Geothermics 57 (2015) 104–110

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Potential of ground source heat pump systems in cooling-dominated environments: Residential buildings

Mohamad Kharseh[a,*], Mohammed Al-Khawaja[a], Muhannad T. Suleiman[b]

[a] Qatar University, Mechanical & Industrial Engineering Department, Qatar
[b] Lehigh University, Department of Civil & Environmental Engineering, United States

ARTICLE INFO

Article history:
Received 18 January 2014
Received in revised form 7 June 2015
Accepted 15 June 2015
Available online 2 July 2015

Keywords:
Ground source heat pump
Economic viability
Hot climate
Air conditioning
Residential buildings

ABSTRACT

For countries in the Arabian Peninsula, air conditioning (A/C) systems account for 65% of the energy consumption, all of which comes from fossil fuel. Given the preparation for the 2022 World Cup, which will be held in Qatar, the possibility of implementing ground source heat pump systems (GSHP) for A/C purposes is investigated. Due to its high thermal performance, GSHP is considered a viable solution for reducing the energy consumption of heating and A/C systems. However, for the GSHP system to gain popularity in cooling-dominated environments such as Qatar, financial and environmental benefits need to be demonstrated. These benefits strongly depend on local design practices and standards and on working conditions.

The work presented in this paper demonstrates the energy savings by using GSHP systems in the residential buildings sector in cooling-dominated environments. To achieve this goal, a common type of residential house located in Doha, Qatar, was chosen as a case study. The cooling load of the case study and the driving energy of two different air conditioning systems were estimated. The two considered air conditioning systems are the conventional air source heat pump system (reference system) and the ground source heat pump system. Finally, economic analysis of the proposed system for construction practices in Qatar was carried out.

The performed analyses show that the reduction in the prime energy demand and, consequently, the greenhouse gas emissions for the GSHP is 19% when compared to the conventional air source heat pump system. In addition, the analyses show that for the local conditions in Qatar the payback time of GSHP is 9 years.

1. Introduction

The global energy demand has exceeded 15×10^{10} MWh/year, 85% of which comes from fossil fuels, while renewable energy sources supply only about 6% (Seyboth et al., 2008; Moomaw et al., 2011; Jaber et al., 2011). Given the strong belief that climate change is anthropogenic and attributed to fossil fuel consumption, improving the performance of existing energy systems is a major challenge.

Heating and air-conditioning (A/C) systems account for about 33% of the world's total energy consumption (Wong et al., 2010; IEA, 2007; Seyboth et al., 2008). In hot, cooling-dominated, and underdeveloped countries, such as those in the Arabian Peninsula, A/C systems are the biggest energy consumer. In Saudi Arabia, for instance, A/C systems account for 65% of the total energy consumption in buildings (Said, 2010; Hasnain, 1999). Therefore, investigating the possibility for improving the performance of A/C systems in cooling-dominated environments is of great potential to save energy and reduce environmental impacts of fossil fuel.

Ground source heat pump (GSHP) system might be considered as a viable solution to reduce the energy consumptions of A/C systems. Several studies have been conducted to investigated the feasibility of GSHP systems in residential and commercial buildings (e.g., Esen and Yuksel, 2013; Balbay and Esen, 2010). In 2010, the total capacity of installed GSHP systems in the world was 51 GW producing 122 TWh/year with a capacity factor of 0.27 (actual operation hours/annual hours) (Lund et al., 2010). The GSHP system is one of the fastest growing applications of renewable energy, with installed capacity annual growth of 12.3% (Lund et al., 2010). A comparison with energy consumption of conventional A/C systems (i.e. air source heat pump) shows that GSHP system may results in a reduction of energy consumption by 60%, which is

* Corresponding author. Tel.: +974 3357 6314; fax: +974 4403 4301.
E-mail addresses: kharseh@qu.edu.qa (M. Kharseh), khawaja@qu.edu.qa (M. Al-Khawaja), mts210@lehigh.edu (M.T. Suleiman).

http://dx.doi.org/10.1016/j.geothermics.2015.06.009
0375-6505/

Nomenclature

$C_{d,an}$	the annual saving in driving energy of A/C system ($)
C_{inv}	the total ground heat exchanger cost ($)
C_p	the present value of the income of the first year of operation ($)
d	the nominal discount rate (%)
E	required driving energy of the air conditioning system (MWh)
er	the escalation rate of electricity price (%)
L_b	the total borehole depth (m)
PBT	the payback time of GSHP system (year)
PW(GSHP)	the present worth of the cash inflows from the GSHP system ($)
Q_c	cooling demand (MWh)
$q_{hc,i}$	the cooling demand at hour i (MWh)
$q_{mc,j}$	the cooling load of the month j (MWh)
RCOE	the current real cost of electricity in Qatar ($/kWh)
$SCOP_A$	seasonal coefficient of performance of ASHP (dimensionless)
$SCOP_G$	seasonal coefficient of performance of GSHP (dimensionless)

expected to improve in the future (Jaber et al., 2011; Seyboth et al., 2008; Michopoulos et al., 2011). However, the benefits of GSHP systems in saving energy and construction costs strongly depends on local working conditions. These conditions include buildings thermal performance, ground thermal characteristics, and annual air temperature amplitude. In other words, the viability of GSHP systems may significantly differ from one region to another. For example, under the operation conditions in Saudi Arabia, it was shown that the implementation of GSHP systems in residential buildings could result in energy saving of A/C systems by 14–20% (Said, 2010). Another example, the utilization of GSHP systems in agricultural applications in Syria leads to 31% saving in energy consumption of heating and A/C system (Kharseh and Nordell, 2011; Kharseh, 2011). It is worth mentioning that, unlike Qatar where the ground water is shallow, the groundwater depth in Saudi Arabia is relatively large and, therefore, the geothermal boreholes are commonly backfilled (Sharqawy et al., 2009; Kharseh, 2011). In cooling-dominated environments, like Saudi Arabia, heat injection into the ground may lead to an increase of the ground temperature and, consequently, a decrease of the performance of GSHP systems. However, the presence of groundwater at shallow depths enhances the thermal dispersion, which helps in recovering the ground temperature and improving the performance of the GSHP systems (Diao et al., 2004; Sutton et al., 2003; Lee and Lam, 2007; Choi et al., 2013). Fortunately, the groundwater level in Qatar is only few meters below the ground surface, eliminating or reducing the need to backfill geothermal boreholes. In such conditions, the temperature plume is minor and, the long-term performance GSHP systems is expected to be better than backfilled ones.

Given the significant needs for air-cooling in Qatar, significant energy saving and environmental benefits could be realized by improving the performance of A/C systems. Therefore, the objectives of this study are to investigate the potential of energy saving of GSHP systems and evaluate their economic viability in cooling-dominated environment like Qatar.

The scope of this study is limited to space cooling in residential buildings and vertical closed-loop GSHP systems. The study will provide valuable reference for future evaluations of groundwater-filed GSHP systems in cooling-dominated environments.

2. Outline of ground source heat pump system

The heat pumping technology has been used for heating and A/C since mechanical heat pumping technology was invented. During winter, such system extract energy from a relatively cold source to be injected into the conditioned space. During summer, the system extract energy from conditioned spaces to be injected into a relatively warm sink. The temperature difference between the conditioned space and the heat source/sink is referred to as temperature lift. This temperature plays a major role in determining of the coefficient of performance (COP) and, consequently, the energy consumption of the heat pump. More specifically, extracting heat from a warmer source during winter or injecting heat into a colder sink during summer results in less energy consumption by the heat pump.

Due to the thermal inertia of the ground, the ground temperature below a certain depth (usually between 12 and 15 m) is almost constant throughout the year. Thus, the ground is warmer than the outdoor air during winter and colder than the outdoor air during summer. Therefore, using the ground as a heat source during winter or as a heat sink during summer leads to a reduced energy consumption of the heating and A/C systems. This fact has increasingly introduced GSHP systems as a smart solution for reducing energy consumption of HVAC systems.

Essentially GSHPs refer to a combination of a heat pump and a system for exchanging heat with the ground. The GSHP system extracts heat from the ground to heat buildings during winter or alternatively, inject heat from the buildings into the ground during summer. This heat transfer process is achieved by circulating a heat carrier (water or a water–antifreeze mixture) between a ground heat exchanger (GHE) and heat pump. The GHE is usually plastic pipe buried vertically or horizontally under the ground surface (Esen and Yuksel, 2013).

3. Methodology

Two stand-alone residential houses with the same specification were chosen as a case study. The thermal quality of the houses' envelope complies with the current building regulations in Qatar. An hourly analysis-based model was designed to simulate the cooling requirements of the two houses. For this purpose, weather data for Doha city was obtained from Meteonorm (METEONORM, 2004). Space cooling was provided by either air-source heat pump (ASHP) system (representing a reference system) or GSHP system (proposed system). Earth energy designer (Blomberg et al., 2000), which is a well-known commercial software, was utilized to design the GSHP system. Hour-by-hour energy simulations of the ASHP and GSHP systems were conducted for each house and the energy consumptions were compared. Finally, economic analysis was utilized to assess the merit of the GSHP systems including net present value, internal rate of return, and the payback time.

3.1. Case study

To investigate the potential of GSHP systems in Qatar, two common types of residential houses located in Doha were chosen as a case study. The model houses have a floor area of 144 m^2 and consist of four identical external walls, 12 m in length and 3 m in height, with a total window opening area of 5 m^2 on each wall. The houses were treated as one zone and were assumed to have a flat roof. The thermal quality of the buildings envelope complies with the current building regulations in Qatar. Table 1 shows the summary of the specifications of the modeled houses and the key design parameters.