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Impact of soil surface heat fluxes and weather conditions on the performance of near surface inter-seasonal ground energy collection and storage systems

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ABSTRACT

A numerical model based on the finite element method is applied to study the thermal performance of a near-surface inter-seasonal heat storage facility. The model is validated comparing 2D numerical results with experimental measurements from a case study project undertaken by others [Carder et al 2007]. The model is used to assess the impact that three alternative formulations of thermal fluxes at the soil surface have on the estimation of seasonal variations of temperature and stored thermal energy in the soil close to the surface. It is also shown that the choice of surface heat fluxes and initial conditions have an effect on the number of yearly cycles required to reach steady state conditions. The influence of weather conditions on the performance of the system is explored using weather data obtained from publicly available sources for three representative climates (hot, mild and cold).

Keywords: *Thermal Energy Storage ; Numerical modelling ; Soil surface heat flux ; Inter-seasonal Heat Transfer ; Inter-seasonal Thermal Storage*

1. Introduction

The process of inter-seasonal heat collection and storage imply taking thermal energy from a season with high availability to a season with high demand through the use of a suitable medium. A possible source of solar thermal energy for inter-seasonal heat storage systems are road surfaces [1]. In this case, the operation of the system is highly dependent on the interactions between the ground and pavement surfaces and the atmosphere since this determines the amount of energy available for the system. It is therefore necessary to correctly understand the processes of energy flux and heat balances at the surface of the ground. This is particularly true in near-surface systems. This paper presents selected results from a more comprehensive numerical investigation [2] of the processes affecting the performance of inter-seasonal heat storage systems. Numerical simulations are undertaken using a numerical model which is validated against an excellent dataset produced by others [3] in the course of a two year-long inter-seasonal heat storage system demonstration project. The results presented in this paper are selected with the purpose of exemplify the impact that different parameters have in the operation of these systems and the simulation of their behaviour, in particular the effect of: formulation of heat transfer coefficients at the soil surface, selection of bottom boundary conditions and initial conditions and weather influence in system performance are considered.

2. Theoretical and numerical model

The temperature variation in a soil domain is obtained by solving the transient heat transfer equation:

$$\frac{dT}{dt} = \alpha \nabla T \tag{1}$$

where T (˚C) and α (m^2/s) are the soil's temperature and thermal diffusivity. In this work equation (1) is solved by using a boundary condition of the third kind at the soil surface that takes into account heat transfer by solar and infrared radiation, convection and evaporation:

$$-k\frac{dT_{ss}}{dx}=(1-\alpha_S)R+\sigma\varepsilon_{ss}\left(\varepsilon_s T_{a,k}^4-T_{ss,k}^4\right)+h_E(q_a-q_{ss})+h_C\left(T_a-T_{ss}\right) \quad (2)$$

where T_{ss} (˚C), $T_{ss,k}$ (K), q_{ss}, k (W/mK), α_s and ε_{ss} are the soil's surface temperature, absolute surface temperature, surface specific moisture content, thermal conductivity, albedo and infrared emissivity respectively, R (W/m^2) is solar radiation, σ (W/m^{2}K^4) is the Steffan-Boltzmann constant, ε_s is the infrared emissivity of the sky, T_a (˚C) and $T_{a,k}$ (K) are the temperature and absolute temperature of air, q_a is the specific moisture content of air, h_E (W/m^2) and h_C (W/m^{2}K) are evaporative and convective heat transfer coefficients respectively.

Three approaches are used to investigate the impact that alternative theoretical formulations of the convective and evaporative heat transfer coefficients: i) a *turbulent* approach [4] that assumes turbulent conditions between the surface and the atmosphere; ii) a *non-turbulent* approach [5] that assumes the presence of natural convection and iii) an additional approach [6,7] that takes into account the presence of a canopy cover on top of the soil surface through a second heat balance equation additional to (2). A full description of the heat transfer coefficients and heat balance including a canopy cover as well as values for coefficients in equation (2) can be found in [2,8].

3. Case study

The experimental measurements used in this work have been provided by the Transport Research Laboratory (TRL) [3] from a two year-long demonstration project at Toddington, UK. The objective of that project was to assess the feasibility of recovering thermal energy in summer in order to be used for thermal maintenance of roads and/or building heating in winter. Approximate positions of two boreholes used in this paper and the position of the system are shown in Figure 1b. Full details regarding system operation, material properties, soil and meteorological data can be found in [2,3].

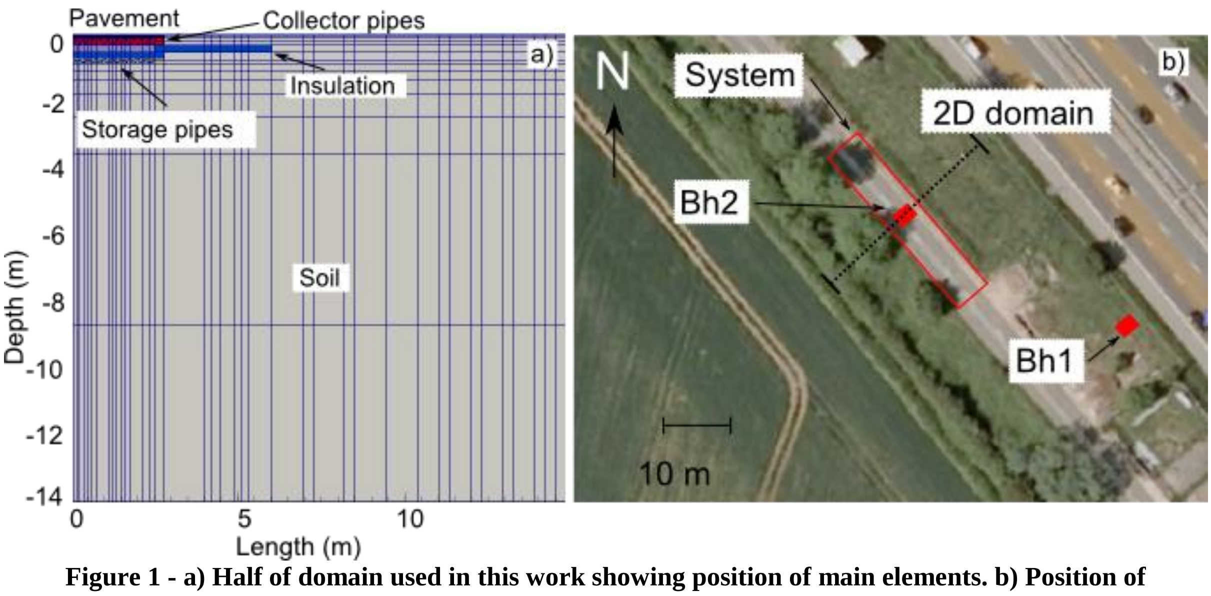

Figure 1 - a) Half of domain used in this work showing position of main elements. b) Position of experimental system and boreholes used in this work and approximate position of 2d domain.

4. Numerical study

The numerical model developed in this study is based on solving equation (1) using the finite element method. The boundary condition at the soil surface is assumed to be of the third type and given by equation (2). Far field boundary conditions are assumed to be adiabatic. The effect of the boundary condition at the bottom of the domain is part of the study of this work. Time discretization is performed using the Crank-Nicholson method using hourly time steps. Figure 1a shows a sub region of the domain considered in this work, full domain details, mesh refinement and representation of pipe system operation can be found in [2].

Figure 2 shows typical results from validation of the proposed model, comparing numerical results and recorded experimental measurements provided by Carder et al [3]. It can be seen that both are in good agreement. The validated model is further used to explore the effect of varying different parameters:

- *The effect of bottom boundary condition and initial temperature profile on the number of yearly cycles required to reach steady state conditions in the domain*. Two options are considered: a fixed value using experimental measurements; and adiabatic conditions allowing free variation at the bottom of the domain. Three initial temperature profiles are considered: homogeneous temperature profile, profile based on experimental measurements and a profile produced with analytical equations available in the literature [9].
- *The influence of using alternative formulations of heat transfer coefficients in the amount of thermal energy stored in the ground*. Two formulations are compared at the soil surface: non-turbulent formulation and a formulation considering the inclusion of a canopy layer.
- *The effect of different weather conditions in the collection performance of an inter-seasonal heat collection and storage system*. Three representative types of weather are explored: cold, mild and hot. Weather data is constructed using analytical functions available in the literature [9] based data obtained from publicly available meteorological sources from Iceland, UK and Mexico.

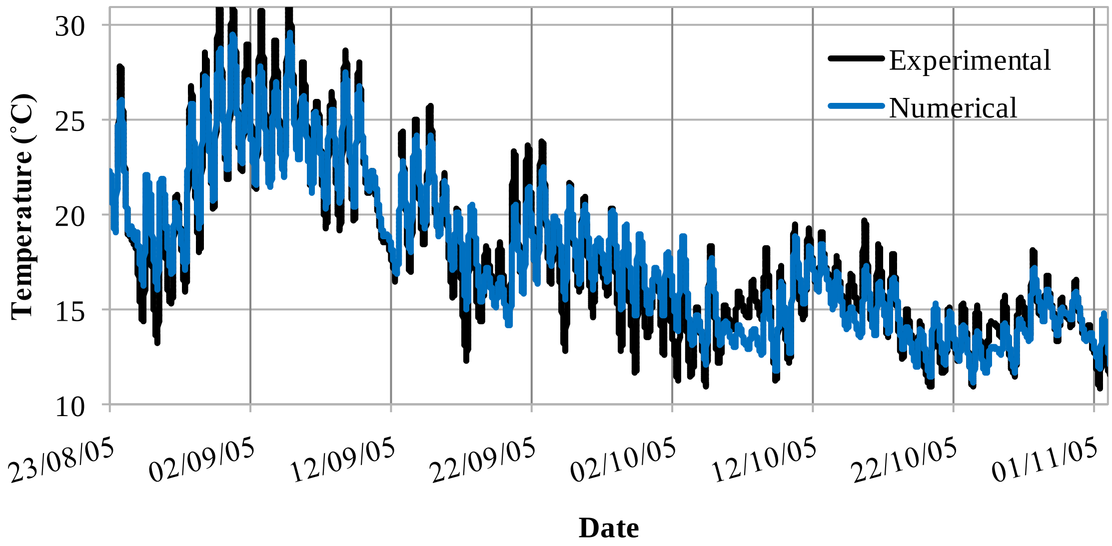

Figure 2 - Comparison between numerical results and experimental data at 0.1325 m depth (collector pipes depth) under the paved surface.

5. Discussion and conclusions

Analysis of the impact of initial and bottom boundary conditions in the number of yearly cycles necessary to reach a steady state near the bottom of the domain found that a fixed condition drastically reduces the number of cycles, however, it is dependent on suitable experimental measurements that might not always be available. On the other hand, an adiabatic condition requires a comparatively higher number of cycles and is dependent on the heat balance formulation assumed at the surface. However, it requires less information about the temperature in the domain. It was also found that the initial condition has a minimal impact in the number of cycles required.

Figure 3a presents the impact of the heat balance theoretical formulation assumed at the soil surface on the amount of thermal energy stored in a far field region of the ground. The thermal energy variation is compared from 23/08/05, it can be seen that as winter approaches, the soil energy content in the soil decreases as expected. However, a bare-soil formulation has a relatively higher loss of heat than a formulation that includes the presence of a canopy cover.

Figure 3b presents the influence of weather conditions on thermal energy collected by the system. It can be seen that hotter weathers have a comparatively higher energy potential than colder climates. However, the feasibility of the system needs to include also the potential demand for this thermal energy that is expected to be higher in colder regions than in hotter ones.

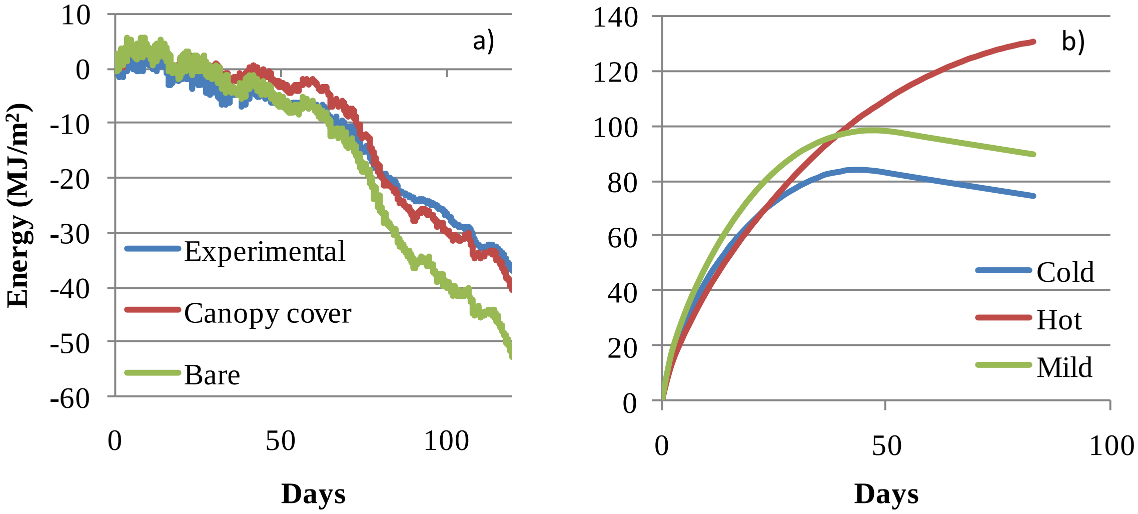

Figure 3 - a) Effect of theoretical formulation of heat balance at the soil surface on the amount of thermal energy stored in the far field ground. b) Influence of weather conditions on amount of estimated thermal energy collected by the system. Day 0 corresponds to 23/08/05.

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