High temperature aquifer thermal energy storage performance in Middenmeer, the Netherlands: thermal monitoring and model calibration

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ABSTRACT

In 2021, the first full scale high-temperature aquifer thermal energy storage (HT-ATES) system became operational in Middenmeer, the Netherlands. The system is operated by ECW Energy and realized within the framework of the GEOTHERMICA HEATSTORE project. A dedicated monitoring program, including distributed heating sensors (distributed temperature sensing, DTS) at the hot well, cold well and monitoring well was deployed to keep track of the field performance.

In this study, a first attempt at monitoring data evaluation and model calibration is done based on data from the first loading phase (heat injection), the resting phase, and the unloading (heat production) phase at the HT-ATES site in Middenmeer. Although a technical flaw in the cable resulted in frequent noise signals, an improved output could be generated using a filtering technique. The DTS measurements in the monitoring well in Middenmeer were able to capture the relevant processes such as the passing of the thermal front during injection and production, the upward flow of hot water due to buoyancy and permeability variations, and the heating of over- and underlying clay layers. A baseline model and three uncertainty scenarios have been analysed, and the first results show a good fit between the monitoring data and the thermal model scenario with a coarsening upward sequence in the aquifer. The DTS data and reservoir parameters will be investigated in more detail in a follow-up history matching project. History matching might be a crucial step in the initial operational phase in order to improve future performance prediction and adapt, where necessary, the operational control.

1. INTRODUCTION

In order to limit the impact of climate change, the use of fossil fuels in our heat supply systems needs to be replaced by sustainable heat sources, such as geothermal, solar and residual waste heat. Yet, a seasonal mismatch exists between the supply of heat from these sources and the demand by the built environment and energy-intensive industry such as the horticultural sector. Large scale seasonal heat storage in the subsurface provides a suitable solution: excess heat can be stored (summer) and recovered in times demand is higher (winter).

Although low-temperature subsurface heat (and cold) storage is a proven technology, with more than 2500 systems in the Netherlands, only a limited number of pilots and field tests on high-temperature aquifer thermal energy storage (HT-ATES) have been successfully developed (Kallesøe et al., 2019). Within the GEOTHERMICA HEATSTORE project[1], ECW Energy, in collaboration with IF Technology and TNO, has designed and realized the first large scale HT-ATES pilot in the Netherlands. For research purposes, an extensive monitoring programme was deployed, which provides an exceptional opportunity to evaluate and improve monitoring techniques, and to investigate the impact of cyclic heat storage activities on the subsurface, as well as the technical performance of a full-scale HT-ATES system. Improving cost-effective monitoring and providing insights in thermal, geochemical, microbial and geomechanical impact will facilitate the accelerated implementation of HT-ATES as an essential component in our future sustainable heat systems.

In this study we focus on the thermal developments in the subsurface during the first operational year of the HT-ATES system in Middenmeer. This system is

[1] www.heatstore.eu

described in Oerlemans et al. (2022, this issue). Flow measurements and temperature monitoring data are evaluated and used for the calibration of a subsurface thermal transport model. Improved predictions of thermal processes for future storage cycles and their impact on system efficiency are based on the calibrated model.

2. HT-ATES IN MIDDENMEER

Agriport A7 is a large horticultural area in the Wieringermeer polder in the north-western part of the Netherlands. Three geothermal systems in the area cover part of the heat demand by the greenhouses. In the summer, the geothermal heat production is minimized due to the low heat demand. The HT-ATES system was designed and realized within the HEATSTORE project to store available heat from the geothermal sources during summer and make this heat available to the greenhouses in winter, thereby increasing the annual geothermal yields. The test drilling of 2019 provided the geological information for a robust system design. The system has well screens in an unconsolidated sand layer from the Maassluis Formation at a depth of 360-383 m, and can store ~440,000 m^3 of hot water per year (~27 GWh), with an intended flow rate of 150 m^3/h and storage temperature of ~85°C (Driesner et al., 2021). The test drilling was completed as a monitoring well. The hot (85 °C) and ‘cold’(30 °C, the return temperature will be higher than the in situ temperature) wells of the system, were drilled and completed in 2020. Figure 1 shows the layout of the wells.

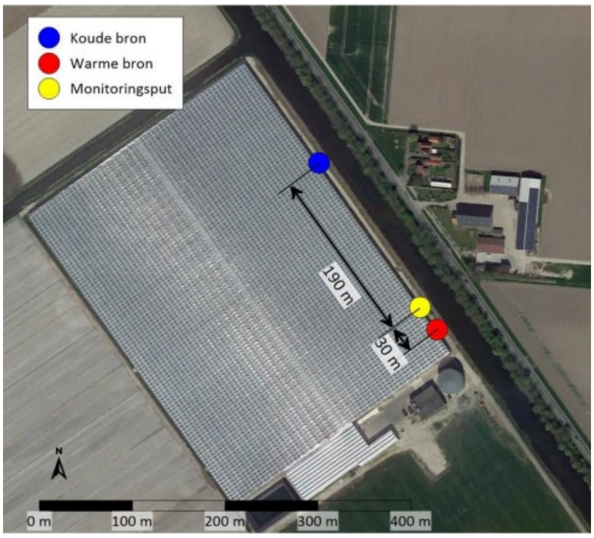

Figure 1 - Layout of the hot well (red), ‘cold’ well (blue) and monitoring well (yellow) of the HT-ATES system.

3. METHODOLOGY

3.1 Monitoring

Several metering and monitoring technologies have been implemented in the HT-ATES system in Middenmeer. There are, among others, single sensors that measure flow and temperature of injected and produced thermal water. A state-of-the-art fibre-optic Distributed Temperature Sensing (DTS) system was also installed outside of the well casing of the hot, cold and monitoring wells. The schematic of the DTS fibre-optic cable is shown in Figure 2.

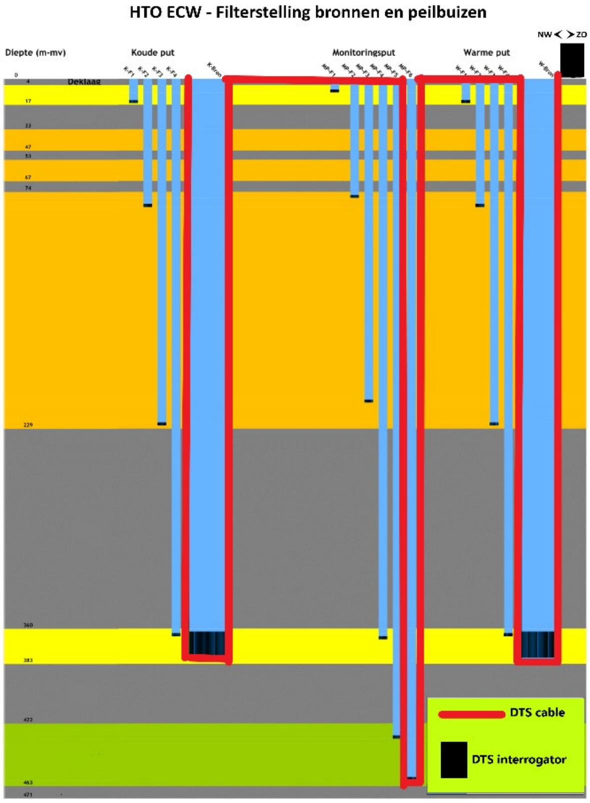

Figure 2 - Schematic of DTS cable along the three wells. Modified from Driesner et al. (2021).

The DTS cable is a single cable spanning all three wells and is connected to a DTS interrogator. The total cable length is approximately 2900 m long with a temperature measuring point every ~2 meters. The depth of the DTS cable in the monitoring well is ~450 m. The temperature along the full length of the DTS cable (1450 points) is measured once every ~10 minutes, resulting in approximately 144 measurements per day.

3.2 Thermal simulations

To analyse the thermal development of the injected and produced heat by the HT-ATES system, thermal flow simulations were performed with ROSIM v0.2[2].

ROSIM v0.2 is a public Microsoft Windows application developed by TNO, containing a workflow for 3D simulation of geothermal production and high-temperature aquifer thermal energy storage. With ROSIM, a static 3D subsurface simulation grid (including grid definition, layer properties and well data) and flow input deck (flow constraints) can easily be created.

[2] Beta version available via rosim@tno.nl

The dynamic flow simulation is done with DoubletCalc3D, an in-house model developed by TNO, which is a 3-dimensional extension of existing tools for 1D and 2D simulation[3]. It is a dedicated single phase simulator which enables the numerical simulation of temperature and pressure development using temperature dependent density and viscosity. It is based on a staggered coupling of a steady state solution for the pressure and flow field, coupled to a transient solution of the thermal field. The flow and thermal field are solved with a finite volume finite difference formulation (cf. Pluymaekers et al., 2016; Lipsey et al., 2016). For the flow and thermal solution the model has been benchmarked with Eclipse for 2D flow problems (Pluymaekers et al., 2016), for density driven flow the model has been benchmarked for reproducing correctly Rayleigh instability (Lipsey et al., 2016).

The geological model input for ROSIM/DC3D is based on the well data from the hot, 'cold' and monitoring well of the HT-ATES in Middenmeer. A layer cake baseline model with homogeneous layers has been created based using estimated rock properties (Table 1). The hot and cold wells are 220 m apart. The monitoring well is located in between, at 30 m distance from the hot well (Figure 1).

Table 1 Geological input parameters baseline model. Based on: Driesner et al. (2021); Diaz-Maurin & Saaltink eds. (2021).

Layer name	Base depth	Thickness	Perm x y	Perm z	Temperature	Salinity	Porosity	Rock matrix conductivity
	mbgl	m	mD	mD	°C	ppm	-	W/mK
aquitard	360	12	13	1	16.0	17478	0.45	4.43
aquifer	383	23	16847	5611	16.3	18569	0.37	5.35
aquitard	395	12	13	1	16.6	20894	0.43	4.11

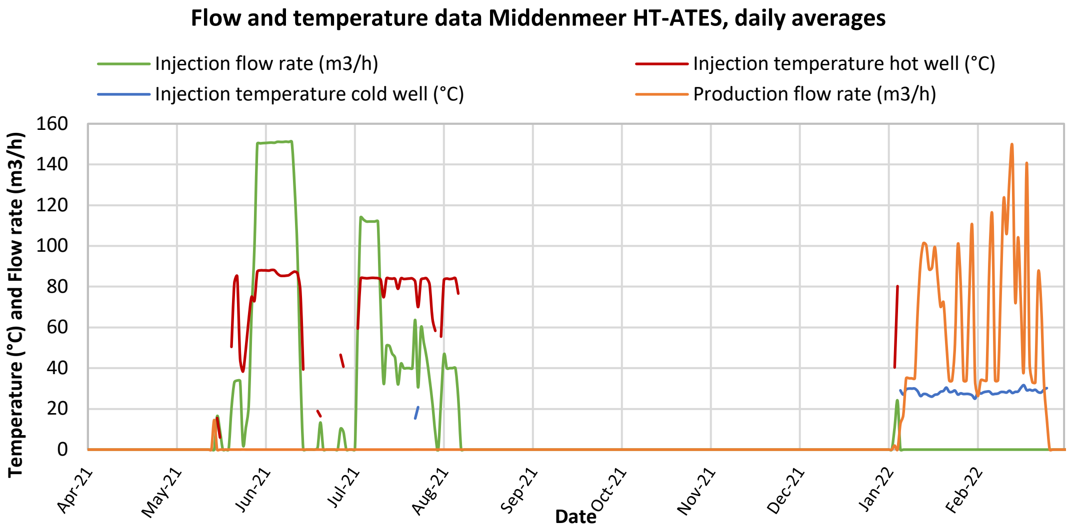

Figure 3 - Daily averages of flow and temperature injection data of the hot and cold well at the Middenmeer HT-ATES site.

The pumping scheme is derived from the temperature data gathered at the hot side of the heat exchanger (TSA) and the flow rate in the hot well (Figure 3). The measurement frequency of the monitoring data is ~10 minutes, but the graph shows the daily averages. Also the pumping activity during the test phase at the beginning of the loading cycle (mid to end May) is included in the simulation. The maximum injection temperature is 88 °C, and the maximum flow rate is 151 m^3/h.

3.3 Thermal model calibration

The temperature output of the model at the location of the monitoring well has been compared with the DTS data from the monitoring well. The data from the hot and cold wells are not used, as the DTS measurements are influenced by the water flowing through the well pipes. To 'fit' the thermal model to the DTS data from the monitoring well, several subsurface parameters from the baseline model were adapted.

4. RESULTS

4.1 Distributed temperature sensing

The DTS system delivers high-quality and reliable time-lapse measurements. However, there are occasional temperature spikes on the DTS profile. These are non-physical events caused by electronic

[3] www.nlog.nl/tools

noise that need to be suppressed by noise-reduction techniques.

A Savitzky-Golay polynomial filter was used to run over the DTS data in the time direction to suppress the time-variant spikes. Figure 4 shows that the sharp time-variant spikes are successfully suppressed, however, a low-frequency trend of elevated temperature in the central part of the time series remains. This could be an actual warming up of the monitoring well due to the summer season, but it may as well be a remaining bias due to the DTS system electronics. Therefore, we suggest to treat these temperatures with an uncertainty of ± 5 °C.

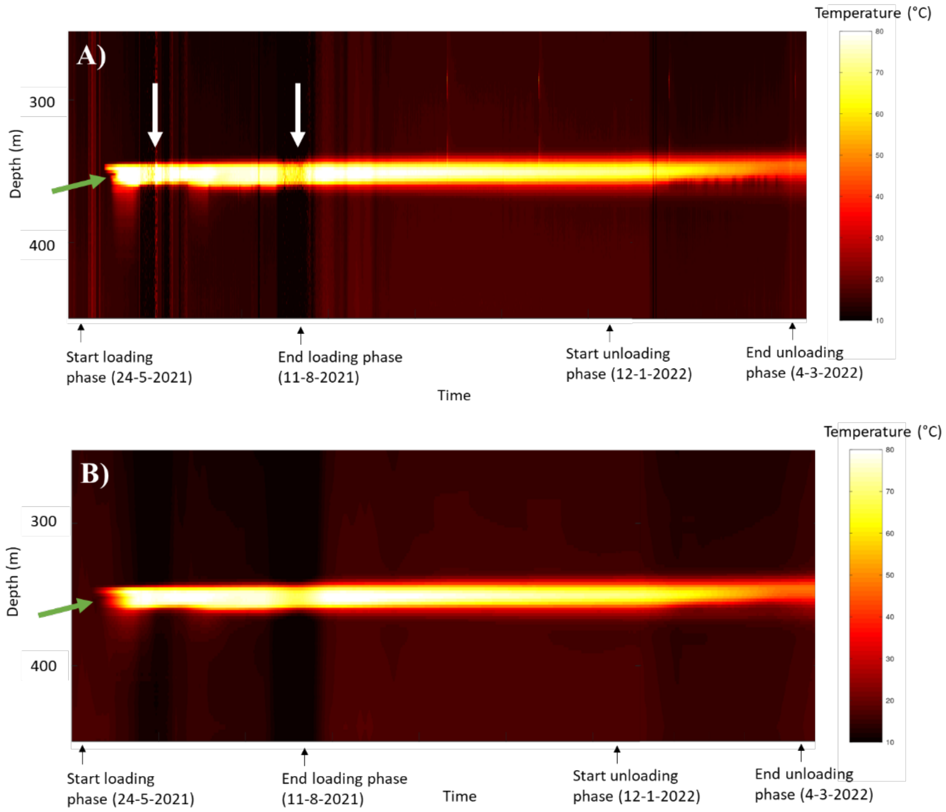

Figure 4 - Timeseries of DTS cable measurements in monitoring well. Y-axis represents the depth interval of 250 – 450 m, X-axis spans the time series from the 19th of May 2021 to the 14th of March 2022. The colour bar ranges from 10°C (black) to 80°C (light yellow). A) The unfiltered time series, with white arrows indicating large temperature spikes, as seen in Figure 6, B) the Savitzky-Golay filtered time series.

Description of monitoring data

The thermal front can be seen to arrive at the monitoring well about 10 days after the start of the first loading phase (24-5-2021). It clearly moves faster in the upper part of the aquifer than in the lower part (Figure 4). In the middle of the aquifer, a thin vertical interval is observed for which the thermal front lags behind (green arrows in Figure 4 and Figure 5). At the end of the loading phase, the temperature has shifted from close to 80°C to ~73°C (Figure 5).

During the resting phase (11-8-2021 till 12-1-2022) significant drop in temperature can be observed, primarily in the bottom part of the aquifer. During unloading/production (12-1-2022 till 4-3-2022) the thermal front retreats gradually with maximum temperatures of ~47°C at the end of production. The 'wiggle' that was seen during loading where the thermal front lagged behind, cannot be observed during production (Figure 5).

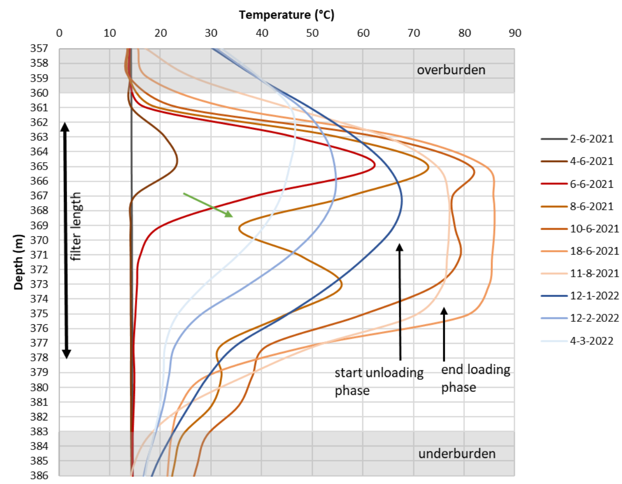

Figure 5 - DTS data (filtered) showing temperature profiles at the monitoring well at different dates. The unloading phase started on 12 January 2022. Note that the time intervals are not equally distributed, and consider ±5 °C uncertainty in the DTS data.

4.2 Thermal model

The results of the baseline geological model simulations are shown in Figure 6 and Figure 7.

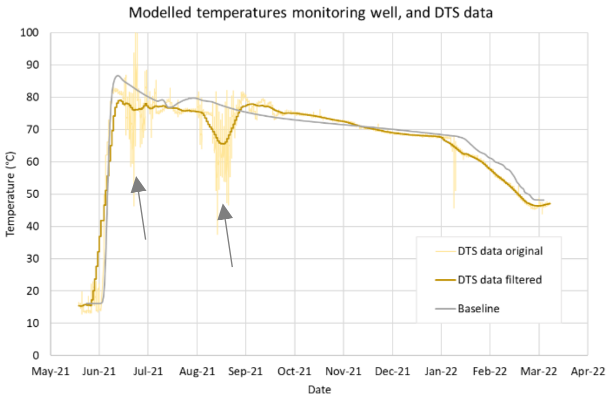

Figure 6 - Temperature development of the DTS data (original and filtered) and the modelled scenarios over time, at a depth of 365 m. With grey arrows indicating the large temperature spikes, as seen in Figure 4.

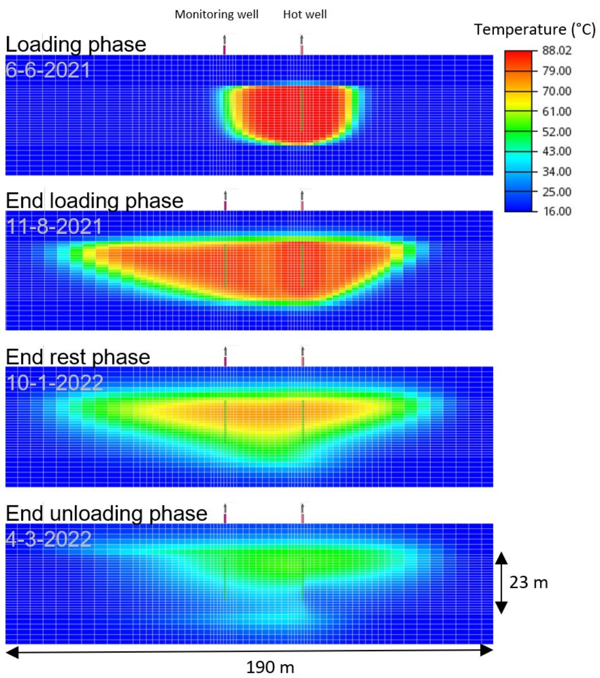

Figure 7 - Vertical profiles of the baseline scenario model results over time.

Figure 6 shows the temperature development in the monitoring well of the model and the DTS data, both at a depth of ~365 m. The overall trend of the model shows a fit with the DTS data, keeping in mind an uncertainty of ±5 °C. The model shows a slightly higher temperature at the arrival of the thermal front (beginning of June) than the DTS data. Also when, on the 23rd of June lower temperatures (~16-40 °C) are injected, alternated with periods of no injection until the 6th of July, this is seen in the model data, but not in the DTS data. On the other hand, the decrease in temperature in the DTS data in mid-August is not simulated by the model. This decrease cannot be explained by the injection profile which is why it does not seem to show actual in situ conditions in the subsurface. This is likely an artefact, related to issues in the cable.

Vertical cross-sections through the hot and monitoring well show the thermal development of the hot water in the modelled aquifer (Figure 7). The hot water clearly flows towards the top of the reservoir, resulting in the typical shape caused by the tilting of the thermal front. Also heating of the over- and under burden is seen in the model. During the resting phase, a lot of the heat has dissipated, which is also visible in Figure 5 (comparison of yellow vs. dark blue line).

4.3 Thermal model calibration

Aiming to calibrate the thermal transport model, the following simulations have been performed with adaptations to the baseline scenario parameters:

- *Baseline*: this scenario used the homogenous model input as shown in Table 1.
- *Clay layer*: the monitoring data show a thin interval at approximately 369 m depth at which the thermal front arrives relatively late. This might indicate the presence of a low permeable streak relative to the surrounding permeable layers. A ‘clay layer’ at 369 m depth with a horizontal hydraulic conductivity of 0.1 m/d (corresponding to ~0.13 Darcy permeability) is implemented in the baseline model. The upper part, above the clay layer, is given a higher horizontal hydraulic conductivity of 20 m/d (~27 Darcy) relative to the baseline value of 12.7 m/d (~17 Darcy).
- *Coarsening up I*: towards the end of the loading phase, the buoyancy effect is larger than predicted for buoyancy in a homogeneous reservoir. The well logs from all three wells showed a potential coarsening upward sequence in the storage aquifer. For an alternative model the upper part, from 361-370 m depth is given a higher horizontal hydraulic conductivity of 20 m/d (~27 Darcy), while the lower part remains 12.7 m/d (~17 Darcy).
- *Coarsening up II*: in addition, to create a slower arrival of the temperature front in the lower part of the well, a second coarsening up scenario with lower hydraulic conductivity values in the lower part of the aquifer, has been introduced with the upper 15 m having a horizontal hydraulic conductivity of 12.7 m/d (~17 Darcy) and the lower 8 m of 3 m/d (~4 Darcy).

Figure 8 shows the vertical profiles of the three modelled scenarios, with the effect of a clay layer and the coarsening upward effects compared to the baseline scenario.

Figure 9 allows comparison of the simulated temperature development at the monitoring well with measurements at various time intervals for the different scenarios. The time intervals are chosen in such a way that the significant distinct phases observed in the monitoring data are incorporated: the start of the loading phase (in higher detail), the end of the loading phase (11-8-2021), the end of the resting phase, i.e. start of the unloading phase (12-1-2022) and the end of the unloading phase (4-3-2022). Both the original and filtered DTS data are shown.

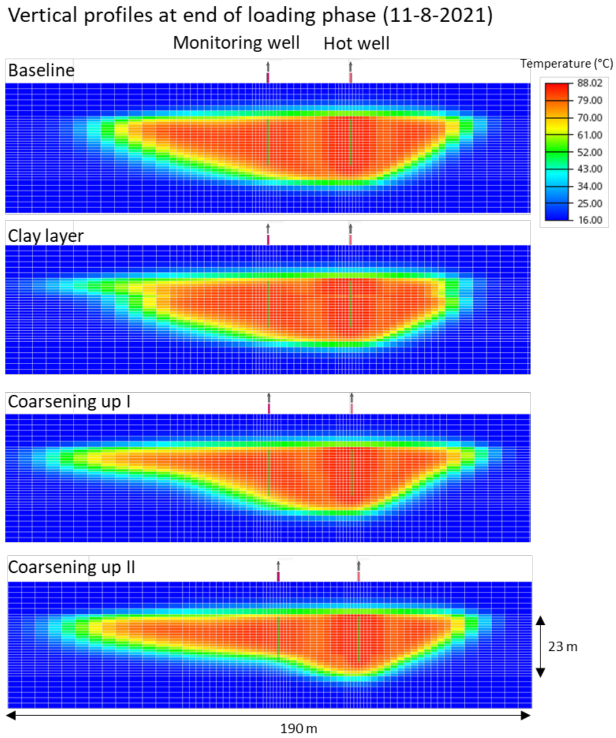

Figure 8 - Vertical profiles of the different simulated scenarios at the end of the loading phase (11-8-2021).

For all model scenarios the thermal front arrives first in the upper part of the aquifer. Until 7-6-2021, the ‘clay layer’ scenario seems to fit the monitoring data, however, a few days later this pattern of a slow/low thermal front in the middle of the aquifer has disappeared. This could be resolved by adopting a slightly higher permeability for the clay layer or interpreting the anomaly to be the effect of a different stratification (i.e. thinner clay layer). It can also not be excluded that the anomaly in the DTS data could be an artefact.

The coarsening up I scenario shows a better fit with the DTS data after the local lag in the thermal front has disappeared. However, in part of the production phase and the resting and unloading phase (lower six graphs), the DTS data shows lower temperatures in the lower part of the well compared to the model. Evidently, the lower hydraulic conductivity for the coarsening up II scenario, with lower hydraulic conductivities in the lower part of the aquifer, indeed slightly improves the fit with the data in the resting and unloading phase.

Despite the remaining mismatch of the model with observations in the lower part of the model, the model serves well to demonstrate that the higher temperatures at the upper part of the aquifer cannot be caused by buoyancy only, but seem to be enhanced by aquifer properties. This is evident from the upward flow of hot water as indicated by the DTS data, compared to the simulations.

Figure 10 shows the temperature development of the DTS data and the modelled scenarios over time at a depth of ~365 m, located relatively close to the top of the aquifer. All modelled scenarios show (slightly) higher temperatures at the beginning of the loading phase compared to the DTS data. This could be due to differences in the hydraulic conductivity or the thermal properties (heat capacity, thermal conductivity) between the actual aquifer and the model. In the resting phase, the scenarios show more or less similar temperatures compared to the DTS data. During the unloading phase, it can be seen that the baseline scenario shows higher temperatures in the monitoring well compared to the DTS data.

The clay layer scenario shows a steeper temperature decline compared to the other scenarios. This can be explained by an enhanced production of water above the clay layer due to the higher permeability implemented in the model.

In the coarsening up I scenario this effect is not visible due to a more gradual stratification and cooling of the aquifer during production. In the coarsening up II scenario, the temperatures in the monitoring well at 365 m depth are high, due to the large difference in hydraulic conductivity in the upper (12.7 m/d) and lower (3 m/d) part.

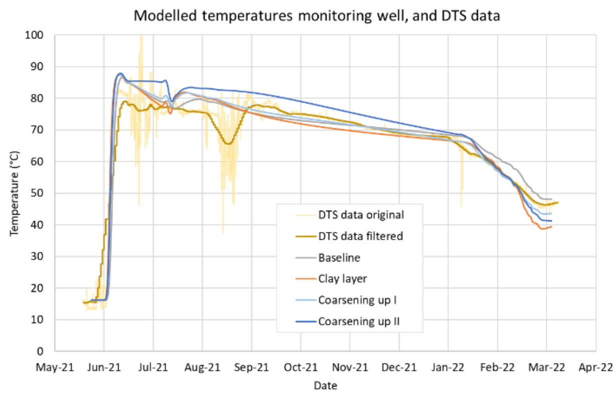

Figure 9 - Temperature development in the monitoring well by the DTS data (original and filtered) and the modelled scenarios over time, at a depth of 365 m.

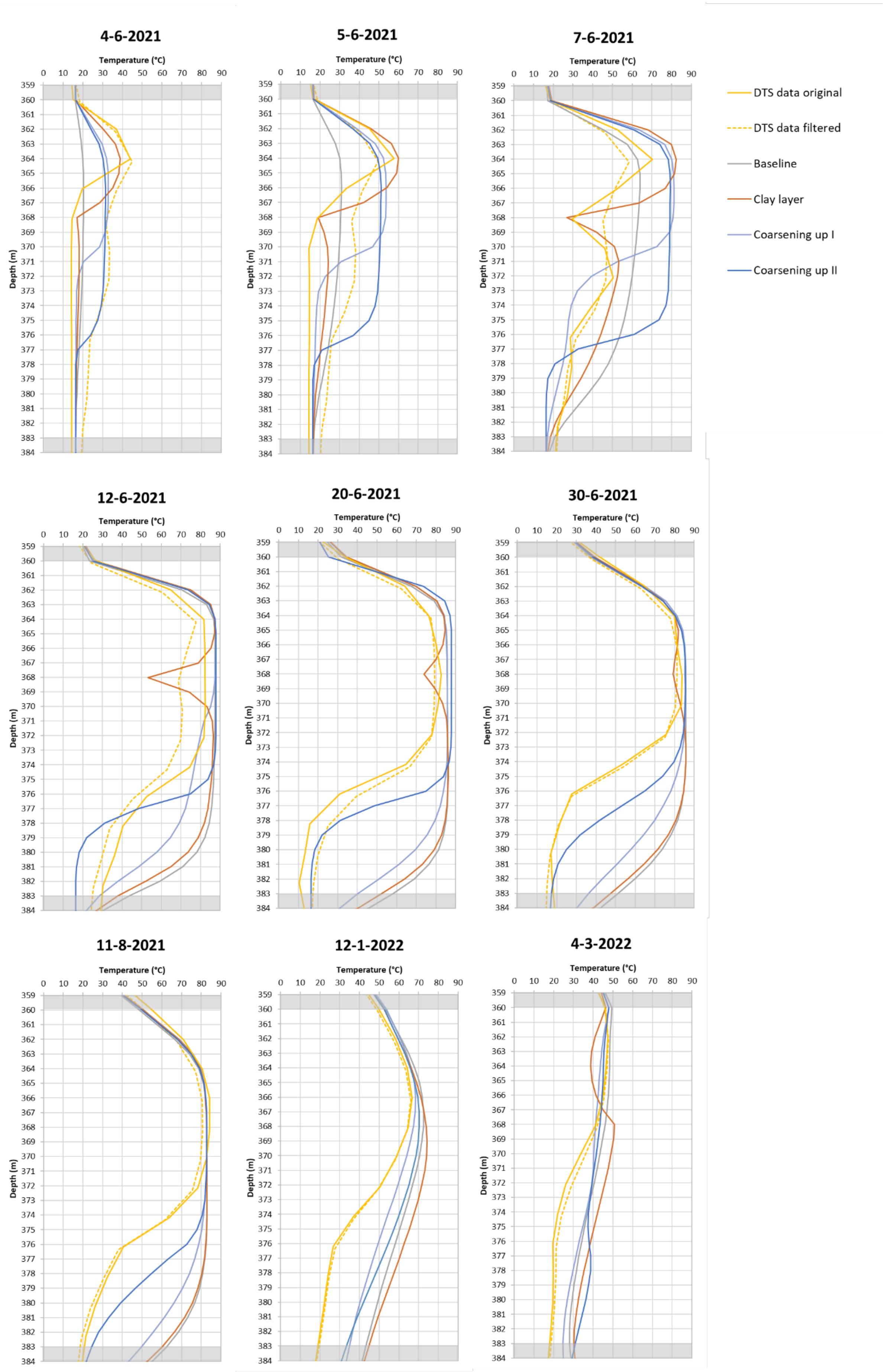

Figure 10 - Comparison of the DTS data (original and filtered) temperature profiles over depth with four different model scenario results: baseline, coarsening up I & II and clay layer.

Efficiency calculation

With the modelled temperature data of the hot and cold well from 24-5-2021 to 4-3-2022, yearly energy efficiency is calculated (assuming that no more heat is produced after this date). The baseline and the coarsening up II scenario efficiencies are ~29%, the clay layer scenario gives a slightly higher efficiency of 32%, while the coursing up I scenario gives a lower efficiency of 26%.

The explanation for these differences can be found in the temperature data of the hot well (Figure 11), with the clay layer and the coarsening up II scenario showing the highest production temperatures and the coarsening up I scenario the lowest. This differs from the temperatures in the monitoring well, as these are 30 m apart. In the coarsening up I scenario, on the contrary, more heat is lost during the resting period due to a higher hydraulic conductivity in the upper part, which results in a lower production temperature. In the coarsening up II scenario, this effect is lower due to the overall lower hydraulic conductivities.

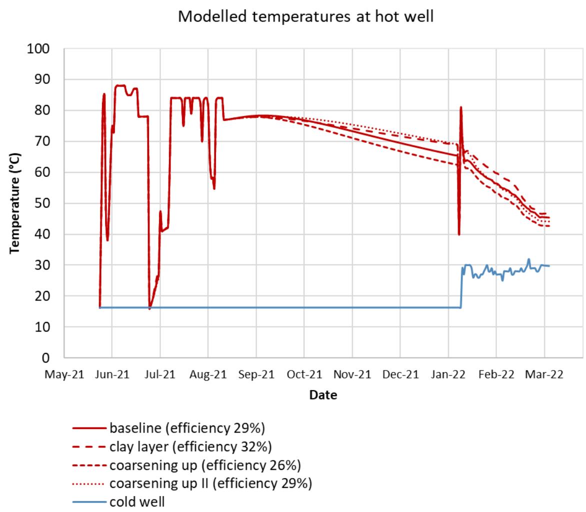

Figure 11 - Modelled temperature development in the hot well for the different scenarios. The energy efficiency is shown for each scenario.

5. IMPACT ON HT-ATES PERFORMANCE AND OUTLOOK

DTS is an existing, proven technology to perform temperature measurements in the subsurface. A DTS system is relatively easy to install and the continuous high frequent temperature measurements are essential for obtaining insight in subsurface processes. During monitoring of the MT-ATES in Wageningen (NIOO), it became clear that two temperature measurements a year was not sufficient for robust monitoring, therefore continuous DTS measurements are advised. The application of DTS in HT-ATES systems to evaluate the heat evolution requires some new thinking, as well as continued testing in real life. This study shows that temperature measurements in a dynamic setting, with highly variable flow rates and temperatures, are feasible. Although a technical flaw in the cable resulted in frequent noise signals, an improved output could be generated using a filtering technique. Even though several inexplicable observations were made, the DTS measurements in the monitoring well in Middenmeer were able to capture the relevant processes such as the passing of the thermal front during injection and production, the upward flow of hot water due to buoyancy, as well as permeability variations, and the heating of over- and underlying clay layers. Future experience will show the extent to which DTS data is valuable for the heat storage management, anticipation and optimization of the HT-ATES operation by the operator.

The DTS monitoring data by itself cannot be used to monitor the spreading of the heat within the storage aquifer in a detailed 2D view, unless they are installed at multiple locations in a strategic set-up to follow the thermal front in time. Such an approach was applied to the heat storage site in Koppert-Cress, the Netherlands, where four monitoring wells are present at increasing distance from the hot wells (Diaz-Maurin and Saaltink, 2021). Their system was at a much smaller scale and at a shallower depth. For high-temperature storage at greater depth, such an approach would be too expensive. Yet, the combination of DTS measurements in a single monitoring well and thermal modelling provides the opportunity to improve the predictions of long term heat evolution, and with that, the predictions of storage efficiency. By simulating the actual flow in and out of the storage aquifer, rather than using idealized pumping schemes, and comparing DTS measurements with thermal simulation results, we were able to calibrate the model. Changes in the geological parameters were implemented to obtain a better fit between the model and the monitoring data. A similar approach for model calibration was used for the low- to medium-temperature ATES of Koppert-Cress (Diaz-Maurin and Saaltink, 2021). By implementing a low permeable clay layer within the reservoir, the delayed arrival of the heat front in a specific depth interval as observed in the DTS data could be reproduced in the model. Implementing a gradual coarsening upward in the model by lowering the hydraulic conductivity of the sand layers in the lower part of the aquifer resulted in a better fit with the DTS data during production, but is still marked by a significant misfit between model predictions and the data.

The efficiency calculations for the four scenarios show significant differences. Considering that the scenario with a clay layer has a poor fit in the production phase, the models with coarsening up of the aquifer sand is (for now) probably the best scenario. For an operator, it is highly beneficial to have more realistic expectations of the efficiency for future storage cycles, signifying the importance of model calibration by monitoring data.

Uncertainty remains in reservoir parameters such as the ratio of horizontal over vertical hydraulic conductivity (anisotropy), heterogeneity, thickness of sand and clay layers, inflow characteristics, salinity and bulk heat capacity. The model scenarios give a first-order indication of the possible aquifer properties. However, to find out more about the heterogeneity in the aquifer, we need a more thorough history matching approach, capable of taking into account a full spectrum of potential flow zone interpretations and associated flow and thermal properties, complemented by more detailed knowledge about the (hydro)geological properties. To this end, a follow-up study will be performed to improve model fits and simulate future aquifer behaviour with a higher degree of confidence.

Also, the DTS data needs a detailed evaluation to assess the technical robustness and exclude technical issues.

In addition, another monitoring technique to determine the thermal front, reported in the paper by Fokker et al. (2022, this issue) will be compared to the methodology described in this paper, and a cost-benefit analysis will be performed comparing the two methodologies.

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