Janiszewski, Mateusz; Caballero Hernandez, Enrique; Siren, Topias; Uotinen, Lauri; Rinne, Mikael

Numerical predictions for underground thermal energy storage experiment in the Otaniemi research tunnel

Published in:
3rd Nordic Rock Mechanics Symposium NRMS 2017

Published: 11/10/2017

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Janiszewski, M., Caballero Hernandez, E., Siren, T., Uotinen, L., & Rinne, M. (2017). Numerical predictions for underground thermal energy storage experiment in the Otaniemi research tunnel. In E. Johansson, & V. R. (Eds.), *3rd Nordic Rock Mechanics Symposium NRMS 2017 : Symposium Proceedings* (pp. 77-85). (RIL / Suomen rakennusinsinöörien liitto). Suomen rakennusinsinöörien liitto RIL.

NUMERICAL PREDICTIONS FOR UNDERGROUND THERMAL ENERGY STORAGE EXPERIMENT IN THE OTANIEMI RESEARCH TUNNEL

Mateusz Janiszewski (mateusz.janiszewski@aalto.fi)
Department of Civil Engineering, School of Engineering, Aalto University
Finland

Enrique Caballero, Topias Siren, Lauri Uotinen, Mikael Rinne
Department of Civil Engineering, School of Engineering, Aalto University
Finland

ABSTRACT

Seasonal storage of solar thermal energy is an attractive way to utilise the underground space to increase the share of renewables and tackle the global challenge of climate change. One of the methods to store the solar energy is the borehole thermal energy storage (BTES), where the thermal energy is stored in the rock mass using borehole heat exchangers. This study presents preliminary results of numerical predictions for an *in situ* experiment of underground thermal energy storage in the research tunnel under Otaniemi campus. The in-situ experiment site consists of two horizontal boreholes of 5 m length drilled into granitic rock. One borehole is equipped with a single U-tube heat exchanger, and the hot water is circulated through it to heat up the rocks, while the second hole is used for temperature measurement of the rock. The *in situ* experiment set-up is modelled numerically using finite element method to investigate the influencing factors and predict its long-term thermal performance. The three-dimensional problem is solved with the transient heat conduction equations and the temperature distribution in the subsurface is obtained during 21 days of operation. A parametric study is performed to find the optimal operating conditions. The results of the numerical predictions are used for a detailed plan of the experiment. The simulated results will be later compared to the measured values obtained in the experiment.

KEYWORDS

Underground thermal energy storage, numerical modelling, *in situ* experiment, borehole heat exchanger

1. INTRODUCTION

The problem of the global climate change requires a considerable effort to reduce the greenhouse gas emissions by increasing the use of renewable sources of energy. The public awareness to use alternative energy sources is growing, and market possibilities are emerging. Besides the solar electricity produced by photovoltaic (PV) solar cells, one of the typical applications of renewable energy is the solar heat, where energy from the sun is used to heat up water and space in buildings. Although the price of PV cells is continuing to drop dramatically every year (Kurtz *et al.*, 2017), the solar thermal energy is still considered to be simpler to storage for extended time periods. The seasonal storage is of particular importance in high latitudes, as it is the case in Finland, where solar insolation is highest in the summer when the heating demand is low and lowest in winter when the demand is high. In Tackling the Challenges of a Solar Community Concept in High Latitudes, Academy of Finland (AOF) project, the solutions for seasonal heat storage in high latitudes are sought.

Previously the authors concluded that the borehole thermal energy storage (BTES) is the recommended method for seasonal solar heat storage for a small solar community (Janiszewski *et al.*, 2016). Numerical methods to optimise storage modelling has been developed (Siren *et al.*, 2017; Janiszewski *et al.*, 2017, Oosterbaan *et al.,* 2017). BTES storages may contain over 150 of BHEs, and when operation times up to 10 years are simulated the models take hours or days to run. Thus a faster way of calculating the thermal performance is needed. In Siren *et al.* (2017) and Janiszewski *et al.* (2017), the authors implemented a weak form edge borehole heat exchanger (BHE) element in COMSOL Multiphysics® 5.3 software eliminating need to explicitly model the U-tube, thus dramatically speeding up the numerical calculation process.

An *in situ* experiment to validate a numerical modelling approach of the heat storage capacity of rocks at shallow depth has been carried out in the research tunnel under Otaniemi Campus. The results will be summarised in a Master’s thesis (Caballero, 2017). The experiment consists of monitoring the heat field generated by a BHE. The experimentation process is divided into two stages. The first stage is the conduction of a Thermal Response Test (TRT) in the BHE to determine the local thermal properties of the borehole and the host rock. For this stage, the BHE is subjected to a constant heat flux provided by an electric water heater. The inlet and outlet temperatures of the carrier fluid are recorded for around 60 hours from which the thermal parameters are calculated. The results obtained from the back-calculation are the overall borehole thermal resistance R_b and the effective thermal conductivity λ_{eff}, which includes the different local effects of the borehole (e.g. discontinuities, groundwater flow, thermal parameters, etc.) as stated by Sanner *et al.* (2005). These *in situ* values are of importance to update the current model for a better simulation of the heat transfer from the BHE to the host rock and the analysis of its storage capacity in the second stage. The second stage consists of an evaluation of the host rocks heat storage capacity by continuously heat injection monitored in two phases. In the first phase, hot water is circulated through the installed BHE for 21 days at a constant temperature of 50°C. In the second phase (cooling), the circulation of the carrier fluid is stopped by cutting the constant source of thermal flux to the host rock.

The BHE is installed in a 5.0 m long, Ø107 mm borehole drilled in the granitic rock wall with an inclination of 12° and deviation of 5° (from the y-axis and the z-axis, respectively). A parallel drilled 5.3 m long, Ø57 mm monitoring borehole provides information about the rock temperature at a distance of 0.94 m (y-axis direction) from the heat source. Multiple thermal probes monitor the development of the heat field at the monitoring borehole. The observed temperatures will then be compared against the results obtained in the numerical modelling. The differences between the modelling and the observation will be considered as influenced by the singularities in the BHE as well as the ones localised between the emission and the monitoring points.

In this study, the 21 days heating phase and 15 days cooling phase of the second stage of the *in situ* experiment are modelled numerically using the finite element package COMSOL Multiphysics®. The goal is to investigate the influencing factors and predict its long-term thermal performance. A sensitivity analysis of the input parameters is performed to forecast the influence of each parameter on the changes in the thermal behaviour of the system. A better understanding of the numerical model will be useful when the simulated results will be later compared to the measured values obtained in the experiment.

2. METHODOLOGY

In the numerical model, the borehole heat exchanger was represented as explicitly modelled 3D grout domain with 1D lines embedded into it that represent the pipe-in and pipe-out (see Figure 1). The assumption used is that the flow inside the pipes is fully developed, so it can be represented by an average flow velocity that is then used for computation of the heat transfer (Equation 1). This simplification improves the computational time and saves memory requirements. The fluid inlet temperature of the pipe-out was set as the outlet fluid temperature of the pipe-in at the bottom of the borehole to accommodate the connection between the two pipes. The heat transfer in pipes was described using the following equation:

$$\rho A C_p \frac{\partial T}{\partial t} + \rho A C_p u \cdot \nabla T = \nabla \cdot A k \nabla T + f_D \frac{\rho A}{2 d_h} |u|^3 + Q + Q_{wall} \tag{1}$$

where ρ is the fluid density, C_p is the fluid heat capacity, u is the tangential fluid velocity, and k is the fluid thermal conductivity. The A is the inner area of the pipe, d_h is the hydraulic diameter of the pipe (equal the inner diameter for circular pipe), and f_D is the flow resistance friction factor (according to Churchill friction model). The Q is the heat source (inflow of fluid at a given temperature) and the Q_{wall} is the heat transferred through the pipe wall (see Equation 2).

$$Q_{wall} = (hZ)_{eff}(T_{ext} - T) \tag{2}$$

The heat transfer through the pipe wall (Equation 2) depended on the temperature difference, and the effective heat transfer coefficient $(hZ)_{eff}$ was calculated according to Equation 3:

$$(hZ)_{eff} = \frac{2\pi}{\dfrac{1}{r_o h_{int}} + \dfrac{\ln(\frac{r_o}{r_i})}{k_{pipe}}} \tag{3}$$

where r_o and r_i are the outer and inner radii of the pipe, respectively. The h_{int} is the internal film heat transfer coefficient calculated as: $h_{int} = Nu\frac{k}{d_H}$, where Nu is the Nusselt number.

The heat exchange between the fluid in pipes and the surrounding grout (and further to the surrounding rock mass) was done through coupling the heat transfer through the pipe wall to the heat transfer in solid, where the Q_{wall} was used as a heat source in the solid. The transient heat conduction in the rock and in the grout was calculated using Equation 4:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot -k\nabla T = Q \tag{4}$$

where ρ is the rock/grout density, C_p is the rock/grout heat capacity, k is the rock/grout thermal conductivity and Q are heat sources and sinks.

The numerical model in COMSOL Multiphysics® consisted of three domains: rock, grout and water (for pipe-in and pipe-out). The properties of rock and grout are given in Table 1, and the properties of water were taken from the built-in material database in COMSOL. The model geometry was a cuboid with height, depth, and width equal to 31.9 m, 40 m, and 32.7 m, respectively (see Figure 1). The model was symmetrical along the xz plane. The upper surface was located at +10.9 m on the z-axis and represents the ground surface above the tunnel. The model consisted of a rectangular tunnel with the tunnel floor at -11 m on the z-axis. The inlet of the experiment and monitoring boreholes were located at 1.5 m above the tunnel floor and are inclined upwards at 12° from the horizontal plane. The experimental hole was 5 m long, and the monitoring hole was 5.3 m long.

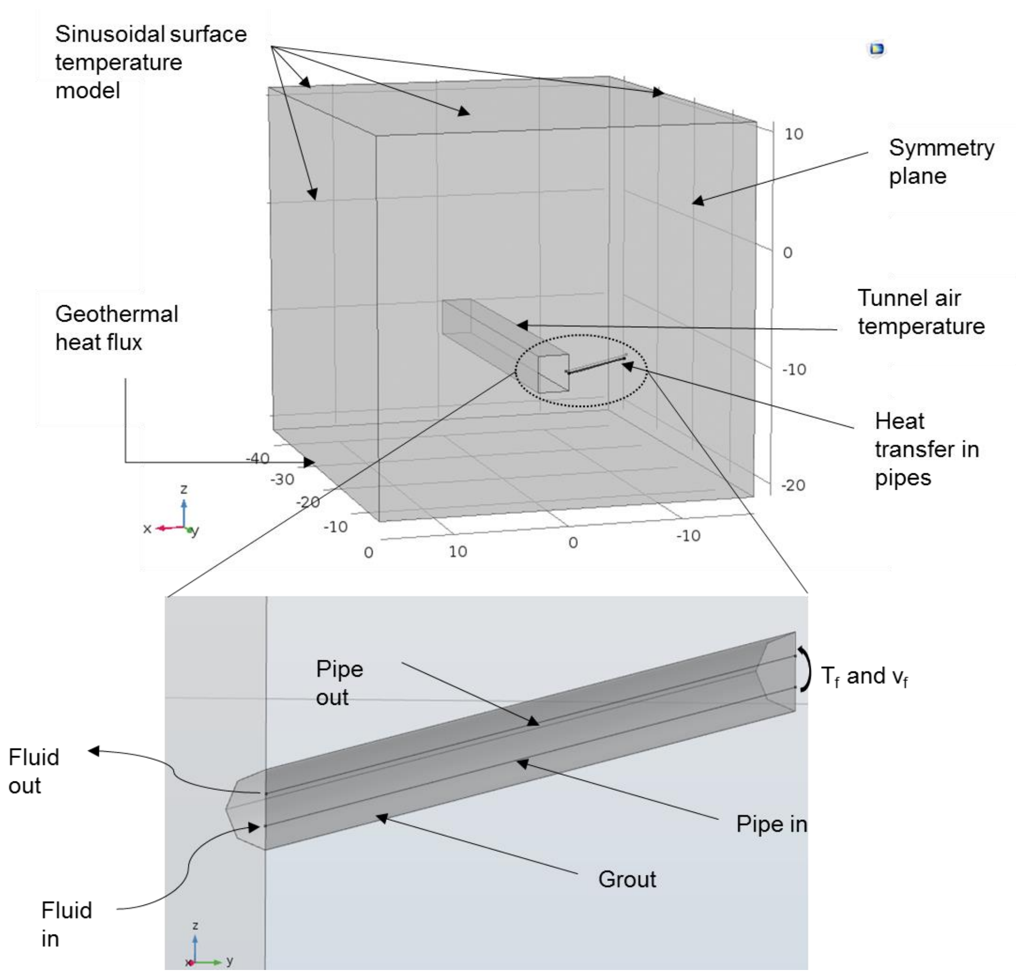

Figure 1. Numerical model set-up.

The temperature prescribed as a boundary condition of the upper surface and outer walls was modelled using the sinusoidal surface temperature variation given by Carslaw and Jaeger (1959). The temperature fluctuated with time according to the annual ground surface temperature change and attenuated with depth according to the thermal diffusivity of the ground. The temperatures at depth were calculated using the Equation 5:

$$T(z,t) = T_{z,0} + \Delta T_{z,0} e^{-z\cdot\sqrt{\frac{\pi}{P\alpha}}} \cdot \cos\left(\frac{2\pi t}{P} - z \cdot \sqrt{\frac{\pi}{P\alpha}}\right) \tag{5}$$

Where $T(z,t)$ is the ground temperature at depth z (calculated from the ground surface) and time t, and $T_{z,0}$ is the annual mean ground surface temperature calculated from the annual mean surface air temperature using the following relationship $T_{z,0} = 0.71 \cdot T_A + 2.93$ proposed by Kukkonen (1986) to account for the temperature differences of ground and air due to snow cover. The $\Delta T_{z,0}$is the amplitude of annual ground surface temperatures, P is the period equal to one year (given in seconds), and α is the thermal diffusivity of the ground.

The air in the tunnel was heating up the surrounding rock, and the process was modelled as a heat convection. This convective boundary condition was used for the preheating of the model to account for the increase in rock mass temperature since the construction of the tunnel. Due to lack of sufficient temperature data from the tunnel, the preheating was fixed to one year. The heat flux through the tunnel walls was modelled using the Equation 6:

$$q_0 = h_{air}(L, p_A, T_{ext}) \cdot (T_{ext} - T) \tag{6}$$

where the q_0 is the heat flux through tunnel surfaces, and h_{air} is the convection coefficient that depends on the dimensions of the tunnel surface, air pressure (equal to 1 atm) and the tunnel air temperature T_{ext}. Additionally, a constant geothermal heat flux was prescribed on the bottom surface of the model.

The input parameters for the numerical model and some dimensions are given in Table 1.

Table 1. Input parameters for the numerical model of the in situ experiment.

Parameter	Unit	Value
Rock thermal conductivity	W/(m·K)	3.3
Rock density	kg/m^3	2700
Rock heat capacity	J/(kg·K)	800
Grout thermal conductivity	W/(m·K)	1.7
Pipe thermal conductivity	W/(m·K)	0.4
Geothermal heat flux	mW/m^2	37
Air temperature in the tunnel	°C	15
Distance between pipes	cm	3
Grout density	kg/m^3	1800
Grout heat capacity	J/(kg·K)	750
Flow velocity	m/s	0.6
Pipe inner diameter	mm	16
Pipe outer diameter	mm	20
Borehole diameter	mm	100
Experiment borehole length	m	5
Monitoring borehole length	m	5.3
Tunnel height	m	3.1
Tunnel width	m	2.7
Tunnel length	m	30
Fluid inlet temperature	°C	50
Annual mean air temperature, T_A	°C	5.6
Annual mean surface temperature $T_{z,0}$	°C	6.1
Amplitude of the annual surface temperature ΔTz,0	°C	8.3

The mesh sensitivity was performed by varying the distance between nodes along the borehole heat exchanger (h_L) to be 0.03, 0.02, 0.01, and 0.005 m, which increased the total number of elements accordingly. The fluid temperature at the borehole outlet was measured to find the optimum mesh size. The temperature was growing with the increase in the number of elements and stabilised at about 400 000 elements (Figure 2). The h_L of 0.01 m was selected for further analysis as further increasing the number of elements increased the temperature only by 0.004% and the calculation time was increased by 150%. The final mesh consisted of 387 268 elements with an average element quality of 0.75.

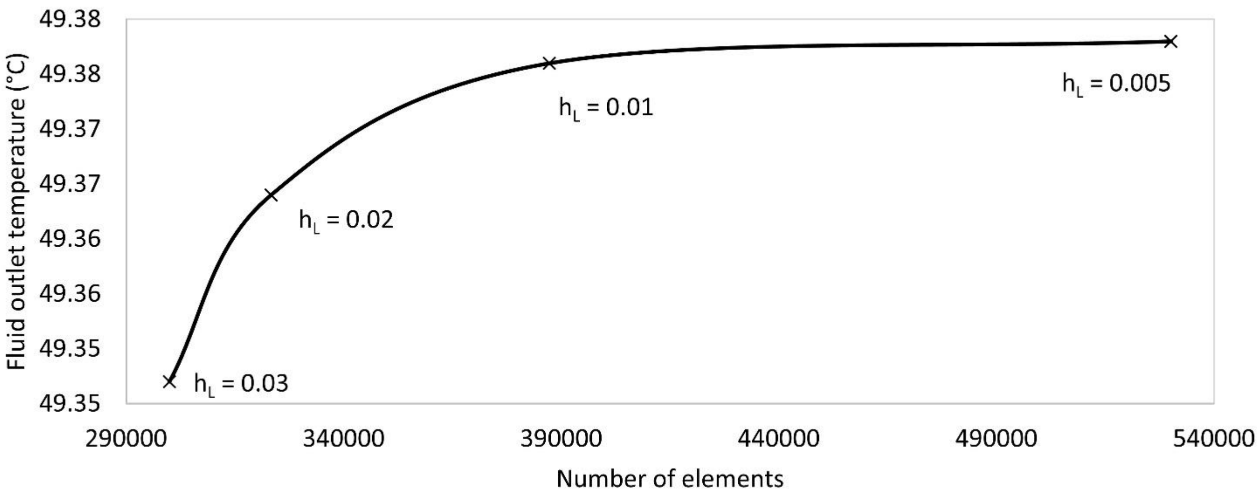

Figure 2. Mesh sensitivity study.

A parametric study was performed to find the most sensitive parameters in the numerical model. Selected parameters were varied by ±25% to find the most influencing ones (see Table 2). The temperature of the fluid at the outlet was used as an output value for comparison of the effect of each parameter.

Next, the fluid temperature at the outlet was calculated as a function of most sensitive parameters found in the previous step.

Table 2. Low (-25%), base, and high (+25%) values of parameters from the COMSOL model selected for the sensitivity analysis.

Parameter	Unit	Low	Base	High
Rock thermal conductivity	W/(m·K)	2.475	3.3	4.125
Rock density	kg/m^3	2025	2700	3375
Rock heat capacity	J/(kg·K)	600	800	1000
Grout density	kg/m^3	1800	2400	3000
Grout heat capacity	J/(kg·K)	562.5	750	937.5
Grout thermal conductivity	W/(m·K)	1.275	1.7	2.125
Pipe thermal conductivity	W/(m·K)	0.3	0.4	0.5
Geothermal heat flux	mW/m^2	27.75	37	46.25
Air temperature in the tunnel	°C	11.25	15	18.75
Distance between pipes	cm	3	4	5
Fluid velocity	m/s	0.45	0.6	0.75

3. RESULTS

After 21 days of continuous heating, the temperature of the rock surrounding the experimental borehole was increased as shown in Figure 3. The maximum temperature of the grout in the borehole reached 46.7 °C and the maximum temperature increase was expected in the middle of the borehole. The temperature profile decreased with distance from the experimental hole. The average temperature of the grout reached 35 °C and the expected rock temperature at the monitoring hole was 15 °C on average (see Figure 4). After the heating was stopped, the rock temperature decreased to around 11 °C after 15 days (see Figure 4).

The temperature profile of the fluid inside the BHE is shown in Figure 5. The expected temperature drop of the fluid after circulation in the U-tube decreased from 0.8 to 0.6 °C. Such low temperature drop was caused by the fast fluid velocity assumed in the model.

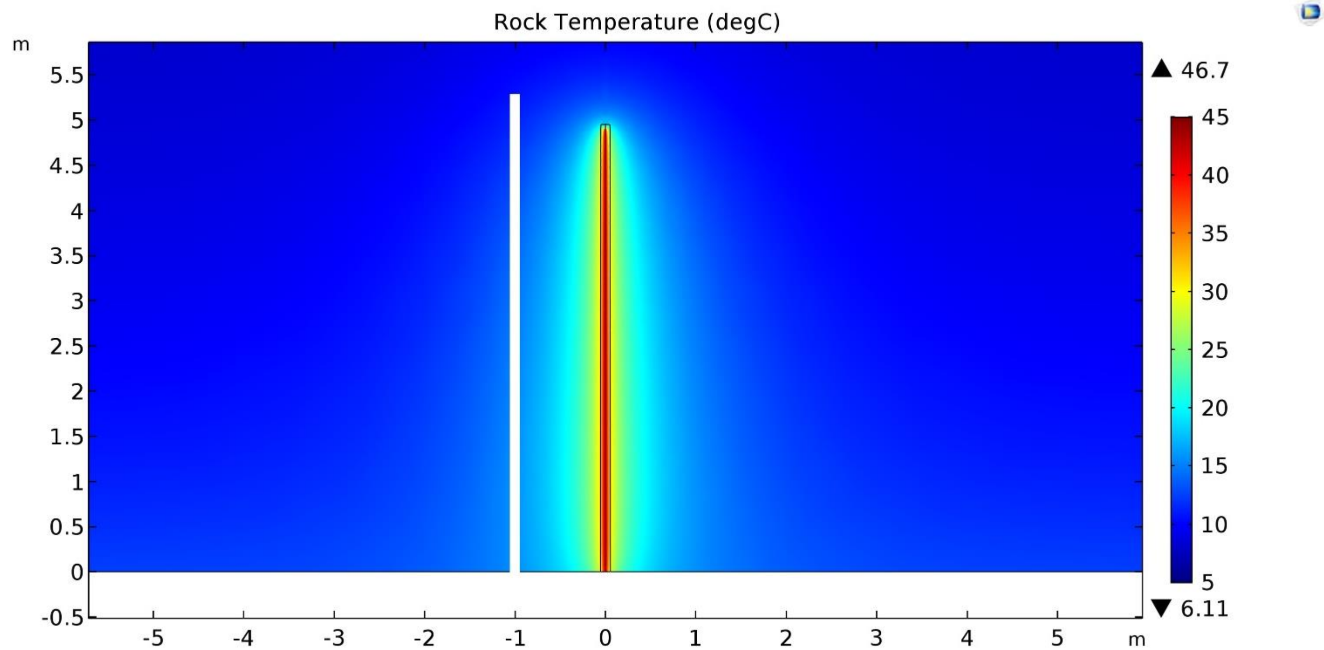

Figure 3. Rock temperature profile at a plane parallel to the experimental and monitoring boreholes after 21 days of heating.

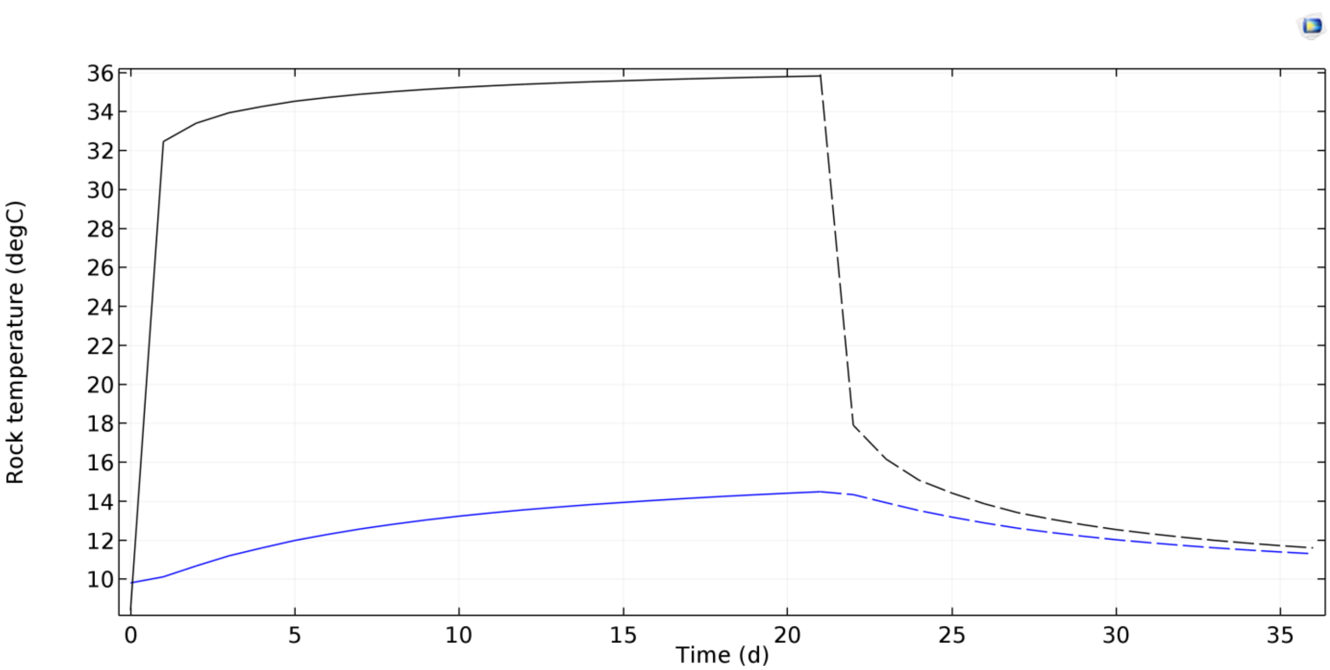

Figure 4. Average temperatures of the grout in experiment borehole (black), rock at the monitoring borehole (blue) during 21 days of heating and 15 days of cooling.

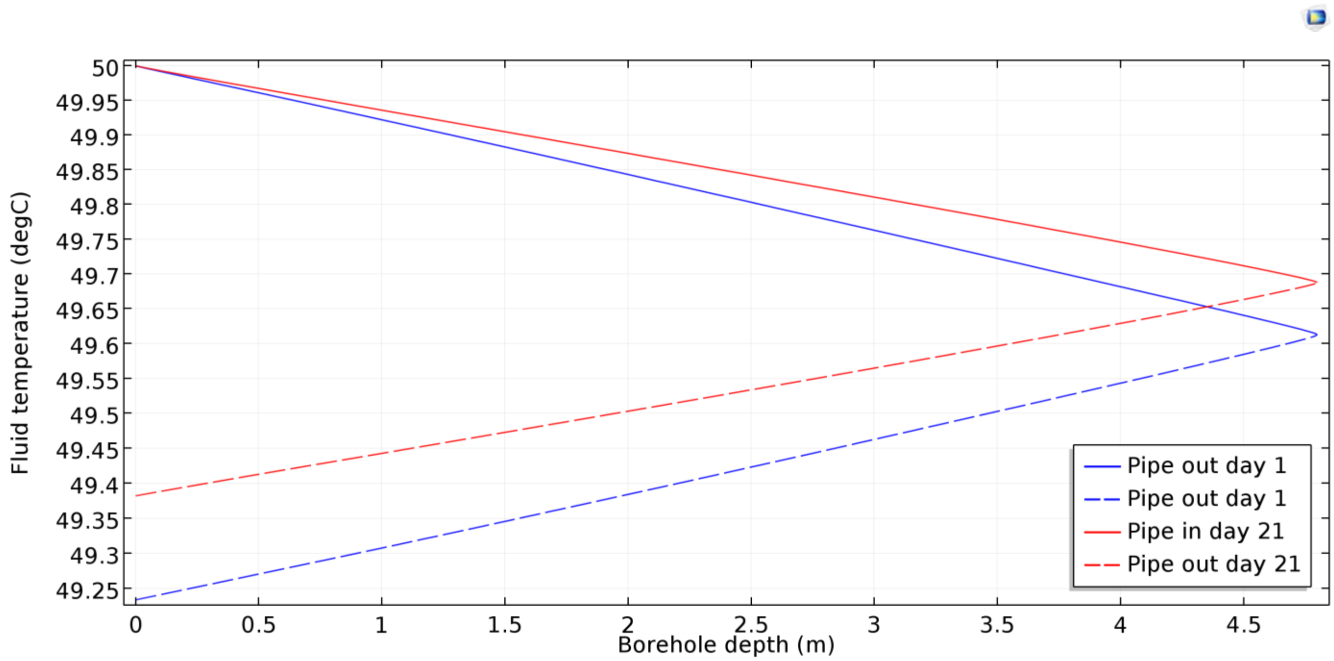

Figure 5. Fluid temperature profile inside the borehole heat exchanger on day 1 (blue) and day 21 (red).

The results of the sensitivity analysis of input parameters are plotted on a tornado graph depicted in Figure 6, where the effect of varying each parameter by ±25% is investigated. An increase of the temperature at the borehole outlet measured after 21 days of heating resulted in less heat transferred into the rock mass and vice versa. It was observed that the most important factors in the experiment results were the fluid velocity and thermal conductivity of rock and grout. The fluid temperature is also plotted as a function of the influencing parameters that were found in the previous step (see Figure 7). It can be seen that increasing the fluid velocity increased the temperature at the borehole outlet, which caused less heat transfer into the rock mass. Hence the measured temperature increase in the monitoring hole was smaller (Figure 7a). Opposite effect was observed for thermal conductivity of rock and grout, so their increase resulted in more heat transfer from the fluid into the rock, which is reflected by the lower fluid temperature at the borehole outlet (Figure 7b and 7c). The Smaller influence was expected from changes in the air temperature in the tunnel, the distance between the pipes, and the thermal properties of the pipe material. Variations in the heat capacity of the grout and the rock did not have any influence on the amount of heat transfer.

It should be noted that some parameters that affect the result can be modified in the experiment (e.g. fluid velocity and grout thermal conductivity) and should be set accordingly. Other parameters cannot be changed as they are governed by the local conditions (e.g. thermal properties of rock or air temperature in the tunnel). However, they can be measured precisely to be used for the detailed comparison of the measured and simulated results in the future.

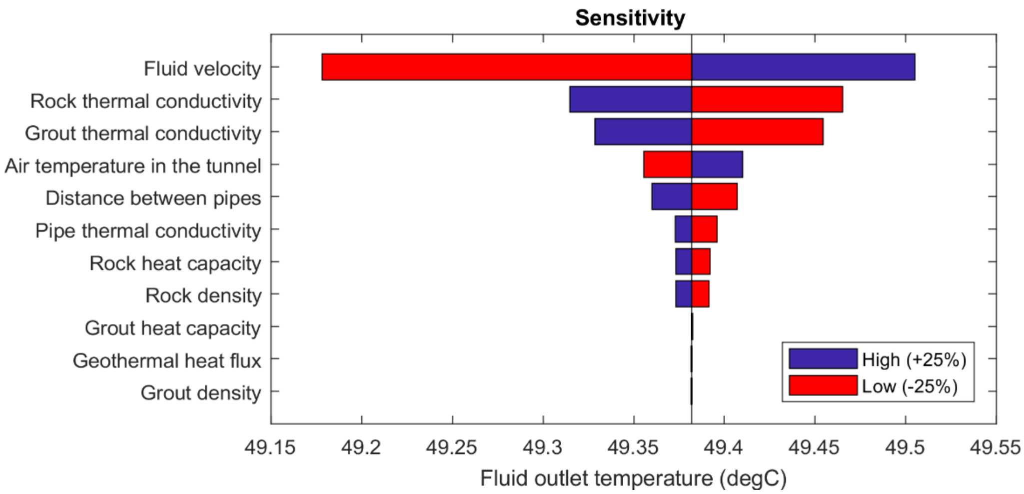

Figure 6. Sensitivity analysis of selected parameters of the COMSOL model. The output value compared in the analysis is the fluid temperature at the borehole outlet.

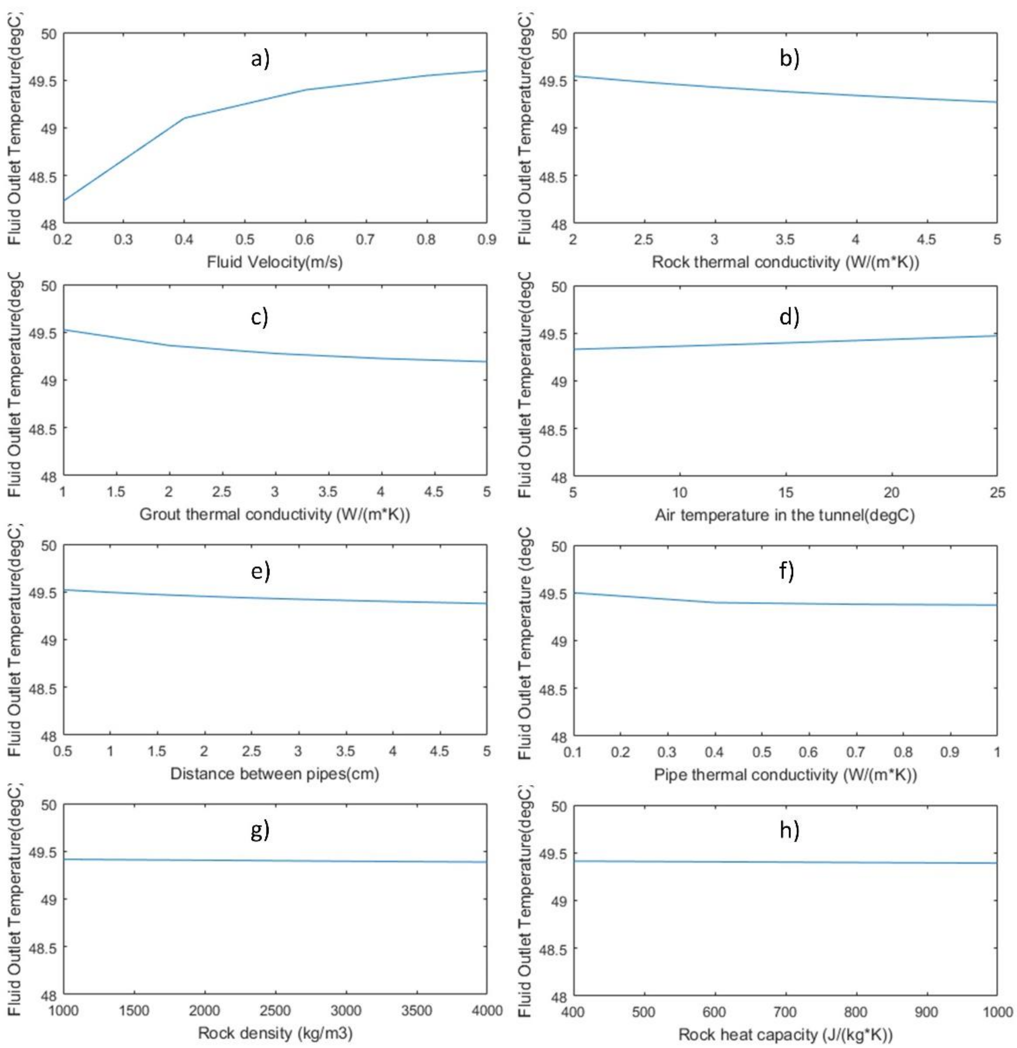

Figure 7. Fluid outlet temperature as a function of the eight most sensitive input parameters.

4. CONCLUSIONS

The *in situ* experiment set-up was successfully modelled numerically using finite element method. From the results of this study, it is clear that the most important factors influencing the experiment results are the fluid velocity and the thermal conductivity of rock and grout. The aim of the *in situ* test is to cause a measurable change in temperature in the rock. Thus the suggested modifications of the experiment to achieve an overall increase of the heat transfer into the rock mass is to decrease fluid velocity and to increase grout thermal conductivity. Other parameters are defined by the local conditions (e.g. rock thermal conductivity) or are less sensitive (e.g. pipe thermal conductivity). The results highlight the importance to conduct laboratory measurements of the used rock and grout thermal properties as their influence on the output is relatively high among the model input parameters.

In future studies, the simulated results will be compared to the measured values obtained in the experiment, and the numerical model will be calibrated.

ACKNOWLEDGEMENT

This study has been funded by the Academy of Finland through the New Energy research programme under grant no. 284977. The authors appreciate and acknowledge the financial support.

REFERENCES

Caballero, E. (2017). In situ experimentation and numerical model validation of thermal flow in shallow crystalline rock, Otaniemi case. Master's thesis. Delft University of Technology, Delft, The Netherlands (In progress).

Carslaw, H. S., Jaeger, J. C. (1959). *Conduction of Heat in Solids (2nd Ed.)*. Oxford University Press.

Janiszewski, M., Kopaly, A., Honkonen, M., Kukkonen, I., Uotinen, L., Siren, T. and Rinne, M., (2016). Feasibility of underground seasonal storage of solar heat in Finland, *Int. Conf. on Geomech., Geoen. and Geores.*, Melbourne, Australia: Monash University, pp. 959–965.

Janiszewski, M., Siren, T., Uotinen, L., and Oosterbaan, H. (2017). Modelling of Borehole Solar Energy Storage Concept in High Latitudes. *Geomechanics and Engineering* (In review).

Kukkonen, I., (1986). *Menneisyyden ilmastomuutosten vaikutus kallion lämpötilaan ja lämpötilagradienttiin Suomessa (The effect of past climatic changes on bedrock temperature gradients in Finland)*. Working report YST-55: Geological Survey of Finland.

Kurtz, S., Haegel, N., Sinton, R., and Margolis, R. (2017). A New Era for Solar. *Nature Photonics* 11 (1), pp. 3-5. doi:10.1038/nphoton.2016.232.

Oosterbaan, H., Janiszewski, M., Siren, T. and Uotinen, L. (2017). Numerical Thermal Back-calculation of the Kerava Solar Village Underground Thermal Energy Storage. *Procedia Engineering* 191(2017), pp. 352–360. doi:10.1016/j.proeng.2017.05.191.

Sanner, B., Hellström, G., Spitler; J. and Gehlin, S. (2005). Thermal Response Test – current status and world-wide application, *Proc. WGC 2005*, Antalya, 1–9.

Siren, T., Janiszewski, M., Uotinen, L., and Oosterbaan, H. (2017). Modelling of Borehole Solar Energy Storage Concept in High Latitudes. *YSRM2017 Conference*. Jeju, South Korea, May 11-13, 2017.