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Factors influencing collection performance of near surface interseasonal ground energy collection and storage systems

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HIGHLIGHTS

- Impact of surface boundary, climate and materials on performance is investigated.
- Numerical model is validated and applied with varying system parameters.
- System heat losses are strongly influenced by the performance of insulation layers.
- Reduced amplitude of air temperatures in warmer climates affects collection rates.
- Correct surface boundary conditions are critical in modelling systems dynamics.

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ABSTRACT

The influence of surface boundary conditions, varying climatic conditions and engineering material parameters on the collection performance of near surface interseasonal ground energy collection and storage systems are investigated. In particular, the performance of a proposed design of an interseasonal heat storage system which has also been investigated by others as part of a full scale demonstration project is considered. A numerical model is developed and validated against field data. It is then applied to undertake a series of simulations with varying system parameters. It is found that (i) higher values of thermal conductivity of the storage layer result in increased storage of thermal energy and lower peak temperatures, (ii) system heat losses are strongly influenced by the performance of insulation layers, (iii) warmer climatic conditions provide more thermal energy available to be stored; however, changes in the amplitude of seasonal air temperature variations have an effect on the rate of collection of thermal energy and (iv) the use of correct surface boundary conditions is critical in modelling the dynamics of these systems.

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1. Introduction

The use of the ground as a reservoir or source of thermal energy is long established. In recent times, systems utilising modern engineering materials and technology have become more widespread, examples include ground source heating (e.g. Ref. [1]), shallow energy piles (e.g. Ref. [2]), passive heating and cooling of buildings (e.g. Refs. [3,4]) and inter-seasonal thermal energy storage (e.g. Ref. [5]).

The performance of near surface ground energy collection and storage systems is highly dependent on the spatial and temporal variation in the amount of energy present in the near-surface region of the soil as well as the specific design and operation characteristics of the system. Inter-seasonal heat storage systems are of use in applications that have a cyclical annual thermal energy demand typically driven by energy demands in the winter that may be met by using excess heat energy stored in the summer. In some cases, waste heat may be captured from heating and ventilation systems. Applications include heating of buildings, winter maintenance of highways and minimising ice formation at aircraft stands.

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The ability to model such facilities offers potential benefits at the design stage, in particular for scenario testing to help optimise the system. However, for a model to be representative it must be capable of simulating the transient temperature regime in the surrounding soil with reasonable precision. To this end, a significant body of research has appeared in the literature. For example, Ma et al.[6] implemented a 2D heat transfer FEM model to obtain soil temperature profiles suitable to be used as initial conditions in problems involving heat and mass transfer in soils. Quin et al.[7] presented a detailed algorithm for the computation of soil surface heat fluxes and temperature changes using a complete description of the surface energy balance under bare soil conditions. Their model was validated against experimental measurements using publicly available meteorological data for a desert in southern Israel. Rajeev et al.[8] developed a 1D numerical model to describe the ground–atmosphere interaction and soil moisture and temperature profiles to a depth of 2 m below ground surface over a period of 2 years. Their model was validated with data measured at a site in Melbourne, Australia and meteorological data was obtained from a station installed on-site. Liu et al.[9] used a simplified 1D model that estimated the soil surface temperature as a function of air temperature measured close to the soil surface. They predicted underground temperature profiles over a summer season in Nanjing, China.

In the context of the numerical analysis, the methods and assumptions employed vary depending on the specific physical characteristics of the problem in hand. For example, Yumrutaş et al.[10] developed a semi-analytic model to investigate the annual periodic performance of a cooling system which coupled a chiller with a spherical underground thermal energy storage element. Shang et al.[11] studied the temperature recovery of the ground surrounding a relatively deep (50 m vertical U-tubes) ground-source heat pump under intermittent operation. Several influencing factors were taken into account including the soil thermal conductivity, air temperature and solar radiation. Wu et al.[12] assessed the performance of a shallow (1.2 m depth) horizontal slinky ground source heat exchanger under UK (Oxfordshire) weather conditions. A 3D numerical model was validated with experimental measurements collected over a 2 month period using soil thermal properties measured from in situ undisturbed soil samples. The model was then used to study the impact of varying pipe diameters and slinky interval distances. Esen et al.[13] developed a 2D numerical model to evaluate a shallow (1 m depth) ground-coupled heat pump system designed for space heating. They validated the numerical model using experimental measurements[14] and measured soil thermal properties. Congedo et al.[15] performed a set of 3D numerical simulations to study the performance of shallow (1 m depth) horizontal ground heat exchangers under varying pipe distributions, heat carrier fluid velocities, pipe depths and soil thermal properties. It was concluded that most important parameter for the heat transfer performance of the system was the soil thermal conductivity with higher values (1, 2 and 3 W/m K considered by the authors) delivering a better performance. Ramírez-Dávila et al.[16] studied the performance of a relatively shallow earth-to-air heat exchanger (10 m depth) under three different types of weather in Mexico: desert (Cd. Juárez, Chihuahua), mild weather (México city) and hot-humid weather (Mérida,Yucatán). It was found that the performance of the system is dependent on the weather conditions and the season under which it operates.

For effective assessment and design of ground energy collection and storage systems, and in many geomechanical environmental and energy related applications, it is necessary to be able to correctly represent a number of key factors. These include (i) the transfer of heat between the ground surface and the atmosphere, (ii) the movement of heat within the engineered soil mass and (iii) the movement of heat energy within the collector and storage systems. This paper explores how the performance of interseasonal heat storage systems may be affected by meteorological conditions, surface flux boundary conditions, and the thermal properties of the storage materials. It appears that these factors have not been fully explored and so the objective of the paper is to investigate and quantify these three factors via a series of numerical analyses of a typical system. To this end, a numerical framework is developed and validated against a comprehensive dataset produced by others.[5] The impact on system performance is assessed in terms of soil temperature profiles and thermal energy stored.

2. Modelling framework

The analysis of thermal problems usually requires the solution of the transient heat transfer equation for a 2D or 3D soil domain. This may be coupled with the solution of the transient heat advection equation (in 3D) or a suitable mathematical algorithm able to represent the transfer of heat in the soil–pipe–fluid system in 2D. In both cases, suitable boundary conditions are required to represent both energy balance at the soil surface and energy transfer between the soil mass and the pipes. In the present study, the mathematical framework for a 2D case is presented (full details are given in Ref. [17]). In order to simplify the analysis, only heat transfer by conduction is considered in the soil mass while other physical processes like convection and mechanical deformation are neglected.

Since the current model addresses the performance of a near-surface thermal device, the theoretical representation of heat transfer at the soil surface includes several terms that are typically not required in models dealing with systems buried deep into the ground and therefore comparatively insulated from soil–surface interactions. The relative contribution of these flux terms is of course problem dependent but in general terms solar radiation is the most significant followed by infrared radiation and then smaller convective and evaporative heat fluxes.

2.1. Heat transfer

Transient heat transfer, when only conduction is considered, can be expressed as[18]

$$C_{p,b}\frac{\partial T_s}{\partial t} = \nabla \cdot (\lambda_b \nabla T_s) \tag{1}$$

where $C_{p,b}$ (J/m^3 K) is the volumetric heat capacity of the soil, λ_b (W/m K) is its thermal conductivity, T_s (°C) is the

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