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# Modelling of Borehole Solar Energy Storage Concept in High Latitudes

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## Abstract

Globally there is an increasing pressure to reduce the greenhouse gas emissions and increase the use of renewable sources of energy. The storage of solar heat is a crucial aspect for implementing the solar energy for heating purposes especially in high latitudes, as it is the case in Finland, with sun insolation high in summer and almost negligible in winter when the domestic heating demand is high. To use the solar heating during winter thermal energy storages are required. In this paper, equations representing the single U-tube heat exchanger are implemented in weak form edge elements in COMSOL Multiphysics to dramatically speed up the calculation process for modelling of a borehole storage layout. Borehole seasonal solar heat storage of 6425 m$^3$ volume with 64 boreholes is successfully simulated. After 10 years of operation the simulated borehole pattern recovers 62.8% of the stored seasonal thermal energy and provides 380 MWh of thermal energy for heating in winter.

**Keywords:** Solar energy, Seasonal storage, Numerical modelling, COMSOL, Weak form

## 1. Introduction

Globally there is an increasing pressure to reduce the greenhouse gas emissions and increase the use of renewable sources of energy. One of the common applications of renewable energy is the solar heat, where energy from the sun is used to heat up water and space in buildings. The storage of solar heat is a crucial aspect for implementing the solar energy for heating purposes. This is especially important in high latitudes, as it is the case in Finland, where sun insolation is highest in the summer when the heating demand is low and lowest in winter when the demand is high.

Previously the authors concluded that the borehole thermal energy storage (BTES) is recommended method for seasonal solar heat storage for small solar community (Janiszewski *et al.*, 2016). In this paper, the implementation of a weak form edge element is presented with the modelling results of a borehole storage layout using COMSOL Multiphysics® 5.2a software. The models can be used for optimisation of the thermal energy borehole storage concept for a small solar community.

Numerical modelling of borehole heat exchangers (BHE) requires much computational power due to the high ratio of length (over 100 m) and diameter (around 0.1 m) of the borehole. The types of BHE that are commonly used are the coaxial, double or single U-tube. BTES facilities may contain over 150 of BHEs, so a faster way of calculating their thermal performance is needed.

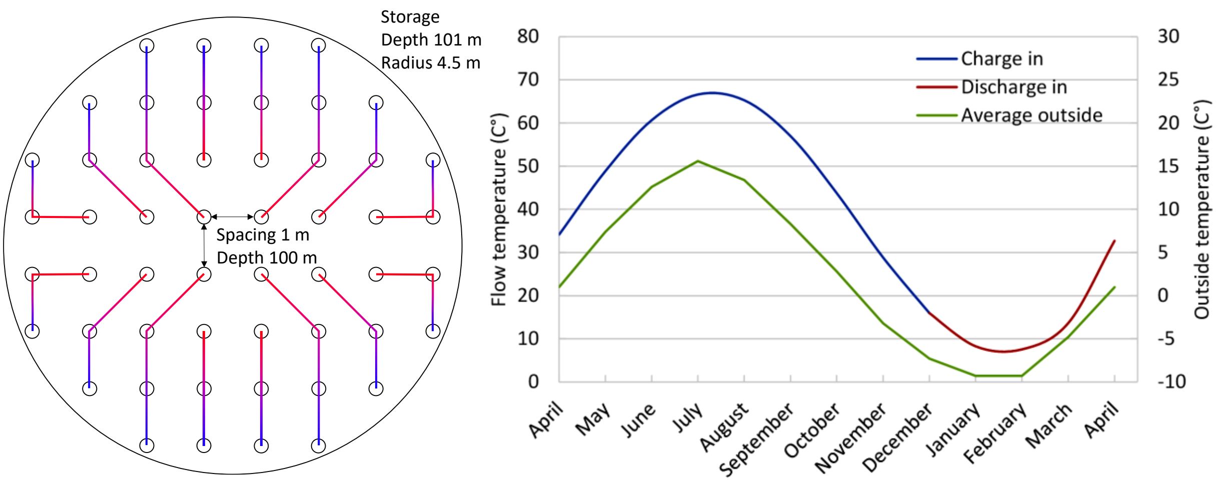


Fig. 1. The borehole pattern used in the modelling (on left) and the annual charge/discharge cycle temperatures (on right) with average reference outside temperature in Finland (FIM, 2017).

While the internal behaviour of a single U-tube borehole heat exchanger can be represented analytically through three equations (Eq. 1–3), it is not possible to solve them directly. However, the solution can be approximated using the weak form equations which interact with the external FEM through shared node points on the edge. This makes the modelling of large borehole fields possible in minutes, allowing the optimisation of the BTES.

In this paper, a borehole field of 64 boreholes with single U-tube heat exchangers and 6425 $m^3$ storage volume is calculated using a quarter symmetric 3D model. In charging mode, the hot water is inserted from the centre of the borehole field, and it exits at the perimeter. In discharging mode cold water is inserted from perimeter and exits at the centre. To simplify the model, the average monthly charge/discharge temperatures are used and the only discharge cycle during the year is used in winter. The system is designed to provide heating for 25 houses. The used borehole field charge/discharge cycles starting from March with charging cycle is visualised in Fig. 1.

## 2. Theoretical framework

In this study, the long-term behaviour of an underground thermal storage is studied with one 8 month charge and one 4 month discharge period annually. The input temperature is changed using continuous function throughout the year, averaging daily fluctuations out. Therefore, the steady-state heat transfer can be assumed. The set of strong form differential equations (Eq. 1–3) of the steady-state heat transfer in a single U-tube are given by Al-Khoury *et al.* (2005):

$$-\lambda_r \frac{d^2 T_i}{dz^2} dV_i - \rho_r c_r \frac{\alpha u h}{2} \frac{d^2 T_i}{dz^2} dV_i + \rho_r c_r \mathrm{u} \frac{dT_i}{dz} dV_i + b_{ig}(T_i - T_g) dS_{ig} = 0 \tag{1}$$

$$-\lambda_r \frac{d^2 T_o}{dz^2} dV_o - \rho_r c_r \frac{\alpha u h}{2} \frac{d^2 T_o}{dz^2} dV_o - \rho_r c_r u \frac{dT_o}{dz} dV_o + b_{og}(T_o - T_g) dS_{og} = 0 \tag{2}$$

$$-\lambda_g \frac{d^2 T_g}{dz^2} dV_g - \lambda_g \left(\frac{\mathrm{d}T_g}{\mathrm{d}z} n_z\right) dS_g - b_{ig}(T_g - T_i) dS_{ig} + b_{og}(T_g - T_o) dS_{og} = 0 \tag{3}$$

where the $\rho_r$ is the density and $c_r$ is the heat capacity of the refrigerant fluid. The $T_i$, $T_o$, and $T_g$ are the temperatures of the flow-in, flow-out, and grout, respectively. The $h$ is the characteristic length, $\alpha$ is the diffusion term, $\lambda_r$ and $\lambda_g$ are the thermal conductivity of the fluid and grout, respectively, and the $b_{ig}$, and $b_{og}$ are the reciprocals of the thermal resistance between the pipe-in and grout, and pipe-out and grout, respectively. The strong form equations are converted into a set of weak form equations (Eq. 4–6) by multiplying with a test function $N^T$, integrating by parts, and using the boundary conditions to get:

$$\int_{V_i} \lambda_r \frac{dN^T}{dz} \frac{dT_i}{dz} dV_i + \int_{V_i} \rho_r c_r u \left(\frac{\alpha h}{2} \frac{dN^T}{dz} + N^T\right) \frac{dT_i}{dz} dV_i + \int_{S_{ig}} b_{ig} N^T (T_i - T_g) dS_{ig} = 0 \tag{4}$$

$$\int_{V_o} \lambda_r \frac{dN^T}{dz} \frac{dT_o}{dz} dV_o + \int_{V_o} \rho_r c_r u \left(-\frac{\alpha h}{2} \frac{dN^T}{dz} + N^T\right) \frac{dT_o}{dz} dV_o + \int_{S_{og}} b_{og} N^T (T_o - T_g) dS_{og} = 0 \tag{5}$$

$$\int_{V_g} \lambda_g \frac{dN^T}{dz} \frac{dT_g}{dz} dV_g - \int_{S_g} b_{sg} N^T (T_g - T_s) dS_g - \int_{S_{ig}} b_{ig} N^T (T_g - T_i) dS_{ig} - \int_{S_{og}} b_{og} N^T (T_g - T_o) dS_{og} = 0 \tag{6}$$

where $b_{sg}$ is the reciprocal of the thermal resistance between the grout and surrounding rock. The weak form equations (Eq. 4–6) are then implemented in COMSOL Multiphysics as weak form edge PDEs and illustrative example of their interactions is shown in Fig. 2.

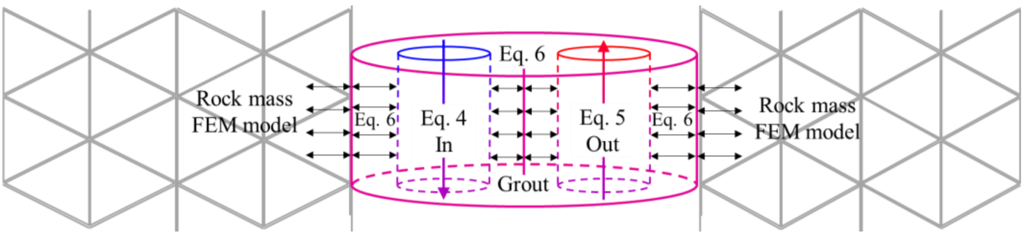


Fig. 2. An illustrative example of the interactions of the implemented heat transfer equations.

The Eq. 4 and Eq. 5 represent the in- and out-going flow temperature at a calculation node, respectively, and Eq. 6 the temperature of the grout that interacts both with the in and out-going flows and the rock mass through FEM mesh.

The list of input parameters for the numerical model is given in Table 1. The reciprocals of thermal resistance factors between both pipes and grout, and grout and rock are calculated using the analogy between Fourier's and Ohm's laws for heat flow and current flow, respectively (see Al-Khoury *et al.*, 2005).

Table 1. Input parameters for the numerical model.

| Parameter | | Value | Unit | Reference |
|---|---|---|---|---|
| $T_s$ | Initial ground temperature | 5.39+z·1.2/100 | °C | Sedighi *et al.* (2013) |
| $L$ | Borehole length | 100 | m | |
| $r_b$ | Borehole radius | 110 | mm | Al-Khoury *et al.* (2005) |
| $r_{i,o}$ | Inner and outer pipe radii | 16 and 19 | mm | Al-Khoury *et al.* (2005) |
| $\lambda_p$ | Pipe thermal conductivity | 0.3 | W/(m·K) | Al-Khoury *et al.* (2005) |
| $b_{ig},b_{og}$ | Reciprocal of thermal resistance pipe to grout | 58 | W/(m$^2$·K) | Al-Khoury *et al.* (2005) |
| $\lambda_s$ | Ground thermal conductivity | 3.2 | W/(m·K) | Kukkonen and Peltoniemi (1998) |
| $\rho_s$ | Ground density | 2635 | kg/m$^3$ | Kukkonen *et al.* (2011) |
| $c_s$ | Ground heat capacity | 840 | J/(kg·K) | Kukkonen and Peltoniemi (1998) |
| $\lambda_g$ | Grout thermal conductivity | 5.5 | W/(m·K) | Al-Khoury *et al.* (2005) |
| $b_{sg}$ | Reciprocal of thermal resistance grout to rock | 15 | W/(m$^2$·K) | Al-Khoury *et al.* (2005) |
| $\lambda_r$ | Fluid thermal conductivity | 0.5 | W/(m·K) | Al-Khoury *et al.* (2005) |
| $\rho_r$ | Fluid density | 1336 | kg/m$^3$ | Al-Khoury *et al.* (2005) |
| $c_r$ | Fluid heat capacity | 2830 | J/(kg·K) | Al-Khoury *et al.* (2005) |
| $\nu_r$ | Fluid kinematic viscosity | $4.2\cdot10^{-6}$ | m$^2$/s | Al-Khoury *et al.* (2005) |
| $\alpha$ | Diffusion term | 0.3 | - | Al-Khoury *et al.* (2005) |
| $h$ | Characteristic length | 2 | m | Al-Khoury *et al.* (2005) |
| $Pr$ | Fluid Prandtl number | 10.2 | - | Pitts and Sisson (1998) |

## 3. Results

The mean storage temperature increases up to 30 °C during 10 year modelling period (see Fig. 3). After 5 years the operation of the thermal energy storage is almost balanced. After 10 years of operation, the BTES can provide 380 MWh of the seasonal thermal energy out of the 605 MWh thermal energy stored into the system during summer, as shown in Fig. 4. The calculated energy loss during the 10th year is 225 MWh. The energy required to operate the storage is not included.

The maximum error of the temperature in the model is 1 % momentarily, while the flow direction is changed, caused by the use of steady state functions. However, the total error is less as only two flow direction changes during each modelled year. The total calculation time for the ten ye<ar simulation with 16 boreholes using Intel i7-4900MQ processor is 1 hour.

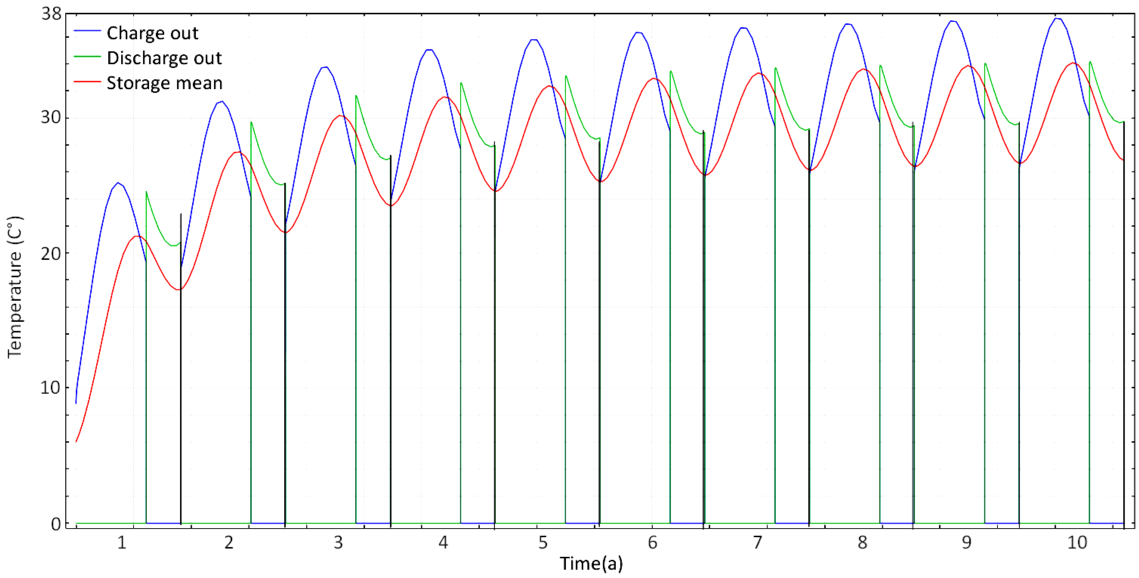


Fig. 3. Outgoing charge, discharge and mean storage temperatures, first year starting with charging from March.

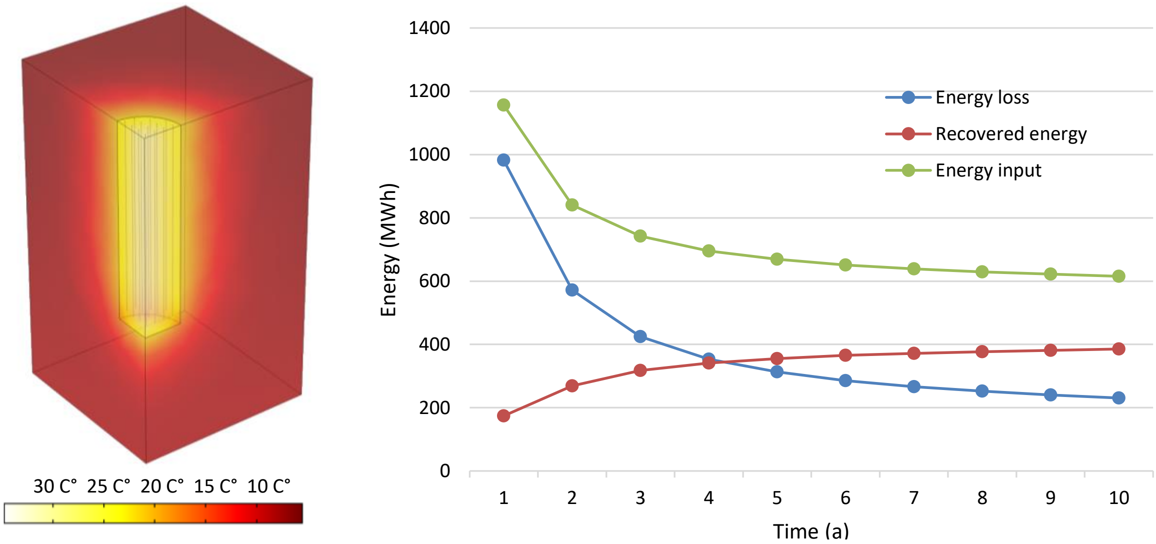


Fig. 4. Temperature distribution in the model after 10 years of heating (on left), energy input, loss and recovered thermal energy (on right) during 10 year modelling period.

## 4. Conclusion

In this study, the thermal performance of seasonal solar heat storage is successfully simulated using the weak form equations of the heat transfer in a single U-tube. The implementation of weak form equations reduces the computing time significantly to reasonable for running multiple calculations for optimisation purposes. The suggested borehole pattern of the BTES can recover 62.8% of the stored seasonal thermal energy after 10 years of operation.

In future research, the transient equations will be implemented into the weak form edge PDEs to allow better resolution when the flow direction is reversed or the fluid temperature is altered.

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