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On the maximum thermal load of ground heat exchangers

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Abstract

Ground heat exchanger (GHE) coupled heat pumps constitute an alternative system for the air conditioning of buildings, with the vertical U-tube type being the most popular. The installation cost and the overall performance of the system strongly depends on the designing and dimensioning, which however present significant difficulties. The critical parameter in designing vertical systems is the thermal power per meter of borehole that the GHE can handle. This paper presents a calculation algorithm, which aims to redefine the maximum thermal load allowable in vertical ground heat exchangers.

Keywords: Ground heat exchanger (GHE); Maximum loading of GHE; Heating; Cooling

1. Introduction

Heat pump based systems for heating and cooling residential and commercial buildings continuously gain in popularity, mainly because of their high coefficient of performance. They utilize practically all types of soft energy tanks, i.e. ambient air, surface or underground water and soil.

The utilization of soil requires an adequate construction, the ground heat exchanger—GHE, with the aid of which heat is exchanged between the water of the primary circuit of the heat pump and the ground. The heat pump is usually of water-to-water type, with the secondary circuit exchanging heat with the building for heating or cooling.

Recent data [1] reveal that the GHE-heat pump systems installed globally sum up to about 12,000 MW_{th}, corresponding to 20,000 GWh. The total number of systems is estimated to be 1,100,000.

Of all topologies available for the GHE, it was found that 46% of the systems in the USA are of vertical closed loop type and 38% of horizontal closed loop, while the remaining refers to open loop systems [2]. For the vertical GHEs, the most commonly adopted form is the one with one or two U-type tubes per borehole.

The size of the GHE depends on the thermo-physical properties of both the soil (density, specific heat capacity, thermal conductivity, thermal diffusivity, humidity, etc.) and the drilling (thermal conductivity of the tube and grout materials) and of course on the ground temperature.

During the last 15 years, significant research effort has been devoted in quantifying the effect these properties have on the GHE performance, the ultimate goal being the determination and optimization of the heat the GHE is capable to exchange with the specific ground of installation.

According to Kavanaugh [3,4], the maximum thermal power expected to be handled by a vertical U-tube GHE for steady-state operation is 50–80 W/m. For typical ground conditions, Pahud and Matthey [5] suggest to design a GHE with 50 W/m, a suggestion adopted by ASHRAE as well [6].

Taking into account, however, the fact that:

- the thermal load of the building has a strongly dynamic character;
- the time interval required by the GHE in order to reach steady-state operation is comparatively very long, because of the size of the system (more than 30 tonnes

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Nomenclature

L	tube length (m)
n	constant (−)
Q	heat flux (W)
r	radius from borehole center (m)
r_{out}	borehole radius (m)
t	time (h)

Greek letters

α	ground thermal diffusivity (m^2/h)
ϑ	temperature (°C)
ϑ_∞	undisturbed ground temperature, before heat injection or absorption (°C)
λ_g	thermal conductivity (W/m K)
π	constant = 3.14159 (−)

of soil per m^2 of building) and the corresponding thermal inertia;

- the system usually is used for both heating and cooling purposes, meaning that the heating period starts at a ground temperature higher than the normal of the area, while the cooling period starts at a ground temperature lower than the normal.

The question is how often, under which conditions and to what extend the above-mentioned limit can safely be surpassed.

This paper attempts to investigate the loading limit of a GHE. To this aim, a suitable calculation algorithm is developed, determining the capability of GHE thermal loading as a function of the duration of this load.

2. The algorithm

The study of the temperature profile developed by a vertical GHE started more than 50 years ago. The first analytical approach was published by Carslaw and Jaeger [7], simulating the GHE as a linear or cylindrical thermal source (or sink). Ingersoll et al. [8] further developed the linear source approach. The aim of the approach was to determine the soil temperature as a function of time and distance from the source.

The cylindrical approach assumes homogeneous and isotropic soil and yet it remains very complicated and time consuming. The linear approach, based on Kelvin's theory [9], is simpler, giving similar results, provided certain prerequisites are met. Recently, numerical solutions have been presented, based on the finite difference (Rottmayer et al., [10]) or the finite element (Philippacopoulos and Berndt, [11]) methods.

All the models mentioned above calculate the ground temperature profile as a function of the time elapsed since the beginning of the GHE loading, assuming that the GHE load remains constant over time. This assumption is imposed by the fact that a variable GHE load results in differential equations practically impossible to be solved. In the real world, however, this requirement can never be met, since the GHE load depends on the building's energy demand. As a result, and mainly for safety reasons, the GHE designers overestimate the systems, which in turn have an important impact on the installation cost.

The work presented attempts to determine the maximum thermal load the GHE is capable of handling, taking into account the duration of this load, the inlet and outlet water temperatures and of course the initial ground temperature. The maximum thermal load of the GHE is therefore defined as the maximum heat flow the GHE can handle at a specific initial ground temperature.

According to Carslaw and Jaeger [7], the temperature profile developed around a linear source of constant heat flux Q is given by

$$\vartheta(r,t) - \vartheta_\infty = \frac{Q}{4\pi\lambda_g L} E_i(x) \quad (1)$$

with $E_i(x)$ the exponential integral

$$E_i(x) = \int_x^\infty \frac{e^{-u}}{u}\, du \quad (2)$$

Assuming that the grout thermal diffusivity roughly equals that of the surrounding soil (an assumption generally close to reality, for the common combination of grout materials and soils), the drilling diameter can be taken equal to the external diameter of the heat exchanger tube. With this assumption, and for the GHE case, the lower limit x in Eq. (2) becomes

$$x = -\frac{r_{out}^2}{4\alpha t} \quad (3)$$

In the case of heat exchangers with multiple water passing, according to Bose et al. [12], the equivalent external tube radius should be used in Eq. (3):

$$r_{eq,out} = \sqrt{n} r_{out} \quad (4)$$

Based on the above, Eq. (1) allows for the determination of the time required for the temperature at a specific distance from the drill to reach a specific value.

Assuming that there is no thermal resistance between the tube and the surrounding soil, the application of Eq. (1) for $r = r_{out}$ results in the temperature of the outer surface of the GHE tube as a function of time.

The heat flux from the ground to the water can be calculated from the temperature difference between inlet and outlet of the GHE and the water mass flow rate. Taking into account the convection resistance and the thermal conductivity of the tube material, the temperature of the outer surface of the tube can be again calculated, from the