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Post-design system control for integrated space heating systems in residential buildings in cold regions

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A B S T R A C T

Ground source heat pump is an effective and environmentally friendly system for space heating and cooling in residential buildings. For cold regions, where heating demand is greater than cooling demand, multi-source heat pumps integrating renewable energy sources are an alternative that ensures occupant comfort. This paper presents a research methodology for investigating the performance of multi-source heat pump systems in residential buildings in cold regions. One year of monitoring data is collected from a four-storey residential building located in Fort McMurray, Alberta, Canada. This data is analyzed to evaluate the performance of the multi-source heat pump system. Enhanced heating system control is also devised which shows potential benefits for system efficiency improvement and non-renewable energy source savings. A system control set point forecasting model is also proposed for the purpose of reducing operation costs.

1. Introduction

Greenhouse gas emissions in Canada have increased rapidly in recent decades, having grown at a rate of 9 mega tons per year from 591 mega tons in 1990 to the peak point of 749 mega tons in 2007 [1]. There has been significant improvement in reducing CO_2 emissions since 2007 and researchers continue investigating renewable energy sources to replace non-renewable energy sources for heating, transportation, and industry. This paper focuses on the use of renewable energy sources for residential heating purposes.

The use of renewable resources brings environmental benefits through the reduction of greenhouse gas emissions. Due to the benefits of energy savings and low CO_2 emissions, ground source heat pump (GSHP) system is shown to be effective in both commercial and residential buildings for indoor heating, cooling and domestic hot water supply. Akpan et al. [2] showed that the geothermal heat pump is an effective thermal system for cold regions, both economically and environmentally (reducing greenhouse gases by 28% compared with the conventional system), compared with photovoltaics or other thermal collectors. The ground-water heat pump system is also found to offer savings in electrical energy compared with both air-conditioner for cooling and coal-fired boiler for heating [3].

Coefficient of performance (COP) is an effective metric to evaluate the system performance of heat pump systems. The COP for heating is defined as the ratio of energy production to the power consumption of corresponding equipment, whereas the COP for cooling is defined as the ratio of thermal energy removed to the power consumption of corresponding equipment. Benli and Durmus [4] monitored a ground-source heat pump for a year and half in Turkey, having the COP of the GSHP in the range from 2.3 to 3.8 and the system COP in the range from 2 to 3.5. As other studies have shown, GSHP operation hours influence the COP of the heat pump as well. The COP of heat pumps decreases after a long period of operation in cold areas [5]. Involving more compressors may also reduce the COP for the heat pumps and for the entire system.

The system performance can be analyzed in daily, monthly, and seasonal increments. A representative factor is Seasonal Performance Factor (SPF), which evaluates the system performance by heating season or cooling season [6,7]. The GSHP has a higher COP/SPF when the demands for heating and cooling are balanced than when the demands are unbalanced, i.e., the GSHP is sensitive to the weather and potential risks exist when the GSHP is the only dependable system in regions with unbalanced heating and cooling demands [8]. Li et al. [9] explained and compared the geothermal

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field energy distribution of operating the GSHP with both balanced and imbalanced thermal demands, highlighting the significance of using an integrated system. Other researchers have focused on achieving a steady temperature in an underground geothermal field utilized as one of the energy sources. Von Cube and Steimle [10] discussed the advantages of combining a geothermal heating system with other heat sources. As they pointed out, pre-heating the thermal source for the heat pump can lead to an increase of system COP. Li et al. [11] substituted the use of boilers by using a combination of groundwater flow and GSHP for both heating and cooling in twelve greenhouses in a cold region, Akabira, Japan. Their study suggested that adding groundwater flow in the field could reduce the fluctuation of field temperature caused by imbalanced heating and cooling demands, which could further achieve higher system efficiency. The system they described contributed to CO_2 emission reductions of 20% and 22% compared with air-source heat pump and kerosene system, respectively.

Combining a solar energy system with GSHP is another alternative, which has drawn interest among researchers. The idea of using solar energy to assist GSHP was proposed as a desirable system by Metz in 1982. He compared the results from both experimental and computing (through TRNSYS simulation software) approaches. However, the results were found to vary based on different soils, climates, and experimental designs [12]. The depth of the ground exchanger also influences the results. Wang et al. [13] simulated a solar-ground coupled heat pump with better COP for a long-term cooling and heating period due to geothermal field heat recovery and storage during the transitional seasons and summer. They showed that the system performs better with the vertical geothermal exchanger at a depth of more than 50 m than other depth of vertical exchanger. It was also shown that the complexity and properties of soil affect the heat transfer, where water content in the soil facilitates better thermal conduction for the use of the GSHP. Bi et al. [14] measured the performance of a solar source heat pump, a GSHP, as well as of a solar-assisted ground source heat pump (SGSHP) based on an experimental system under observation for five months. They evaluated the feasibility of using SGSHP and provided valuable experimental results.

Bakirci et al. [15] reviewed research results published prior to 2011 and noted that the focus in previous research had been on either solar-assisted heat pump or GSHP individually, with only limited research focusing on systems that integrate both sources. More recently the solar-assisted GSHP system is of increasing interest among researchers. Research results have proven that the utilization SGSHP is advantageous both economically and environmentally compared with conventional energy sources [16,17]. Numerous simulations have been conducted by researchers to analyze SGSHP for the purpose either of revising the existing system or proposing new system designs prior to practical implementation [18–20]. Si et al. [12] designed two solar-GSHP systems for space heating, cooling, and hot water heating and introduced two models. In the first model, the solar thermal collectors not only reheat the circulating fluid from the geothermal field to the heat pump during winter, but also deliver the surplus energy in order to recover the field in summer, while the second model only stores solar energy to the water tank in daytime and recharges the field at night. The results of a simulation carried out as part of their study showed that the first model had better capacity for restoring field temperature than the second model. The system discussed in this paper resembles the first model from the Si et al. study. The challenge of using the GSHP for only heating but not for cooling in a cold region is even bigger. Kjellson et al. [13] simulated different combinations of solar collectors and geothermal exchangers to reduce the electricity demand in the system. They identified two key benefits: (1) that the solar energy system produces heat in summer and recharges the ground in winter; and (2) that, with the support of the solar energy, the thermal interference between boreholes can be reduced so that the ground temperature will be reduced.

Other researchers have also analyzed SGSHP systems built on experimental data based on a system model in a lab or small building [21–26]. Experimental analysis has also validated the notion of using solar as a thermal collector during the daytime and storing energy to the ground for the recovery support of the geothermal field [21]. These studies have revealed that the efficiency of ground heat exchangers can be enhanced from a COP of 2.37–2.72. Ozgener and Hepbasli [22,23] monitored a solar-assisted vertical GSHP heating system for a greenhouse in Turkey and analyzed the performance of this system in terms of energetic and exergetic aspects. The average COP of GSHP achieved 2.84 while the average exergy efficiency was 68.11%, and the COP of entire system was found to be 5–20% lower than the COP of the heat pump itself. Dikici and Akbulut [24] experimented with a solar-assisted heat pump system in a test room and obtained a higher COP of 3.08 during the season with heating demand. Another SGSHP was tested in Turkey with a heat pump COP in the range of 3.0–3.4 [15]. Yu et al. [25] combined solar energy with GSHP with the aim of achieving equilibrium in the geothermal field energy for a villa in the cold region of Beijing, China. Their results showed that the SGSHP not only satisfies heating and cooling demand but also keeps the geothermal field temperature balanced for long-term usage and facilitates a higher COP of the system.

After a long-term investment and acceptance of integrating GSHP with other systems, some researchers have also sought the development of improved control strategies for the system being operated. Yavuzturk and Spitler [26] proposed several control strategies for system operation by simulating the combination of using a supplemental heat rejecter with a cooling-dominated GSHP for a small office building. Other researchers have conducted experiments on the system and enhanced the system control based on the experimental results. Mokhtar et al. [27] utilized a type of artificial neural network system to propose an intelligent building management system control in order to minimize the energy waste, optimize load control, and increase the system efficiency. Wang et al. [28] adjusted the system cooling control strategy based on experiment data collected from a specified short period of time. They recommended a system control strategy reference for the hybrid GSHP system in practice.

Thus, existing experimental data provides useful information for future reference. Without the enhanced system control algorithm, the considerable benefits of using renewable source energy as the heat source may not be maximally achieved. The limitation of these research results is that there is always variation from one system to the other. The system control strategy devised for one system may not be suitable for other systems. However, in this paper, we propose a system control improvement strategy based on live sensor-based system monitoring and live system performance analysis. The research results not only can serve as a reference for future study and implementation, but the methodology can also be implemented in other systems for the purpose of system control. Furthermore, this research is focused on integrated GSHP system control, thereby addressing a gap in the existing body of research.

2. Research objective and methodology

The main objective of the research presented in this paper is to propose enhanced system control and improve the performance of an integrated heating system in a residential building under occupancy based on comprehensive, live, sensor-based experimental monitoring. The framework can be applicable to other buildings as well, with modifications in the control algorithm and set points.