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Improving the Ashrae method for vertical geothermal borefield design

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ABSTRACT

The design of a borehole heat exchanger (BHE) field coupled to a geothermal heat pump requires a suitable dynamic model able to take into account the intrinsic time varying behaviour of the building heat load profile and ground thermal response. In this paper a new method is proposed for the calculation of the Temperature Penalty, the key parameter of the Ashrae dynamic method originally developed by Kavanaugh and Rafferty. The proposed method is conceived for maintaining the simplicity of the original Ashrae model while enabling a much more accurate design of the BHE field. The validation of the new procedure is made with reference to a comprehensive set of 240 BHE configurations, described in terms of the corresponding temperature response factors (i.e. *g*-functions). It is demonstrated that the Ashrae temperature penalty values typically underestimate the corresponding true values with an average deviation of more than 40%. On the other hand the proposed method is able to provide temperature penalty values well centered around the benchmark line and with an average deviation of less than 10%; it is finally demonstrated that the present procedure is also much more accurate than other existing models and simpler to apply in engineering design.

1. Introduction

Ground coupled heat pumps (GCHP) can be considered as one of the most efficient solutions for building air conditioning, especially in heating mode. This technology has widely spread either in Europe or America. GCHP is an energy efficient system for a wide range of energy demand situations, from small residences to large commercial buildings generally yielding higher efficiencies (instantaneous COPs and average SPF) in energy conversion compared to conventional air source heat pumps. Such performance mainly depends on the correct design of the ground side of the plant, more important than the correct selection of the thermal machine or the proper choice of the heat distribution in the building. As it is well known, the most popular solution for exchanging heat to the ground is a closed loop of vertical heat exchangers made by a single or double U-pipe inserted in a drilled borehole. Borehole heat exchangers (BHEs) are usually preferred to horizontal or near horizontal (e.g. trench pipes, coil pipes, pipe baskets) arrangements due a number of reasons, including: the reduced requirement of land surface, the availability of reliable drilling equipment, the stable (and even increasing with depth) ground temperatures, a consolidated history of models and calculation tools for BHE field design. The goal of the borefield design problem is to define the best BHE geometry (with respect to land availability and drilling/connection strategies) and the minimum overall length of vertical pipes. The constraints of the problem and its input information are the building thermal energy demand, the ground thermal properties and a target heat pump performance, in terms of COP, EER or SPF depending on the case. BHE design problem is complex due to the time depending behaviour either of the building thermal profile or the ground response, the latter being a combination of short and long period response modes. The engineering approach to the BHE design process is usually based on a number of assumptions, the most important one being to consider pure thermal conduction and constant ground properties. Under those hypotheses, a number of simple solutions of the transient Fourier problem have been proposed in order to evaluate the ground temperature field when a constant heat flux is imposed at the ground-heat exchanger boundary.

The borehole is usually modelled as a linear or cylindrical source, of finite or infinite length. The most popular solutions for such a problem are the so called infinite linear source (ILS) [1,2] and infinite cylindrical source (ICS) [3]. Both solutions provide the temperature distribution in the ground as a function of a dimensionless time and of the distance (radius) from heat source axis. The two solutions are proved to be in absolute agreement except for the very early times, as also discussed in recent papers [4,5]. The ILS model first proposed by Lord Kelvin [1], and later by Ingersoll et al. [2],

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Nomenclature

Symbols (meaning Units)

B	borehole separating distance (m)
c	ground specific heat (J/kg K)
Fo_{rb}	Fourier number based on BHE radius, $Fo_{rb} = \alpha_{gr}\tau/r_b{}^2$ (–)
Fo_H	Fourier number based on BHE depth, $Fo_H = \alpha_{gr}\tau/H^2$ (–)
H	depth of Borehole heat exchangers (m)
k_{gr}	ground thermal conductivity (W/mK)
L	overall length of borehole heat exchangers (m)
$\dot{Q}$	heat transfer rate (W)
$\dot{Q}'$	heat transfer rate per unit length (W/m)
r	radius, radial coordinate (m)
r_b	borehole radius (m)
R_{bhe}	borehole thermal resistance (mK/W)
T	temperature (K) or (°C)
$T_{gr,\infty}$	undisturbed ground temperature (°C)
T_p	temperature penalty (°C)
T_{p1}	auxiliary excess temperature in Ashrae method (°C)
z	vertical coordinate (m)

Greek letters

α_{gr}	ground thermal diffusivity, $\alpha_{gr} = k_{gr}/(\rho c)$ (m^2/s)
ρ	ground density (kg/m^3)
β	$\beta = r/H$ (–)
γ_f	$\gamma_f = 0.5(Fo_H)^{-0.5}$ (–)
θ_8	excess temperature, equation (17) (°C)
τ	time (s)
$\delta_{i,j}$	distance between borehole i and borehole j (m)

Subscripts

f	secondary fluid
ave	average
b	borehole
A	Ashrae original method
8	present paper method
P	Philippe et al. method
C	Capozza et al. method
y	ten year period
m	one month period
h	six hour period
N	ten years + one month + six hours

approximates the BHE heat source as an infinitely long line, buried in an infinite ground, delivering a constant heat transfer rate to the surrounding medium. The ICS solution [3] considers again a constant heat transfer rate but applied to a cylindrical surface of finite radius and infinite length. Thanks to the work of the Lund research group (e.g. Eskilson [6]), the temperature response factor approach was extended to the description of complex BHE systems, constituted by finite heat sources arranged in regular arrangements. The Lund group named the new response factors "g-functions" and a number of BHE field geometries have been investigated by means of the numerical solution of the single (finite) heat source problem coupled with proper spatial superposition techniques. Finite Line Source problem (FLS) was also analytically investigated in recent studies, the most important ones being those by Zeng et al. [7], Lamarche and Beauchamp [8] and Claesson and Javed [9].

For more general situations where the building heat load profile cannot be considered constant, the temporal superposition approach can be applied for refining the ground/BHE response analysis. As first suggested by Carslaw and Jaeger, superposition in time of basic solutions allows variable heat transfer rates at the ground to be accounted for. This technique was successfully applied by several authors, including Eskilson himself, Yavuzturk and Spitler [10], Bernier et al. [11].

The superposition techniques (in time but also in space) can be applied to any temperature response factor including the ICS and ILS solutions. Deerman and Kavanaugh [12] and later Kavanaugh and Rafferty [13] employed the ICS solution to superpose in time a series of three heat pulses of different duration, from hours to a decade. This model is also known as the ASHRAE method (Ashrae Handbook [14]) and it was recently adopted as national standard for BHE field design in Italy too (UNI standard 11466 [15]).

The strength of the Ashrae method is its simplicity that allows a fast BHE design, in terms of BHE overall length, without the need of dedicated computer codes as those based on monthly or hourly descriptions of the building heat load profiles (Hellström and Sanner [16], Spitler et al. [17]). In the Ashrae method the short to long term thermal history of the building (and of the ground) is described by three primary pulses, named yearly, monthly and hourly thermal loads. The ICS solution is adopted to describe the corresponding ground thermal resistances and the ILS solution is applied to evaluate the ICS correction term.

Since the ICS solution has intrinsic limitations in describing the ground response to multiple BHEs in the long period, the Ashrae method introduces a correction parameter named the Temperature Penalty (T_p) which is in charge of taking into account the mutual interactions among the ground heat exchangers (Philippe et al. [4]).

The Ashrae standard does not explain the genesis and the physical meaning of this additional parameter. Fossa [18] demonstrated that the T_p is proportional to the difference between the ICS solution value and the g-function one corresponding to the BHE field geometry into consideration, both evaluated at the end of the (multi)yearly period considered in the method. As the calculation of the pertaining g-function is anything but straightforward, a number of approximated methods have been proposed in literature to tackle the problem of the temperature penalty evaluation. The first method is of course the one suggested in the Ashrae standard [13], which unfortunately is far from being reliable, as this paper is going to demonstrate. Other contributions to the temperature penalty estimation (without exact g-function calculation) have been recently offered by Philippe et al. [19], Fossa and Rolando [20] and Capozza et al. [21].

The present paper is addressed to the evaluation of the T_p parameter according to a new procedure that was able to maintain the original Ashrae formalism while just substituting its ILS part on "annual heat storage" with a physically based temperature excess calculation which applies a spatial superposition scheme. The new procedure is based on a limited set of constants that have been derived through optimum search analysis based on the comparison with "true" g-function values pertaining a comprehensive set of BHE field configurations, including square, rectangular, in-line, L-shaped, U-shaped and open rectangles. The new, method, in spite of its simplicity, demonstrated to be able to provide much more accurate predictions of the temperature penalty values and overall BHE lengths with respect to the original Ashrae procedure and also with respect to the other literature models.

2. Theoretical background

The thermal interaction between the ground and a BHE arrangement, when underground water circulation can be neglected, is governed by the three-dimensional time-dependent conduction equation.

A number of one-dimensional (in the radial direction) and two-dimensional (radial and axial) analytical solutions have been