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Evaluation of polyethylene and steel heat exchangers of ground source heat pump systems based on seasonal performance comparison and life cycle assessment

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ABSTRACT

Material characteristics of Ground Heat Exchangers (GHE) greatly influence the heat transfer efficiency of Ground Source Heat Pump (GSHP) system, i.e. polyethylene (PE) and steel for the current study. Most of the relevant studies applied numerical simulation or small-scale experiments, which either simplified or neglected the effects of different GHE design on the energy consumption during the operation process of GSHP system. This paper aimed to investigate the seasonal performance (winter and summer) for both PE and steel GSHP systems by using the methods of full-scale experiment monitoring (buried tubes with the depth of 100 m) and life cycle assessment (LCA), which includes energy benefits, economic and environmental impacts. Heat exchange performance was evaluated by heat exchange per tube depth (Q_L) and real-time monitoring of system power consumption. Energy benefits, economic and environmental impacts were further indicated through four indices including coefficient of performance (COP), energy payback time (EPT), cost payback time (CPT) and CO_2 reduction ratio (CRR). In general, we found the seasonal performance of steel system was superior to PE one in the current study. We also noticed that both PE and steel systems showed better performance in summer than winter. For both winter and summer, the annual averaging inlet and outlet temperature difference of steel tubes was 1.4–1.7 °C higher than PE one and the Q_L of steel tubes increased by 70%. The energy consumption and cost of steel system were decreased by 43.6% and 24.6%, respectively in the whole life cycle compared to PE one. The EPT, CPT and the CRR of steel system (compared to PE system) were calculated as 0.24 year, 1.83 years and 0.45 accordingly. This work further shows future promise of steel GHE application for GSHP systems.

1. Introduction

As the rapid development of global economy, energy consumption has become an acute problem with the fossil energy being the main source [1] and accounting for about 78% of the global energy consumption [2]. Moreover, since the environmental pollution caused by fossil energy has seriously produced a negative influence on the global ecological security [3], exploiting renewable energy is one major strategic objective of improving global environment which includes solar, hydro, wind, geothermal energy, biomass and ocean energy [4,5]. Geothermal energy is one of the renewable energy resources with the widest application, which has been favored by an increasing number of countries (China, American, Europe, Indonesia, etc.) [6–9]. On the development potential of geothermal energy, the worldwide installed capacity of geothermal power has reached 13452 MWe by 2017 with about 150 MWe added every year [10–12]. By temperature, geothermal resources can be divided into high enthalpy geothermal resources, low enthalpy geothermal resources and shallow geothermal resources [13]. The categories and applications of geothermal resources are shown in Table 1. Ground source heat pump (GSHP) is the increasingly applied air-conditioning technology in use of shallow geothermal energy for environmental friendliness [14]. GSHP system mainly includes ground heat exchangers (GHE) system, heat pump unit system and air conditioning system, in which the GHE plays an important role [15–17]. The schematic structure of GSHP is shown in Fig. 1.

With the promotion of GSHP system, its energy consumption increases by 7.7% annually, which has drawn global attention in recent years [18]. Therefore, systematic assessment of GSHP has been discussed in many studies. The first target for this assessment is in general to improve energy efficiency of GSHP, which includes

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Nomenclature

GSHP	Ground source heat pump
PE	Polyethylene
GHE	Ground heat exchanger
LCA	Life cycle assessment
Q_L	Heat exchange per tube depth (W/m)
LCI	Life cycle inventory
LCEC	Life cycle energy consumption
LCC	Life cycle costing
COP	Coefficient of performance
EPT	Energy payback time (year)
CPT	Cost payback time (year)
CRR	CO_2 reduction ratio
MWe	Megawatts of electricity
T	Temperature (°C)
TPT	Thermal performance test
t	Service time of ground source heat pump system (year)
n	Life cycle time of ground source heat pump system (year)
$EC_{d,CS}$	Direct energy consumption of construction stage (kJ)
$EC_{i,CS}$	Indirect energy consumption of construction stage (kJ)
$EC_{d,OS}$	Direct energy consumption of operation stage (kJ)
$EC_{i,OS}$	Indirect energy consumption of operation stage (kJ)
IC	Initial investment cost of ground source heat pump system (RMB)
OC_t	Operation cost of ground source heat pump system in the t year (RMB)
MC_t	Maintenance cost of ground source heat pump system in the t year (RMB)
Q_s	Heating (cooling) capacity of ground source heat pump system (W)
W_s	Total equipment power of ground source heat pump system (W)
L	Length of buried tubes (m)
$E_{in,CS}$	Increased energy consumption in construction stage (kJ)
$E_{de,OS}$	Decreased energy consumption in construction stage (kJ)
$C_{in,CS}$	Increased cost in construction stage (RMB)
$C_{de,OS}$	Decreased cost in construction stage (RMB)
E_A	CO_2 emission of system a during the life cycle (kg)
E_B	CO_2 emission of system B during the life cycle (kg)

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Table 1
The categories and applications of geothermal resources.

Resource types	Temperature range	Applications
High enthalpy geothermal resource	$T \geq 150\,^{\circ}C$	Electricity generation, steam production
Low enthalpy geothermal resource	$90\,^{\circ}C \leq T < 150\,^{\circ}C$	Hot working, desiccation, hot spring
Shallow geothermal resource	$T < 90\,^{\circ}C$	Heating, aquaculture, greenhouse

improvement of heat transfer efficiency, soil thermal conditions, coefficient of performance (COP), energy efficiency ratio, thermodynamic perfectibility, optimal design of GHE etc., which has been covered in research [19–25] and our previous studies [26,27]. In the previous studies, Kong [26] and Cao [27] conducted experiments to investigate heat transfer performance of GSHP systems with designed buried tubes (different pipe shapes and configurations) and different tube materials (PE and steel) in summer. However, these researches were mainly focused on the short-term efficiency of GSHP in several days or one season and the omissions of studies on seasonal performance (summer and winter) still existed.

Besides, the other target is to assess GSHP system by considering environmental and economic impacts with the methods of life cycle assessment (LCA) and life cycle costing (LCC). LCA is one evaluation method primarily considering environmental terms and LCC mainly focuses on economic aspect. Some studies about LCA [28–30] and LCC [31–33] of GSHP system were contained as follows. Saner et al. discussed environmental benefits of geothermal heat pump systems by employing the method of LCA, and this research demonstrated that the electricity for the operation of heat pump mainly contributed to the environmental impacts of GSHP system [28]. Huang et al. proposed an evaluation method based on the LCA to examine the energy saving ratio and environmental impact of GSHP system, which was useful for illustrating compre-