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Equivalent energy wave for long-term analysis of ground coupled heat exchangers

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ABSTRACT

This paper presents a robust approach to develop ground thermal loads to be used for the long-term analysis of ground-coupled heat exchangers. The thermal loads developed using the proposed approach are simple, yet accounts for the hourly variation of the thermal loads. The analysis to develop these ground thermal loads is based on the change-point statistical analysis to determine the heating and cooling episodes. Heating and cooling loads are then converted into sine waves with an equivalent amplitude and the episodes determined from the change-point statistical analysis. Using the approximated equivalent sine waves, finite element or finite difference methods can be utilized to predict the long-term performance of the heat exchangers. The proposed methodology is compared to other existing approaches and showed better representation of the varying hourly ground thermal loads for a 1 year period. Moreover, a long-term thermal performance is predicted using the equivalent sine waves developed for balanced and unbalanced ground loads.

1. Introduction and Background

Long-term performance of geothermal systems such as vertical boreholes, energy piles, and shallow horizontal trenches is one of the pressing challenges that need to be addressed for the optimum design of these systems. Typically a long-term energy pulse is considered to account for the long-term heat exchange behavior of these systems in addition to the daily energy pulse used to consider the short-term effects (Kavanaugh and Rafferty, 1997). This simplified approach has many drawbacks, especially in cases of unbalanced seasonal loads (in hot or cold climates) where it leads to large over-predictions of the required geothermal loop configurations. Another way to consider long-term effects is to perform a comprehensive energy analysis for the building and the geothermal system using one of the commercially available computer packages (ASHRAE, 2009). This approach necessitates the integration of the geothermal system design with building energy analysis, which can be time consuming and not computationally feasible. Therefore, the detailed comprehensive analysis is not commonly performed for small-scale geothermal systems required for residential and commercial buildings.

Another approach to predict the long-term performance of ground heat exchangers (GHE) is performed using numerical analysis via finite element (FE) or finite difference methods. Following this approach, numerous research efforts on the prediction of the long-term performance of single heat exchanger and fields of heat exchangers are reported in the literature. Lazzari et al. (2010) investigated the long-term performance of heat exchanger fields and concentrated on the dramatic decay in system efficiency over time judged by the fluid temperatures. Zanchini et al. (2012) studied the effect of the ground water flow on reducing the impact of the hourly peak thermal loads and on the long-term performance of various borehole fields. Zanchini et al. (2012) concluded that the ground water flow does not reduce the impact of the hourly thermal loads significantly; however, it showed an improvement in the long-term thermal performance.

Lazzari et al. (2010) and Zanchini et al. (2012) have several assumptions adopted in their models including; (1) the annual ground thermal loads estimated for the initial year are assumed constant over the considered operational period of the system which inherently assumes that constant building energy demand over the entire operational period, and (2) the annual ground thermal loads were modeled using a sine wave which has equal durations for heating and cooling episodes. Balanced and

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Nomenclature

A	area of wall surface (ft^2)
C_P	heat capacity (kJ/kg °C)
COP	coefficient of performance of ground coupled heat pumps in heating mode
E	input electrical energy to the ground-coupled heat pump (W)
EER	energy efficiency ratio of ground coupled heat pumps in cooling mode
EWT	entering water temperature (°C)
$GCHP$	ground-coupled heat pump
Q	heat assigned to a volumetric domain (W/m^3)
q	heat (W)
q''	heat flux (W/m)
K	building heat loss coefficient
k	thermal conductivity (W/m K)
N	number of walls
n	number of thermal load hours = 24 × P
P	thermal load (heating or cooling) duration (days)
r	tube radius (m)
T	temperature (°C)

Greek symbols

θ	time (s)
γ	density (kg/m^3)

Subscripts

amp	ambient
bal	balance
c	cooling mode
cond	conduction
conv	convection
d	design
ext	exterior wall surface
f	fluid domain
g	internal gains
gr	ground
h	heating mode
i	internal
inf	gain due to infiltration
int	interior wall surface
int-conv	Convection portion of internal heat gains due to people, lights, or equipment
j	wall number
max	maximum
occ	occupied building
rad	radiation
s	adsorbed solar
set	indoor design set temperature
sys	gain due to heating/cooling system
unocc	unoccupied building

unbalanced loads are represented by varying the amplitudes of the loads. The annual sine wave is assumed to represent the ground thermal loads regardless of whether the loads have balanced durations (i.e., 6 months heating and 6 months cooling) or whether they were unbalanced. This means that significant errors in the prediction of long-term performance, especially in unbalanced climates, can be expected.

In an effort to use a realistic thermal loads in the numerical models, Zanchini and Lazzari (2013) proposed a method to account for the monthly averaged heat flux in the predictions of the long-term performance of a field of GHE. The proposed methodology by Zanchini and lazzari (2013) can be easily extended to account for the hourly averaged thermal loads. The results of this study imply that the varying monthly thermal loads do not affect the overall long-term performance of a field of GHE, however an increased accuracy of the predicted temperatures is achieved. Since the use of thermal loads with gradually varying amplitudes over short periods (months, days, or hours) in numerical models increases the computational time with no effect on the predicted overall long-term performance, it is the intention of our study to consider the hourly varying loads in a representative sine wave which is used to predict the long-term performance of ground-coupled systems.

We provide a new methodology for modeling the long-term loads of buildings with ground-source systems. In this approach, the energy demands from the building are converted to equivalent energy loads in the ground and statistical analyses are used to convert these loads into a continuous representative sine wave function. The approach provides a simple connection between the building and the ground loads, yet more accurate than balanced sine-waves and quicker that the detailed monthly or hourly models discussed earlier. It can more accurately model seasonal variations even for extreme climates. Thus, this equivalent sine wave approach offers refinement and convenience for the long-term design of ground-source systems.

2. Simplified building and ground energy analysis

The heat balance method (HBM) is generally used to estimate the thermal loads for buildings by solving three different balancing formulas simultaneously (McQuiston et al., 2004; Pedersen et al., 1998): (1) heat balance for exterior surfaces, (2) heat balance for interior surfaces, and (3) heat balance for the zone air. The exterior surface formula balances the heat conduction at the exterior surfaces with the summation of heat generated from the adsorbed solar energy, ambient air convection, and radiation at each surface. The interior surface formula balances the heat conduction at the interior surfaces with the summation of heat collected from the adsorbed solar energy, zone air convection, and radiation at each surface. The zone air formula balances the building heating and cooling thermal loads with the total rate of heat from occupants, lights, equipment, zone air convection, and infiltration.

The design ambient dry bulb temperature is one of the main inputs for the HBM and these values can be looked up from the ASHRAE Fundamentals Handbook (2009) for different locations in the United States. Furthermore, the energy components that should be considered in the three balance equations for a zone with four walls, a roof, and a floor are (1) the solar energy coming through the windows, (2) heat conducted through the exterior walls and the roof, and (3) internal heat gains due to lights, equipment, and occupants. The exterior, interior, and zone balance equations are presented in Eqs. (1), (2), and (3), respectively. McQuiston et al. (2004) present the detailed formulation for each of the components presented in these equations.

The heat balance equation for an exterior surface j at time θ is

$$q''_{cond,ext,j,\theta} = q''_{s,ext,j,\theta} + q''_{conv,ext,j,\theta} + q''_{rad,ext,j,\theta} \tag{1}$$

$$q''_{cond,int,j,\theta} = q''_{s,int,j,\theta} + q''_{conv,int,j,\theta} + q''_{rad,int,j,\theta} \tag{2}$$

$$\sum_{j=1}^{N} A_j q''_{conv,int,j,\theta} + q_{inf,j,\theta} + q_{sys,j,\theta} + q_{int-conv,j,\theta} = 0 \tag{3}$$

Based on the balance equations for the exterior and the interior surfaces of a given wall, the temperature of the exterior surface of the wall can be expressed as a function of the temperature of the interior surface (McQuiston et al., 2004). Therefore, an iterative solution is required to solve for these two temperatures since each