Applied Thermal Engineering 96 (2016) 130–136

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Finite cylinder-source model for energy pile heat exchangers: Effect of buried depth and heat load cyclic variations

Tatyana V. Bandos [a,*], Álvaro Campos-Celador [b], Luis M. López-González [c], José M. Sala-Lizarraga [d]

[a] Departamento de Máquinas y Motores Térmicos, University of the Basque Country UPV-EHU, Alda. Urquijo s/n, 48013 Bilbao, Spain
[b] Grupo de Investigación ENEDI, Departamento de Máquinas y Motores Térmicos, University of the Basque Country UPV-EHU, Avda. Otaola 29, 20600 Eibar, Spain
[c] Grupo de Investigación GI-TENECO, Universidad de La Rioja, C/Luis de Ulloa 20, 26004 Logroño, Spain
[d] Grupo de Investigación ENEDI, Departamento de Máquinas y Motores Térmicos, University of the Basque Country UPV-EHU, Alda. Urquijo s/n, 48013 Bilbao, Spain

HIGHLIGHTS

- Integral mean temperature method for buried ground heat exchanger is proposed.
- The method is based on finite cylinder-source (FCS) of heat.
- Exact mean temperature inside and outside FCS of variable heat flow is derived.
- Steady-state temperature response to periodic cylinder-source of heat is obtained.

ARTICLE INFO

Article history:
Received 16 August 2015
Accepted 21 November 2015
Available online 2 December 2015

Keywords:
Ground heat storage
Energy piles
Borehole heat exchangers
Ground-coupled heat pumps

ABSTRACT

A solution to the finite cylinder-source model for the ground heat exchangers at a different buried depths that takes into account the heat capacity inside them and allows arbitrary heat rate changes is presented. Analytical expressions for the average ground temperature are derived by integrating the exact solutions over the cylinder-source depth for vertical and time-dependent changes of heat rate. The influence of buried depth variations on thermal response to a constant and uniform mean heat rate of the cylinder-source is examined by the integral mean temperature method in a self-consistent approach. In addition, approximate expressions for steady-state average temperature are derived for periodic heat rate in the long-time limit.

1. Introduction

A ground-coupled heat pump (GCHP) is one of the sustainable energy technologies for heating and cooling buildings. Long-term financial reward and space requirements retard wide spread of the GCHP systems. Heat exchangers embedded into foundations known as energy piles are less expensive than ground heat exchangers attached to nearby buildings, and a number of the ground heat exchangers (GHEs) installed in foundations rapidly grow [1–7].

Most methods of design ignore transient thermal processes within piles or boreholes when solving external heat conduction problem in the ground. Some commercial software for field of GHEs [8,9] is based on solutions to the traditional cylindrical surface source [10–12] or line-source [13–15] models. In terms of heat conduction, an energy pile can be modeled in the same way as a borehole heat exchanger (BHE). However, vertical temperature variations for energy piles differ from that of BHEs due to larger depth to radius ratio given the same distance from the ground surface. Therefore, to understand the effect of using a foundation pile as heat exchanger, both the thermal capacity of large diameter piles and heat transfer to grout and ground surrounding in radial and vertical directions need to be taken into account simultaneously [16]. To this purpose, one can use solution to model called "solid" cylinder-source of heat [17], which represents pile lateral surface densely covered by helical or *U*-tubes with heat-carrier fluid in thermal analysis of piled foundations [18,19]. This model's parameters, depending on an arrangement of heat pipes inside the pile, its length and buried depth, influence the thermo-mechanical design of the energy piles [6]. Therefore, it is desirable to have upper bound and lower bound

* Corresponding author. Tel: +34 946018249; fax: +34 946014040.
E-mail address: tbandos@uv.es (T.V. Bandos).

http://dx.doi.org/10.1016/j.applthermaleng.2015.11.073
1359-4311/

solutions for temperature response for arbitrary buried depth D within the finite cylinder-source (FCS) model in addition to the solutions at $D = 0$ [20] for the upper bound and lower bound geometries of energy pile [5].

For the design purpose, the best approach is to use an average temperature [21]. It was first developed for the finite line-source (FLS) [22–24] and then generalized for the case of finite cylinder-source, starting from the ground surface [20]. However, currently, an average temperature field from buried ground heat exchanger can only be determined by means of further numerical integration over the thermo-active length of the z-dependent solution [25] to finite "solid" cylinder-source model, which is rather time consuming.

This study aims to develop the integral mean approach for temperature response [20] to finite cylindrical surface source of heat embedded into the ground on a finite distance D from its surface. The effect of buried depth for a borehole field was examined on the base of the mean solution to a buried FLS [24] in references 16 and 26. However, an analysis by the mean FCS method is highly desirable to account for thermal capacity of a single energy pile itself. The influence of the distance D is beyond the scope of infinite cylindrical heat source (CHS) [10,12,27], so-called "hollow" cylinder-source, or infinite two composite-medium line-source models [28]. For estimating short-term temperature response, it was proposed to use the former analytical model for the ground outside the boreholes in conjunction with the numerical model for the grout inside the boreholes to account for thermal capacity of the borehole [29]. The influence of difference between thermal properties of grout and ground was analyzed by a method based on the one-dimensional composite-medium model, which is applicable for the short time interval and several years for deep boreholes [28]. This study accounts for vertical and radial dimensions of shallow pile, its thermal capacity in the integral mean temperature approach, though it doesn't include the different thermal capacities of grout and ground within the FCS model.

There are some approaches of combining solutions to a number of composite-medium short-term models [27,29,30] and integral mean solution for temperature response to buried FLS model for long times [24], in particular, to design hybrid GCHPs [31]. A drawback of proposed analytical joint solution consisting in a certain discontinuity in time between short-term and long-term solutions, noticed in reference 24, was overcome by accounting the pile heat storage effect in the mean FCS approach developed for $D = 0$ [20]. However, the mean solution to the FCS buried at arbitrary D in the intermediate time interval, where interplay between vertical and radial temperature dependencies is significant, is still unknown. For evaluating thermal response of pile to a time-varying heat demand, it is of an especial importance that the joint solution obeys continuity condition in time.

Sizing GHEs relies on the thermal conductivity of ground that may be estimated by field method in an *in-situ* thermal response test (TRT) [3]. The effect of the heat exchanged with the ground surface and pile interior might be significant in the transient thermal analysis, in particular, in the analysis of TRT data to estimate the thermal properties of the ground [20].

Ground thermal response to heat transfer from a line-source of time-dependent heat rate, which represents a power transmission tower foundation, was described by the solution to FLS [32]. These solutions have a limitation involving the double integrals of high CPU cost. To mitigate this problem, the transient z-dependent FLS solution was approximated to a single integral for sinusoidal variations of the heat rate representing seasonal temperature oscillations [32]. It was also shown the importance of finite length effects even for the case of operational period of one year in the heat injection mode [32]. However, such intermediate-time period between the short- and long-terms corresponds to the model of a cylinder heat source, capturing thermal storage effects, rather than to the FLS model. Therefore, it is still desirable to obtain temperature response to a variable heat rate from a finite cylinder-source in the integral mean approach. One of the aims of this paper is to develop mean solution to the FCS model for time-varying rate in a single integral form, thus, decreasing computational cost. A self-consistent approach to evaluate temperature response from the input and output temperatures of heat carrier fluid assumes uniform heat rate averaged over the FCS or FLS length. The influence of heat rate variations along a borehole on its temperature response was considered in the FLS model [26]. This effect needs to be taken into account for a shallow energy pile in the FCS model in the same lumped approach in order to increase accuracy and decrease computational costs.

This paper presents (i) analytical expression for the mean temperature response to buried FCS of constant heat flow; and (ii) exact analytical solution for the integral mean thermal response function (G-function) to buried FCS that allows arbitrary heat flow variations, and approximate formula for quasi-steady behavior of temperature response to periodic cylinder-source of heat when time tends to infinity. The limitations of the mean temperature approach to design buried GHE are discussed for different geometries of ground heat exchangers from borehole to pile: the algorithm is highly configurable by user who can select radius of cylindrical source of heat.

The rest of the paper is organized as follows. Section 2 introduces the cylinder- and line-source model formulations, and presents exact integral mean solution to the buried solid cylinder-source model for a constant heat rate. Section 3 proposes integral mean solution to the buried FCS model for a time-varying heat rate, and summarizes these results, comparing them with the predictions of the line-source model. The findings are then analyzed through illustrative example. Section 4 concludes and gives a direction for further investigation. Finally, Appendix presents the generalization of the proposed solution for time-dependent vertical variations of heat rate.

2. Temperature response from buried finite cylinder-source at a constant heat rate

For the analysis of thermal response to the heat source, the ground is assumed to be a homogeneous medium characterized by its thermal conductivity λ and thermal diffusivity α, which are assumed to be the same for the external and internal heat conduction problem, i.e. for $r_0 < r$, and $r_0 > r$, respectively.

In [17] Man et al. presented the two-dimensional formulation for the finite cylinder-source of heat, approximating energy pile or borehole, starting at the ground surface, i.e. at $D = 0$, and then this was generalized to arbitrary D [25]. This paper develops the integral mean approach and considers heat flow from vertical cylindrical surface of radius r_0 oriented in the direction of z-axis, and ranging from the surface of semi-infinite medium at $z = D$ to $z = H + D$ as shown in Fig. 1. The model contains a parameter r_0 naturally corresponding to GHE geometry through a radius of circumference with heat-carrier fluid in the cross section of the energy pile. It can be close to the radius of the pile or to its center, e.g. if a vertical BHE consists of U-tube loop and is connected to a heat pump through which a heat-carrier fluid is circulated [27].

It is assumed that the ground surface temperature is kept constant at the $z = 0$; this is to say it obeys the Dirihlet boundary condition for $D = 0$. The heat is released at a constant rate q_z along the borehole or pile, and is transferred by thermal conduction to surroundings with undisturbed temperature T_0. Analytical expressions for the average temperature are derived by integrating the exact solution over the cylinder-source depth, i.e. from $z = D$ to $z = D + H$.