also for improving the energy efficiency.

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