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Temperature fields induced by geothermal devices

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ABSTRACT

Efficient and sustainable exploitation of low-enthalpy geothermal energy relies on accurate representations of heat transfer processes in the subsurface. An analytical model, which provides such a representation by predicting the dynamics of thermal fields induced by shallow GHEs (ground heat exchangers), is derived. The model accounts for atmospheric temperature fluctuations at the ground surface, an arbitrary geometry of GHEs operating in time-varying heating/cooling modes, and anisotropy and uncertain spatio-temporal variability of thermal conductivity of the ambient soil. To validate the model, its predictions of a thermal field generated by a shallow flat-panel GHEs are compared with experimental data. This comparison demonstrates the model's ability to provide accurate fit-free predictions of soil-temperature fields generated by GHEs. The analysis presented shows that a single horizontal GHE may affect soil temperature by several degrees at distances on the order of 1 m. The volume of influence is expressed in terms of soil thermal properties. Such modeling predictions are invaluable for screening of potential sites and optimal design of geothermal systems consisting of multiple GHEs.

1. Introduction

Atmospheric temperature fluctuations affect soil temperature at depths of up to 20 m below the ground surface. Thermal inertia of this subsurface region induces both attenuation and time delay of surface temperature. As a result, temperature of the subsurface is higher/lower than that of air during the cold/hot seasons. (At depths exceeding 20 m, subsurface temperature is not affected by its atmospheric counterpart; it is controlled, instead, by the geothermal gradient.) GHEs (ground heat exchangers) exploit such differences between air and soil temperatures for heating/cooling purposes [1]. Among them, ground-coupled heat pump systems are regarded as a sustainable and cost-effective technology [2]. These systems couple a heat pump with the ground via a closed loop through which a working fluid circulates; the heat exchange with the ground occurs by means of GHEs (Fig. 1), which are located either vertically or horizontally at various depths [3]. Horizontal GHEs typically provide little energy, but are cheaper, more compliant with the environment, and easier to operate and maintain. In this configuration, the ground mainly serves as a solar energy buffer, e.g., [4–6].

Success of any GHE ultimately depends upon the ambient STF (soil temperature field) it generates. The latter is used as a key metric in designing GHEs and assessing their effect on the subsurface environment. For example, a GHE used in the heating of a building might cool the ambient soil to the point at which either the GHE operation becomes uneconomical or subsurface biological processes become unsustainable. A shallow horizontal GHE can change soil temperature by several degrees Celsius, with appreciable changes confined to its neighborhood of radius on the order of 1 m [7,8]. The efficiency of such devices rests on one's ability to optimize the surface available for heat transfer and to reduce the mutual interference between exchangers. The former venue was pursued by exploring various GHE geometries, including slinky coils, radiators, and spirals [e.g., [9], and the references therein], as well as flat panels [7]. A flat-panel GHE affects larger volumes of the ambient soil than a radiator GHE does, reducing soil-temperature oscillations. For the same surface of exchange, a flat-panel GHE has lower thermal resistance, resulting in higher efficiency [7].

Regardless of the technology employed, quantification of energy that can be either retrieved or stored in the subsurface requires an accurate estimation of the ambient STF. This task is challenging due

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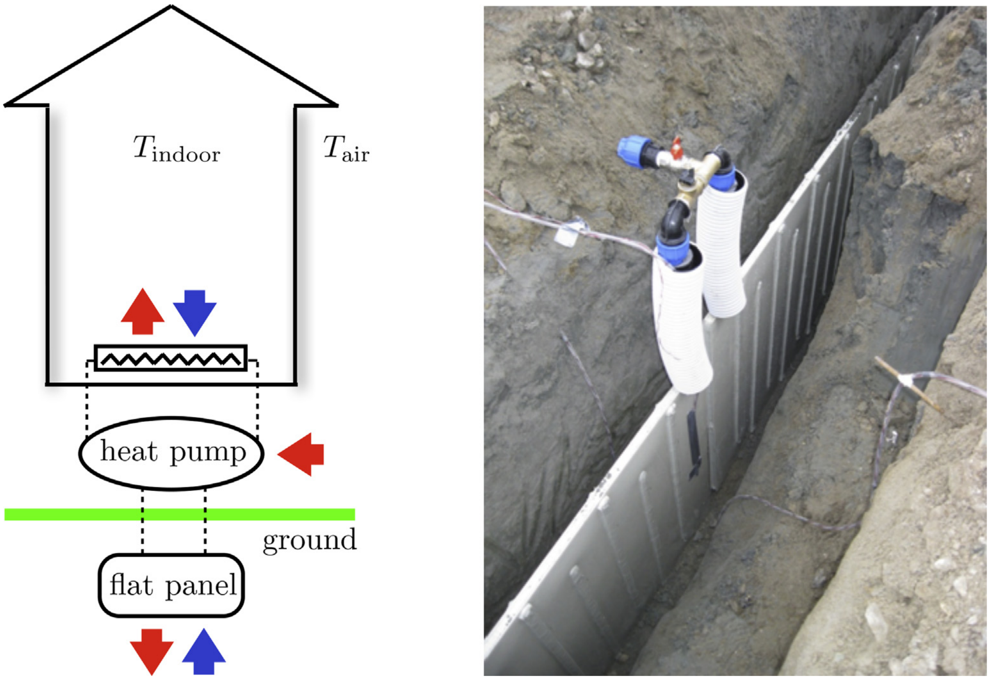

Fig. 1. Left: Schematic representation of a ground-coupled heat pump system. Right: shallow ground heat exchanger with a flat-panel geometry.

to STF's sensitivity to atmospheric dynamics, soil heterogeneity, and spatio-temporal variability of soil water content [10–14]. Although it has been argued that soil heterogeneity might play a minor role in the overall performance of shallow GHEs [15], the impact of temporal variability of soil water content (e.g., due to infiltration and/or evaporation) on the soil's thermal properties and, hence, on the GHE performance is undeniable. Models that treat soil properties as constants have been shown to yield inaccurate predictions of STFs, especially in shallow soils, e.g., [16,11,13]. The minimal model complexity that is necessary to describe the STF dynamics is another potential source of error. While many studies, e.g., [17,18], rely on one-dimensional heat conduction equations to estimate vertical soil temperature profiles under natural conditions, the presence of GHEs increases the modeling complexity.

Here, a general mathematical framework is presented to analytically predict the dynamics of the STFs induced by GHEs in ambient shallow soils. This framework accounts for atmospheric temperature fluctuations at the ground surface, an arbitrary shape and number of GHEs, anisotropy of soil thermal properties, and their spatial variability and spatio-temporal dependence on soil water content. Temporal fluctuations of both surface temperature and soil thermal diffusivity are handled exactly; uncertainty due to spatial variability of soil thermal diffusivity is tackled by employing the effective medium theory [e.g., [19], and the references therein]. This formulation significantly extends the range of predictive analytical models available in the field. It can be employed for a screening-level assessment of potential geothermal sites and for verification of numerical codes.

Section 2 provides a model formulation, including modeling assumptions. A general three-dimensional analytical solution of this problem and its (two-dimensional) application to horizontal flat-panel GHEs are presented in Section 3. In Section 4, the model is validated by comparing its predictions of the STF with the experimental data collected at a field in the vicinity of Ferrara, Italy. Section 5 demonstrates the model's utility by forecasting the STF dynamics induced by operation of a single GHE used to meet the energy requirement of a building during the cold season. A summary of the key findings is provided in Section 6.

2. Model formulation

The subsurface is treated as a semi-infinite domain, $\Omega = \{\mathbf{x} = (x_1, x_2, x_3)^\top : -\infty < x_1, x_2 < \infty, 0 \le x_3 < \infty\}$, and a (possibly multi-connected) region occupied by a GHE is denoted by E. A macroscopic (Darcy-scale) description of subsurface temperature, $T(\mathbf{x},t)$, at any "point" $\mathbf{x}$ and time t is provided by a heat conduction equation

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (\mathbf{K} \nabla T) + g, \qquad t > 0, \quad \mathbf{x} \in \Omega, \tag{1}$$

where ρ, c and $\mathbf{K}$ are the average density, specific heat, and thermal conductivity of the soil, respectively; and $g(\mathbf{x},t)$ represents the heat source generated by the GHE, such that $g(\mathbf{x},t) \equiv 0$ for $\mathbf{x} \notin E$. The three soil parameters, ρ, c and $\mathbf{K}$, vary, to different degrees, in space and time due to soil heterogeneity and changing water content [e.g., [13], and the references therein]. Soil anisotropy gives rise to the thermal conductivity tensor $\mathbf{K}$, whose principle components are aligned with the coordinate system, such that the off-diagonal components of this tensor are $K_{ij} = 0$ for $i \neq j$. Without loss of generality, we set $K_{11} = K_{22} = K_h$ and $K_{33} = K_v$, where K_h and K_v are the horizontal and vertical thermal conductivities, respectively.

Equation (1) is subject to an initial condition

$$T(\mathbf{x}, 0) = T_m, \tag{2}$$

where T_m is the average temperature of soil in the stable layer; it is commonly set to the average temperature of air [4,20]. This temperature varies in response to atmospheric fluctuations at the ground surface ($x_3 = 0$), which manifest themselves through a boundary condition