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High-temperature mono-well aquifer thermal energy storage (ATES) system in a carbonate dominated horizon

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Introduction

In the Earth's sunbelt a significant part of the electricity consumption is used for cooling. In the framework of the GeoSolCool project, a collaborative project between The Research Council (TRC) of Oman and the German Research Centre for Geosciences (GFZ), a thermally driven cooling system is developed. The system will use an absorption chiller for cold supply, which requires temperature between 70-100 °C provided by a solar thermal plant. In order to stabilize the system during night times and peak demand a **high temperature** aquifer thermal energy storage (HT-ATES) is considered. The whole system will be installed at the Innovation Park Muscat (IPM). In this study the efficiency of a HT-ATES, designed as a mono-well system, is anlayzed using a 3D hydro-thermal finite element model of the target horizon (the carbonate dominated Seeb Formation). Focus is laid on the effect of hydraulic conductivity changes within the aquifer and the adaption of the well screen distance on the system's efficiency.

Study site

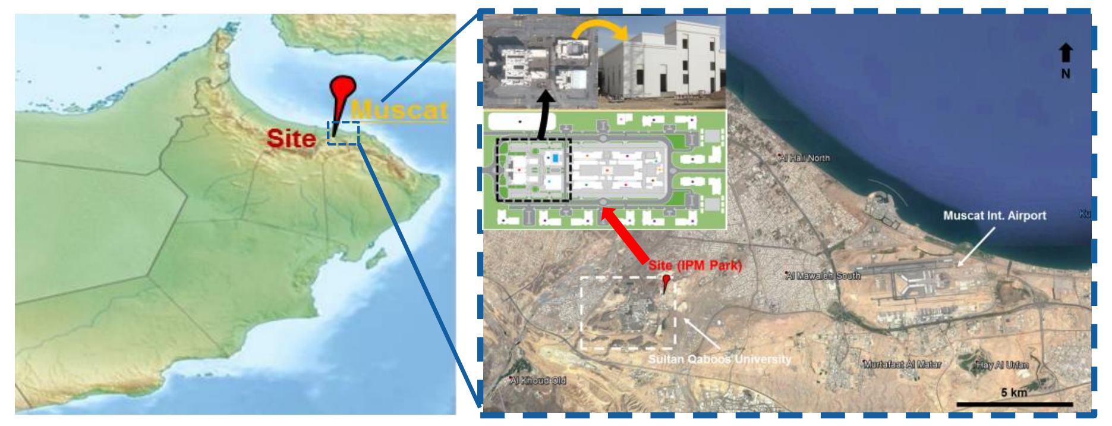


Fig. 1: (left) Overview map of Oman with the location of Muscat and the site. (right) Satellite image of the study area with the target building in the upper left corner.

Motivation

In arid climates a high cooling demand is existent over the whole year with minor seasonal changes, but significant daily changes (see Fig. 3). To bridge the gap between supply and demand a daily storage system is necessary. Motivation of this study is to simulate a mono-well HT-ATES system as a daily heat storage. In contrary to a typical doublet ATES system a mono-well design is chosen because of the possibility to reduce drilling costs.

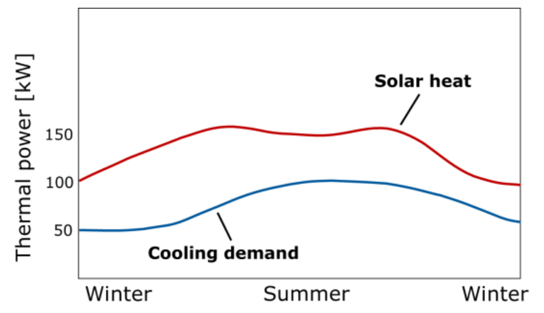


Fig. 2: Seasonal availability of solar heat in Muscat and the cooling demand of the representative institute building determined after Cordes 2017.

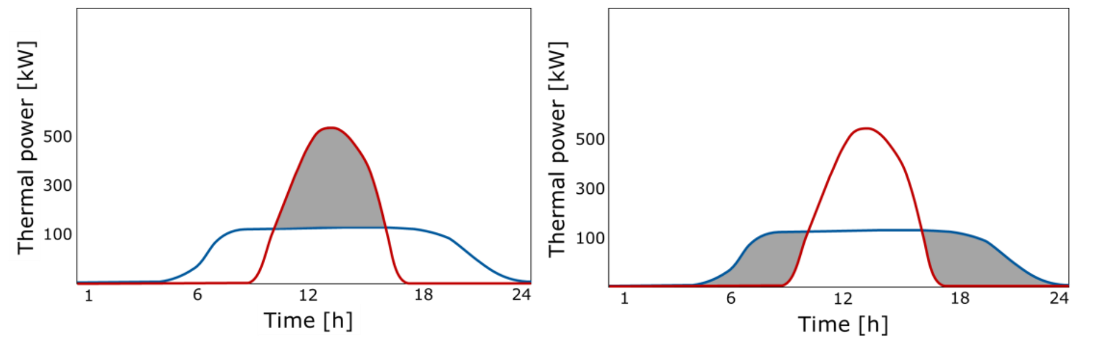
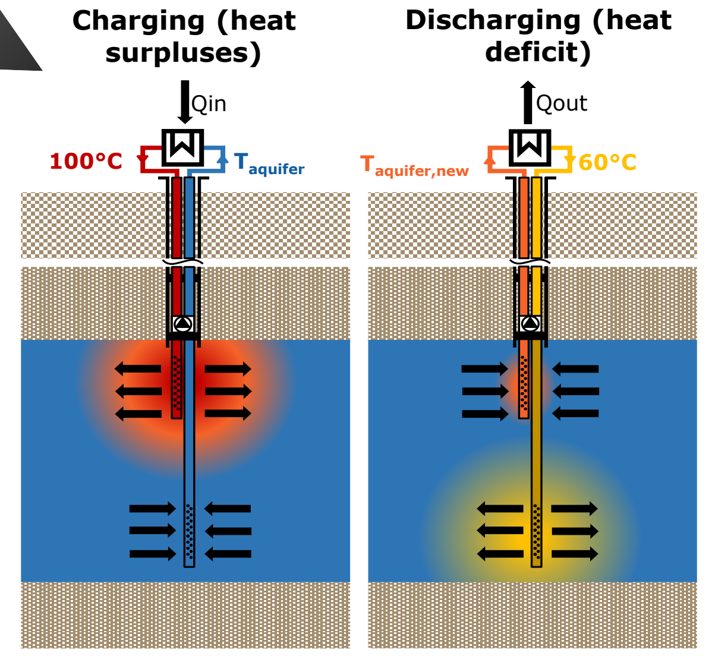


Fig. 3: Daily availability of solar heat in Muscat and the cooling demand of the representative institute building determined after Cordes 2017. (left) Grey area represents the heat surpluses which can be stored. (right) Grey area represents the stored heat which can be used as heat supply.

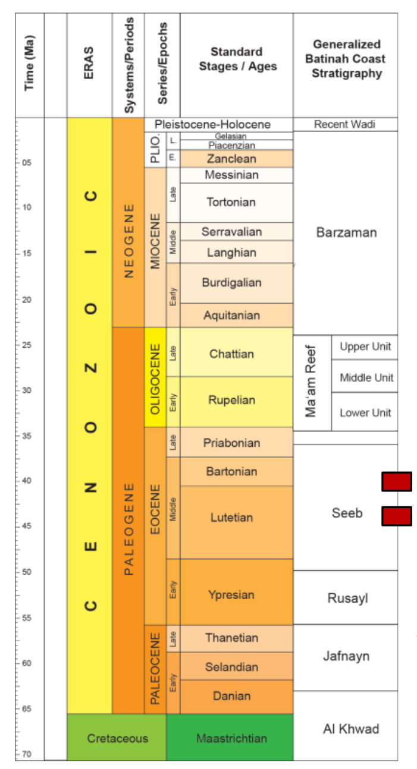
Concept of a mono-well HT-ATES system

(modified after Zeghici et al. 2015)



Determination of required model parameters

Sedimentary rocks of the target horizon



Outcrop Sampling

Fig. 4: Stratigraphy of the late Cretaceous to Cenozoic post-obduction sediments and the generalized stratigraphy at the study area (Batinah Coast). Red boxes mark the sampled stratigraphic formation.

- Seeb Fm. is characterized by a carbonate ramp geometry
- The Ramp geometry results in a layer cake architecture
- Homogenous rock properties within the layers but different discrimination between the layers (Winterleitner at el. 2018)
- Outcrop samples were taken to determine physical rock properties like thermal conductivity, porosity, permeability and density (Schütz et al. 2018, Winterleitner et al. 2018)

Temperature depth analysis

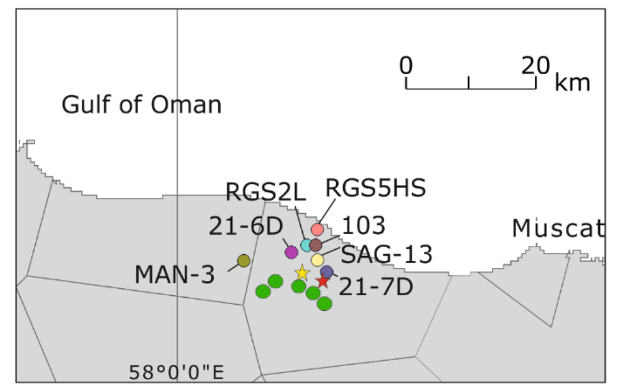
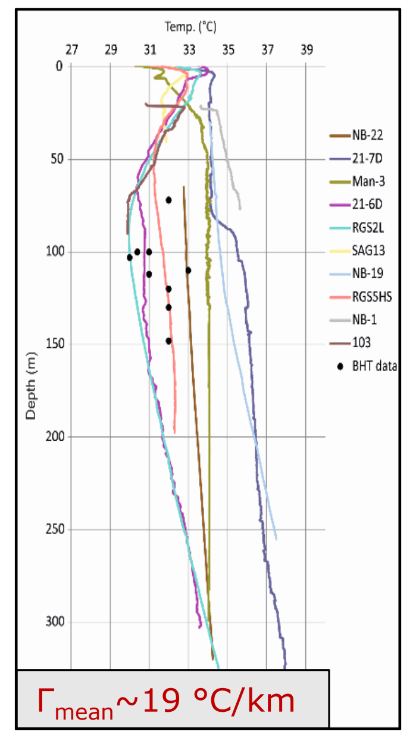


Fig. 5: (right) Continuous T-logs measured with a conventional temperature probe in seven wells around the study area to identify the corresponding T-gradient Γ. Additionally three continuous T-logs (NB-1; NB-19; NB-22) and bottom-hole temperatures (BHT), provided by the Ministry of Regional Municipalities and Water Recourses are plotted. (above) Location were T-log measurements were performed, green dots describe the location of outcrop sampling, red star shows the location of the study site and yellow star shows the location of the well field with corresponding BHT data (Schütz el al. 2018).



Sensitivity study of the heat recovery factor (HRF)

Adaption of hydraulic conductivity kf between warm and cold well screen

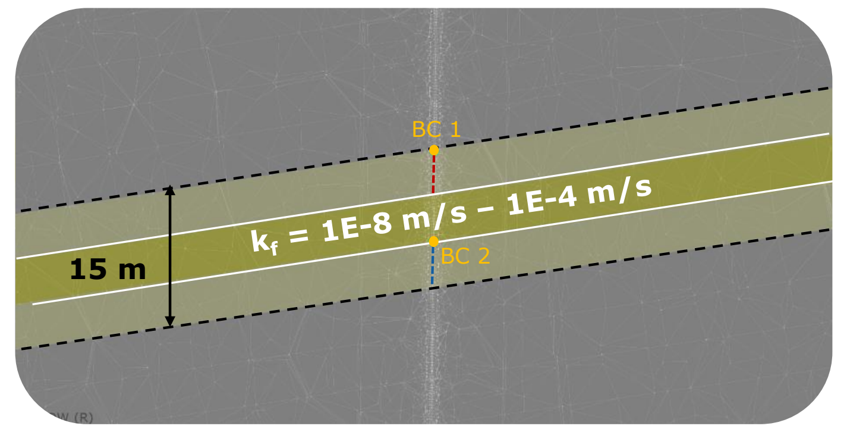


Fig. 7: Cross-sectional view of the 3D model with an adjustable layer within the aquifer. The aquifer thickness is kept constant.

Adaption of distance D between warm and cold well screen

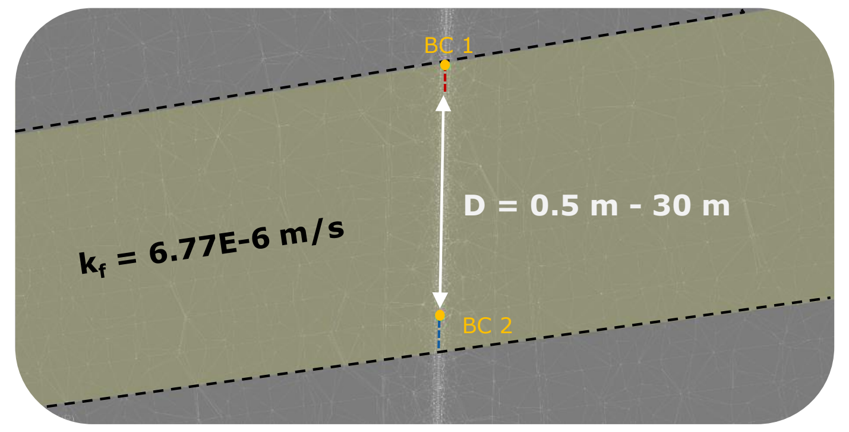


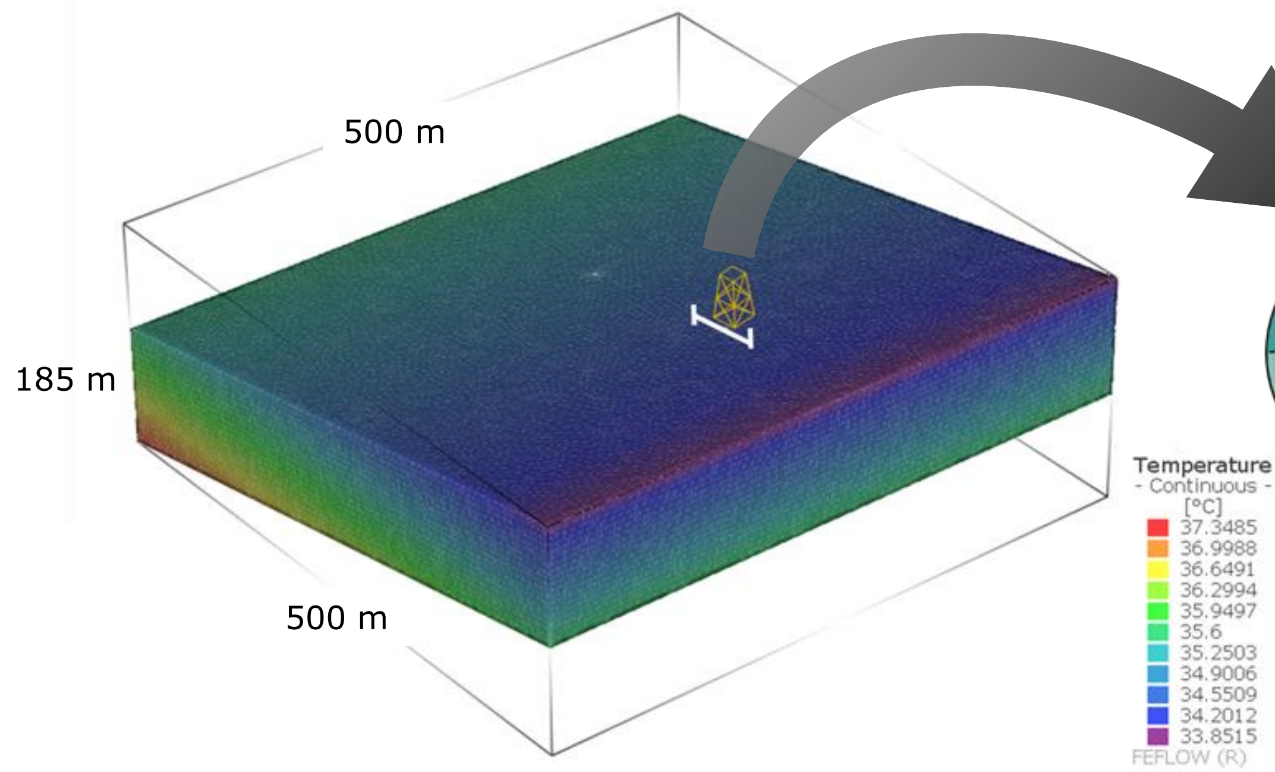
Fig. 8: Cross-sectional view of the 3D model with adjustable well screen distance and aquifer thickness. The reservoir conditions are kept constant.

$$HRF = \frac{heat\ output}{heat\ input} = \frac{\int_0^{t_{discharge}} cv_w \dot{V}_{discharge}(t)\left(T_{out,w}(t) - T_{in,c}(t)\right)}{\int_0^{t_{charge}} cv_w \dot{V}_{charge}(t)\left(T_{in,w}(t) - T_{out,c}(t)\right)}$$

With c_{vw} as volumetric heat capacity of water [J/m³/K], $\dot{V}$ as flow rate while charging and discharging [m³/d], $T_{out,w}$ as production temperature at the warm well [°C], $T_{in,w}$ as injection temperature at the warm well [°C], $T_{out,c}$ as production temperature at the cold well [°C], $T_{in,c}$ as injection temperature at the cold well [°C] and t as time [d].

- A mean HRF was calculated after one year operation using the shown equation from Kranz et al. 2015
- Each simulation contained 365 charging/discharging periods
- First, all simulations were realized with a constant $\dot{V}$ = 100 m³/d
- All simulations were repeated for $\dot{V}$ = 500 m³/d to investigate possible HRF changes
- The injection temperature at the warm well screen was kept constant with 100 °C during charging (at BC 1) and 60 °C at the cold well screen during discharging (at BC 2)

3D unstructured hydro-thermal finite element model of Seeb Fm.



Enlarged cross-sectional view of the Base model

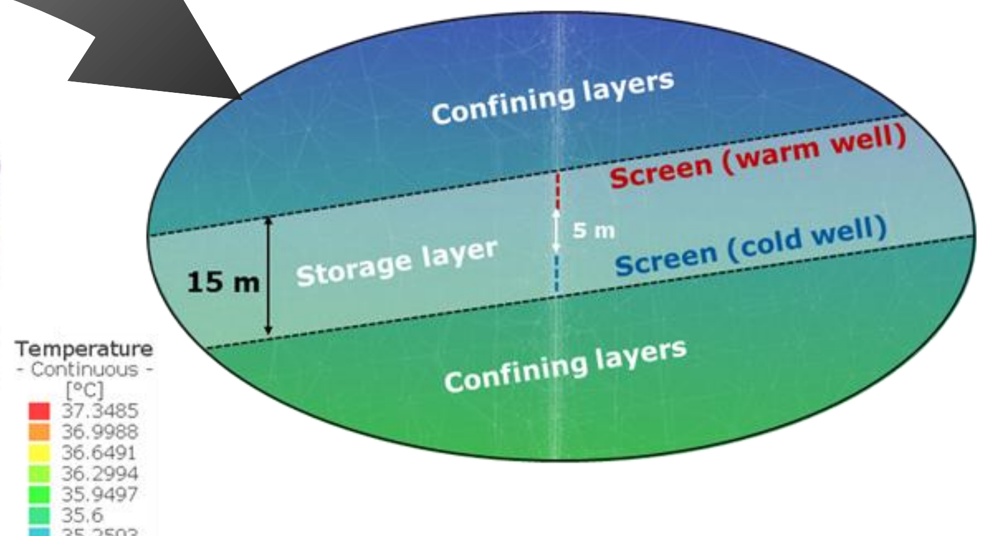


Fig. 6: (right) Hydro-thermal FEM Base model of Seeb Fm. (left) Enlarged cross-sectional view of the well with target storage layer.

- FEFLOW simulation platform is used for the flow and heat transport modelling
- Base model contains a 15 m thick storage layer confined by two low permeable layers (thickness = 40 m)
- Well screens are represented by a 1D tubular discrete feature (length = 5 m)
- Flow rate and temperature boundary conditions (BC) are placed at the head of each screen
- A constant hydraulic head of 25 mbgl is set to the whole model
- Starting depth of the storage layer in 375 mbgl (Base model)
- T-gradient of 19 °C/km is implemented to define initial model temperatures

Hydraulic and thermal input parameters (Base model)

	Hydraulic conductivity [1] (10⁻⁴ m/s)	Specific storage [1] (10⁻⁴ 1/m)	Porosity (effective) [2] (-)	Volumetric heat capacity (matrix)[2] (MJ/m³/K)	Thermal conductivity (matrix)[2] (W/m/K)
Confining layer (head)	0.0014	0.96	0.07	2.63	2.83
Storage layer	0.0677	0.22	0.32	1.52	2.36
Confining layer (bottom)	0.0014	0.96	0.07	2.63	2.83
Pore fluid (fresh water)	-	-	-	4.20	0.65

[1] Winterleitner et al. 2018, [2] Schütz et al. 2018

Results

Effect of hydraulic conductivity changes on the ATES process

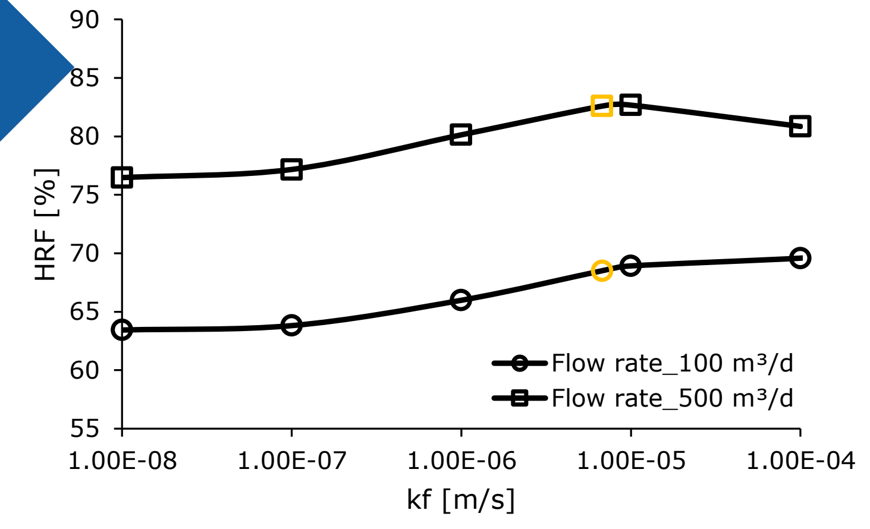


Fig. 9 : Mean HRF of one simulated year plotted versus different kf values within the storage layer. Orange marked areas show the HRF of the base case.

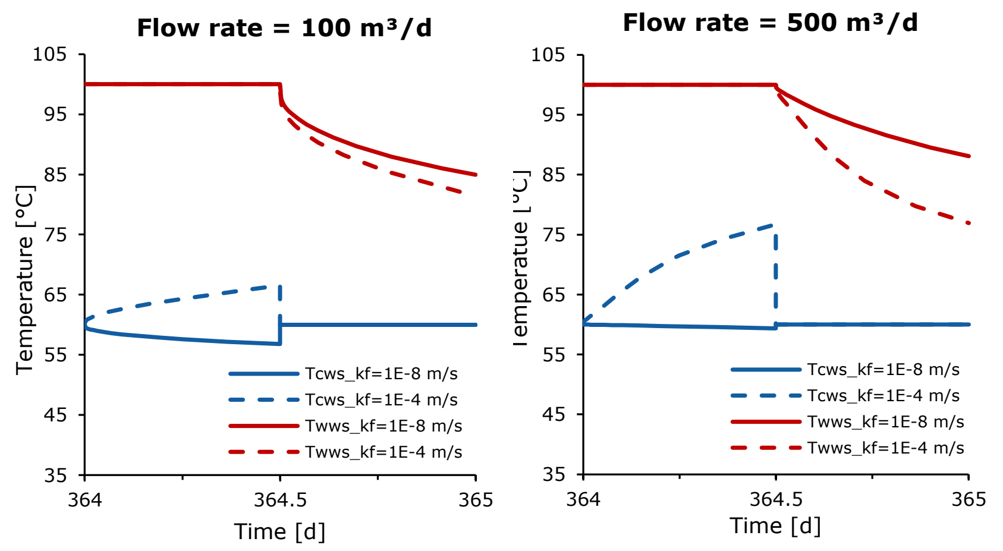


Fig. 10 : Temperature plot of the last simulated operational cycle. Red lines represent the temperature versus time at the warm well screen (wws), blue lines represent the temperature versus time at the cold well screen (cws).

- Increase of $\dot{V}$ leads to an increase of the HRF
- Decrease of kf between the screens causes a decrease of the HRF
- $\dot{V}$ = 100 m³/d: An increase of kf only slightly influence the HRF
- $\dot{V}$ = 500 m³/d : A significant increase of kf results in a decrease of the HRF

- The higher the kf between the screens the higher the thermal interaction between the warm and the cold well
- Increase of the temperature at the cold well screen during charging & decrease of the temperature at the warm well screen during discharging
- Increase of $\dot{V}$ intensifies the thermal interaction

Effect of different screen to screen distances on the ATES process

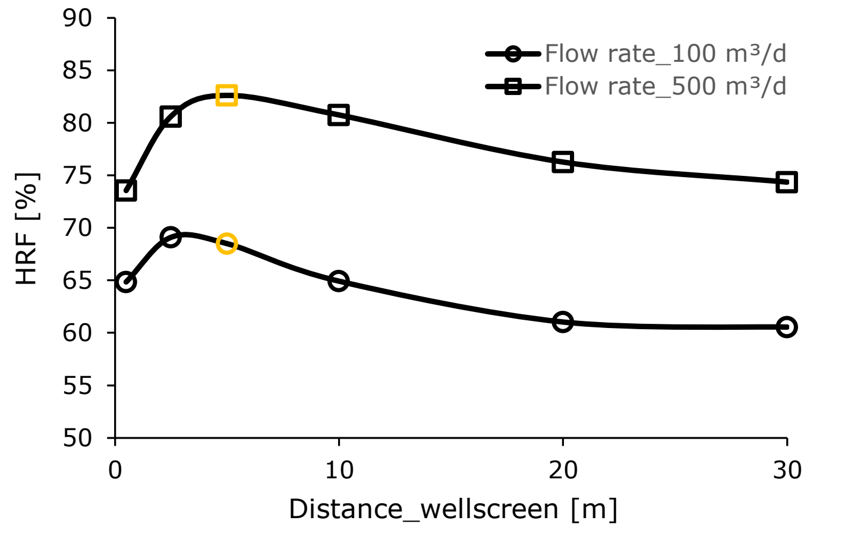


Fig. 11 : Mean HRF of one simulated year plotted versus different distances between the well screens. Orange marked areas show the HRF of the base case.

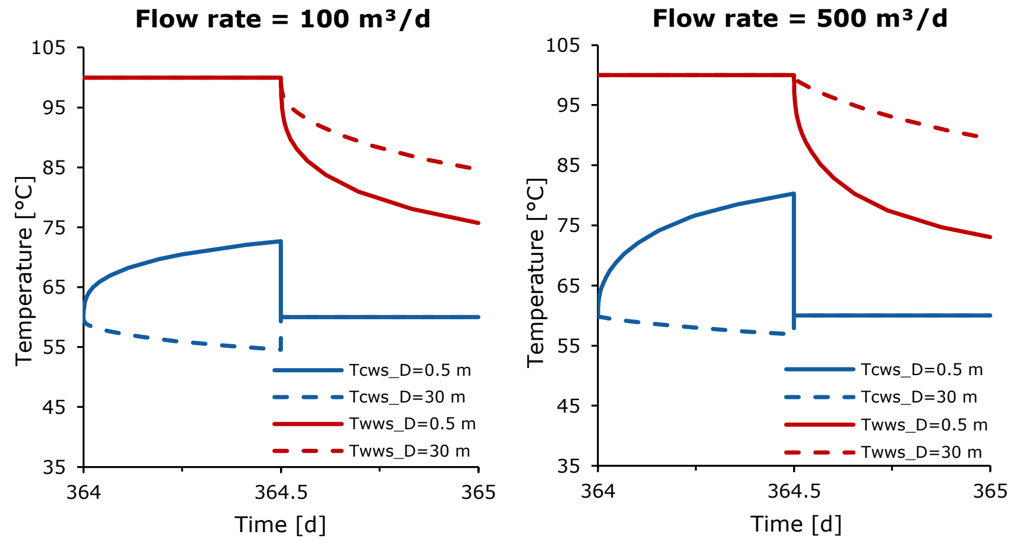


Fig. 12 : Temperature plot of the last simulated operational cycle. Red lines represent the temperature versus time at the warm well screen (wws), blue lines represent the temperature versus time at the cold well screen (cws).

- Too low & too far a distance between warm and cold well screen results in a HRF decrease
- $\dot{V}$ = 100 m³/d : optimal distance at 3 m
- $\dot{V}$ = 500 m³/d : optimal distance at 5 m

- The lower the distance between the screens the higher the thermal interaction between the warm and the cold well resulting in higher temperature at the cold well screen during charging but lower temperature at the warm well screen during discharging
- Results confirm former findings by Kranz et al. 2015

Conclusion

- The rock characterization of the carbonate dominated Seeb Fm. showed good storage qualities with an effective porosity up to 32 % and a hydraulic conductivity up to 7E-6 m/s.
- The temperature depth analysis of several wells around the study area showed an average T-gradient of 19 °C/km resulting in an expected initial aquifer temperature of 35 °C in 375 m depth.
- The study clarifies that a high-temperature mono-well ATES is suitable as a daily storage to stabilize cooling systems in arid climate areas.
- The adaption of the hydraulic reservoir conditions through changes of the hydraulic conductivity or distance between the two well screens results in significant changes of the HRF.

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Acknowledgments:

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