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New methodology to design ground coupled heat pump systems based on total cost minimization

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HIGHLIGHTS

- A procedure is developed to size and design GCHP systems to minimize cost.
- Total cost includes initial (drilling, heat pump…) and operating costs (energy).
- The number of boreholes, their length and spacing, and the peak load ratio are varied.
- The method is tested with different cases (loads, ground conductivity, etc.).
- An economical analysis of thermal response tests is performed.

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ABSTRACT

This paper introduces a method for designing vertical ground heat exchangers and heat pump systems, by minimizing the total cost of the project. The total cost includes an initial cost composed of drilling, excavation, heat pump and piping network. An operational cost is also included to account for the energy consumed for heating/cooling a building. The procedure allows determining the optimal number of boreholes, their depth and spacing, and the optimal size of the heat pump. The method is tested for different ground conductivity and heat demands. The method can also be used to determine the economical viability of a TRT. For tested cases, results show that the excess cost due to uncertainty on ground thermal conductivity increases with the number of boreholes. Also, a cost sensibility analysis shows that the most influential parameters are the number of boreholes and their depth.

1. Introduction

Among available options, geothermal energy is known to be a particularly good alternative for heating and cooling buildings, in terms of energy efficiency and environmental impacts [1]. That explains in part why the world's direct utilization of geothermal energy grew up by 43% from 2000 to 2005 [2,3]. In Canada, ground temperature is relatively cold (around 6 °C [4]), and therefore, building heating based on geothermal energy requires a ground coupled heat pump (GCHP) system. Vertical heat exchangers are among the most widely used configurations, but other types of ground heat collector designs can also be considered (e.g., horizontal heat exchangers, open loop systems, etc.).

Although GCHP systems can yield significant and recurrent energy savings compared to "more traditional" heating/cooling systems [5], the high investment that they require is one of the main reasons preventing these systems to be more widely used in practice. Therefore, accurate and efficient sizing procedures are particularly important in order to avoid under or over-designs which is accompanied by a reduction of energy savings or by excess initial costs. On the other hand, present design and sizing strategies rely mostly on approximate "rules of thumbs" (e.g., specified number of meters of borehole per kW of heating/cooling) or on achieving an acceptable level of performance based on a worst case scenario. In particular, in the latter category, ASHRAE's proposed method [6] is among the most widely used. Given the heating/cooling load assumed by the ground, the procedure essentially estimates the required length of borehole in order to satisfy the heating/cooling needs after ten years, in the peak period. In that procedure, a certain grid of borehole is assumed by the designer, and a penalty temperature is considered in order to

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Nomenclature

A	area, m^2
B	distance between boreholes, m
C	cost, \$
c	specific heat, J kg^{-1} K^{-1}
D	diameter, m
H	borehole depth, m
j	interest rate, %
k	thermal conductivity, W m^{-1} K^{-1}
L	length, m
$\dot{m}$	mass flow rate, kg s^{-1}
N	number of boreholes in x or y direction
$\Delta P'$	pipe head loss per unit length, Pa m^{-1}
p	percentage of total heat load
Q	thermal energy, kWh
$\dot{Q}$	heat transfer rate, W
q	heat load per length unit, W m^{-1}
R	conduction resistance, K W^{-1}
T	temperature, °C
t	time, h
W	work energy, kWh
$\dot{W}$	work or power, W
X	price, \$
Greek symbols	
α	thermal diffusivity, m^2 s^{-1}
μ	viscosity, kg s^{-1} m^{-1}
ρ	density, kg m^{-3}

account for borehole-to-borehole thermal interactions in that configuration [7].

Despite their valuable and practical usefulness, current design methods for geothermal systems also have limitations. For example, the designer has to decide or impose a priori the proportion of the building heating and cooling needs that will rely on geothermal energy. Also, and most importantly, there is no guarantee that the final design is the most cost-effective.

Total cost minimization procedures have been developed to design many systems, including different types of heat exchangers, e.g. Refs. [8–11]. Overall, this body of work showed that it is possible to determine the 'best' heat exchanger geometrical and operational features to minimize its overall cost, for a given duty. In this paper, we thus propose a new design and sizing method for vertical ground heat exchangers coupled to a heat pump based on total cost minimization.

2. Evaluation of the cost function

In the present section, we explain how the total cost of a ground source heat pump system project was evaluated. Eventually, this global cost will be minimized with respect to a series of design variables in order to determine optimal design features (see Section 4). The total cost of the project is obtained by summing the operating costs with the initial capital invested. Every annual money flux was converted into its present value, in such a way that the total cost could be expressed as:

$$C_{tot} = C_{initial} + \sum_{y=1}^{n} C_{a,y}(1+j)^{-y} \quad (1)$$

where n is the number of years of the project, j, the interest rate [%] and $C_{a,1}\ldots C_{a,n}$ are the annual operating cost for years 1 to n. The two next sections explain how the operating and initial costs were calculated.

2.1. Operating cost

The operating cost is mostly governed by the energy consumed by three devices: the heat pump, the heat transfer fluid circulation pump, and the backup heating/cooling system.

The instantaneous power needed by the heat pump depends on its coefficient of performance (COP) as well as on the building heat load that the geothermal system is taking care of. In the present analysis, it is considered that only a ratio p of the building peak load $\dot{Q}_{max}$ is provided by the geothermal system. In other words, the system is sized in such a way that when the instantaneous building heating requirement is larger than $p\dot{Q}_{max}$, a backup system is used to supply the exceeding heating requirement. In the present study, it is supposed that the system operates in a heating dominant environment. Therefore, no backup system for the cooling load was considered (i.e. all cooling is provided by the borefield). The method outlined in this paper could easily be adapted to situations where the cooling load is more important by including the cooling backup cost. Mathematically, the building heating load provided by the geothermal heat pump can be written as:

$$\dot{Q}_{build,HP}(t) = \begin{cases} \dot{Q}_{build}(t) & \left(\dot{Q}_{build}(t) \le p\dot{Q}_{max}\right) \\ p\dot{Q}_{max} & \left(\dot{Q}_{build}(t) > p\dot{Q}_{max}\right) \end{cases} \quad (2)$$

Then, the instantaneous power requirement is:

$$\dot{W}_{HP}(t) = \dot{Q}_{build,HP}(t)/COP(t) \quad (3)$$

Note that in current practices, p is usually assumed by the designer, whereas in the present procedure, it will be optimized in order to minimize total cost.

The power required for the backup system is determined by subtracting the heating requirement provided by the geothermal system from the total building heat load (with a COP = 1 for the backup system):

$$\dot{W}_{b}(t) = \dot{Q}_{build}(t) - \dot{Q}_{build,HP}(t) \quad (4)$$

The power required for heat transfer fluid circulation depends on the head loss and flow rate in the piping network of the borefield. It is thus a function of the piping layout, which depends on the distance B between boreholes, their depth and the number of boreholes. The borefield grids considered in the present work have a number N_x of boreholes in x direction, and N_y in the y direction, as shown in Fig. 1. All boreholes are connected in parallel and are assumed to experience the same fluid mass flow rate (balancing valves employed to achieve equally distributed flow). Although Fig. 1 shows a direct return configuration, it should be noted due to the simplifying assumptions of the head loss calculations, a reverse configuration would yield the same pumping power. Each row of boreholes aligned in the x-direction is connected and then, the final y-column of boreholes collects all x-rows (see Fig. 1). In order to simplify the problem and limit the number of design variables, no piping diameter optimization was attempted. The head loss by unit length was assumed to be equal to $\Delta P' = 0.4$ kPa/m for all pipes, a