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Feasibility of combined solar thermal and ground source heat pump systems in cold climate, Canada

Farzin M. Rad*, Alan S. Fung, Wey H. Leong

Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, Canada M5B 2K3

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ABSTRACT

This document presents a study for examining the viability of hybrid ground source heat pump (GSHP) systems that use solar thermal collectors as the supplemental component in heating dominated buildings. Loads for an actual house in the City of Milton near Toronto, Canada, were estimated. TRNSYS, a system simulation software tool, was used to model yearly performance of a conventional GSHP system as well as a proposed hybrid GSHP system. Actual yearly data collected from the site were examined against the simulation results. This study demonstrates that hybrid ground source heat pump system combined with solar thermal collectors is a feasible choice for space conditioning for heating dominated houses. It was shown that the solar thermal energy storage in the ground could reduce a large amount of ground heat exchanger (GHX) length. Combining three solar thermal collectors with a total area of 6.81 m^2 to a GSHP system will reduce GHX length by 15%. Sensitivity analysis was carried out for different cities of Canada and resulted that Vancouver, with mildest climate compared to other cities, was the best candidate for the proposed solar hybrid GSHP system with a GHX length reduction to solar collector area ratio of 7.64 m/m^2. Overall system economic viability was also evaluated using a 20-year life-cycle cost analysis. The analysis showed that there is small economic benefit in comparing to the conventional GSHP system. The net present value of the proposed hybrid system based on the 20-year life-cycle cost analysis was estimated to be in a range of 3.7%–7.6% (or \$1500 to \$3430 Canadian dollar) lower than the conventional GSHP system depending on the drilling cost.

1. Introduction

Geothermal applications for buildings are mostly limited to full dependence on ground for 100% of heating and cooling. Although there are advantages of having the lowest energy and maintenance costs, cost in favour of this approach, space limitations and high initial costs may restrict a full geothermal installation. Restrictive regulations such as mandating minimum borehole size, grouting materials, wage rates and heat exchange method, will generally increase the cost of such a system. The initial cost may put the project above the budget, and in some cases, the drilling conditions may prevent the use of a large conventional closed-loop borehole field [1].

On an annual basis in many buildings, the amounts of heat extracted from and injected to the ground are not balanced. One common type of earth coupling is the vertical closed-loop type, which is mostly used in buildings that have limited land areas. In designing this type of system, the thermal response of the ground throughout the expected project life must be considered (i.e., 25 years) [2]. An annual imbalance in ground load will lead to lower heat pump entering fluid temperatures in heating-dominated buildings or higher heat pump entering fluid temperatures in cooling-dominated buildings, to a point where equipment capacity may be compromised if the ground loop heat exchanger is not long enough. This imbalance requires either a very large ground loop heat exchanger or some mechanisms for assisting the system by supplementing deficit heat or rejecting excess heat. Because the cost of installing a very large ground loop heat exchanger may be excessive, a number of alternative ways of assisting a ground source heat pump can be used. These include solar collector, which injects additional heat into the ground for heating dominated buildings, and cooling tower, which rejects excess heat into the atmosphere for cooling dominated buildings [3,4]. Systems that incorporate a ground heat exchanger and an above-ground heat exchanger are commonly referred to as hybrid ground source heat pumps. In hybrid systems, the peak heat pump entering fluid temperatures from year to year should be approximately equal. In this study, the system utilizes a solar thermal collector as an above-ground heat exchanger, called a solar assisted ground source heat pump (SAGSHP) [5,6].

The purpose of this study is to evaluate the performance and viability of hybrid geothermal heat pump systems with solar thermal

* Corresponding author. Tel.: +1 416 979 500x4917.
E-mail addresses: fmasoumi@ryerson.ca, rad.farzin@gmail.com (F.M. Rad).

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collectors. The main objective of this work is to perform system simulation approach to assess the feasibility of this kind of hybrid systems in heating dominated buildings. An actual residential building is modelled and result is compared to the actual data that were collected by monitoring the related operation of equipments through some specific months. Different types and approaches of SAGSHP systems have been investigated and analysed [7–10].

It would be ideal that this study along with others will attract the interest of designers and contractors for designing and installing this kind of hybrid systems in heating dominated buildings in Canada.

2. House model description

The house selected for the proposed study is located in the town of Milton, which is about 60 km (38 miles) west of the City of Toronto, Ontario, Canada. The house was one of the two energy efficient demonstration houses built by a local builder in 2005. The house is a detached two-storey building having 498 m^2(5360 ft^2) living area including the basement with the following characteristics:

Construction Light wood frame, 50 mm × 150 mm (2 in. × 6 in.), installed on 610 mm (24 in.) centres, exterior wall construction with brick.

Insulation Spray foam insulation for walls with RSI 3.6 m^2 K/W (R20 ft^2 h °F/Btu), RSI 7 m^2 K/W (R40 ft^2 h °F/Btu) attic insulation.

Windows Double glazing with low emissivity coating/argon filled with insulated spacers, vinyl, RSI 0.38 m^2 K/W (R2 ft^2 h °F/Btu).

Occupant 2 adults and 2 children for 50% of time.

Basement flooring Concrete floor, hydronic slab under heating, RSI 2.22 m^2 K/W (R12 ft^2 hr °F/Btu).

As per builder specifications, the house temperature is set at 21 °C (70 °F) in heating and 24 °C (75 °F) in cooling period, respectively. Air leakage at 50 Pa (0.007 psi) is 1.41 ACH. As per CAN/CSA-F326 and Ontario Building Code (OBC) a continuous ventilation of 0.16 ACH is required and the fresh air through heat recovery ventilation system (HRV) is 61 L/s (130 cfm). The sensible internal heat gain from occupants is set to be 2.4 kWh/day. The occupancy of the house is two adults and two children for 50% of the time with hot water consumption of 225 L/day (59.44 USgal/day). The base load for the house is considered to be 22 kWh/day that includes lighting, appliances, exterior use and others.

TRNBuild [11], a component of TRNSYS simulation software was used to generate the house thermal load profile. TRNBuild has been developed as a part of TRNSYS for simulating multi-zone buildings. This component models the thermal behaviour of a building divided into different thermal zones. In order to use this component, a separate pre-processing programme must first be executed. The TRNBuild programme reads in and processes a file containing the building description and generates two files that will be used by TRNSYS simulation.

To get the idea of total house load, internal TRNBuild equipment component characteristics are used and later in this study separate equipment components will be linked externally to the house model. TRNBuild uses a simulation time step that may not be equal to the time steps that the wall transfer function relationships are based. Finally, the optical and thermal window model, the way in which solar and internal radiation are distributed within each zone, the moisture balance calculations and the integrated model for thermo-active walls are considered. Thermo-active building elements (slabs or walls of a building) are used to condition buildings by integrating a fluid system into massive parts of the building itself. An example is radiant floor heating system that has been used in the basement floor.

Table 1
House heating and cooling requirements.

	TRNSYS	HOT2000
Total heating load	95 GJ (89 MMBtu)	92 GJ (87 MMBtu)
Total cooling load	19 GJ (18 MMBtu)	18.5 GJ (18 MMBtu)
Maximum heating demand	11.5 kW (39 MBH)	17.6 kW (60 MBH)
Maximum cooling demand	9.5 kW (32.4 MBH)	9.4 kW (32 MBH)

The climate of Toronto is chosen for this study because it is the closest city to Milton which has available weather data in TRNSYS.

For the purpose of comparison and validation, the house is also modelled with HOT2000 v. 10.12 software developed by Natural Resources Canada [12]. HOT2000 is a simplified residential heat loss/gain analysis programme, which is widely used in North America by builders, engineers, architects, researchers, utilities and government agencies and by a number of users in Europe and Japan [12]. Utilizing current heat loss/gain and system performance models, the programme aids in the simulation and design of buildings for thermal effectiveness, passive solar heating and the operation and performance of heating and cooling systems. HOT2000 uses a bin-based method and long term monthly weather files to analyse the performance of the house. HOT2000 is a three zone model (attic, main floors and basement) which considers utilized solar and internal gains and heat transfer between zones when calculating loads. It also accounts for on and off cycling and part load factors when determining the performance of the heating system.

In TRNBuild the house has been separated in three zones, 1 – basement, 2 – first floor, and 3 – second floor. Maximum heating and cooling demand are 11.5 kW (39 MBH) and 9.5 kW (32.4 MBH), respectively. The house load results from HOT2000 and TRNSYS are shown in Table 1. Comparing with TRNSYS results it can be seen that there is good agreement between two models. The differences between the two simulations are most likely attributed to the difference in analysis method between TRNSYS and HOT2000. As mentioned earlier TRNSYS is an hourly simulation programme using transfer function method, and HOT2000 uses the much simpler bin method.

3. SAGSHP model description

A scheme of the solar assisted ground source heat pump (SAGSHP) system is shown in Fig. 1. The system is constructed from the following major components:

1. An 18 kW (5 tonnes), Atlas AT060 [13], water-to-air ground source heat pump with desuperheater. The unit has an Energy Efficiency Ratio (EER) of 15.6 with entering fluid temperature of 25 °C (77 °F) in cooling mode and a Coefficient of Performance (COP) of 3.9 with entering fluid temperature of 0 °C (32 °F) in heating mode.
2. Three flat-plate solar thermal panels, Enerworks [14], connected in series with the total area of 6.81 m^2 (73 ft^2), installed at 45° angle.
3. A 0.22 m^3 (60 USgal) hot water tank, Rheem 620 T [15], with 2 × 4.5 kW electric heaters.
4. Power-pipe grey water heat recovery [16] model R3-60. It consists of copper tubes wrapped around copper drain pipe. Incoming cold water to the house can get as much as 35% of waste water (grey water) heat energy.
5. Venmar Vane 1.3HE heat recovery ventilator (HRV) [17]. An air-to-air HRV with 62 L/s (130 cfm) capacity. In heating mode the unit sensible efficiency at 0 °C (32 °F) is 80% and the total heat recovery efficiency in cooling mode at 35 °C (95 °F) is 26%.