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Authors
Baser, Tugce
McCartney, John S
Moradi, Ali
et al.

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Impact of a Thermo-Hydraulic Insulation Layer on the Long-Term Response of Soil-Borehole Thermal Energy Storage Systems

Tugce Baser[1], M.S., S.M.ASCE; John S. McCartney[2], Ph.D., P.E., M.ASCE; Ali Moradi[3], M.S.; Kathleen Smits[4], Ph.D.; and Ning Lu[5], Ph.D., F.ASCE

[1]Graduate Research Assistant, University of California San Diego, Department of Structural Engineering, 9500 Gilman Dr. La Jolla, CA 92093-0085, tbaser@ucsd.edu.
[2]Associate Professor, University of California San Diego, Department of Structural Engineering, 9500 Gilman Dr. La Jolla, CA 92093-0085, mccartney@ucsd.edu.
[3] Graduate Research Assistant, Colorado School of Mines, Department of Civil and Env. Engineering, 1500 Illinois St. Golden, CO, 80401. amoradig@ mines.edu.
[4]Associate Professor, Colorado School of Mines, Department of Civil and Env. Engineering, 1500 Illinois St. Golden, CO, 80401. ksmits@mines.edu.
[5]Professor, Colorado School of Mines, Department of Civil and Env. Engineering, 1500 Illinois St. Golden, CO, 80401. ninglu@mines.edu.

ABSTRACT: This study focuses on the effect of including a surficial insulation layer above a soil-borehole thermal energy storage (SBTES) system installed in a low plasticity clay deposit in the vadose zone. SBTES systems function by injecting heat collected from solar thermal panels into an array of vertical boreholes containing closed-loop geothermal heat exchangers. The goal of placing an insulation layer on top of the soil layer is to retain as much heat as possible within the borehole array to increase the efficiency by preventing the heat loss from the system to the atmosphere. A two-dimensional (2D), transient finite element model was built in COMSOL to consider the coupled heat transfer and water flow processes in the unsaturated soil layer within the SBTES system. Results indicate that presence of an insulation layer leads to a lower upward heat loss from SBTES system, but it is not significant. The insulation was observed to play a more significant role when coupled heat transfer and water flow was considered than when heat transfer was due to conduction alone.

INTRODUCTION

Soil-Borehole Thermal Energy Storage (SBTES) systems are used to store heat collected from renewable sources so that it can be used later for heating of buildings (Sibbitt et al. 2012; Zhang et al. 2012; McCartney et al. 2013; Başer and McCartney 2015). They function in a similar way to conventional geothermal heat exchange (GHE) systems, where heat is transferred from a source to a sink via circulation of fluid through a series of closed-loop heat exchangers. Because SBTES systems are meant to store heat, the spacing of the heat exchangers in SBTES systems is closer than that in conventional GHE systems (Başer and McCartney 2015). During operation of SBTES systems use of solar thermal panels as the heat source, the temperature of the ground within the array is expected to increase from its initial temperature (approximately 10-20 °C) to potentially more than 60 °C (Sibbitt et al. 2012; Bjoern 2013), which is much higher than that encountered in GHE systems. McCartney et al. (2013) noted the potential advantages of installing SBTES systems in the vadose zone, where the thermal conductivity of the surrounding soil is relatively low and lateral heat loss will be minimized. The relatively high temperatures associated with SBTES systems may lead to different mechanisms of heat transfer in the vadose zone than those expected under lower temperatures (Lu 2001; Smits et al. 2013). An additional difference between SBTES and GHE systems is that the borehole heat exchanger array in a SBTES system is usually overlain by a hydraulic barrier to retain pore water within the subsurface and a thermal insulation layer to minimize heat losses to the atmosphere. A schematic of a typical SBTES system with the location of the surficial insulation layer and hydraulic barrier is shown in Figure 1. The objective of this paper is to understand the impact of the insulation layer, and whether it has a major effect on the heat storage performance of SBTES systems. To achieve this objective, simulations of coupled heat transfer and water flow in the unsaturated soil within the SBTES system were performed using COMSOL to evaluate the role of the surficial boundary conditions.

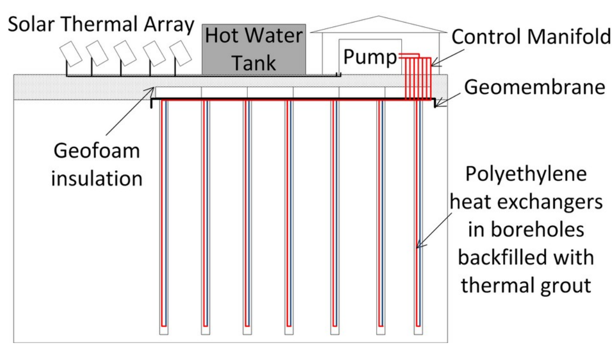


FIG. 1: Schematic of a SBTES system with heat from solar thermal panels

BACKGROUND

While SBTES systems are gaining popularity throughout the world, a better understanding of their thermal performance is required as their thermal storage capacity and heat loss highly depend on the average soil temperature during a heating or cooling period. The capacity of a SBTES system is the quantity of heat that the ground can retain and depends on the thermal properties of the subsurface. Heat loss could occur in all directions (upward, downward and laterally), and is dependent on the spacing of boreholes, number of boreholes, heat injection rate, and heat injection duration, along with the subsurface thermal properties (Chapuis and Bernier 2009; Başer and McCartney 2015). The primary mode of heat loss from an SBTES system is laterally to the surrounding subsurface. The upward and downward heat losses are not as significant because the small area of heated soil around each borehole heat exchanger. Further, the upper surface of an SBTES system is typically insulated with layers of expanded polystyrene (EPS) even though there has not been thorough evaluation of the role of the insulation. In addition to the insulation, the SBTES system is typically installed beneath the frost depth at a particular location, so the surficial soil layer also provides an insulating effect. Heat loss decreases as the size of the system increases, while it increases with the temperature difference between the storage and ambient ground temperature (Nordell and Hellström 2000).

During operation of a typical SBTES system, heat is injected at a relatively constant rate during the summer months. During this time, the soil within the array increases in temperature. Heat is injected into the central borehole heat exchanger first, then to the surrounding borehole heat exchangers. Although the heat supply in most SBTES systems is from solar thermal panels that only produce heat for a certain period of time during the day, the heat injection rate is stabilized through the use of an intermediary fluid-filled heat storage tank (Sibbitt et al. 2012). The temperature of the soil increases rapidly due to the high thermal gradient, and the rate of increase in temperature decreases as the soil reaches its storage capacity. During the fall, heat may continue to be injected into the array depending on the climate setting, or the heat injection may be stopped at the end of the summer. After heat extraction in the winter, the system may rest after which the cycle begins again. As some heat is typically retained around the perimeter of the SBTES array, the heat extraction efficiency of SBTES systems increases over time (Sibbit et al. 2012; Zhang et al. 2012; Catolico et al. 2015).

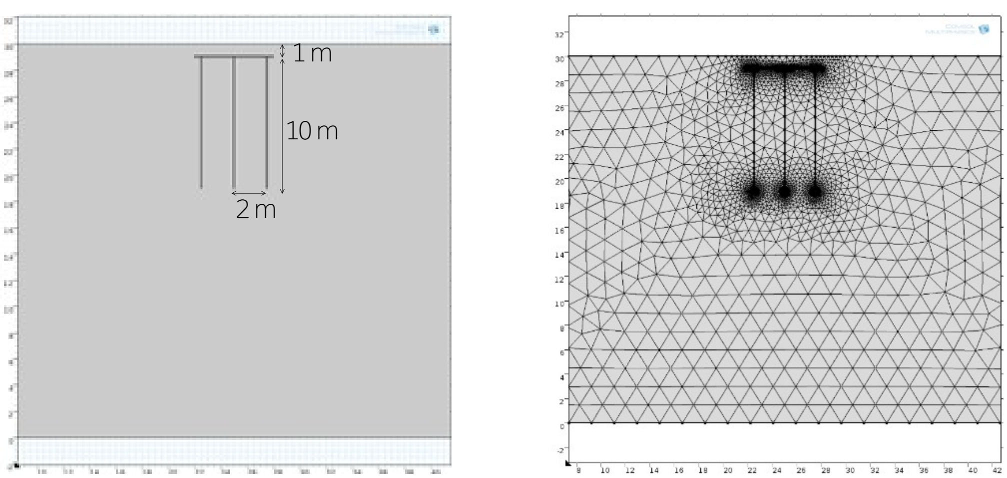
Design parameters of SBTES systems include energy injection and extraction rates, borehole spacing as well as thermal properties of the unsaturated soil. Two commonly used design models available for predicting the heat storage in SBTES arrays for variable injection and extraction rates are the duct storage (DST) model developed by Claesson and Hellström (1981) and Hellström (1989) and the superposition borehole model (SBM) developed by Eskilson (1987). As the borehole array investigated in this study was constructed for research purposes, it was not designed using these models to reach a certain energy storage needed for a building. Claesson and Hellström (1981) also proposed several analytical formulae based on the DST model for selecting the spacing of the boreholes, and found that the optimal spacing between borehole heat exchangers in an SBTES system is 1.5-4.0 m. Başer and McCartney (2015) performed a series of simplified numerical analyses of heat conduction that indicate that soils with lower thermal conductivity have less lateral heat loss, and that arrays with smaller borehole spacing permit more concentrated storage of heat at higher temperatures.

Although there have been several successful SBTES systems in Scandinavia since the late 1970’s (Claesson and Hellström 1981), there are two recent examples of successful community-scale SBTES systems. The SBTES system in Braedstrup, Denmark, supplies heat from 18,000 m^2 of solar thermal panels to an array of 50 boreholes having a depth of 47-50 m and 3 m spacing (Bjoern 2013). This system provides 14000 homes with 20% of their heat. The Drake Landing Solar Community

(DLSC) site in Alberta, Canada includes an SBTES system in operation since 2007. This system supplies heat from solar thermal panels to an array of 144 boreholes that are 35 m-deep and equally spaced at 2.25 m within a 35 m-wide grid. The SBTES system at this site has provided more than 90% of the heating requirements to 52 houses (Sibbit et al. 2012). Zhang et al. (2012) performed a numerical simulation of the heat exchange processes at the DLSC site using TOUGH2, and found that the efficiency of heat transfer, defined as the amount of heat extracted divided by the amount of heat injected, is approximately 27%. Although this seems low, the thermal energy injected into the SBTES system is from a renewable source and the heat extracted met the heating needs. The TOUGH2 analysis was further developed by Catolico et al. (2015), who matched simulation results with observed data from the DLSC site and considered conditions leading to a convective cycle in SBTES systems with saturated soils. At both sites, heat is permitted to escape laterally from the SBTES array. The DLSC site also includes a surficial hydraulic barrier to minimize evaporation of water from the soil as the groundwater table is 6 m below the surface.

NUMERICAL MODEL

A transient finite element model developed in COMSOL Version 4.4 was used to predict the temperature distributions and heat flux within the soil inside and around a SBTES array. For simplicity, a 2-dimensional cross-section of an array consisting of three equally-spaced boreholes having a depth of 10 m was used, as shown in Figure 2. The purpose of the simulations is to understand the effect of an insulation layer on heat transfer in unsaturated soil within a SBTES array for the situations that heat transfer occurs due to conduction alone or due to coupled heat transfer and water flow. Although the 2-dimensional analysis, which was performed for speed of simulation of coupled processes, does not represent the 3-dimensional flow processes in SBTES systems, it still permits comparison between simulations to understand the role of different processes on the performance of the SBTES system. When included, the insulation layer above borehole array has a thickness of 0.1 m and a thermal conductivity of 0.2 W/mK. The results of interest are the temperature distributions in the soil and heat loss vertically and laterally from the array.



(a) (b)

FIG. 2. Details of the model simulated in COMSOL: (a) Geometry; (b) Mesh

First, a simplified model was built assuming that heat transfer is due to conduction alone. The governing equation for conductive heat transfer in soils is:

$$(\rho C_p)\frac{\partial T}{\partial t} - \nabla\cdot(-\lambda\nabla T) = Q \quad (1)$$

where ρ (kg/m^3) is the total density of soil, C_p (J/(kgK)) is the specific heat capacity of the soil, T (K) is the absolute temperature, t (s) is time (s), λ (W/(mK)) is the apparent thermal conductivity of soil, and Q (W/m^3) is the heat source/sink.

A second model using the same geometry was built to incorporate coupled heat transfer and water flow. When either a partially- or water-saturated soil is subjected to a temperature gradient, convection occurs in the fluid phases due to thermally-induced changes in density of both wetting (water) and not-wetting (gas) fluids. The role of coupled heat transfer and water flow has been considered in several studies (Philip and de Vries 1957; Lu 2001; Smits et al. 2011, Moradi et al. 2015), who found that the convective movement of fluids can play a major role in the total heat transfer in soils. To consider the convective fluid flow, two different equations are defined for flow of the liquid and gas phases. The total gas phase is assumed to be dry air. These two equations are related by capillary pressure to form the following coupled differential equations (Bear 1972; Moradi et al. 2015):

$$n\frac{dS_w}{dP_c}\frac{\partial(\rho_w P_c)}{\partial t} + \nabla\cdot\left(\frac{-\rho_w k_{rw} k_{\mathrm{int}}}{\mu_w}(\nabla P_w + \rho_w g)\right) = -Q_m \quad (2)$$

$$n\frac{dS_g}{dP_c}\frac{\partial(\rho_g P_c)}{\partial t} + \nabla\cdot\left(\frac{-\rho_g k_{rg} k_{\mathrm{int}}}{\mu_w}(\nabla P_g + \rho_g g)\right) = Q_m \quad (3)$$

where n is the porosity, S_w and S_g (dim.) are the degrees of saturation of water and gas, respectively, μ_w and μ_g (Pa·s) are the dynamic viscosities of water and gas respectively, P_c (kPa) is the capillary pressure, equal to the difference between the pore gas pressure P_g and pore water pressure P_w, k_{int} is the intrinsic permeability of soil (m^2), k_{rw} and k_{rg} (dim.) are the relative permeabilities of water and gas, respectively, g is the gravitational acceleration (m^2/s), and Q_m ($kg/(m^3s)$) is the mass source per unit volume. Since phase change between liquid water and water vapor was neglected in this study, Q_m was assumed to be to zero. By taking averages at the scale of a representative elementary volume, the energy equation can be applied for each phase separately. Assuming local thermal equilibrium, the energy equations for each phase are combined to yield a general form of the heat transfer equation for porous media, as follows:

$$(\rho C_p)^*\frac{dT}{dt} + \nabla((\rho_w C_{p,w})v_w T + (\rho_g C_{p,g})v_g T) - \nabla\cdot(-\lambda\nabla T) = Q \quad (4)$$

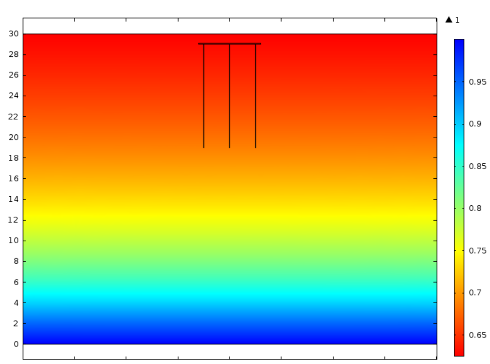
where v_w and v_g are the water and gas velocities (m/s), respectively, ρ_w and ρ_g are the temperature-dependent densities of water and gas, $C_{p,w}$ and $C_{p,g}$ are the water and gas specific heat capacities, and $(\rho C_p)^*$ represents the effective heat capacity of the soil.

The van Genuchten (1980) model is used for the soil water retention curve (SWRC), and the relative permeabilities for water and gas in the unsaturated soil were calculated using the van Genuchten-Mualem model (van Genuchten 1980). The thermal conductivity function (TCF) for unsaturated soil proposed by Lu and Dong (2015) was used, which estimates the apparent thermal conductivity from the degree of saturation and the parameters of the van Genuchten SWRC. The parameters of the different constitutive relationships for the soil and insulation are summarized in Table 1. The soil properties are representative of a low-plasticity clay, with high air entry suction and low saturated hydraulic conductivity. The nonisothermal properties of water and air were obtained from Moradi et al. (2015). After defining the initial and boundary conditions, equations (2), (3), and (4) were solved simultaneously.

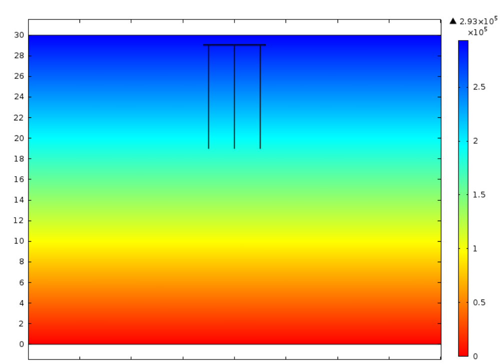
Table 1. Material properties used in the analyses

Layer	Insulation	Low plasticity clay
Thermal conductivity for Conduction-only model, λ (W/mK)	0.03	1.39
Specific heat capacity for saturated conditions, C_p (J/kgK)	900	1000
Total density, ρ (kg/m^3)	1200	1750
van Genuchten parameter, α_{vG} (kPa^{-1})	-	0.03
van Genuchten parameter, n_{vG}	-	1.45
Residual volumetric water content, θ_r	-	0.08
Saturated volumetric water content, θ_s	-	0.36
Saturated hydraulic conductivity, k_s (m/s)	-	3.5×10^{-7}

The initial ground temperature was assumed to be uniformly equal to 12 °C. and The water table was assumed to be at a depth of 30 m, and the initial conditions for degree of saturation and matric suction are assumed to be hydrostatic as shown in Figures 3(a) and 3(b). Zero heat flux boundary conditions were applied on the sides of the domain, and the temperature at a depth of 30 m was fixed at 12 °C. The surface temperature was assumed to be a sinusoidal function fitting the ambient air temperature in Golden, CO presented by Başer et al. (2015). Heat flux was applied to the outer borehole boundaries for 90 days. For water transfer, zero mass flux was applied to all boundaries. The soil within the region of the borehole array has an average initial degree of saturation of 0.65. Using the model of Lu and Dong (2015), this corresponds to a soil thermal conductivity of 1.39 W/mK.



(a)



(b)

FIG. 3. Initial conditions: (a) Degree of saturation; (b) Matric suction in Pascals

RESULTS

The temperature distributions with radial distance within the soil above the borehole array from the conduction-only analysis are shown in Figure 4 for the time at the end of 90 days of heat injection. Temperature values above the insulation layer is lower than the array without insulation as expected. Also the temperature behavior of the soil is highly dependent on thermal conductivity of insulation material as well as ambient temperature. Although not shown, a lower thermal conductivity for the insulation layer was observed to result in lower increase in temperature in the soil above the borehole array surface.

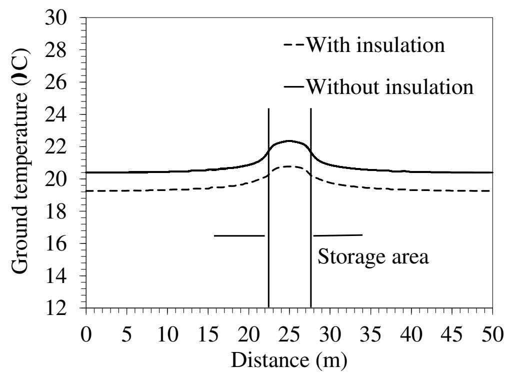


FIG. 4. Temperature distributions within the soil above the borehole array (depth of 0.5 m) for conduction-only heat transfer after 90 days of heat injection

The upward heat loss is shown in Figure 5(a) for the situations with and without insulation. The insulation leads to only a slight decrease in heat loss. Although not shown, the upward heat loss did not change significantly when the thermal conductivity of the insulation layer was changed. To evaluate lateral heat loss from the SBTES array, Başer and McCartney (2015) defined the storage volume of the array as 2 radial spacings from the center. Although this assumption is conservative as the borehole heat exchangers may be able to extract heat from the subsurface outside of the array as well. Using this definition of the array size, the lateral heat losses from the borehole arrays with and without surficial insulation are shown in Figure 5(b). According to energy conservation, when the heat flow is limited at the upper boundary, there should be an increase in lateral heat loss assuming that downward heat loss is negligible.

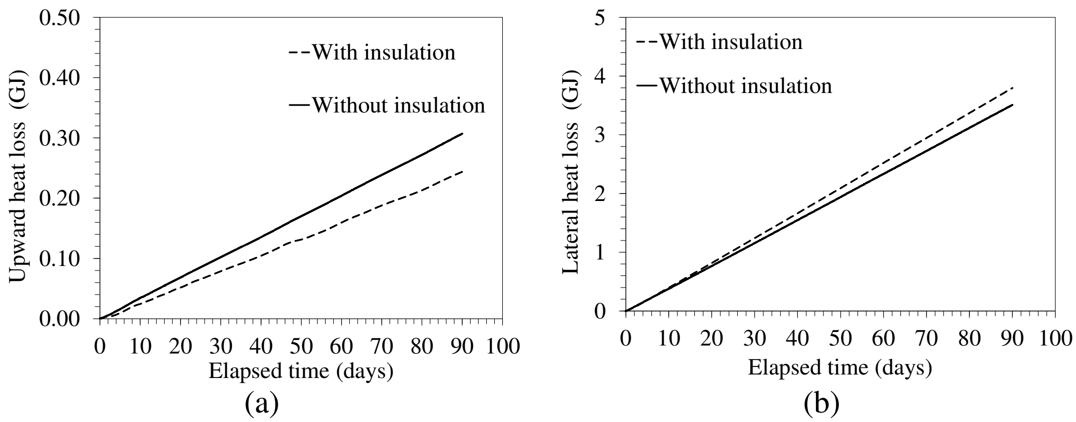


Fig. 5. Conductive heat loss from the borehole array: (a) Upward; (b) Lateral

The second analysis considers coupled heat transfer and water flow in the unsaturated soil layer in and around the SBTES system. In this case, the thermal conductivity was initially similar to that in the conduction analysis due to the relatively uniform initial degree of saturation in the soil. The temperature distribution in the soil above the borehole array is shown in Figure 6. Different from the analysis with conduction alone, the temperature distributions for the situations with and without insulation are similar, possibly due to heat homogenization by convection.

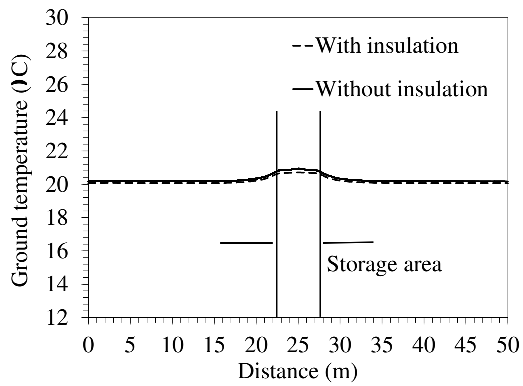
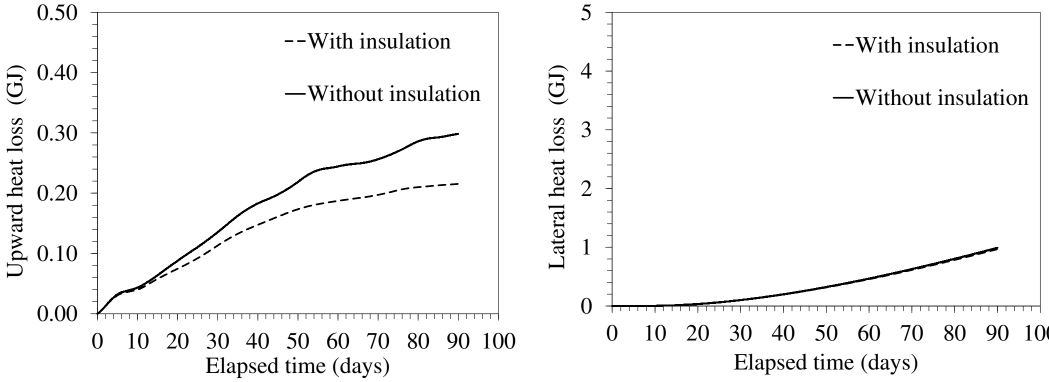


FIG. 6. Temperature distributions in the soil above the borehole array (depth of 0.5 m) for coupled heat transfer and water flow after 90 days of heat injection

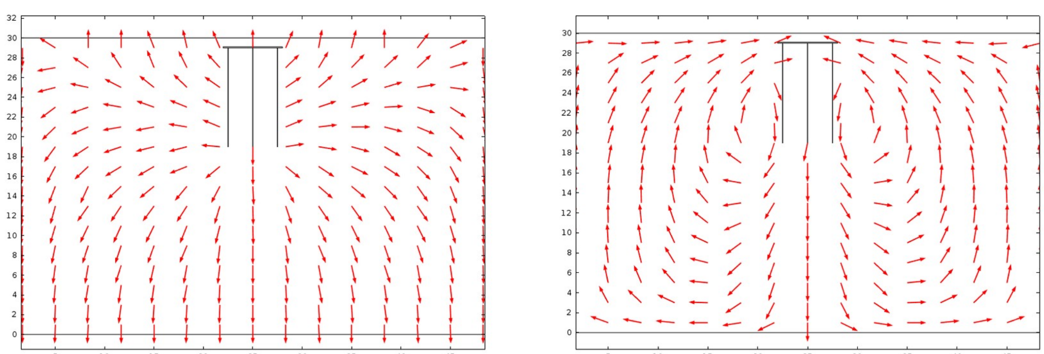
The analyses of upward and lateral heat losses considering convection are given in Figures 7(a) and 7(b), respectively. Similar magnitudes of upward heat loss are observed to the simulations with conduction only, although the insulation layer has a greater effect in this case. The lateral heat loss is unaffected by the insulation layer, likely due to the patterns of heat flux created by the convective cell. The magnitude of the lateral heat loss is lower when considering coupled heat transfer and water flow than when considering conduction alone. Although the differences in behavior of the arrays are similar for the two analyses with and without convection, upward heat loss in the coupled case is lower when the insulation layer is present. Although not presented here, the total heat injection after 90 days of heating was 9.8 GJ. The upwards heat loss of 0.31 GJ is only 3% of the total heat injected.



(a) (b)

FIG. 7. Heat loss from the array in coupled conditions: (a) Upward; (b) Lateral

The lower lateral heat loss observed in the coupled analysis may be due to the patterns of heat flow within the system. Consideration of convection was found to preserve a greater amount of heat within the array as shown in Figure 8(b). This behavior was also observed by Catolico et al. (2015) in the simulation of the DLSC site using TOUGH2. Lu (2001) and Catolico et al. (2015) observed that the hydraulic conductivity of the soil needs to be sufficiently high for convection to play a major role in heat transfer, or for a convective cycle to start forming.



(a) (b)

FIG. 8. Heat flux directions: (a) Conduction alone (b) With convection

CONCLUSIONS

This study focused on comparative numerical simulations of the thermal response of soil-borehole thermal energy storage (SBTES) systems with and without a surficial insulation layer. A transient finite element model was built to consider the coupled heat transfer and water flow processes in an unsaturated soil layer in and around the SBTES system. Although the upward heat loss was always found to be reduced by including an insulation layer, this reduction is relatively small due to the small area of heated soil around the borehole heat exchangers. Consideration of coupled heat transfer and water flow in the unsaturated soil caused the insulation to have a slightly greater role in reducing the upward heat loss, potentially due to the formation of a convective cell in the soil. When only conduction is assumed, including an insulation layer causes the lateral heat loss to increase. However, when considering both conduction and convection, the lateral heat loss was lower and the insulation layer did not have a major effect on the lateral heat loss.

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