Borehole thermal energy storage for industrial heat waste

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Abstract: - Analysis of the heat waste recovery consists of evaluation of the borehole thermal energy storage capacity to inject and extract heat energy. The establishment of Vaasa Energy Business and Innovation Center (VEBIC) platform in Finland, is to promote energy business in the country, was chosen as a test building to study the energy storage. One of the feature of the platform is to test diesel engine technology for marine industry. During the operation of these engines, ultra-exhaustion heat is produced which may be stored in a borehole thermal energy storage (BTES). This study investigates heat waste recovery operation to find optimal parameters for the BTES. There are five examples made to estimate an appropriate size of the storage with respect to the given heat waste signal. The configuration consist of nine boreholes with varying depth and the borehole to borehole distances. Results showed that the storage with a depth of 250 meters has the most stable response and it was suitable for the given system. Heat transfer in the selected storage is calculated by varying the volumetric flow rate. Optimal flow rate for the selected system was found to be 1.5 liter per second. A case study is proposed for extraction of the heat energy with a heat pump. The required heating demand of the test building is estimated to be met with a series connection of four boreholes from the charged BTES.

Key-Words: - Industrial heat waste recovery, Borehole thermal energy storage, Heat extraction, Heat injection, Comsol modeling.

1 Introduction

There are two aspects of borehole thermal energy storage (BTES) considered in this study. One aspect deals with injection of thermal energy extracted from exhaustion of the diesel engines tested in the engine laboratory. The second aspect deals with extraction of the stored energy and using it to heat the test building. Industrial heat waste can be a significant heat energy source. By replacing fossil energy sources, it might also reduce emission of greenhouse gases. In order to achieve this goal, the potential of thermal energy storage with respect to injection/extraction must be analyzed. The availability of industrial heat waste varies from country to country [22]. The potential energy conversion of the heat waste could be estimated by collecting data of the industry producing heat waste [21]. In Finland, the amount of heat waste might be big enough to make investments in order to use it. The potential to use industrial heat waste may also be estimated by investigating the heat demand and statistical analysis of energy consumption in a region [20 23]. The applications of using industrial exhaust heat are elaborated in details in [24]. These applications include a variety of heat harvesting operation with energy storage from small scale to large scale projects. Thermal energy storage (TES) is one of the widely considered application that is used in some cases of industrial heat recovery [25]. The use of TES plays an important role in improving the overall efficiency of a heat waste recovery system [17]. The technical constraints of heat recovery may be influenced due to mismatching demand and availability of energy, heat lost and charging rate [18 19].

BTES should be precise enough to be able to absorb all the heat energy charges into it. Implementing a large size BTES significantly increases the capital investment and small size BTES results into heat loss from storage. Design of heat storage should also be analyzed with respect to the thermal constraints of the ground [8]. There are many models proposed over the years to analyze the heat transfer from a heat source to the surrounding ground. The most popular remains line source and cylinder source model [4 9]. These models predict heat propagation into soil induced by infinite heat source. Line source model was later improved for a finite heat source in the ground to elaborate heat transfer in geothermal heat exchangers [16]. Temperature distribution in the ground has also been proposed by using finite element method in [11 12]. Ground heat exchangers are essentially U-tube (single/double) or coaxial tube in most of the applications. Spiral coils are also used in some small scale applications [7 1]. The influence of groundwater flow on these applications may increase heat loss [6 13]. Heat loss may be prevented by grouting these boreholes. Another constraint that may contribute to the rise of heat loss in the BTES is thermal resistance of boreholes. Proper assessment of thermal resistance is required [2]. The efficiency of BTES comprises of the individual performance of boreholes in any configuration and the energy output produced in any network [15 14]. Heat extraction is proposed in details in [5]. The use of ground heat exchanger combined with heat pump is elaborated in [10].

Performance of energy storage reveals the feasibility of BTES in an industrial application. Economical and technical specifications may be modeled to minimize the risk of investment and evaluate the efficiency of the system [28]. Flexibility of TES may also be determined on a district scale to conduct a ratio analysis of energy production and consumption [29]. Performance of TES in shallow ground in rural areas (off-grid) may bring insights to compare the economic aspects between large and small scale application [3]. Optimal use of BTES may also depend on the distribution side assessment. These systems may be designed to serve a specific building in space heating and domestic hot water production [27]. Large scale injection/extraction applications require heat management either storage or distribution side [26]. This study is arranged in sections where an overview and research questions are stated. Modeling parameters for the given system is presented in the following section. In the consequent section, injection and extraction processes for the given system are elaborated and results are discussed. Finally, study is concluded with predictions and queries.

2 Overview and aims of the study

The studied system is illustrated in (Fig. 1). It combines two aspects of this study namely injection and extraction of heat energy in BTES. More heat waste, generated by diesel engine, results in more heat gain in the storage. In the first part of this study, depth of BTES is estimated by trial and error. There are five examples of BTES made with varying depth from 40 - 250 meters. When heat energy injected in BTES, the storage with the most stable thermal response is selected to be the optimal for the given parameters. The second part deals with extraction capability of BTES to supply heat energy to a test building. This study aims to answer the following questions:

- The size and configuration of BTES for given heat waste?
- To estimate the amount of heat transferred to the BTES?
- To calculate the amount of heat extracted from the BTES?

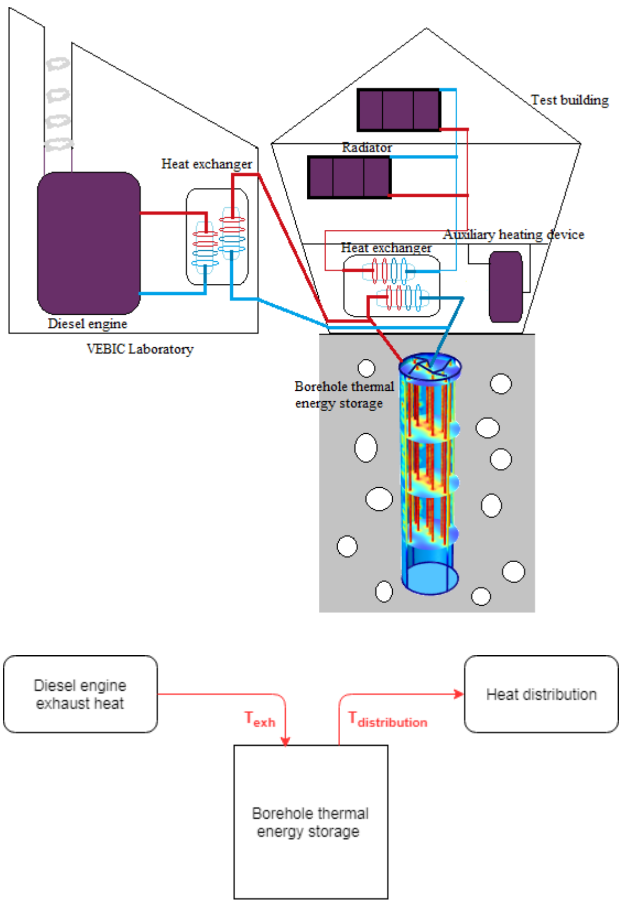

Figure 1. The system illustrates a diesel engine connected with a heat exchanger to store heat energy in a BTES. BTES is used to supply heat energy to a building. The block diagram shows a comprehensive process of heat injection and extraction of BTES.

3 Modeling borehole thermal energy system

The BTES is modeled in Comsol. The configuration consists of a series connection of nine boreholes shown in (Fig. 2). This series connection is made to facilitate the injection process. The constructed configuration shows an inlet followed by four boreholes which enable four outlet. The constructed configuration is modeled with five depths of (40, 100, 150, 200, 250) meters. In 40 meters deep configuration, borehole to borehole distance is selected to be 2.5 meters. The rest are implemented with a 5 meters borehole to borehole distance. Material of the ground is assumed to be metamorphic rock (common rock type in Finland).

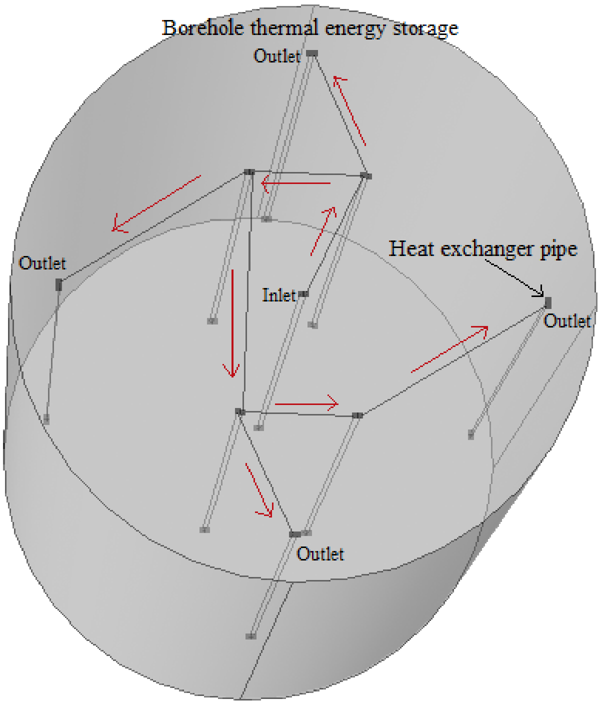

Figure 2. 3D Model of the BTES with a series connection depicting the inlet and outlet points in the configuration.

Heat transfer in the ground is defined as:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla . q = Q \quad (1)$$

$$q = -k \nabla T \quad (2)$$

Where, ρ (kg/m^3) is density, C_p (J/kg·K) is specific heat capacity, T (°C) is temperature, t (s) is time duration, q (W/m^2) is heat flux, k (W/m·K) is thermal conductivity of the ground and Q (W/m^3) is volumetric heat source in the region. Heat transfer in pipe reacting by the pipe flow is described as:

$$\rho A C_p u . \nabla T = \nabla . A k \nabla T + f_D \frac{\rho A}{2 d_h} |u|^3 + Q_{wall} \quad (3)$$

Where, u (m/s) is velocity, d_h (m) is hydraulic diameter, f_D is dimensionless Darcy friction factor, and A (m^2) is cross sectional area of the pipe.

$$Q_{wall} = hZ(T_{ext} - T) \quad (4)$$

Where, Q_{wall} (W/m) is external heat transfer, Z (m) is wetted parameter, and h (W/m^2·K) convective heat transfer at the boundary. The element size in mesh setting produced 29441 domain elements, 1512 boundary elements and 979 edge elements. Parameters used in this simulations are presented in Table 1.

Table 1. Parameters used in the simulations.

Parameter	Symbol	Value
Radius of the ground	r_g	12 (m)
Depth of the BTES	L	40, 100, 150, 200, 250 (m)
Distance between boreholes	d_g	2.5, 5 (m)
Flow rate of fluid	q	1 (l/s)
Thermal conductivity of ground	k_g	3.4 (W/m·K)
Initial ground temperature	T_0	6 (°C)
Surface temperature	T_{sur}	5 (°C)
Inner pipe diameter	d_i	35.2 (mm)
Thermal conductivity of pipe	k_p	0.4 (W/m·K)

4 Heat injection

A trial and error approach is taken to analyze the heat injection process. An input signal is assumed with respect to the given information of the system in (Fig. 3). Heat waste from diesel engine is connected with a heat exchanger where carrier fluid absorbs heat and circulates to the BTES.

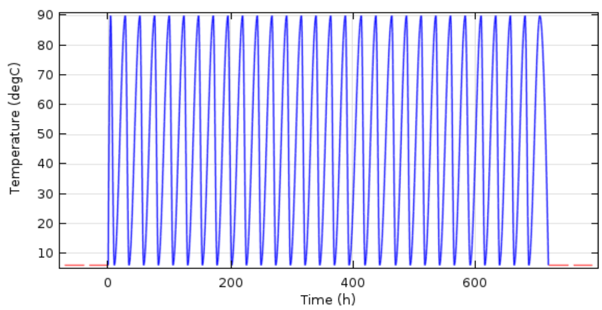

Figure 3. The input signal applied at the BTES.

Exhaustion temperature is not taken into account in this study since BTES is the prime focus in this study. The input signal is established with the knowledge of incoming fluid temperature rise up to 90 ºC for a couple of hours a day. The temperature maintains at 6 ºC for the rest of the time in a day. An hourly simulation is conducted with one hour time step for a duration of one month. The amount of heat transferred to the BTES depends on constraints such as flow rate of the fluid, depth of the heat exchanger and thermal properties of the fluid and the ground. Heat energy transferred to the ground is illustrated in (Fig. 4).

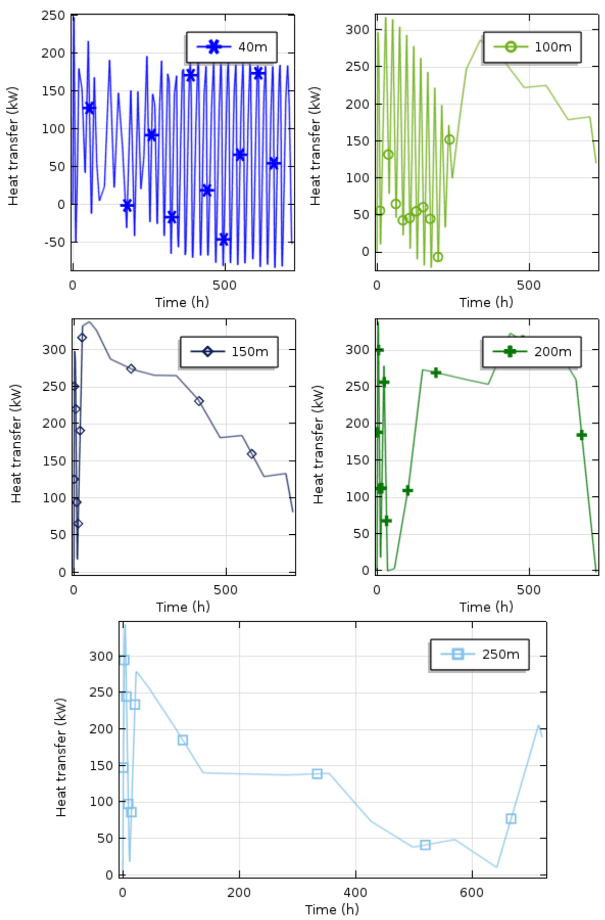

Figure 4. Heat transfer power estimated for variety of BTES. Each plot is calculated by modeling different depths of BTES.

There are five plots made for five models of BTES with varying depth. In the first two plots of 40 meters and 100 meters, heat transfer varies drastically as the input signal varies with time which means that BTES with small depths show high fluctuations because the carrier fluid did not get enough time to transfer heat energy to the BTES. The rest of the BTES models with higher depths than 100 meters show steady change in the heat transfer power which means carrier fluid gets enough time to transfer heat energy to the BTES. The amount of heat transfer in all the models found to be similar except the difference projected in the fluctuations of the signal is found most stable in the BTES with 250 meters depth.

The average temperature of BTES is shown in (Fig. 5) where surface temperature of BTES is presented with varying depth after one month of operation. The BTES with 40 meters depth displays a maximum temperature of 30 ºC and most of the storage maintains at 15 ºC. The surface temperature of 100 meters depth shows a maximum temperature of 40 ºC but the rest of the storage maintains as low as 10 ºC. The maximum surface temperature of 150 meters and 200 meters storage found at 30 ºC and 25 ºC. There is approximately a 5 ºC temperature difference including all the regions of the BTES. The surface temperature of BTES with 250 meters depth is seen to be between 10 ºC and 25 ºC. Most of the region in the storage shows small temperature rise. For a long term operation, BTES with 250 meters depth would be suitable in the given situation since heat transfer to the BTES is most stable and the temperature of the surface would have to gradually rise up.

The amount of heat transferred to the BTES can be controlled by varying volumetric flow rate of the carrier fluid. The volumetric flow rate were kept constant in the previous simulations at 1 (l/s). There are six simulations made to demonstrate the effect of volumetric flowrate on heat transfer to the BTES. Heat transfer to the BTES with 250 meters depth is shown in (Fig. 6). The stability of the response signal suggests the most appropriate flowrate for the given system. Figure 6 reveals that as the flowrate rises too high, the response signal fluctuates more. It is observed that flowrate between 0.5 – 1.5 (l/s) produce stable response signals. The flowrate of the carrier fluid may be increased as the heat source power increases. On the other hand, flowrate may be kept relatively low if the intensity of heat source is low. The average temperature of the ground is observed in all simulations. BTES with a depth of 250 meters introduces some technical difficulties in installation. Insulation of ground in this case is difficult and expensive which may escalate the heat loss from the horizontal sides and bottom of the storage. Another technical difficulty is unusual groundwater movement which may also intensify the heat loss from the storage. Grouting should be considered in this case so the heat loss may be

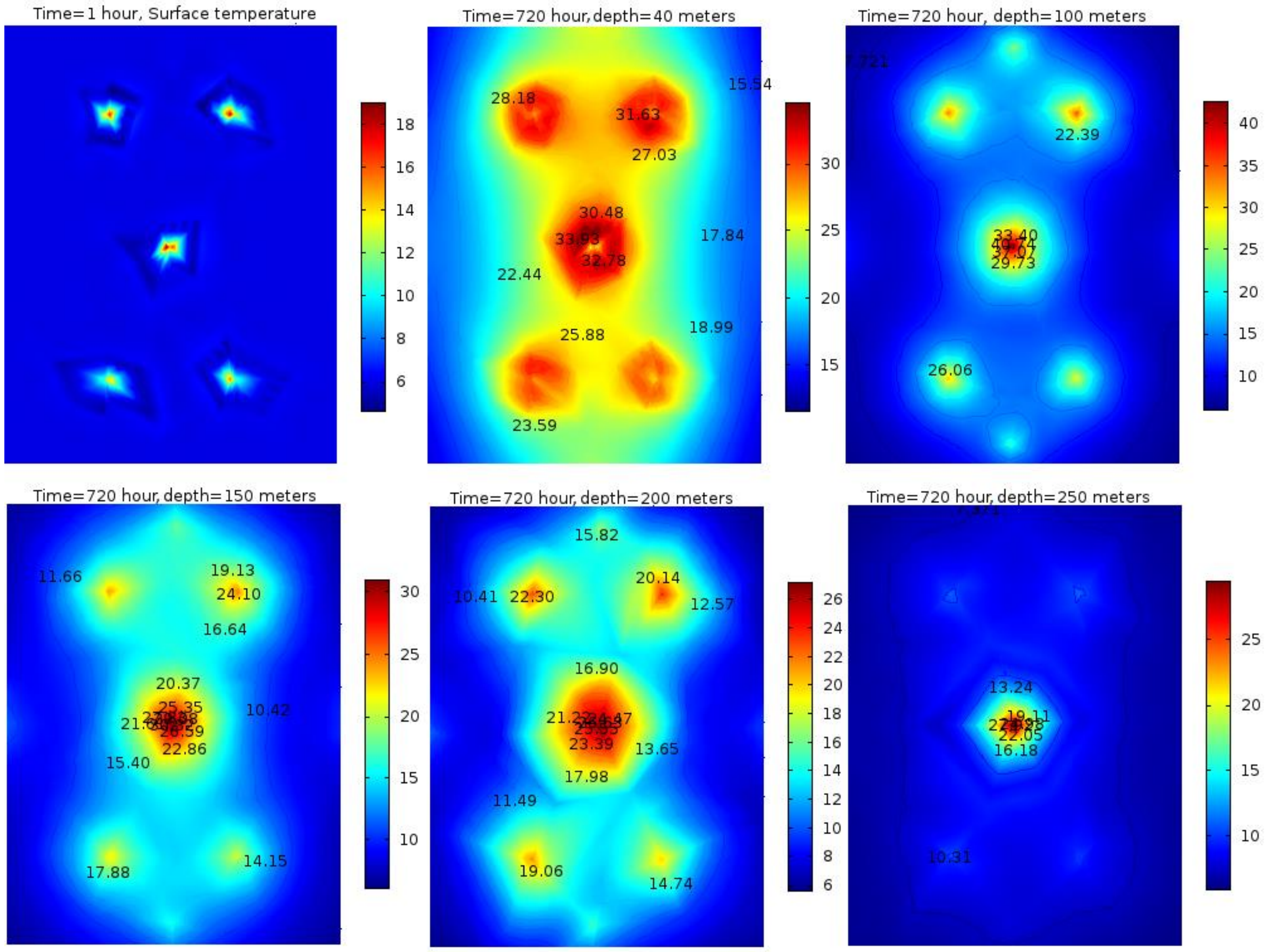

Figure 5. Surface temperature distribution of BTES with varying depths. Plots depict the last time step of the simulations.

minimized. Natural groundwater movement may not escalate the heat loss in the storage [5].

5 Heat extraction (A case study for a test building)

Heat extraction from a BTES is usually combined with a heat pump distribution channel to a building. Heating demand of a building is taken into consideration to estimate the amount of heat extraction from a BTES. In order to estimate the amount of heat extraction from the given BTES that is charged in the previous section, a test building is assumed. Standardized statistics are used for the test building. An appropriate heating demand for this test building is stated as follows:

- Area of the test building = 3268 m^2.
- Net Heating demand = 25 – 105 kWh/m^2 [30].
- Heating demand of test building = 10.39 – 43.65 kW.
- Heat pump capacity of the test building = 60 kW.

The heat capacity of the heat pump seems to be higher than the heating demand of test building but the above statistics only considers space heating and leave out domestic hot water production. The test building is a reflection of VEBIC lab where a 60 kW heat pump is installed to meet the demand of the building. The assumptions made for the test building bring the study closer to real case scenario.

In the previous section, heat waste signal was injected into a BTES which lead to the rise of temperature of the storage illustrated in (Fig. 5) in a period of one month. The implication of surface temperature rise in the BTES is presented in this section for the heat extraction process. The heat

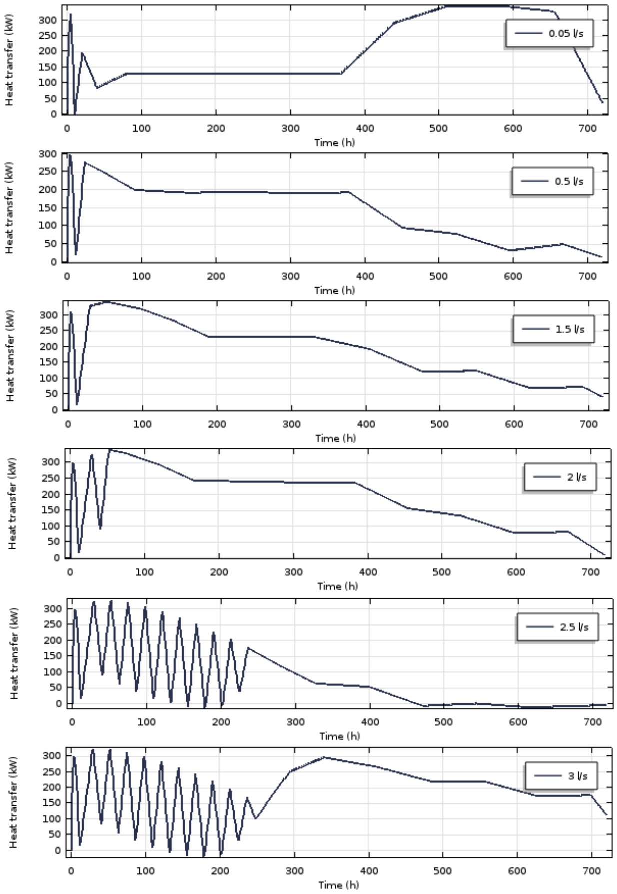

Figure 6. Heat transfer power variation with respect to volumetric flowrate in the BTES with 250 meters depth.

transfer for one borehole is calculated and then the number of boreholes required to meet the above mentioned demand of the test building is estimated. Table 2 presents the parameters used for this calculation. Heat capacity is calculated for a single U-tube ground heat exchanger [10]:

$$L = \frac{Q\left(\frac{COP-1}{COP}\right)(R_b+R_gF_h)}{T_g-\left(\frac{EWT_{min}+LWT_{min}}{2}\right)} \quad (5)$$

Where Q (W) is heat capacity of heat pump, COP is coefficient of performance, L (m) is length of borehole, R (m·K/W) is thermal resistance, F_h is run fraction, T_g (ºC) is temperature of ground, EWT_{min} (ºC) is entering water temperature, and LWT_{min} (ºC) is leaving water temperature. The average entering and leaving water temperatures recommended to be 0 ºC [30]. Figure 7 illustrates the estimated heat transfer for the given scenario. It predicts the capacity of individual borehole and form a series connection with respect to the given heat requirement for the test building. On x-axis, one borehole represents a depth of 250 meters ground heat exchanger. Heat demand of the test building is met by a series connection of four boreholes as depicted in (Fig. 7).

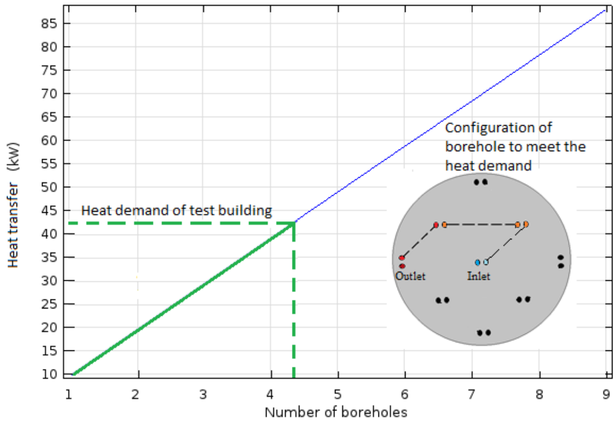

Figure 7. Heat transfer in the BTES. Heat demand of the test building is displayed with green line which is met by the given configuration of the BTES.

Table 2. Parameters used in calculation of heat capacity

Parameter	Symbol	Value
Borehole diameter	D_b	140 (mm)
pipe outer diameter	D_o	40 (mm)
pipe inner diameter	D_i	35.2 (mm)
Mean temperature of source	$(EWT_{min} + LWT_{min})/2$	0 (ºC)
Ground temperature	T_g	10 (ºC)
Coefficient of performance	COP	4
Thermal conductivity of ground	k_g	3.4 (W/m·K)
Thermal conductivity of grout	k_b	0.57 (W/m·K)
Thermal conductivity of pipe	k_p	0.4 (W/m·K)

6 Results and discussion

This study is focused on utilizing BTES for injection and extraction of heat energy. Both processes may run individually or simultaneously. The BTES does not reflect as a seasonal heat storage where heat injection is dedicated for summer season and heat extraction process left for the rest of the year. In the given scenario, heat waste can be injected in BTES during any season in which case it should be flexible enough to operate both

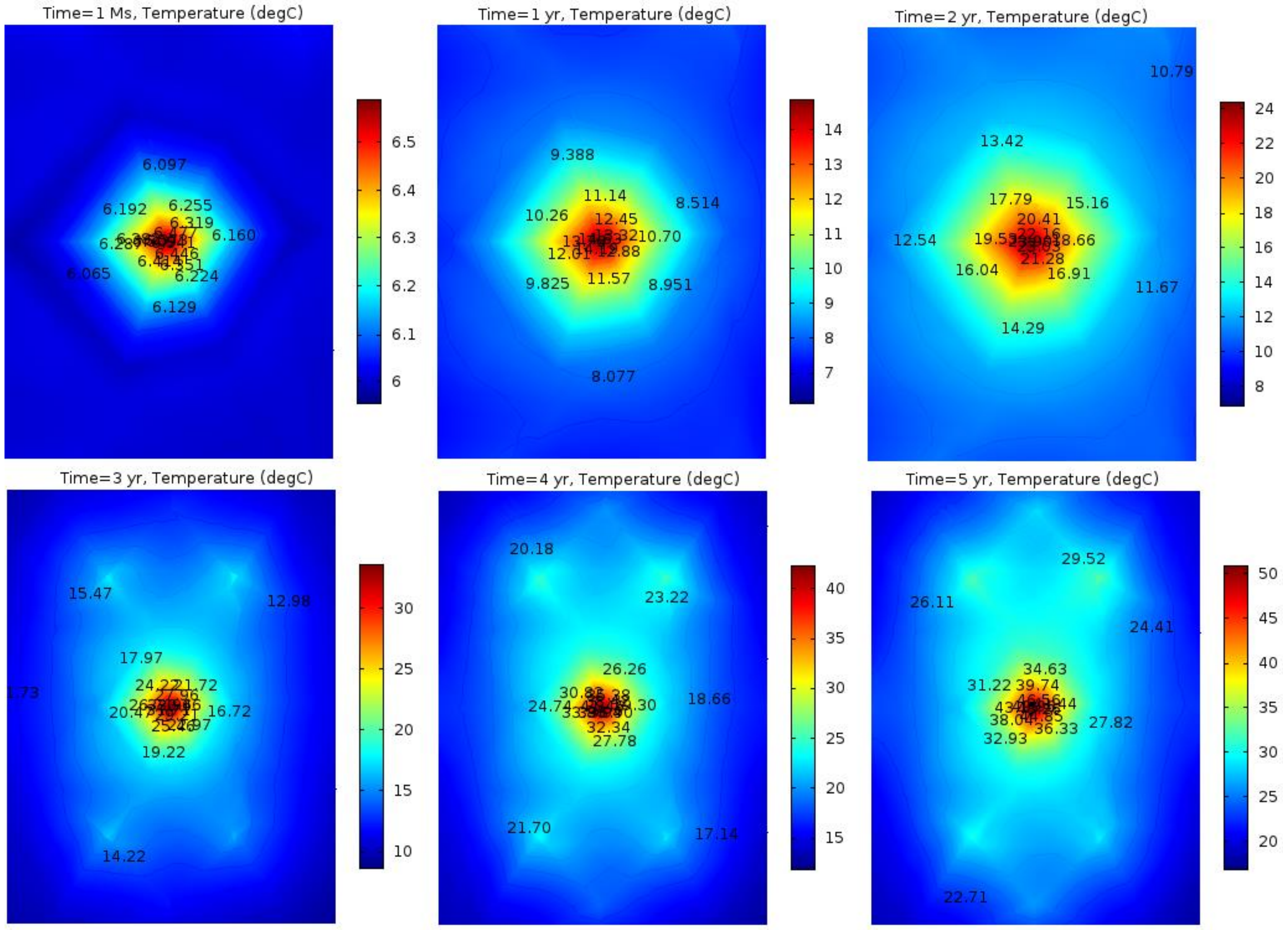

Figure 8. Surface temperature distribution over five years of operation.

operations simultaneously. The ultimate goal of heat injection in BTES is to increase the temperature of the ground which is contained with the help of insulation of the heat storage. Increased ground temperature can significantly increase the efficiency of a heat pump during heat extraction process. This can be mathematically understood with eq. (2) where ground temperature is inversely proportional to the length of the ground heat exchanger (borehole). As the temperature of the ground increases, the required length of the ground heat exchanger decreases which in practice results in the efficiency increase. BTES with a reasonably increased temperature would increase the efficiency of a heat pump which results in decreased electricity consumption. Figure 8 shows temperature rise in the BTES with the same input injection signal approximated from industrial heat waste. The five year simulation results in the temperature rise from 6 °C to 20 °C at a minimum. This graph represents only the injection process without considering heat extraction.

In this study, heat transfer in the extraction process is estimated for a single borehole. A combined network analysis may also be done for a precise calculation. This study approximates heat transfer for all the boreholes with a single borehole estimation. Coefficient of performance is considered to be 4 which is an international standard for a reasonable performance with an average of entering and leaving carrier fluid temperature of 0 °C (also standard in Finland [30]). The performance of the heat pump may be improved even more if the average fluid temperature rise over 0 °C. The heat extraction discussed in the previous section suggests a series connection of four boreholes to meet the demand of the test building. This proposition can be enhanced with respect to the increase or decrease in heat demand. If heating demand of the test building increases, additional boreholes can be connected in series to increase the required heat transfer. If heating demand of the test building decreases, less than four boreholes can be used to meet the demand.

7 Conclusion

The aim of this study was to investigate the use of BTES for industrial heat waste recovery. The injection process discusses the size of the storage with respect to the input heat waste signal. The size of the storage may vary which depends on the intensity of the heat injection signal. The role of volumetric flowrate in the heat transfer to the BTES is discussed. Thermal response of various depth of BTES is presented. Results indicated that BTES with 250 meters depth is suitable for the given scenario.

In order to utilize this charged BTES, a test building with a sufficient heating demand is assumed which is based on VEBIC laboratory. Extraction process is approached with respect to heat transfer in the BTES with a suitable heat pump. Results suggested that out of nine boreholes, a series combination of four boreholes may be sufficient to deliver the required heating demand of the test building.

This study presents a comprehensive model to investigate the use of BTES for injection and extraction processes. To store heat energy in the BTES, it is important to realize the size of boreholes with respect to the amount of heat waste to be injected. Section 4 estimated the amount of heat transferred in BTES with varying depths by applying the same input signal. Heat extraction process from a BTES depends on the heat capacity of selected heat pump and required heating demand of the building. Section 5 calculated the heat capacity of individual borehole in this small scale application and presented a series combination of boreholes to meet the required heating demand.

References:

[1] Y. Man, H. Yang, N. Diao, J. Liu, and Z. Fang, “A new model and analytical solutions for borehole and pile ground heat exchangers,” Int. J. Heat Mass Transf., vol. 53, no. 13–14, pp. 2593–2601, 2010.

[2] D. Marcotte and P. Pasquier, “On the estimation of thermal resistance in borehole thermal conductivity test,” Renew. Energy, vol. 33, pp. 2407–2415, 2008.

[3] M. Jradi, C. Veje, and B. N. Jørgensen, “Performance analysis of a soil-based thermal energy storage system using solar-driven air-source heat pump for Danish buildings sector,” Appl. Therm. Eng., vol. 114, pp. 360–373, 2017.

[4] H. S. Carslaw, J. C. Jaegar, “Conduction of heat in solid,” (Oxford University Press.) Oxford, 1947.

[5] P. Eskilson, “Thermal Analysis of Heat Extraction Boreholes,” Doctoral Thesis, (University of Lund.) Sweden, 1987.

[6] A. Nguyen, P. Pasquier, and D. Marcotte, “Borehole thermal energy storage systems under the influence of groundwater flow and time-varying surface temperature,” Geothermics, vol. 66, pp. 110–118, 2017.

[7] P. Cui, X. Li, Y. Man, and Z. Fang, “Heat transfer analysis of pile geothermal heat exchangers with spiral coils,” Appl. Energy, vol. 88, no. 11, pp. 4113–4119, 2011.

[8] G. Hellström, “Ground heat storage: thermal analyses of duct storage systems,” Doctoral Thesis, (Lund University.) Sweden, 1991.

[9] L. R. Ingersoll, O. J. Zobel, and A. C. Ingersoll, “Heat conduction with engineering, geological and other applications,” (McGraw-Hill,) New York, 1954.

[10] G. Narsilio, I. Johnston, A. Bidarmaghz, O. Mikhaylova, A. Kivi, and R. Aditya, ”Geothermal Energy: Introducing an emerging technology,” International conference on advances in civil engineering for sustainable development, Suranaree University of Technology, 2014.

[11] R. Al-Khoury, P. G. Bonnier and R. B. J. Brinkgreve, “Efficient finite element formulation for geothermal heating systems. Part I : Steady state,” Int. J. Numer. Meth. Engng, April 2004, pp. 988–1013, 2005.

[12] R. Al-Khoury, P. G. Bonnier and R. B. J. Brinkgreve, “Efficient finite element formulation for geothermal heating systems. Part II : Transient,” Int. J. Numer. Meth. Engng, pp. 988–1013, 2006.

[13] J. Hu, “An improved analytical model for vertical borehole ground heat exchanger with multiple-layer substrates and groundwater flow,” Appl. Energy, vol. 202, pp. 537–549, 2017.

[14] L. Lamarche, “Mixed arrangement of multiple input-output borehole systems,” Appl. Therm. Eng., vol. 124, pp. 466–476, 2017.

[15] A. Lazzarotto, “A network-based methodology for the simulation of borehole heat storage systems,” Renew. Energy, vol. 62, pp. 265–275, 2014.

[16] H. Y. Zeng, N. R. Diao, and Z. H. Fang, “A Finite Line-Source Model for Boreholes in Geothermal Heat,” Heat Transfer-Asian Research, vol. 31, no. 7, pp. 558–567, 2002.

[17] M. Chinnapandian, V. Pandiyarajan, A. Prabhu, and R. Velraj, “Experimental Investigation of a Cascaded Latent Heat Storage System for Diesel Engine Waste Heat Recovery,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 37, no. 00, pp. 1308–1317, 2015.

[18] V. Pandiyarajan, M. Chinnappandian, V. Raghavan, and R. Velraj, “Second law analysis of a diesel engine waste heat recovery with a combined sensible and latent heat storage system,” Energy Policy, vol. 39, no. 10, pp. 6011–6020, 2011.

[19] V. Pandiyarajan, M. C. Pandian, E. Malan, R. Velraj, and R. V Seeniraj, “Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system,” Appl. Energy, vol. 88, no. 1, pp. 77–87, 2011.

[20] S. Brueckner, L. Miró, L. F. Cabeza, M. Pehnt, and E. Laevemann, "Methods to estimate the industrial waste heat potential of regions – A categorization and literature review," Renew. Sustain. Energy Rev., vol. 38, pp. 164–171, 2014.

[21] C. Forman, I. K. Muritala, R. Pardemann, and B. Meyer, "Estimating the global waste heat potential," Renew. Sustain. Energy Rev., vol. 57, pp. 1568–1579, 2016.

[22] L. Miró, S. Brückner, and L. F. Cabeza, "Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries," Renew. Sustain. Energy Rev., vol. 51, pp. 847–855, 2015.

[23] L. Miró, S. Brueckner, R. Mckenna, and L. F. Cabeza, "Methodologies to estimate industrial waste heat potential by transferring key figures : A case study for Spain," App. Energy,vol. 169, pp. 866–873, 2016.

[24] S. B. Viklund, and M. T. Johansson, "Technologies for utilization of industrial excess heat : Potentials for energy recovery and CO 2 emission reduction," Energy Convers. Manag. Conv. Manag, vol. 77, pp. 369–379, 2014.

[25] L. Miró, J. Gasia, and L. F. Cabeza, "Thermal energy storage (TES) for industrial waste heat (IWH) recovery : A review," Appl. Energy, vol. 179, pp. 284–301, 2016.

[26] D. F. Dominkovic, B. Cosic, Z. Bacelic, and N. Duic, "A hybrid optimization model of biomass trigeneration system combined with pit thermal energy storage," Energy. Conv. Manag, vol. 104, pp. 90–99, 2015.

[27] E. Kjellsson, G. Hellstrom, and B. Perers, "Optimization of systems with the combination of ground-source heat pump and solar collectors in dwellings," Energy, vol. 35, pp. 2667–2673, 2010.

[28] Y. Huang, Y. D. Wang, H. Chen, X. Zhang, J. Mondol, N. Shah, and N. J. Hewitt, "Performance analysis of biofuel fired trigeneration systems with energy storage for remote households," Appl. Energy, vol. 186, pp. 530–538, 2017.

[29] T. Nuytten, B. Claessens, K. Paredis, J. Van Bael, and D. Six, "Flexibility of a combined heat and power system with thermal energy storage for district heating," Appl. Energy, vol. 104, pp. 583–591, 2013.

[30] A. Laitinen, P. Tuominen, R. Holopainen, P. Tuomaala, J. Jokisalo, L. Eskola, and K. Siren, "Renewable energy production of Finnish heat pumps, Final report of the SPF-project," VTT Technology, 164, 2014.