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An analysis of solar assisted ground source heat pumps in cold climates

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ABSTRACT

Exploiting renewable energy sources for air-conditioning has been extensively investigated over recent years, and many countries have been working to promote the use of renewable energy to decrease energy consumption and CO_2 emissions. Electrical heat pumps currently represent the most promising technology to reduce fossil fuel usage. While ground source heat pumps, which use free heat sources, have been taking significant steps forward and despite the fact that their energy performance is better than that of air source heat pumps, their development has been limited by their high initial investment cost. An alternative solution is one that uses solar thermal collectors coupled with a ground source heat pump in a so-called solar assisted ground source heat pump.

A ground source heat pump system, used to heat environments located in a cold climate, was investigated in this study. The solar assisted ground source heat pump extracted heat from the ground by means of borehole heat exchangers and it injected excess solar thermal energy into the ground. Building load profiles are usually heating dominated in cold climates, but when common ground source heat pump systems are used only for heating, their performance decreases due to an unbalanced ground load. Solar thermal collectors can help to ensure that systems installed in cold zones perform more efficiently. Computer simulations using a Transient System Simulation (TRNSYS) tool were carried out in six cold locations in order to investigate solar assisted ground source heat pumps. The effect of the borehole length on the energy efficiency of the heat pump was, in particular, analyzed. Finally, a suitable control strategy was implemented to manage both the solar thermal collectors and the borehole heat exchangers.

1. Introduction

The massive use of fossil fuels over the last decades and the problems linked to the limited quantity of energy resources in the subsoil have intensified the interest in developing renewable energy resources. The challenge of reducing CO_2 emissions to control its impact on the environment has likewise become a world priority.

The recently developed concept of nearly Zero-Energy Building (nZEB) introduced by the recast directive on the Energy Performance of Buildings (EPBD) [1] combined with the 20–20–20 target objective [2] are considered important challenges linked to energy consumption reduction, particularly with regard to the construction sector that accounts for nearly 40% of total energy use. The potential of improving energy efficiency in this sector is high in view of the old uninsulated buildings and plants.

The major problem with exploiting renewable energy sources and waste energy is the difficulty in conserving heat for long periods of time. In the past, attention has been focused on improving the single components used to exploit renewable energy or waste heat. Improving storage efficiency over long time periods, especially when renewable energy sources need to be preserved, is currently considered a major challenge. In this respect, the most widespread small- to large-scale renewable technologies concern solar energy. Some examples of these technologies are solar thermal plants that produce heat to provide warmth for buildings or domestic hot water, as well as hybrid desiccant cooling systems and solar-driven absorption plants. The most widespread solar collectors are the flat-plate and evacuated tube type; the latter are used to reach high temperatures or to reduce the area of the solar field. While other kinds of collectors can be found on the market, their use is limited to special applications. The unglazed type, for example, is used to heat swimming pools; the concentric tube collectors, parabolic trough solar collectors, and solar parabolic dish collectors are all used for power plant systems.

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Nomenclature

a_1	heat loss coefficient (W/(m^2 K))
a_2	temperature dependence of the heat loss coefficient (W/(m^2 K^2))
COP	coefficient of performance (–)
F_{sc}	short-circuit heat loss factor (–)
L	length (m)
L_{bore}	borehole length (m)
PLF$_m$	part-load factor during the design month (–)
q	heat load (W)
q_a	net annual average heat rate to the ground per unit length (W/m)
R	ratio between the maximum and nominal thermal capacity (–)
R_b	thermal resistance of the borehole (m K/W)
R_{ga}	thermal resistance corresponding to the annual pulse per unit length (m K/W)
R_{gm}	thermal resistance corresponding to the monthly pulse per unit length (m K/W)
R_{gd}	thermal resistance corresponding to the daily pulse per unit length (m K/W)
S-COP	seasonal coefficient of performance (–)
T	temperature (K)
T_{cond}	condensing temperature (K)
T_{evap}	evaporating temperature (K)
T_{mean}	mean external air temperature (K)
T_{min}	annual minimum external air temperature (K)
T_{max}	annual maximum external air temperature (K)
T_g	undisturbed ground temperature (K)
T_p	penalty temperature (K)

Subscripts

b	building
c	cooling
D	design condition
f	fluid
g	ground
h	heating
in	inlet
out	outlet

Greek symbols

η_0	zero-loss collector efficiency (–)

Abbreviations

ASHP	air source heat pump
BHE	borehole heat exchanger
GSHP	ground source heat pump
HVAC	heating ventilation and air conditioning
SAGSHP	solar assisted ground source heat pump
TRNSYS	transient system simulation
TRY	test reference year

Ground Source Heat Pump (GSHP) technology has been extensively investigated over recent years in view of the fact that it is the most competitive Heating, Ventilation and Air Conditioning (HVAC) system compared to the more widely used Air Source Heat Pump (ASHP) system [3]. GSHP systems are a promising technology that is able to exploit the ground both as a heat source and a heat sink for energy storage [4]. The temperature of the heat source–sink affects the efficiency of the heat pump. In air-to-water heat pump applications, the ambient temperature is quite variable throughout the year depending on the location's weather; the energy efficiency of the ASHP is likewise variable over time [5]. Defrosting, which is a phenomenon that can occur when heat pumps run on the heating mode, can cause performance degradation [6]. It is possible to obtain a more stable performance of the heat pump when the ground is used because the ground temperature is affected only by air temperature fluctuations at the first meters below the surface [7]. The ground temperature usually increases with depth reaching a gradient of about 0.03 °C/m unless the site is characterized by anomalous thermal activities in which case the ground temperature can reach 70–90 °C even at shallow depths (100–200 m) [3]. This last situation is not very widespread but can occur in local magma chambers and volcano active areas. The average ground temperature is thus too high, meaning that the GSHP can be used only to heat buildings and not to cool them [8]. To this purpose, Kurevija et al. [9] analyzed the effect of the geothermal gradient on the design of borehole heat exchangers, considering the characteristics of the city of Zagreb; in a 5 × 4 grid with boreholes 103.5 m long and spaced 6 m apart, when the geothermal gradient was considered on the calculation of the ground temperature, the total borehole length was 5.3% higher than that when a constant undisturbed temperature was used.

GSHPs are used in a wide range of applications, ranging from small- to large-scale commercial and residential buildings. The core of the system is the Borehole Heat Exchanger (BHE), which consists of a closed pipe loop buried in the ground; it can be a horizontal network or, more commonly, vertical or directional boreholes filled with single or double U-tubes (or other geometries) and grouting material are utilized [10].

GSHP systems work efficiently when heating and cooling loads are nearly balanced. During winter months, in fact, the heat is extracted from the ground for heating purposes and during the summer ones it is rejected to the ground so that it can be thermally recharged. When the building load profile is heating or cooling dominated, the ground loads are not balanced and the mean ground temperature decreases or increases over the year. Known as "thermal drift," the main consequence of this phenomenon is that it reduces the heat pump's long-term efficiency. In some cases, despite the unbalanced thermal load of the building, the effect of the thermal drift could be reduced by groundwater flow that reinstates the thermal conditions of the surrounding area.

You et al. [11] proposed a novel heat compensation unit with thermosyphon (HCUT). The system consists of an air-source thermosyphon and an air-source heat pump and it is used to transfer heat from ambient air to the ground in order to solve the problem of the decrease of ground temperature in heating dominated buildings. In the HCUT system, when the temperature difference between air and heat-carrier fluid from borehole heat exchangers is high, the compressor of the heat pump is switched off and the thermosyphon effect moves the refrigerant fluid and, consequently, heat flows from air to the ground. You et al. [11] analyzed the long-term performance of the HCUT system in Harbin (China) by means of simulations carried out with the TRNSYS tool. In addition, they compared the new system with a traditional installation of a boiler and split air-conditioning. They concluded that the energy performance of the new system was 15% higher than that of the traditional installation.

You et al. [12] also investigated a hybrid ground source heat pump with multi-functional HCUT (i.e. for heat compensation, domestic hot water production and direct space heating) in a hotel installation. They concluded that the multi-functional HCUT provided more energy savings than common configuration.