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Influence of groundwater flow on cost minimization of ground coupled heat pump systems

Martin Samson, Jonathan Dallaire, Louis Gosselin*

Department of Mechanical Engineering, Université Laval, Quebec City, Quebec, Canada

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ABSTRACT

This paper introduces a new sizing methodology for ground coupled heat pump (GCHP) systems which takes into account groundwater flow (by using G-functions based on analytical models) in order to achieve an economic optimization of the total cost of the project. The procedure includes the calculation of the initial and the annual operational costs. Optimal design variables (boreholes depth, distance between consecutive boreholes, etc.) and borefield layouts (number of boreholes in the *x*-direction) are presented for different values of the thermal conductivity of the ground. In addition, a parametric study is done to measure the impact of the groundwater flow velocity and angle with respect to the borefield on the economics of the project. It is shown that the effects of the groundwater flow velocity on total cost become apparent only for high velocities, i.e., $Pe \gtrsim 10^{-2}$. On the other hand, the groundwater flow angle is less impactful regardless of the groundwater flow velocity, i.e., the net economic gain that can be obtained by choosing the optimal orientation is much smaller compared to total cost of the system (less than 2%). A simultaneous comparison of the initial and operational costs shows that for all *Pe* values, higher initial costs usually result in lower operational costs. Finally, optimized designs are tested under off-design operating conditions. It can be observed that the economic consequences of operating under off-design conditions are far worst if the groundwater flow velocity is overestimated, which can lead to an increase of the operational costs of as high as 5.8%. A wrong estimation of the flow angle in the design phase, however, only leads to an increase of the operational costs of at most 2.4% for the cases considered in this paper.

1. Introduction

Ground coupled heat pump systems are an interesting option for heating and cooling buildings, since they provide energy savings and have low environmental impacts compared to other systems (Nguyen et al., 2014; Mustafa Omer, 2008). They are particularly attractive for projects in which both cooling and heating are needed, such as a large variety of buildings in Canada (Lund and Boyd, 2016). Vertical heat exchangers, or boreholes, are the most widely used configuration in Canada. Despite of their clear advantages, the main obstacle to the installation of such systems is the high investment required, which can be prohibitive. Thus, an efficient sizing methodology is needed to avoid undersized or over sized designs which can lead to a reduction of the energy savings or an augmentation of the initial cost.

Current sizing procedures are based on finding the required total borehole length for specified heating and cooling loads (Kavanaugh and Rafferty, 1997). Recent studies, on the other hand, have proposed another approach to the GCHP system sizing problem by identifying the design minimizing the total cost of the system (including purchase cost and cost of operation) (Hénault et al., 2016; Robert and Gosselin, 2014). Such an approach has the advantage of identifying the optimal fraction of the building thermal loads to be supplied by the GCHP rather than imposing this fraction.

In these sizing calculations, the ground is usually simplified and represented by a homogenous medium in which conduction is the only heat transfer mechanism. However, groundwater is commonly found in many geological environments. Groundwater flow can significantly affect heat transfer around boreholes (Fan et al., 2007; Chiasson and O'Connell, 2011; Bertagnolio et al., 2012; Choi et al., 2013; Tolooiyan and Hemmingway, 2014). Many analytical models have been developed to quantify its effects (Diao et al., 2004; Molina-Giraldo et al., 2011; Angelotti et al., 2014a; Rivera et al., 2015; Zhang et al., 2016). Previous studies have also developed relatively fast heat transfer computational methodologies with groundwater flow, such as calculating a thermal ground resistance (Sutton et al., 2003) or a thermal conductivity (Deng et al., 2005), using fast Fourier transform combined with cubic spline (Marcotte and Pasquier, 2008), or correlations for G-functions based on analytical models for groundwater flow (Tye-

* Corresponding author.
E-mail address: louis.gosselin@gmc.ulaval.ca (L. Gosselin).

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Nomenclature

B	Distance between consecutive boreholes, [m]
C	Cost, [$]
COP	Coefficient of performance, [−]
Fo	Fourier number $\alpha_g t/r_b^2$, [−]
G	G-function, [−]
H	Borehole depth, [m]
L	Length, [m]
N	Number of boreholes, [−]
$\Delta P'$	Pipe head loss per unit length, [Pa m^{-1}]
Pe	Péclet number $u_g r_b/\alpha_g$, [−]
R	Thermal resistance, [K W^{-1}]
T	Temperature, [°C]
X	Specific price, [$/m or $/kWh or $/kW]
c	Specific heat, [J kg^{-1} K^{-1}]
f	Fraction of maximal load, [%]
j	Interest rate, [%]
k	Thermal conductivity, [W m^{-1} K^{-1}]
$\dot{m}$	Mass flow rate, [kg s^{-1}]
n	Duration of the project, [years]
q	Thermal load, [W]
r	Radius, [m]
t	Time, [s]
u	Groundwater flow velocity, [m s^{-1}]
w	Work energy, [k W h]
$\dot{w}$	Work or power, [W]

Greek Symbols

α	Thermal diffusivity, [m^2 s^{-1}]
θ	Average temperature change, [°C]
ρ	Density, [kg m^{-3}]
ϕ	Groundwater flow angle, [°]

Subscripts

a	Annual
b	Borehole
$build$	Building
$drill$	Drilling
ex	Excavation
f	Fluid
g	Ground
ini	Initial
op	Operational
$pipe$	Piping
tot	Total
x, y	Cartesian directions
$E1, 2$	Electricity rates
GHX	Ground heat exchanger
HP	Heat pump
P	Power peak rate

Gingras and Gosselin, 2014).

Given the influence of groundwater flow on GCHP systems (Hecht-Méndez et al., 2013; Angelotti et al., 2014b; Liuzzo-Scorpo et al., 2015; Geng et al., 2016) and the advantages of a design method based on cost minimization, this paper introduces a new sizing methodology that takes in account groundwater flow. The total cost is in fact composed of the initial and operational costs, which both depend on different design parameters and are influenced by groundwater flow. The GCHP system that is optimized in the present paper is introduced in Section 2. The methods used to calculate the total cost of the system and the energy output of the GCHP are described in Sections 2 and 3, respectively. The optimization strategy and numerical model are detailed in Section 4, whereas the results of the different optimization runs and their implications in terms of design strategies are discussed in Section 5.

2. Cost estimation

The general layout of the geothermal system studied in this paper is presented in Fig. 1 of (Robert and Gosselin, 2014). The system consists in grids made of N_x by N_y equally spaced boreholes in the x and y directions, respectively. The total number of boreholes N is thus given by:

$$N = N_x N_y \tag{1}$$

Boreholes in the x-direction are connected in parallel and linked together through the final column in the y-direction. It is assumed the all boreholes experience the same fluid mass flow rate via balancing valves. The borefield inlet and outlet pipes are connected to a circulating pump and to a heat pump, the latter being used for the heating or cooling of the building.

The total cost of the ground coupled heat pump system project is achieved by summing the initial cost of the installation and the annual operating costs, which are then converted to their present values:

$$C_{tot} = C_{ini} + \sum_{i=1}^{n} C_{a,i}(1 + j)^{-i} \tag{2}$$

where n is the number of years of the project, j is the interest rate [%], and $C_{a,i}$ are the annual operating cost for years 1 to n. An interest rate of 6% has been used for every simulation presented in this paper.

2.1. Initial cost

The initial cost is obtained by summing the costs of the heat pump, drilling, excavation and piping:

$$C_{ini} = C_{HP} + C_{drill} + C_{ex} + C_{pipe} \tag{3}$$

A correlation developed by (Croteau and Gosselin, 2015) is used to evaluate the heat pump cost as a function of its design load capacity:

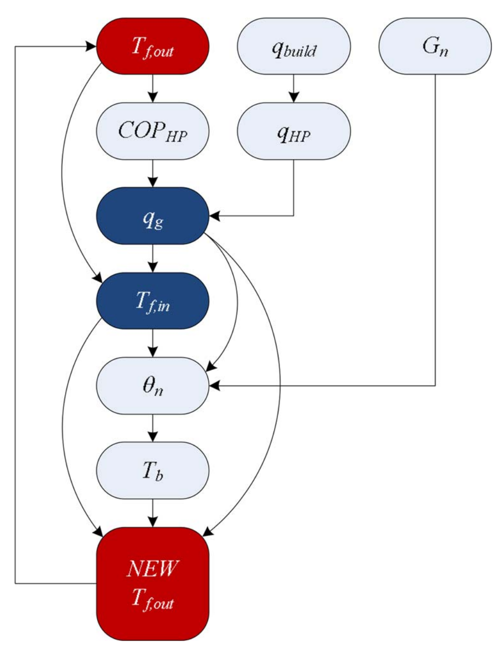

Fig. 1. Overall simulation procedure.