IGSHPA Research Track
Las Vegas, December 6-8, 2022

Modeling and performance evaluation of fractured thermal energy storage (FTES)

Max Hesselbrandt **José Acuña**

ABSTRACT

Fractured thermal energy storage (FTES) is an open-loop type system that uses hydraulically propagated horizontal fracture planes for storage and extraction of heat in low-permability hard rock formations. Groundwater circulation through the fracture system is accomplished by pumping and injection via a set of vertical peripheral wells symmetrically positioned around a central well. In this paper, a numerical approach for modeling of FTES systems based on the finite element method is presented. The modeling approach that is established can be used to investigate various storage design configurations and operation conditions. To demonstrate the application of the approach, an illustrative long-term simulation using a 3D model of a FTES system is performed, and the thermal performance of the modeled storage is evaluated in terms of energy and exergy efficiency indicators.

INTRODUCTION

Fractured thermal energy storage (FTES) systems involve the use of natural or artificially induced fractures in low-permeability rock for storage and extraction of thermal energy in the shallow ground. This type of open-loop storage system consists of multiple stacked sub-horizontal fractures that are interconnected by a number of vertically drilled boreholes. Typically, the boreholes are drilled in a symmetrical arrangement including a central well and peripheral wells spaced therefrom. In charging mode, heated groundwater is injected through the central well into the fractures, where the heat exchange with the rock matrix takes place. Once cooled, the water is extracted through the peripheral wells back to the heat exchanger where the cycle continues. During discharging, the water is circulated through the system in opposite direction.

The method of creating artificial fractures for promoting fluid flow and heat transport in hard rock, referred as the Hydrock concept in earlier publications, was introduced and tested already in the 1980's (Larson, Fridh, and Haag 1983; Larson 1984). Since then, the FTES technology has not received interest compared to other underground heat storage methods, such as borehole thermal energy storage (BTES) and aquifer thermal energy storage (ATES). However, FTES does not require the presence of a pre-existing permeable aquifer formation and could thus be, like BTES systems, more universally applicable than ATES systems. Also, being of open-loop type like ATES systems, FTES typically requires considerably fewer boreholes compared to a BTES system with comparable storage capacity (Hellström and Larson 2001). Hence, FTES could potentially combine some of the benefits associated with these conventional geothermal storage technologies.

Previous research on FTES systems has mainly focused on the rock fracturing processes employed to construct the

Max Hesselbrandt (max.hesselbrandt@bengtdahlgren.se) is an energy consultant at Bengt Dahlgren AB. José Acuña (jose.acuna@bengtdahlgren.se) is a PhD and researcher at the Royal Institute of Technology (KTH) as well as a manager at Bengt Dahlgren AB.

DOI: https://doi.org/10.22488/okstate.22.000026

storage plant as well as hydraulic aspects of operation of the system, while less effort has been devoted to study the thermal processes involved. In the early experimental studies described by Larson (1984), the results from field tests performed in Bohus granite at Rixö, Sweden, demonstrated that fluid-driven crack propagation could effectively be controlled to produce approximately horizontal, parallel stacked fractures. Subsequent in situ studies investigated the effect of using propping agents for fracture stimulation (Eliasson, Sundquist, and Wallroth 1988). A research project aiming to develop equipment and methodology for utilization of shallow geothermal energy based on the Hydrock concept was initiated in the late 1990's in Norway. Within the project an extensive field test programme was conducted at two pilot plants (Bryn and EAB) located in the Oslo area, including hydraulic fracturing with water-only and with sand as propping agent as well as pumping tests and geophysical logging of the boreholes at the test sites (Ramstad 2004). Recently, Janiszewski et al. (2019) developed a numerical coupled hydro-mechanical model to study the interaction between natural fractures and hydraulically propagated fractures created for the construction of FTES plants. However, to the authors' best knowledge, there are only two studies in the literature that have focused on the thermal analysis of FTES systems. Hellström and Larson (2001) developed a coupled conduction-convection heat transport model of a FTES system using the explicit finite difference method (FDM) and performed a parameter study considering various geometrical parameters (e.g., spacing between fracture planes, number of peripheral wells, and storage diameter), operation conditions and fracture hydraulic properties. In the work by Ramstad (2004), results from the hydro-thermal finite element modelling of the Bryn and EAB pilot plants are presented. According to these studies, some important design considerations for FTES systems involve, for example, the spacing, number and aperture of fractures, the spacing between central and peripheral wells, and the heat conduction capability of the rock material within the storage.

Within the design process, the use of simulation models is critical for proper characterization and evaluation of FTES systems, yet the complex nature of coupled hydro-thermal processes in fractured rock imply serious challenges to the accurate analysis of the flow and transport problem under consideration. Therefore, adequate modeling techniques applicable to FTES need to be further explored. This paper presents a numerical approach for modeling of FTES systems based on the finite element code FEFLOW. In the model, wells and fractures are discretely represented by one- and two-dimensional finite elements embedded in a three-dimensional triangular mesh which represents the low-permeability rock matrix. Variations in inlet temperature and flow direction when shifting between charging and discharging mode of operation are considered. An illustrative simulation model is used to demonstrate the modeling approach presented in the paper, and the thermal performance of the modeled storage is evaluated in terms of energy and exergy efficiency.

FRACTURED THERMAL ENERGY STORAGE

A schematic sketch of a FTES system is given in Figure 1. The storage consists of the following main components:

1. Rock matrix – the solid part of the the rock mass, i.e., the storage medium.
2. Fracture planes – ideally horizontal or subhorizontal transmissive planar conduits that constitute the flow paths for the heat carrier as well as heat exchange surfaces between the heat carrier and the rock matrix.
3. Central and peripheral wells – vertical wells with packers installed at the sections of the boreholes that intersect the fracture planes.

The peripheral wells are symmetrically arranged around the central well. Fluid flow within the fracture planes is driven by a hydraulic gradient between the central wells and the peripheral wells, where sections with borehole-fracture intersections are packed-off from the remaining intervals of the well. During charging the flow is directed from the central well to the peripheral wells, and in the opposite direction during discharging. This operation strategy serves the purpose of creating thermal stratification within the storage to improve temperature retention during the course of storage cycle. A similar design and operation approach can be employed for high temperature BTES systems, where the borehole heat exchangers are joined together in parallel strings containing series-connected loops ordered from the center to the peripheral region of the storage.

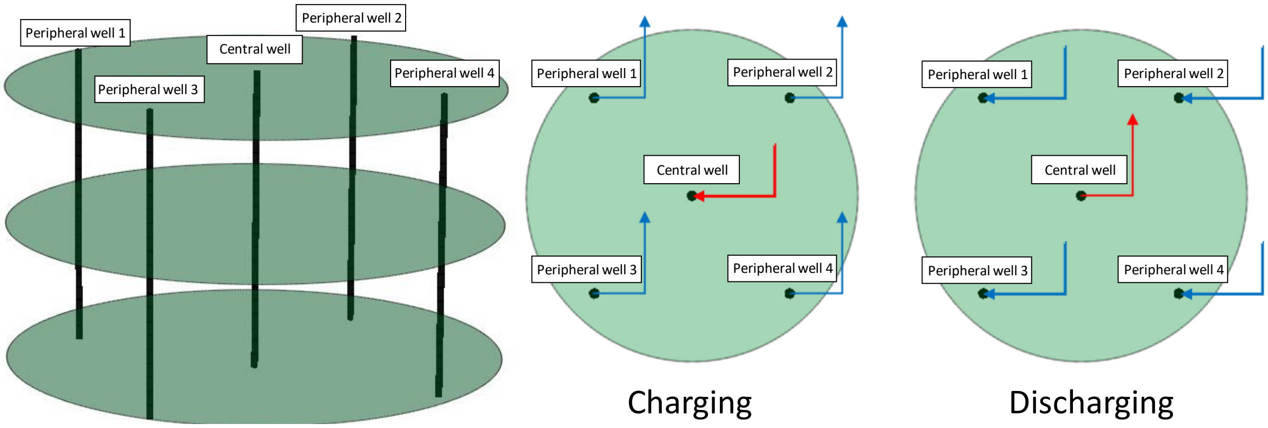

Figure 1 Principle sketch of a FTES system.

METHODOLOGY

Modeling of FTES systems involves solving the coupled problems of fluid flow and heat transport within fractures and the rock matrix. Since fluid flow in the rock mass is concentrated on preferential flow paths due to the presence of distinct fractures, the common assumption of the ground as a single continuum may not be suitable to adequately describe the processes occurring within the fractured medium (Berre, Doster, and Keilegavlen 2019). Instead, hybrid discrete-continuum models or approaches where fracture geometries are represented fully explicitly may be better suited.

In this work, the commercial finite element code FEFLOW 7.4 is selected for modeling of groundwater flow and heat transport within the FTES system (Diersch 2014). Application of the so-called discrete feature approach available in FEFLOW allows for modeling of flow and transport in fractures and other features that can be described by geometric representations of a lower dimension than the porous host medium structure. Considering a three-dimensional problem, 1D line or 2D areal elements representing e.g., wells and fractures can be embedded in and combined with the 3D discretization that represents the host rock matrix. The lower-dimensional elements are placed along the edges and faces of the 3D mesh. Flow and transport related properties (e.g. type of law of flow motion, hydraulic aperture) are assigned to each discrete feature. As thoroughly described by Diersch (2009), FEFLOW solves the coupled system of flow and transport balance equations governing in the discrete feature domains and the 3D finite element domain.

In the following sections, the general modeling approach applied in this work is described. Conceptually, the model features are divided into three groups i.e., solid rock matrix features, fractures, and wells. For simplification purposes, only saturated flow is considered, and the rock matrix is modeled as a homogeneous, isotropic and impermeable material. Fracture properties are assumed to be uniform and homogeneous within each fracture plane, and all fractures are assumed to be identical. All fractures and wells are assumed to extend only in horizontal and vertical directions, respectively.

Model development

Figure 2 shows an example of discretization of a FTES system model consisting of 5 pumping wells and 11 fracture planes. The discretization of the octagonal-shaped model domain is accomplished by first constructing a horizontal 2D unstructured mesh. The 2D mesh is refined locally in the region occupied by fracture planes, including the interspace between the well locations. Specifically, the mesh around the wells is refined in such that an ideal spacing between the well nodes and surrounding nodes is applied to achieve highest numerical accuracy (Diersch et al. 2011). The 2D mesh plane is extruded along the depth axis to create a 3D vertically structured mesh structure. The grid is partitioned into plane layers of triangular prismatic elements. As shown in Figure 2 b), the vertical grid is locally refined along the depth interval containing (packed-off) well sections and fracture features.

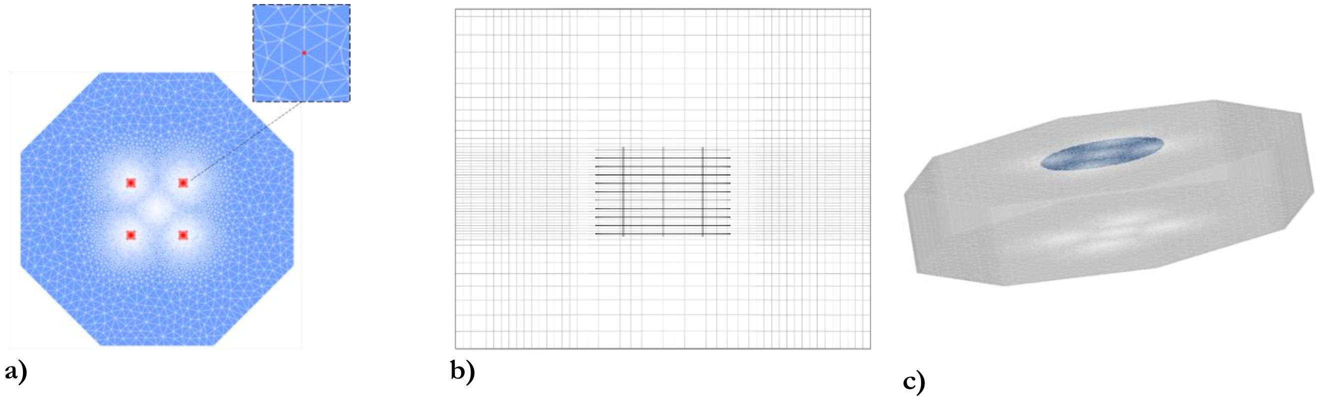

Figure 2 Overview of the model discretization. a) Horizontal 2D unstructured mesh. b) Vertical structured mesh including positions of fractures planes and wells. c) Two-dimensional fracture features (highlighted in blue) assigned to the model along the horizontal faces of the 3D finite elements.

As mentioned previously, FEFLOW allows inclusion of fractures using 2D discrete features that can be added onto the faces of the 3D elements representing the rock matrix. In this work, fracture planes (approximately disc-shaped) are added to the model by assigning discrete features along horizontal element faces located at the interface between the layers of the discretization grid (see Figure 2 c)). Fluid flow along discrete features can be determined using either the Darcy, Hagen-Poiseuille or Manning-Strickler laws of flow. In this study the Hagen-Poiseuille law is used for fracture flows, which assumes the fluid flow to be laminar between two smooth, parallel plates. It uses the hydraulic aperture as frictional input parameter to characterize the hydraulic conductivity of the fracture, and is closely related to the well-known cubic law that states that the fracture transmissivity is proportional to the cube of its aperture (Diersch 2009).

Due to the assumption of the rock matrix being impermeable, fluid flow within the model will exclusively occur along the fractures and the well sections that connect the fracture planes. In FEFLOW, well features (or more precisely the packed-off sections of the wells in the present case) can be modeled using the special “multilayer well” boundary condition (BC). Multilayer wells are assigned along vertical edges of the discretization and are thus represented by 1D elements. This kind of BC is technically a combination of a point sink/source BC assigned at the lowermost node of the well and a highly conductive linear discrete feature along the well section. The multilayer wells intersect with all fractures, thus allowing the flow to be distributed within the model and between the injection and extraction wells (Figure 3). The injection and extraction of heat into and from the model domain is modelled using a fixed inlet temperature condition by imposing a Dirichlet type BC on the lowermost node of the multilayer wells that are operating as injection wells. The calculation of the heat outflow from the model domain is handled internally by the solver, by imposing a heat sink BC on the lowermost nodes of the extraction wells.

The specified boundary conditions for flow and heat transport can be set to vary during transient simulation according to a predefined time series. During charging the central well is set as injection well and the peripheral wells are set as extraction wells, and vice-versa during discharging operation. The BCs at the well locations can also be turned off during simulation to simulate operation inactivity periods.

Undisturbed hydraulic and thermal conditions are assumed to be uniform throughout the model domain. A steady state-solution is run to established initial conditions for the transient simulation, assuming hydraulic and thermal Dirichlet BCs on the lateral surfaces of the model while no-flux conditions are assumed and imposed on the top and bottom boundaries.

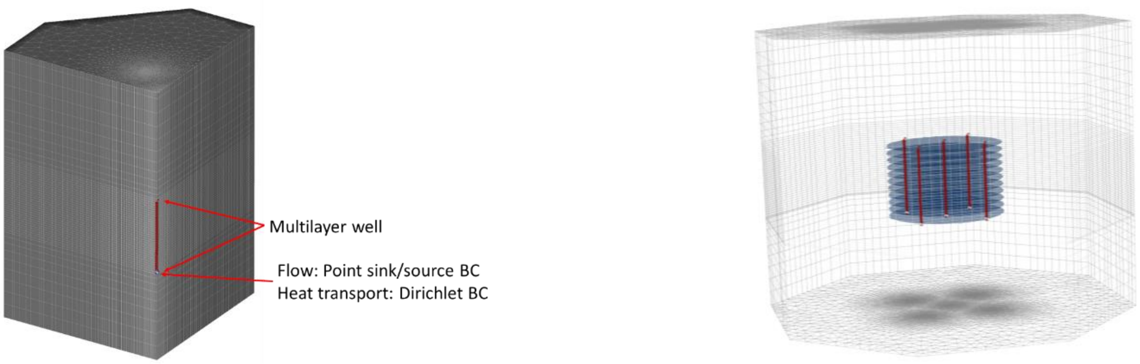

Figure 3 Assignment of multilayer well and heat transport BC for modeling injection and extraction of heat and water.

Model application

An illustrative simulation case is developed to demonstrate the modeling approach presented in the previous section. Table 1 summarizes the key design, material and operation parameters and their values.

Table 1. Storage design and operation parameters.

Design and material parameters	Value	Operation parameters	Value
Storage radius (well spacing)	31.0 m	Total fluid flow rate	4 l/s
Well diameter	0.165 m	Charging inlet temperature	90 °C
No. of central/peripheral wells	1/4	Discharging inlet temperature	45 °C
No. of fracture planes	22	Charging period	180 days
Fracture spacing	3.73 m	Inactivity after charging	30 days
Fracture radius	37.2 m	Discharging period	110 days
Fracture hydraulic aperture	800 µm	Inactivity after discharging	45 days
Rock vol. heat capacity	2.16 MJ/m^3/K	Total length of storage cycle	365 days
Rock thermal conductivity	3.0 W/mK		
Rock hydraulic conductivity	1e-17 m/s		

The storage design consists of 4 peripheral wells spaced 31 m apart from a single central well. The fracture system consists of 22 horizontal, circular planes evenly distributed along the packed-off sections of the wells that extend from 49 m to 129 m below the top of the model domain. The hydraulic conductivity of the rock matrix is assumed to be very low (1e-17 m/s), meaning that the fluid exchange between fractures and matrix is practically negligible. Considering also that the undisturbed hydraulic head is assumed to be uniform throughout the model, any effect of heat losses due to natural groundwater movements is neglected. For all other material properties, default values have been adopted (FEFLOW 7.4 n.d.). As initial conditions, an undisturbed ground temperature of 7 °C and an hydraulic head of 0 m are assumed throughout the model. The FTES system is simulated for 16 annual cycles according to the operation scheme shown in Table 1. The octagonal-shaped model domain is discretized into a mesh of 1 465 426 finite elements portioned into 75 layers. Within the storage region the vertical discretization is 1.87 m. The total height and width of the model domain are 213.6 m and 147.8 m, respectively.

Thermal performance evaluation

The performance of the FTES system is evaluated based on the approach proposed by Lazzarotto et al. (2020) for the analysis of seasonal system energy and exergy efficiency of thermal storages. The seasonal system energy efficiency (η) is defined by the ratio of extracted and injected thermal energy per storage cycle (Eq. 1).

$$\eta = \frac{Q_d}{Q_c} = \frac{\int_{\tau_c}^{\tau_c+\tau_d} \dot{m}(t)c_p[T_r(t)-T_f(t)]\,dt}{\int_0^{\tau_c} \dot{m}(t)c_p[T_f(t)-T_r(t)]\,dt} \tag{1}$$

In Eq. 1, T_r and T_f are the return and forward temperatures of the circulating water, $\dot{m}$ is the mass flow, and τ_c and τ_d are the time duration of charging and discharging periods, respectively. The seasonal system exergy (ψ) efficiency is expressed as

$$\psi = \frac{Ex_d}{Ex_c} = \frac{\int_{\tau_c}^{\tau_c+\tau_d} \dot{m}(t)c_p\left\{[T_r(t)-T_f(t)]-T_0\ln\frac{T_r(t)}{T_f(t)}\right\}dt}{\int_0^{\tau_c} \dot{m}(t)c_p\left\{[T_f(t)-T_r(t)]-T_0\ln\frac{T_f(t)}{T_r(t)}\right\}dt} \tag{2}$$

where T_0 is a reference temperature that is equal to the undisturbed temperature of the ground (280.15 K). All temperatures in Eq. 2 are expressed in Kelvin.

RESULTS AND DISCUSSION

The simulation model of the FTES system described in the previous sections is used to determine the return temperature of the circulating water under the scenario conditions specified in Table 1, and the amount of injected and extracted thermal energy and exergy as well as seasonal system performance indicators are evaluated according to Eq. 1 and Eq. 2. The simulation results obtained for 16 storage cycles of operation are summarized in Figure 4. After a few years of temperature build-up within the storage, the amount of extracted thermal energy and exergy stabilizes at around 1 400 MWh/year and 222 MWh/year, respectively, which corresponds to a seasonal system energy efficiency of ~50% and a seasonal system exergy efficiency of ~45%. During the 16th storage cycle, the discharge power varies between 700 kW and 390 kW. Under the conditions considered for the simulation, this range corresponds to return temperatures varying between 87 °C and 68 °C during the final discharging period.

Considering a forward temperature of 90 °C used during charging, these results imply that the FTES system performs relatively well regarding its temperature retention ability (i.e. its exergy efficiency). Achieving a high discharge return temperature, perhaps at the cost of a somewhat lower energy efficiency, may be of crucial significance in high-temperature storage applications as part of the stored heat in the optimal case could be recovered without the use of heat pumps. Due to the open-loop nature of the system, FTES technology possesses a promising potential in minimizing temperature losses and achieving a high exergy performance, for example in comparison with closed-loop BTES systems that also rely on conduction-based heat transfer within the storage medium. It should, however, be emphasized that the fracture system and other ground conditions considered in this study are idealized, hence possible sources of heat losses should be investigated in future work.

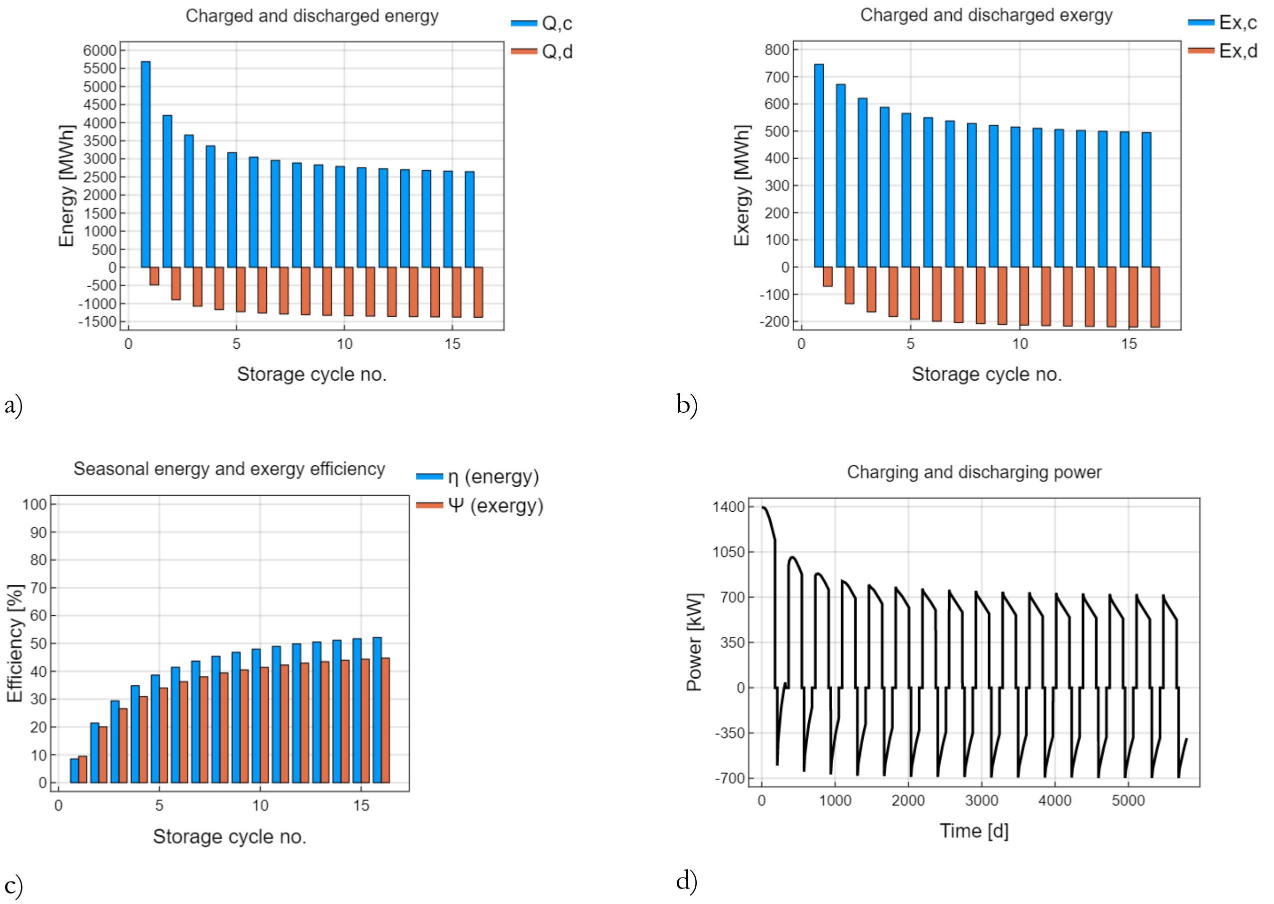

Figure 4 a) Charged/discharged thermal energy per storage cycle. b) Charged/discharged thermal exergy per storage cycle. c) Seasonal system energy and exergy efficiencies. d) Charging/discharging power rates.

CONCLUSIONS

This work presents an approach for the modeling of fractured thermal energy storage systems based on the finite elment code FEFLOW. Although coupled flow and heat transfer problems in fractured rock is highly complex in nature, the discrete feature approach available in FEFLOW for modeling of fracture flow and transport provides a relatively simple and computionally efficient means of simulating the hydraulic and thermal processes occuring within a FTES system. The numerical model that is established can be utilized to study the design and operation conditions of FTES systems, including, for example, well and storage dimensions, different fracture system configurations as well as various heat loading conditions. As demonstrated, long-term simulations can be performed to evaluate the performance of the storage system over its life time. The energy and exergy efficiency indicators employed in this study can usefully be included in the design process for optimization purposes as well as for comparisons with other heat storage technologies. Future work is addressed to investigate the importance of key parameters in FTES design, and to study FTES system performance under more realistic, non-idealized conditions.

ACKNOWLEDGMENTS

The authors acknowledge that this work was funded by Hydroc Energy Storage AB.

NOMENCLATURE

η = energy efficiency (-)
ψ = exergy effiency (-)
τ = time duration
c_p = specific heat capacity (J kg-1K-1)
Ex = exergy (J)
T = temperature (K)
T_0 = reference temperature (K)
Q = energy (J)

Subscripts

c = charging
d = discharging
f = forward
r = return

REFERENCES

Berre, I., F. Doster and E. Keilegavlen. 2019. "Flow in Fractured Porous Media: A Review of Conceptual Models and Discretization Approaches." *Transport in Porous Media* 130 (1): 215–36. https://doi.org/10.1007/s11242-018-1171-6.

Diersch, H.J.G . 2009. "Discrete Feature Modeling of Flow, Mass and Heat Transport Processes by Using FEFLOW." In *DHI-WASY Software FEFLOW: White Papers, Vol. 1, Finite Element Subsurface Flow & Transport Simulation System*, 151–98. Berlin: DHI-WASY GmbH.

Diersch, H.J.G . 2014. *FEFLOW Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media*. Berlin, Heidelberg: Springer Berlin Heidelberg.

Diersch, H.J.G., D. Bauer, W. Heidemann, W. Rühaak, and P. Schätzl . 2011. "Finite Element Modeling of Borehole Heat Exchanger Systems: Part 2. Numerical Simulation." *Computers & Geosciences* 37 (8): 1136–47. https://doi.org/10.1016/j.cageo.2010.08.002.

Eliasson, T., U. Sundquist and T. Wallroth . 1988. "Stimulation Experiments with Water and Viscous Fluid at the HDR Geothermal Research Site in the Bohus Granite, SW Sweden." Publ. Fj-6. HDR Geothermal Energy Project. Göteborg: Department of Geology, Chalmers University of Technology and University of Göteborg.

"FEFLOW 7.4 Documentation - Default Values." n.d. Accessed July 8, 2021. http://www.feflow.info/html/help74/feflow/14_References/default_values.html.

Hellström, G. and S.Å. Larson . 2001. "Seasonal Thermal Energy Storage – the HYDROCK Concept." *Bulletin of Engineering Geology and the Environment* 60 (2): 145–56. https://doi.org/10.1007/s100640100101.

Janiszewski, M., B. Shen and M. Rinne . 2019. "Simulation of the Interactions between Hydraulic and Natural Fractures Using a Fracture Mechanics Approach." *Journal of Rock Mechanics and Geotechnical Engineering* 11 (6): 1138–50. https://doi.org/10.1016/j.jrmge.2019.07.004.

Larson, S.Å . 1984. "Hydraulic Fracturing in the Bohus Granite, SW-Sweden. Test for Heat Storage and Heat Extraction." *Geothermal Resources Council Transactions* 8: 447–49.

Larson, S.Å, B. Fridh and Ö. Haag. 1983. "Hydrock - Värmelager i Berg. Anläggning Av Värmeväxlarytor Med Hjälp Av Hydraulisk Uppspräckning; HYDROCK - Metoden." Publ. B222. Göteborg, Sweden: Chalmers University of Technology/University of Götenburg.

Lazzarotto, A., W. Mazzotti Pallard, M. Abuasbeh and J. Acuña . 2020. "Performance Evaluation of Borehole Thermal Energy Storage Systems Through Energy and Exergy Analysis." In . Reykjavik.

Ramstad, R. K . 2004. "Ground Source Energy in Crystalline Bedrock - Increased Energy Extraction by Using Hydraulic Fracturing in Boreholes." *185*. Doctoral thesis, Department of Geology and Mineral Resources Engineering, Faculty of Engineering Science and Technology, Norwegian University of Science and Technology. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/235847.