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Numerical heat transfer comparison study of hybrid and non-hybrid ground source heat pump systems

Nikola Kuzmic, Ying Lam E. Law, Seth B. Dworkin *

Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria St., Toronto, ON M5B 2K3, Canada

HIGHLIGHTS

- Soil temperature is simulated for a ground source heat pump system.
- A finite volume model is successfully validated against finite line-source solution.
- The model is validated against experimental data with a maximum error of 5.8%.
- Operation of twelve different buildings is simulated over twenty years.
- The effects of system hybridization on ground fouling are quantified.

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ABSTRACT

Ground Source Heat Pump (GSHP) systems, if improperly designed may lead to overheating or overcooling of the ground. Good designs ensure properly balanced energy storage through adequately sizing ground-loops. Hybrid systems combine conventional Heating, Ventilating, and Air Conditioning (HVAC) with GSHPs in order to significantly reduce the high installation costs of GSHPs. The hybrid systems are designed in such a way that GSHPs provide the base building energy demands while the conventional HVAC is used only during the peak hours. In general, all buildings can be divided into two main categories: cooling dominant and heating dominant. If a building is cooling dominant, ground temperature increases with time and in heating dominant cases it decreases. A severe ground temperature increase/decrease is referred to as 'ground fouling' because it can render the GSHP inoperable, as temperature differences are required to maintain controlled heat flow. This paper compares long-term operation of hybrid and non-hybrid GSHP systems in order to investigate the effectiveness of hybridization at alleviating 'ground fouling'. A homespun 2D finite-volume model is proposed to study heat transfer in ground coupled heat pump systems and is verified against an analytical solution as well as experimental data. Through simulation of different building types, it is demonstrated that hybridization has potential to reduce 'ground fouling' but only in limited cases for which a large portion of the energy demands is being met by the conventional HVAC.

1. Introduction

Geo-exchange is an emerging technology which is gaining popularity as an environmentally friendly alternative to conventional Heating, Ventilating, and Air Conditioning (HVAC) systems. Through extracting ground heat in the winter, Ground Source Heat Pump (GSHP) systems heat buildings and reduce natural gas consumption. To cool dwellings in the summer, the systems exploit the ground's ability to remain cool and absorb heat and consequently reduce strain on the electrical grid. It has been reported that replacing 16% of conventional heating systems in Canada by geo-exchange systems would result in a CO_2 reduction equivalent to removing 895,845 cars from the roads [1]. Presently, the lack of understanding of heat transfer in ground coupled heat pump systems is one of the factors that prevents the industry from expanding and being competitive in the marketplace.

Two main categories into which buildings can be divided are: cooling dominant and heating dominant. Cooling dominant type implies that the building requires more cooling than heating. The effect of such imbalanced energy demand for cooling would result in ground temperature increasing over long periods of time, since more heat would be injected into the ground than extracted. In heating dominant cases, ground temperature would decrease as

* Corresponding author.
E-mail address: seth.dworkin@ryerson.ca (S.B. Dworkin).

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Nomenclature

COP	coefficient of performance
CL	cooling load (kW h)
c_p	specific heat capacity (J K^{-1} kg^{-1})
d_b	borehole diameter (m)
d_i	inside pipe diameter (m)
d_o	outside pipe diameter (m)
H	borehole depth (m)
HL	heating load (kW h)
h	integration constant
k	thermal conductivity (W m^{-1} K^{-1})
Lb	depth of soil below borehole (m)
N	number of pipes
PCL	peak cooling load (kW h)
PHL	peak heating load (kW h)
q_l	heat transfer rate (W m^{-1})
R_b	borehole thermal resistance (m K W^{-1})
r	radial distance (m)
$r_{bore.}$	borehole radius (m)
r_{in}	interior grout radius (m)
r_∞	far field radius (m)
T^o	previous temperature (°C)
TCS	total cooling supplied (kW h)
TCN	total cooling needed (kW h)
THS	total heating supplied (kW h)
THN	total heating needed (kW h)
z	depth (m)

Greek letters

α	thermal diffusivity (m^2 s^{-1})
ρ	density (kg m^{-3})
τ	time (s)

Subscripts

e	east interface
hp	heat pump
n	north interface
p	point of interest
s	south interface
sys	system
w	west interface

more heat would be extracted from the ground than injected. When the imbalance is severe, a general term used to describe such ground overheating/overcooling is called 'ground fouling'. As GSHPs relay solely on the ground to either store or provide heat via a ground-loop, a fouled ground ultimately renders the system inefficient or even inoperable, and induces additional costs to the owner. The solution to the problem is complex, but a properly designed system which operates without overheating or overcooling the ground, can be achieved in many cases.

Hybridization of GSHPs implies that a GSHP is installed together with an auxiliary conventional HVAC system. Hybrid GSHP systems are most often designed in such a way that the GSHP provides the base building loads and the auxiliary HVAC system is only used during the peak demands. Hybridization will normally help balance ground heat input/output since GSHPs can utilize the auxiliary system to provide part of the peak loads, whether they are cooling dominant or heating dominant, and not relay on the ground to store/provide all of the heat.

Due to high initial costs associated with installation of GSHPs, Alavy et al. [2] have considered hybridizing systems to make them more affordable. In their study they have shown that reduction in costs associated with hybrid systems are considerable while the GSHP component still remains capable of delivering a high percentage of the total energy demands. Their approach to determining the most economical shave factor is to calculate the required borehole length corresponding to continuously varying shave factors between zero and unity and choose the one which minimizes the total costs which include installation costs and net present value of annual operating costs of the GSHP and conventional systems. The present paper utilizes their methodology in determining the shave factors and builds upon their work as it explores an additional benefit that may be associated with hybrid GSHP systems, namely the potential reduction in the risk of ground fouling.

Kurevija et al. [3] were also motivated by the problem of ground fouling and studied the effect of spacing between adjacent boreholes on the required borehole length using the ASHRAE/Kavanaugh (A/K) and Lund/Eskilson (L/E) models. They examined thermal interference in 7×6 and 21×2 borehole arrays. Their findings have shown that for a 7×6 array with borehole spacing of 4 m, the borehole depth required to provide adequate space conditioning capacity was found to be either 8.2% or 14.9% larger than the required depth in the 21×2 arrangement, according to the A/K and L/E models, respectively. Their work is helpful to GSHP designers since it demonstrates the effects of thermal interference. The focus of our work is to further assist designers through exploring the benefits in terms of energy balance improvement associated with hybridization of GSHP systems.

Koohi-Fayegh et al. [4] used a semi-analytical model to examine theoretical performance of GSHP systems in relation to thermal interference of neighboring boreholes. They were actually interested in quantifying the effects of fouling on the system performance in terms of reversible Coefficient of Performance (COP_{rev}). In order to model heat transfer outside the borehole, they used an analytical finite line-source solution presented by Zeng et al. [5] and coupled it to another semi-analytical solution also presented by Zeng et al. [6] to determine inlet and outlet fluid temperature inside the borehole. The outside and inside models were coupled through two parameters: borehole wall temperature and borehole heat flow. Their study demonstrated that GSHPs with boreholes installed relatively close to each other will not experience COP_{rev} drop of more than 10% as the result of thermal interaction of two neighboring boreholes. The present study is related to their work as it aims to improve operation of GSHPs over long periods of time through ground heat transfer analysis as well. The approach taken in the current work is different from theirs as heat transfer analysis is purely numerical and not semi-analytical. Our work provides designers with information on how hybridization of GSHPs influences temperature increase in the ground, as opposed to investigating the effects of thermal interference.

Salimshirazi [7] presented a discretized 2D finite-volume model and verified it against their own experimental data. The focus of their research was centered on accurately modeling heat transfer in vertical ground heat exchangers utilizing a cylindrical coordinate system and finite line-source solution for inside and outside borehole regions, respectively. They published a fully discretized finite-volume 2D scheme to represent the grout domain. In verifying their model against the analytical finite line-source solution, there were five boundary conditions applied. At the top, far-field, and bottom boundaries, constant temperature boundary conditions of 0 °C were applied as this was the initial domain temperature. Within the borehole depth, a constant heat flux boundary condition was applied at the interior surface. Lastly, at the interior