DESIGN CONSIDERATIONS FOR THERMAL ENERGY STORAGE SYSTEMS IN SUBARCTIC CLIMATE

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Abstract

Borehole thermal energy storage system (BTES) is a mature technology to provide heating needs of buildings. It can thus contribute to the transition to sustainable green energies in northern Canada. Its efficiency strongly depends on the design and the subsurface conditions in which it is implemented. This study presents a sensitivity analysis of the main parameters influencing BTES operating in the subsurface near freezing conditions. Numerical simulations were performed in FEFLOW to estimate the average heat pump coefficient of performance (COP) of 68 different scenarios of a BTES with 25 borehole heat exchangers (BHE). An initial scenario was constructed and the COP was averaged during heat extraction periods. Then, 17 parameters were varied at constant steps (10% and 30% of their initial value) and their averaged COP was compared to the base case scenario. Results highlight parameters that need to be accurately estimated and optimized in order to maximize BTES efficiency. Thermal power injection/extraction, surface/volume ratio, BHE spacing, BTES layout compared to local groundwater direction and subsurface thermal properties are the parameters with the highest influence on the operating temperature. BTES initial scenario averages a COP of 2.92 over 4 years of operation. Worst-case scenario shows a mean COP of 2.74, whereas best-case scenario averages a COP of 3.05. This leads to a 13 GJ (+5.3%) energy gain difference between the worst and the best-case scenario over ~5.6 years of operation of heat extraction.

1. Introduction

Northern communities in Canada rely on fossil fuel to supply heating loads of their buildings. Ground-source heat pumps (GSHP) seem to be an interesting solution (Gunawan et al., 2020; Belzile et al., 2017). They can supply base-load heating needs and reduce fuel oil consumption which is the principal energy source of those communities. However, GSHP range of operation is commonly limited by the temperature of the heat carrier fluid such as -6.7 °C (Belzile et al., 2016). An alternative to prevent low temperature operation is BTES, a technology combining low-enthalpy geothermal technology to other green renewable energies such as solar energy. Solar radiation is converted into heat and transferred to the ground. Heat is stored in the ground throughout summer (maximum solar radiation), and then extracted during winter (maximum building's heating load) to ensure operation of the heat pump within a reasonable temperature range. The study site is located near the *Centre d'Études Nordiques* (CEN) research station at Whapmagoostui-Kuujjuarapik in northern Quebec. The accessibility of the facilities and heating load data of the building was a major reason to choose this site. The regional geology is composed of a low-permeable granitic bedrock, partially covered by unconsolidated sediments, where fractures govern groundwater flow within either a confined or an unconfined aquifer (Fortier et al., 2011). Designing a BTES can be laborious since there are numerous parameters affecting its performance. This study aims to assess the main parameters and their impact on a BTES's performance in a subarctic climate. Numerical simulations are used to calculate the COP of different scenarios.

2. Methods

Numerical modelling is an efficient calculation method to solve coupled heat transfer problems such as BTES operation under groundwater flow influence. Numerical models were thus developed in FEFLOW (Diersch, 2014) to simulate groundwater flow and heat transfer mechanisms of the studied granitic media near the CEN. The developed model distinguishes five input parameter categories: thermal and hydrogeological properties, boundary conditions (BC), BHE configuration, and heating power demand.

For this study, we considered a simplified conceptual model only made of granitic bedrock, the principal geological formation in the area. Eleven granitic outcrops were sampled near the CEN and analyzed for thermal property assessment at the Laboratoire Ouvert de

Géothermie (LOG) at INRS-ETE. Hydrogeological data from previous groundwater research studies in Whapmagoostui-Kuujjuarapik were inventoried (GPR International inc., 2002). These data were used to simulate and calibrate a regional 3D groundwater flow numerical model in order to estimate the bedrock's hydraulic conductivity and the hydraulic gradient at the CEN. This numerical model was also used to define hydrogeological BC to the BTES numerical model. Heat transfer BC were determined according to data collected from previous field campaigns. Ground temperature data were recorded at 1 m and 2 m depth over the 2018-2019 period in unconsolidated sediments near the CEN. Air temperature data recorded at the CEN's meteorological station (CEN, 2017) were also collected. These temperature data were used to define the surface temperature BC at the top of the model from 152 to 304 days. Ground temperature shows the insulating effect of the snow cover. A -1 °C surface temperature was therefore assigned from 0 to 152 days and from 304 to 365 days in order to represent this effect (Fig.1a). Temperature profiles recorded in observation wells (< 120 m depth) in the vicinity of the CEN were used to define a constant temperature boundary at the bottom of the model.

The BTES is composed of 25 BHE spaced by 3 m forming a cubic storage volume of 1728 m³ (12 x 12 x 12 m), with 864 m² (12m x 12m x 6 sides) of exposed surfaces with a minimal surface/volume ratio (0.5 m^{-1}; Skarphagen et al., 2019). The initial BTES configuration was determined to obtain a reasonable thermal storage volume that keeps the heat carrier fluid temperature operating range above -6.7 °C to respect a lower operating threshold temperature typically available in commercial heat pumps.

Extracted energy yearly profile (Fig.1b) of a yearlong inhabited residential building at the CEN in Whapmagoostui-Kuujjuarapik was estimated by the mechanical engineering team of Université Lavalinvolved in this research project. Heating load was estimated with simulations in TRNSYS according to building plans and occupation, and then calibrated with the 2018-2019 diesel energy bills. Injected energy yearly profile was calculated according to the following elements: the recorded solar radiation data at the CEN's meteorological station from 2005 to 2016 (CEN, 2017); the maximum number of photovoltaic solar panels to be installed on the CEN's roofs (162 solar panels of 2 m²); a solar panel efficiency of 14% (standard crystalline silicon panel); a power loss of 5% due to dip and orientation of solar panels (https://re.jrc.ec.europa.eu/pvg_tools/fr/); a hypothetical 10% heat loss due to tank storage/heat circulation.

The numerical model mesh of the initial scenario has 34 400 nodes, 63 745 prismatic triangular elements, 20 layers, 25 interconnected BHEs within 2 arrays (Fig.1a). The total borehole length was always equal to 300 m (12 m depth) even when the BHE spacing (parameter 1, Tab.1) and the surface/volume ratio (parameter 5, Tab.1) were varied (e.g. surface/volume ratio +10% = prismatic rectangle with edges of 6.99m × 20.61 m and a depth of 12 m). Nodal distance around BHE was defined according to Diersch et al. (2011), and the mesh was refined around the BTES. Time steps of 0.1 days were used for ~5.6 years (1955 days), in which there is heat injection from 120 to 274 days and no heat extraction from 274 to 485 days. We assume isotropic and homogeneous material, transient fluid flow /heat transfer and a fully confined aquifer for simplicity.

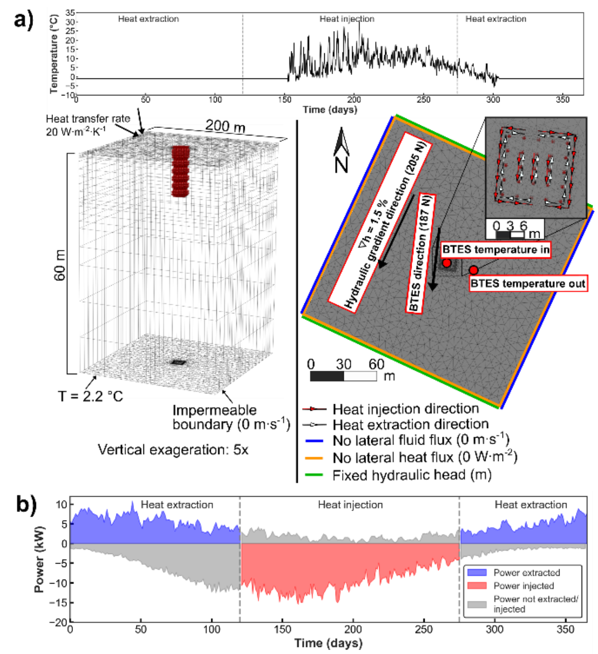

Fig. 1. a) Mesh construction and BC applied to BTES numerical model; b) energy yearly profile of the BTES.

Python scripts were also developed to process and simulate a heat pump when there is heat extraction from the BTES. The outlet temperature fluid of the arrays is retrieved at each time step and the COP is calculated according to technical details of an ecoGEO 1-9 kW heat pump (EcoForest, 2020). Inlet temperature of the arrays at the next time step is then calculated according to the COP. The entry point of the injected heat is at the BTES' upstream while heat extraction starts from the BTES's downstream (Fig.1a). Temperature at 6 m depth in the center of the BTES and 27 m out of the BTES' center is retrieved for each simulation (Fig.1a).

Parameters were varied one at a time by ±10% and ±30% of their initial scenario value to perform a sensitivity analysis. Each time a parameter was varied, the average COP of the four years of energy extraction simulation was estimated and then compared to the initial scenario.

Table 1 presents all parameters considered for the sensitivity analysis where 68 different scenarios were run. Worst and best-case scenarios were then simulated according to the values producing the lowest COP loss (worst-case scenario) or the greatest COP gain (best-case scenario) from the base case scenario. These two scenarios use the power extraction and injection values of the base case scenario in order to compare energy savings on the same basis. The selected value of each parameter for the worst/best-case is the same as its base case scenario value if there is no difference or no positive COP difference.

Table 1. Parameters values to perform the sensitivity analysis.

Category	Parameter		Base case scenario	Difference from initial scenario ±10 %	Difference from initial scenario ±30 %
(A) BTESS configuration	(1) Distance between BHE (m)		3.00	±0.30	±0.90
	(2) Borehole diameter (mm)		152.40	±15.24	±45.72
	(3) Difference between BTESS and hydraulic gradient direction (°)		0.00	±18.00	±54.00
	(4) Flow rate ($m^3 s^{-1}$)		$8.00 \cdot 10^{-4}$	$\pm 0.80 \cdot 10^{-4}$	$\pm 2.40 \cdot 10^{-4}$
	(5) Ratio surface/volume	Ratio (m^{-1})	0.50	0.05	0.15
		Surface (m^2)	864.00	86.40	259.20
(B) Thermal property	(6) Borehole thermal resistance ($m \cdot K \cdot W^{-1}$)		$8.00 \cdot 10^{-2}$	$\pm 0.80 \cdot 10^{-2}$	$\pm 2.40 \cdot 10^{-2}$
	(7) λ_{fluid} ($W \cdot m^{-1} \cdot K^{-1}$)		0.48	$\pm 4.80 \cdot 10^{-2}$	$\pm 14.40 \cdot 10^{-2}$
	(8) $\rho C_{p\ fluid}$ ($MJ \cdot m^{-3} \cdot K^{-1}$)		3.80	±0.38	±1.14
	(9) λ ($W \cdot m^{-1} \cdot K^{-1}$)		2.88	±0.29	±0.86
	(10) ρC_p ($MJ \cdot m^{-3} \cdot K^{-1}$)		2.30	±0.23	±0.69
(C) Hydrogeological	(11) K ($m \cdot s^{-1}$)		$5.80 \cdot 10^{-7}$	$\pm 0.60 \cdot 10^{-7}$	$\pm 1.80 \cdot 10^{-7}$
	(12) S_s (m^{-1})		$4.60 \cdot 10^{-5}$	$\pm 0.50 \cdot 10^{-5}$	$\pm 1.40 \cdot 10^{-5}$
	(13) Θ (-)		$0.02 \cdot 10^{0}$	$\pm 0.02 \cdot 10^{-1}$	$\pm 0.06 \cdot 10^{-1}$
(D) Boundary condition	(14) ∇h (m)		1.50	±0.15	±0.45
	(15) Heat transfer rate ($W \cdot m^{-2} \cdot K^{-1}$)		20.00	±2.00	±6.00
(E) Heat power	(16) Average power extraction (kW)		5.42	±0.54	±1.63
	(17) Average power injection (kW)		-9.63	±0.96	±2.89

3. Results

Results for the initial scenario averaged a COP of 2.92 throughout 4 years, a maximum and minimum simulated heat carrier fluid temperature at the inlet heat pump of 18.16 °C and -2.52 °C, respectively. A maximum and minimum simulated temperature of 16.42 °C and -0.92 °C were recorded in the middle of the BTES at 6 m depth, respectively. A maximum and minimum simulated temperature of 4.18 °C and 1.72 °C, respectively, were recorded outside the BTES at 6 m depth (Fig.2).

The results of the sensitivity analysis and the averaged COP for the worst/best-case scenarios are shown in Table 2. The most influential parameters inducing a relative COP gain/loss > 1 % in the 30% scenarios are parameters 1, 2, 5, 9, 10, 16 and 17 (Tab.2). The least influential parameters inducing a relative COP gain/loss < 0.1 % in the 30% scenarios are parameters 7, 8, 11, 12, 13, 14 and 15 (Tab.2). The worst-case scenario averaged a COP of 2.74 while the best-case scenario averaged a COP of 3.05.

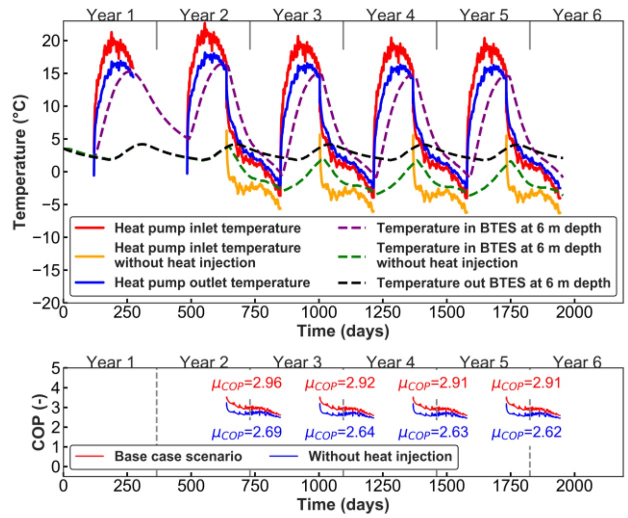

Figure 2. Base case scenario's simulated temperature and COP.

Table 2. Sensitivity of input parameters on averaged COP.

Base case scenario					2.92
Worst case scenario					2.74
Best case scenario					3.05
Category	**Parameter**	**COP difference from initial scenario (%)** -30% scenario	-10% scenario	+10% scenario	+30% scenario
(A)	(1)	- 0.68	- 0.64	- 1.45	- 1.88
	(2)	-1.05	- 0.84	- 0.66	- 0.53
	(3)	- 1.06	- 0.87	- 0.81	- 0.78
	(4)	+ 0.28	+ 0.06	- 0.03	- 0.06
	(5)	-	-	- 2.27	- 4.87
(B)	(6)	+ 0.48	+ 0.16	- 0.15	- 0.46
	(7)	0.00	0.00	0.00	0.00
	(8)	+ 0.27	+ 0.06	- 0.03	- 0.06
	(9)	+ 2.80	+ 0.78	- 0.66	-1.72
	(10)	-1.42	- 0.37	+ 0.30	+ 0.74
(C)	(11)	+ 0.05	+ 0.01	- 0.02	- 0.05
	(12)	0.00	0.00	0.00	0.00
	(13)	- 0.05	- 0.02	+ 0.02	+ 0.05
(D)	(14)	+ 0.05	+ 0.02	- 0.01	- 0.05
	(15)	+ 0.06	+ 0.02	- 0.01	- 0.03
(E)	(16)	+ 4.67	+ 1.51	- 1.57	- 4.46
	(17)	- 4.64	- 1.55	+ 1.56	+ 4.68

4. Discussion

Simulated temperature and calculated COP (Fig.2) show that there is no cumulative thermal energy gain or loss within 6 years. The simulated temperature of the heat carrier fluid and the COP reached an equilibrium suggesting that the BTES internal temperature is affected by seasonal surface temperature fluctuations due to the low depth of the BTES (12 m). However, the BTES cannot only rely on the seasonal temperature recharge during summer since the heat pump inlet fluid reaches a minimum temperature of -6.3 °C which is too close to the heat pump lower operating temperature threshold of -6.7 °C (Fig.2). The sensitivity analysis shows that the BTES performance can be significantly improved or decreased according to uncertainties of the input parameters. For example, the best-case scenario, which averaged a COP of 3.05 (Tab.2), can provide 265 GJ in energy savings with respect to the no-BTES case over 4 years of production, compared to 252 GJ for the worst-case scenario (COP of 2.74) and 245 GJ for the no-heat injection scenario (COP of 2.65; Fig.2). This difference, mainly due to various BTES configurations and geological properties (Tab.2), is expected to rise with increasing BTES volume.

Due to the short BHE length, the internal temperature of the BTES is affected by surface temperature variations and could potentially decrease if there is no snow cover insulating during the winter. Therefore, BHE layout is an important consideration to ensure the performance of this small-scale BTES. Specific storage does not have any influence on the results due to the assumption of a fully confined aquifer in order to simplify the numerical model. This assumption seems reasonable since porosity is a low and the granitic aquifer under study has a low capacity to store water. In addition, thermal conductivity of the heat carrier fluid does not affect the BTES because its effects are included into the borehole thermal resistance calculation in FEFLOW to simplify the analysis. Simulated scenarios did not include parameter interdependency and may sometimes be unrepresentative. Parameters interdependency should be considered in a BTES design when materials and configurations are chosen based on thermal and hydrogeological in situ conditions of the studied site. For example, a permeable aquifer with significant hydraulic conductivity can have a greater effect on the BTES's performance assessment. Indeed, the base case scenario with a greater hydraulic conductivity value would increase COP variations for the sensitivity analysis. Technical details of the ecoGEO 1-9 kW heat pump did not consider a propylene glycol-water mixture to calculate the COP. In fact, this mixture would induce a lower heat pump's COP. However, current results provide an initial assessment of the parameters influencing the BTES' performance with respect to the specific small-scale BTES studied in Whapmagoostui-Kuujjuarapik.

5. Conclusions

This study presented a sensitivity analysis of the main parameters affecting the operation of a BTES for a small residential building in Whapmagoostui-Kuujjuarapik, northern Quebec. BTES configuration, subsurface thermal properties and heat injection/extraction rate are the most influential parameters to consider for BTES design. The sensitivity analysis provided a better understanding of the parameters involved in the design of a BTES operated in a subarctic climate in order to help the implementation of sustainable green energies in this northern community. Future activities will simulate technical details of a heat pump considering a propylene glycol-water mixture to calculate the COP, an artificial insulation at the top of the BTES to analyze heat transfer effects and an in-depth analysis of the energy yearly profil. Methods and tools developed in the present study will also be useful to anticipate BTES efficiency and optimize the design at any latitude worldwide.

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