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A framework to monitor the integrated multi-source space heating systems to improve the design of the control system

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ABSTRACT

Building space heating contributes to high consumption of energy using primarily non-renewable energy sources. Usage of renewable energy sources is constrained by high initial costs and long-term payback. This paper presents an empirical research study to evaluate the design of the control system and the performance of an integrated heating system utilizing renewable energy sources by means of a geothermal field, solar energy, and drain water heat recovery (DWHR) system. Two main challenges we attempt to address are: (1) the ground source heat pump (GSHP) system is designed to function only as a heating system causing heat loss from the geothermal field and (2) high heating load is required in cold-climate regions. The proposed integrated space heating system uses mainly geothermal energy, which is supported by solar and DWHR systems to recover the heat loss from the geothermal field. The framework is validated through a residential building under occupancy where, a monitoring system is installed to evaluate the coefficient of performance of the space heating system. Based on the findings, adjustments in the design of the heating system controls are proposed to enhance system efficiency.

1. Introduction

1.1. Ground source heat pump system

Geothermal heat is an efficient source of energy with significantly lower CO_2 emissions than conventional fossil fuels [1]. Approximately 47% of ground thermal energy is absorbed from the sun [2]. This thermal energy stored in the ground manifests in diverse ways. While the earth surface's temperature fluctuates readily, the ground temperature at shallow depth (below 9 m) remains constant for years [1,3,4]. Furthermore, geothermal energy classified by source temperature is used for power production as well as for cooling and heating systems. Geothermal sources of temperature above $150\,^{\circ}C$ are used for power production, while moderate temperatures (between $90\,^{\circ}C$ and $150\,^{\circ}C$) and low temperatures (below $90\,^{\circ}C$) are suitable for space heating or cooling [5,6]. The residential facility used as a case study in this research uses low temperature sources for space heating [7] in the form of a geothermal heating system using a ground source heat pump (GSHP) system.

A ground source heat pump comprises three main elements: a ground heat exchanger (GHE), a heat pump, and a distribution system [8,9]. The GHE, which is the main component, uses shallow ground as its energy source and a water/glycol mixture as the transport medium. The underground temperature, it should be noted, is warmer than the outside air temperature in winter, but cooler than the outside air temperature in the summer. The mixed fluid flows through buried piping, storing heat, and releasing it into the soil under the building site. A low-power circulating pump circulates the fluid. In winter, a GSHP system can extract heat from shallow ground to provide energy for space heating. In summer, the system is reversed to transfer heat out of the building using the cooler ground as a heat sink [10,11].

GHEs can be further configured as either open-loop or closed-loop [11]. Open-loop exchangers use surface or underground water sources as a direct heat source. Normally, this operation can be completed at a lower cost and with less loss during heat transfer than closed-loop. However, spatial constraints limit usage of the open loop, and the water present in the system usually causes corrosion over time [12]. The closed loop, on the other hand, circulates water through pipes that can be installed either vertically or horizontally. The vertical closed loop is widely used since it is not limited by surface area. However, in this system, initial excavation costs are generally high [13]. In the research described in this

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Abbreviations: GSHP, ground source heat pump; GHE, ground heat exchanger; DWHR, drain water heat recovery; SHTS, solar heat transfer station; SAGSHP, solar-assisted ground source heat pump system; COP, coefficient of performance; HDPE, high-density poly-ethylene.

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Nomenclature

Q	Thermal Energy, kilojoules (kJ)
C	Specific Heat (kJ/kg°C)
M	Mass of fluid within a period of time (kg)
ΔT	Temperature difference (°C)
ρ	Density of fluid (kg/m^3)
V	Volume of fluid (m^3)
R_m	Mass flow rate of fluid (kg/hr)
R_v	Volume flow rate of fluid (m^3/hr)
T_{Return}	Temperature of return pipe (°C)
T_{Supply}	Temperature of supply pipe (°C)
t	Serving time or operation time (hrs)
Ra	sun radiation historical information (kWh/m^2/day)
Avg(E)	Average efficiency factor
W%	Energy wasted percentage

paper, closed-loop GHEs are utilized in an occupied building due to the given space limitations.

GSHP has two other components: a heat pump and a distribution system. The heat pump is operated based on a vapor-compression refrigeration cycle [14]. During this cycle, the pump effectively raises the temperature of the ground source using electrical power to drive the compressor [15]. The lifespan of the mechanical parts involved is approximately 50 years [16]. Since heat pumps consume less primary energy than conventional heating system, fewer harmful CO_2 emissions are produced in the process [17,18]. In this regard, a coefficient of performance (COP) is used to evaluate the performance of heat pumps. According to previous research, ground source heat pumps have a higher COP than regular heat pumps, such as air-source heat pumps [19,20].

As opposed to specific hot-climate regions where the heating and cooling systems require almost equivalent loads all year round, in cold-climate regions larger GHEs are required since the heating load is much greater than the cooling load [21]. Roth, similarly, has identified two major challenges related to use of conventional heat pumps in cold regions: that the heating load is greater than the cooling load, and that heating capacity and COP decrease as the outside temperature drops [22]. Since the cooling load in summer cannot be guaranteed to offset the heating load in winter, long-term operation could result in an irreversible decrease in the temperature of the underground field and end up with a heat loss. In this case, the COP of the heat pump could also be markedly reduced. However, use of a larger GHE is constrained by initial cost and space size [23]. Consequently, the use of an efficiently designed integrated system will supply energy in a manner which ensures energy savings.

Bakirci and Colak have investigated the performance of vertical GSHPs during Turkey's coldest seasons (Jan.–Feb., 2010). They found that the use of a superheating and sub-cooling heat exchanger (SHCHE) can improve COP by 0.1–0.2. Solar energy combined with a GSHP system, which serves to increase the efficiency of the heat pump, is also widely used in cold regions [18]. Zhai et al. have summarized the integrated approaches of GSHP, indicating that integrating a GSHP system with a solar thermal system effectively provides thermal energy to buildings for which heating demands significantly exceed cooling demands, and is able to operate with a high COP of 3.5, which is much better than the performance of a traditional GSHP system [21]. However, the climate conditions, building functions, and thermal balance of the ground field affect the design of such renewable energy-based heating systems. The first solar-assisted GSHP was recommended by Metz in 1982 [23]. It was Penrod, in an earlier study, who established the idea of storing solar energy in the ground [23,24].

In cold regions, the performance of the GSHP can be improved by utilizing solar energy, which is referred as a solar-assisted ground source heat pump system (SAGSHP). For such systems, solar energy system can be installed on the source side of heat pump to increase the inlet temperature of heat pumps. Meanwhile its energy production can be directly sent to the ground field to compensate the heat loss of the field and recover the field back to the balance in cold regions. With the assistance of solar energy, this comprehensive utilization not only offsets the deficiency of GSHPs by facilitating soil temperature field recovery, but also provides intermittent heat to the building [10,25]. Bakirci et al., in a study of cold-climate residential heating in Erzurum, Turkey, found that the COP of a SAGSHP was enhanced to the range of 3.0–3.4, while the overall heating system COP was 2.7–3.0 [26]. Investigating a similar cold-climate region, a research group from Hong Kong, China, has utilized TRNSYS simulation software to forecast the performance for 20 years of continuous operation under the climatic conditions of Beijing, China. Compared to a conventional GSHP system, a SAGSHP system for space heating and domestic hot water improves efficiency by a margin of 26.3% [27]. However, results from another study by the same research group simulating the performance of a SAGSHP in the cold-climate region of Harbin, China, which has comparable weather conditions to Fort McMurray, Canada, showed SAGSHP to perform with a lower efficiency of 2.84. As such, they recommended against its utilization in extreme weather in the interest of energy and cost saving [28]. Using the same software, Niu et al. have concluded that system efficiency decreases more rapidly when there is a greater difference between the heating load and cooling load exerted on the GSHP [29]. The case that is being addressed in this paper is the special condition when only heating load is required.

1.2. Objective and scope

In a cold-climate region such as Fort McMurray, with very low ambient temperature and relatively low underground temperature in winter, only an optimal integration of a number of renewable energy sources can lead to efficient energy production [30]. Solar energy is a clean and renewable resource, and an essential component of sustainable energy for space heating and water heating [26]. It can either as direct heating energy or be stored in summer as spare energy and drawn upon by the geothermal field for energy recovery. Another energy source used in this case study is a drain water heat recovery (DWHR) system, due to the fact that DWHR extracts heat from wastewater, and in this way can collect and reuse up to half of the energy in the wastewater and utilize it to preheat cold water travelling to the water heater. Based on previous studies, this translates to heating cost savings of up to 40% [2,31], and a reduction in greenhouse gas emissions. In this project DWHR is designed to also increase the efficiency of the GSHP system. Natural gas, finally, is widely used as an energy source, particularly in Fort McMurray, which has considerable natural gas reserves underground. This source is used to fuel boilers, which heat fluid to a preset temperature to be circulated throughout the building.

As discussed above, most of the existing research with respect to GSHP systems has investigated cases where these systems are used for both heating and cooling. This paper, however, investigates the use of GSHP in a cold-climate region where only heating load is required, which introduces additional challenges. Therefore, in this paper, an integrated heating system is proposed and implemented in a residential building under occupancy in Fort McMurray, where heating is a major contributor to total energy consumption. For this integrated system, solar, and drain water heat recovery (DWHR) assist the GSHP system in combination with natural gas, which is a highly efficient resource.

Since cold weather challenges the use of the GSHP system, especially when it is not designed as a cooling system to recover heat