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Research paper

Comparative thermal performances of a ground source heat pump and a variable capacity air source heat pump systems for sustainable houses

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HIGHLIGHTS

- Comparative performance investigation of ground and air source heat pumps.
- Experimental study, data extrapolation and TRNSYS simulation were performed.
- Annual performances of GSHP and ASHP systems predicated for major Canadian cities.
- COP of ASHP ranged from 4.7 to 5.7 and GSHP ranged from 4.9 to 5.6 for cooling.
- COP of ASHP ranged from 1.8 to 5.0 and GSHP ranged from 3.05 to 3.44 for heating.

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ABSTRACT

This paper presents a performance comparison of a variable capacity Air Source Heat Pump (ASHP) and a horizontal ground loop Ground Source Heat Pump (GSHP). Both these systems were installed side-by-side at the Archetype Sustainable Twin Houses at Kortright Center, Woodbridge, Ontario, Canada. The heat pumps were tested in both heating and cooling modes for extreme weather conditions of Ontario. For cooling mode, the coefficient of performance (COP) of ASHP ranged from 4.7 to 5.7 at an outdoor temperature of 33 °C and 16 °C respectively, while the COP of GSHP ranged from 4.9 (at an ELT of 8.5 °C and EST of 19.2 °C) to 5.6 (at an ELT of 12.4 °C and EST of 17.8 °C). For heating mode, the COP of ASHP ranged from 1.79 to 5.0 at an outdoor temperature of −19 °C and 9 °C respectively, while the COP of GSHP ranged from 3.05 (at an ELT of 44.4 °C and an EST of 2.7 °C) to 3.44 (at an ELT of 41.5 °C and an EST of 5.48 °C). Data extrapolation and TRNSYS simulation were also performed to predict annual performances of each system for major Canadian cities.

1. Introduction

The building sector, which includes residential, commercial and institutional, consumes approximate one third of Canada's secondary energy and contributes about 33% of total greenhouse gases emissions [1]. As per the long-term policy projection of Natural Resources Canada to curb greenhouse gasses in the building sector, by 2030 all new homes will be built to meet the net-zero energy standards [2]. Several new technologies were developed in the recent past to improve the efficiency, reduce the operational costs, and incorporate sustainability in the buildings. Ground source heat pump (GSHP) systems are promising and growing due to their consistent performance year round [3]. However, the GSHP systems performance declines during the heating and cooling periods due to decrease/increase of ground temperature in the vicinity of the buried pipes [4,5]. In contrast to GSHP, air source heat pump (ASHP) systems are compact in design, relatively inexpensive, and usually provide consistent performance under mild winter conditions. The major concern of ASHP systems is that their heating capacity diminishes as the outdoor air temperature drops below 0 °C [6]. This research provides a further insight about the relative performances of these promising future technologies in sustainable houses.

As mentioned, the coefficient of performance (COP) of ASHP systems decreases as the temperature of outdoor air drops below 0 °C. To meet the high demand of heating during extreme cold days a bigger size of compressor was suggested [7]. However, the heat

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pump with a large size compressor usually operates at part-load and causes a reduction in the COP due to the frequent cyclic operation. Multiple or modulating compressors address mismatched of variable loads with compressor capacity to meet heating demands. But, the problem of reduced heating efficiency as ambient temperature drops below 0 °C still remains [8]. Variable speed/capacity ASHPs offer potential improvements in the efficiency and reliability of operation. These improvements are due to reduction in cyclic operating time at lower operating speeds [9].

The performance of an air-to-water heat pump was monitored under part-load operation by Mountford et al. [10] and it resulted a 15% drop in the COP of the system. The performance testing on an air-to-air ASHP was performed at the Technical University of Nova Scotia, observed COP was 1.8 and 1.1 corresponding to outdoor temperature 4.5 °C and −15 °C, respectively [11]. A two-stage heat pump system coupled with air and water sources was examined for the cold climate of Beijing, China [12] and the average system COP was reported 3.2. Part-load performance analysis has been conducted on an air-to-water heat pump system to investigate the losses associated with compressor cycling and the use of backup heating [13]. The results show that even for an optimal sized system losses in efficiency are about 6% due to on/off cycles and further a 4% drop in the efficiency is caused by the resistant heating element. A testing on a variable capacity heat pump system was carried out in Japan. It was reported that a 15% saving in energy was achieved due to smaller size and variable capacity ASHP [14].

The coefficient of performance (COP) of GSHPs is usually higher than the air source heat pumps mainly because of relatively stable source/sink temperatures [15,16]. Nevertheless, the performance of most GSHP systems declines during later part of heating season due to decrease of ground temperature in the vicinity of the buried pipe. This is due to the significant amount of heat that is extracted from the ground from the beginning to the end of the heating season. Hua et al. presented a model to evaluate the impact of soil temperature on the performance of GSHP. Several scenarios were analyzed to compute the impact of system performance and soil characteristics on the COP. It was noted that the greater heating or cooling loads and smaller borehole pipes cause changes in the soil temperature large enough to negatively affect the heating or cooling capacity of GSHP systems [17].

A three-year study on the GSHP system was performed in Northern Greece [18]. It was reported that the primary energy consumption for heating reduced significantly with GSHP system as compared to that of air-to-water heat pump and oil boiler. In Germany, a GSHP system was installed and continuously monitored in an office building for 4 years. The performance results indicated that GSHP systems performed better in the summer than winter [19]. The cooling performance of a vertical ground loop-coupled heat pump system for a school building in Korea was reported [20]. Ten heat pumps were installed in the school building with a closed vertical type ground heat exchanger with 24 boreholes of 175 m depth. This study indicated that the overall COP of this system was 5.9 at 65% partial load condition. The performance of GSHP system of 15.9 kW of cooling capacity and 19.3 kW of heating capacity was monitored and simulated [21]. The study revealed that the simulation results based on manufacturer's supplied data overestimated the energy performance of GSHP by 15–20%. In another investigation a GSHP system was tested with different ground loop configurations at the Eco House of the University of Nottingham [22]. The heat pump unit had a heating capacity of 8 kW using R-22 as the refrigerant and included a desuperheater to provide hot water. The test results indicated that the difference between the entering water temperature to the evaporator and the outlet temperature from the condenser significantly affect the heat pump COP. An experimental heating performance evaluation of a GSHP system with a ground coupled heat exchanger and a fan coil air delivery system was studied in China [23]. The heat pump of 6.43 kW capacity supplied hot water to an Air handling Unit (AHU) at a temperature of around 50.4 °C. The findings of these experiments indicated that the heating COP (only including the power consumption of the heat pump compressor) turned out to be 3.55 at an evaporative temperature of 3.14 °C and a condensing temperature of 53.4 °C. A TRNSYS simulation was performed to investigate various configurations of GSHP system with solar collector for space heating and domestic hot water [24,25]. The results shown the integration of solar collector with GSHP help in recharging the borehole in winter and provided the domestic hot water in summer.

The successful acceptance of any new building heating/cooling technology depends on its efficiency, cost-effectiveness, and durability [26]. Both ASHP and GSHP are promising technologies for future buildings and this research revel their comparative performances in sustainable houses. Two semi-detached sustainable houses are designed/built to serve as models for the coming generation and used for the present investigation. The main objective of this research was to critically analyze the relative performance of ASHP and GSHP in these houses by producing the heating/cooling performance curves, evaluate the efficiencies (COP) at different load/source temperatures, and observe the cycling characteristics of compressors for both these systems. Subsequently, the ASHP and GSHP were modeled using the performance curves obtained from the experimental data. TRNSYS was used for the modeling of the Archetype Sustainable Twin Houses as well as the heat pumps. The objective of TRNSYS simulation was to make available programs that can be used to predict the performance of similar systems for other major cities of Canada.

2. Houses descriptions and experimental facililty

The Archetype Sustainable Twin-Houses (ASH) located at the Living City Campus of Kortright Centre, Woodbridge, Ontario. These houses demonstrate the sustainable housing technologies for experimentation and research. These houses are among the first few Canadian house projects to receive Platinum Certification from LEED [27]. The first house called House A (the left side in Fig. 1) is designed to demonstrate current sustainable technologies while the second house called House B (the right side in Fig. 1) is designed to demonstrate sustainable technologies for the future. House A uses a two-stage variable capacity air source heat pump (ASHP) for space heating/cooling and a direct expansion coil Air Handling Unit (AHU) for delivery of conditioned air. House B is equipped with a horizontal-loop coupled ground source heat pump (GSHP) and an optional desuperheater for water heating. GSHP provides heating with a radiant in-floor heating system and cooling through a fan coil AHU system. Both houses were constructed to have an air-tight building envelope according to the requirements of ASHRAE 90.1. The major difference between the two houses is the window type; House A has double glazed windows with fibreglass frames while House B has triple glazed windows with wood-clad aluminum frames. In addition, the overall UA values of House A and House B are 160 W/k and 172 W/k, respectively (Table 7). Consequently, House A is slightly better insulated than the House B. The technical information on the heat pump systems and air handling units for both the houses are given in Table 1.

For summer and winter performance monitoring; temperature, flow rate, and power consumption sensors were installed on the ASHP, GSHP, and the twin-houses. The range of accuracy of various sensors and the thermal measurements are given in Tables 2 and 3 Continual experimental data was recorded in the summer and winter using a program called LABVIEW, and stored using Microsoft