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A new energy analysis tool for ground source heat pump systems

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ABSTRACT

A new tool, suitable for energy analysis of vertical ground source heat pump systems, is presented. The tool is based on analytical equations describing the heat exchanged with the ground, developed in Matlab® environment. The time step of the simulation can be freely chosen by the user (e.g. 1, 2 h etc.) and the calculation time required is very short. The heating and cooling loads of the building, at the afore mentioned time step, are needed as input, along with the thermophysical properties of the soil and of the ground heat exchanger, the operation characteristic curves of the system's heat pumps and the basic ground source heat exchanger dimensions. The results include the electricity consumption of the system and the heat absorbed from or rejected to the ground. The efficiency of the tool is verified through comparison with actual electricity consumption data collected from an existing large scale ground coupled heat pump installation over a three-year period.

1. Introduction

The building along with the A/C equipment installed form in fact a system of interacting components that consumes primary energy in order to maintain predefined, in terms of temperature and humidity, internal conditions in the building.

The primary energy consumption of such a system depends on a large number of parameters. Some of them are more or less independent of the system (e.g. the prevailing climate conditions of the area, the use of the building and the required internal conditions) but they strongly affect the heating and cooling loads, while others depend on the system and they affect both the loads imposed and the energy consumed by the A/C equipment to deliver these loads.

System depended parameters affecting the heating and cooling loads include, for example, construction materials, type and thickness of insulation, type and area of windows, orientation of the building, natural ventilation, colors, shading etc.

The energy consumed by the A/C equipment depends of course not only on the load to be delivered but also on the efficiency of the equipment, which in turn depends on its type and construction.

During the design phase of such a system (building and A/C equipment), proper selection of the system depended parameters is required in order to optimize its operation in both financial and environmental terms, i.e. finally in terms of primary energy consumption. To this aim, a simulation of the system is required, and this simulation has to be as accurate as possible, the simulation tool becoming thus a designing tool, permitting the designer to evaluate the effect the available alternatives have on the energy consumption of the system before finalizing the design.

The energy analysis methods can be divided in two main categories, namely the dynamic and steady state methods. The first category, including the "Heat Balance Method" and the "Transfer Function Method" or "Response Factor Method" [1], forms the basis for the most commonly used energy simulation software (e.g. TRNSYS, DOE-2, BLAST, EnergyPlus). The second category consists of the "Single-measure Method" and "Simplified Multiple-measure Method" [2].

The methods of the first category are very detailed and the results of the relevant software are of high accuracy even at small time steps, in the order of hour or smaller. The main disadvantages of these approaches are the amount of data they require, their complexity and the long familiarization time required. A common problem encountered is the lack of proper climate data [2], usually bypassed with the use of synthetic meteorological years that are embedded in the software.

The main disadvantage of the steady state methods is the reduction of their accuracy when the A/C system includes components with temperature depended efficiency, for example heat pumps.

In the case the A/C system is based on ground source heat pumps, the efficiency of the heat pumps is a function of the water temperature at the ground heat exchanger outlet, which in turn strongly depends on the heating or cooling load of the building. In the recent years, experimental, analytical, numerical or combined simulation tools, modeling the performance of ground source heat

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Nomenclature

COP	coefficient of performance
$Ei(x)$	exponential integral
k	thermal conductivity (W m^{-1} K^{-1})
L	length of borehole (m)
n	counter
Q	heat flux (W)
r	radial distance (m)
R	thermal resistance (K W^{-1})
t	time (s)
T	temperature (K)
T_∞	undisturbed ground temperature, before heat injection or absorption (K)
$T_{borehole}$	borehole temperature at the surface between soil and grout (K)

Greek letters

π	constant = 3.14159 ...

Subscripts

b	borehole
B	building
c	cooling mode
con	convection
g	grout
G	ground
h	heating mode
HP	heat pump
p	pipe
tot	total
w	water

pump systems, either vertical or horizontal, have been reported in the literature. For instance there are tools based on the TRNSYS environment [3], CFD platforms [4], or other numerical methods [5], formulating the efficiency and the behavior of the horizontal GHE systems. The number of publications referring to the vertical GHE systems is significantly higher [6–10], due to their improved economical interest and the consequent higher number of installations. To this direction, analytical [11,12], numerical [13-16] or combined [17] simulation models are reported. Based on these approaches, energy analysis tools have been developed for the holistic simulation of ground source heat pump systems.

Aim of this paper is to present a new energy analysis tool for vertical GSHP systems, accounting for the major energy interactions between the components of the system (building loads, ground heat exchanger geometry and properties and soil properties) and the effect of temperature on the efficiency of the heat pumps, based on the line source approach. The results of the tool are compared against actual experimental data of a large scale ground source heat pump application.

2. Description of the energy analysis tool

The basis of the tool is the algorithm developed at the Process Equipment Design Laboratory of the Aristotle University of Thessaloniki, determining the fluid temperature at the outlet of a ground heat exchanger as a function of the heat exchanged with the ground. The calculation is based on the assumption that the ground heat exchanger is a continuous and linear source (or sink) emitting (or absorbing) heat Q. This phenomenon can be described by the linear source equation [18,19]:

$$T(r,t) = T_\infty + \frac{Q}{4 \cdot \pi \cdot k \cdot L} \cdot Ei(x) \tag{1}$$

where r is the radial distance from the source/sink, t is time, T_∞ is the initial soil temperature, k is the thermal conductivity of soil, L is the ground heat exchanger length, and $Ei(x)$ the exponential integral [20].

In real life operation of the ground heat exchanger, the heat flow Q does not remain constant over time, since it depends on the thermal load of the building and on the coefficient of performance (COP) of the heat pump. It can be assumed however that it remains constant for a time interval, this interval becoming the time step of the calculation.

With the assumption that the soil thermal properties do not dependent on the temperature, the superposition technique [21,14], can be applied, since the governing equations become linear [21]. Based on Eq. (1), the soil temperature at a distance r from the borehole axis and at time t, at the end of n^{th} time period, can be calculated from the equation:

$$T(r,t) = T_\infty + \sum_{i=1}^{n} \frac{(Q_i - Q_{i-1})}{4 \cdot \pi \cdot k_g \cdot L} \cdot Ei\left(\frac{r^2}{4 \cdot \alpha \cdot (t_n - t_{i-1})}\right) \tag{2}$$

where k_g is the grout thermal conductivity.

Eq. (2) with $r = r_b$, r_b being the borehole radius, allows for the determination of temperature $T_{borehole}(t)$ at the interface between borehole and soil at time t, from which, taking into account the total thermal resistance (R_{tot}) of the borehole, the water temperature $T_w(t)$ at the ground heat exchanger outlet at any time t, can be calculated.

The total thermal resistance consists of the convection resistance between the fluid and the pipe (R_{con}) and the conduction resistances of the pipe (R_p) and of the grout material (R_g).

$$R_{tot} = R_{con} + R_p + R_g \tag{3}$$

The water temperature at the ground heat exchanger outlet at time t thus can be calculated from the equation:

$$T_w(t) = T_{borehole}(t) - Q(t) \cdot R_{tot} \tag{4}$$

The model and the relevant code were verified using experimental data, recorded over a three-year period at an existing installation in Thessaloniki area, in northern Greece, and the results suggest that the prediction of the model is of an overall acceptable accuracy [22]. In order to further evaluate the model, the electricity consumption of the system was estimated and compared to the actual one. To this aim, the COP of the heat pumps, given by the manufacturer as a function of the primary loop inlet fluid temperature, was determined, based on the predicted outlet water temperature, and consequently the electricity consumption was estimated. The so estimated annual electricity consumption was compared to the corresponding actual one, as the later is determined based on the measured water temperature and the relevant COP. The results of this calculation are listed in Table 1 on annual basis and for the three years of operation examined, using 1 h time step for the simulation. Obviously, the electricity consumption of the heat pumps depends not only on (a) the building load, which in turn depends on the usage of the building but also on the specific climate conditions and (b) on the temperature field of the GHE developed, which affects the temperature of the water entering the primary loop of the heat pumps and hence their COP. These dependencies explain the differences of the annual electricity consumption of the system, listed in Table 1. It is clear from Table 1 that the model underestimates the electricity consumption by 1.8–3.8%, depend-