Renewable Energy 59 (2013) 39–48

Contents lists available at SciVerse ScienceDirect

Renewable Energy

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

A potential solution for thermal imbalance of ground source heat pump systems in cold regions: Ground source absorption heat pump

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ARTICLE INFO

Article history:
Received 30 August 2012
Accepted 16 March 2013
Available online 12 April 2013

Keywords:
Ground source heat pump
Thermal imbalance
Soil temperature
Absorption heat pump
Primary energy efficiency

ABSTRACT

Ground Source Heat Pumps (GSHPs) are extensively used as renewable energy technology over the world. In heating-dominated buildings, the ground thermal imbalance leads to the decrease of the soil temperature and deteriorates the heating performance. Compared with Ground Source Electrical Heat Pump (GSEHP), Ground Source Absorption Heat Pump (GSAHP) extracts less heat from the soil and rejects more heat to it, which can reduce the ground thermal imbalance in cold regions. In this paper, applications of GSEHP and GSAHP in typical cities are comparatively analyzed based on thermal balance, soil temperature variation and energy efficiency. Results show that the thermal balance is well kept by GSAHP in severe cold cities, without obvious decrease of the soil temperature after 10 years of operation, and the Primary Energy Efficiency (PEE) of GSAHP is significantly higher than that of GSEHP. For buildings with heating load only, the average soil temperature of GSAHP can be 4–6 °C higher than that of GSEHP, and the PEE can stay above 0.96 even in Harbin, the coldest city among analyzed typical cities. It can be concluded that GSAHP is advantageous over GSEHP on the point view of the average soil temperature and energy efficiency, which indicates that GSAHP may be a potential solution for ground thermal imbalance of GSHP in cold regions.

1. Introduction

Energy consumption of heating and domestic hot water is very high and is predicted to increase rapidly based on the fact that building areas are increasing rapidly and the requirements of indoor environment are being improved gradually [1]. The most widely used heating system in China is the coal boiler, which is of low energy efficiency as well as high air pollution. Recently, Ground Source Heat Pump (GSHP), which is regarded as a technology of renewable energy, is extensively used for heating and air conditioning in buildings [2,3]. However, the heat extracted from the soil and the heat rejected to it are not necessarily equal in heating-dominated or cooling-dominated areas [4]. As a result, the soil temperature will decrease or increase gradually after long-term operation since the temperature recovery ability of the soil is limited, which will eventually lead to the performance deterioration of heating or cooling [5,6]. This problem is especially obvious in cold regions, where the heat extracted from the soil by the heat pump in winter is much more than that rejected to the soil in summer. Consequently, the thermal imbalance will reduce the soil temperature, degrade the heating performance, and finally affect the heating safety and system energy efficiency [7]. Furthermore, the deterioration caused by thermal imbalance is even serious if there is only heating demand as in the case of many buildings in cold regions.

The approaches to solve the above problems mainly include (1) increasing borehole spacing or depth, (2) increasing borehole numbers, (3) installing auxiliary heat source, and (4) using thermal energy storage [8]. Among these solutions, increasing borehole spacing will increase the occupied area of boreholes, which is not proper in high-density cities, while increasing the borehole numbers will increase the initial investment. Besides, increasing neither the borehole spacing nor its numbers can fundamentally eliminate the ground thermal imbalance [8]. As for the method of installing auxiliary heat source, the boiler, heat network and solar collector are commonly used to undertake the peak load while GSHP just supplies part of the heating load to realize the soil thermal balance [9]. However, the auxiliary boiler or heat network will reduce the advantages of GSHP, while the investment of the auxiliary solar collector will be expensive. Moreover, the auxiliary device may be very large when the heating load is much higher than the cooling load. As for the method of thermal energy storage, it can be implemented by means of auxiliary thermal storage devices or the ground heat exchangers [10,11].

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http://dx.doi.org/10.1016/j.renene.2013.03.020

Nomenclature

N	borehole number
q_{DCL}	design cooling load, kW
q_{DHL}	design heating load, kW
Q_i	hourly building load, kWh
Q_{ACL}	accumulated cooling load, kWh
Q_{AHL}	accumulated heating load, kWh
Q_{AHE}	accumulated heat extraction, kWh
Q_{AHR}	accumulated heat rejection, kWh
Q_g	heat consumption of generator, kWh
$\overline{T}_{air}$	average air temperature, °C
$T_{air\text{-}max}$	maximum air temperature, °C
$T_{air\text{-}min}$	minimum air temperature, °C
$\overline{T}_{soil}$	average soil temperature, °C
W	electricity consumption, kWh

Abbreviations

AHP	absorption heat pump
COP	coefficient of performance
GSAHP	ground source absorption heat pump
GSEHP	ground source electrical heat pump
GSHP	ground source heat pump
IR	imbalance ratio
PEE	primary energy efficiency

Greeks

η	efficiency

Subscripts

ACL	accumulated cooling load
AHE	accumulated heat extraction
AHL	accumulated heating load
AHR	accumulated heat rejection
c	cooling
cw	cooling water
g	generator
h	heating
sw	source water

Among the solutions of thermal energy storage, solar energy storage is very popular at present [12]. Han et al. [13] investigated a solar-assisted GSHP heating system with latent heat energy storage tank, which was demonstrated to play a very important role in operation. The system can be operated more flexibly, effectively and stably by the heat charge and discharge of the energy storage tank. Wang et al. [14] presented an experimental study of a solar-assisted GSHP system in Harbin, where solar seasonal thermal storage was conducted throughout the non-heating seasons. In winter, the solar energy was used as a priority, and the building was heated by GSHP and solar collectors alternately. After a year of operation, the heat extracted from the soil accounted for 75.5% of the heat stored, and the excess heat raised the soil temperature, which was favorable for a better COP of the heat pump. It is reported that in Sweden, the long-term objective of seasonal storage is to store solar heat from summer to winter for heating [15]. In a project, 2400 m^2 solar collectors were installed to realize seasonal borehole storage and the stored energy covered 70–80% of the annual heating and domestic hot water load. During the summer, part of the collected heat was stored underground with 100 boreholes drilled in the bedrock to 65 m depth. Trillat-Berdal et al. [16] presented an experimental study of a ground-coupled heat pump used in a 180 m^2 residence and combined with thermal solar collectors. Solar heat was used with priority for heating. When the preset water temperature was reached, excess solar energy was rejected to the soil via boreholes, which contributed to stabilize the soil temperature. The heat pump's Coefficient of Performance (COP) in the heating mode had an average value of 3.75.

The above analysis shows that a lot of researches have been carried out to solve the problems caused by the thermal imbalance. Among them the hybrid GSHP systems integrated with solar energy storage are especially popular. However, the reliability of solar energy is seriously affected by the weather and the maintenance of solar collector is difficult. Moreover, the initial cost may be an important concern for a wider application. Especially in the severe cold regions, where heating load is much higher than the cooling load or only the heating is required, the heat complement capacity needs to be large enough to keep the ground thermal balance. However, there is not enough space to install so many heat complement devices (such as solar collectors) in high-density cities.

At present, almost all the GSHP systems are Ground Source Electrical Heat Pumps (GSEHP). Compared with the conventional GSEHP, Ground Source Absorption Heat Pump (GSAHP) extracts less heat from the soil and rejects more heat to it, which can effectively reduce the ground thermal imbalance. In this way, either the auxiliary heat sources (or heat complement devices) can be eliminated or their capacities can be reduced. In order to investigate the potential of GSAHP as an alternative, typical cities in northern China are selected for both GSEHP and GSAHP. Then, the COP of heating and cooling, as well as the annual Primary Energy Efficiency (PEE) of the whole system are comparatively simulated.

2. Methodology

2.1. Models of GSEHP

The performance of GSEHP under variable working conditions is fitted from the heat pump sample provide by the manufacturer. The heating COP is fitted as:

$$COP_{heating} = 0.105T_{sw} + 3.103, \quad R^2 = 0.996 \tag{1}$$

where T_{sw} is the temperature of source water entering the evaporator, °C; R^2 is the coefficient of determination. The supplied hot water temperature for heating is 45 °C.

And the cooling COP is fitted as:

$$COP_{cooling} = -0.165T_{cw} + 8.035, \quad R^2 = 0.990 \tag{2}$$

where T_{cw} is the temperature of cooling water entering the condenser, °C. The supplied chilled water temperature for cooling is 7 °C.

2.2. Models of GSAHP

The schematic diagram of the single-stage GSAHP is shown in Fig. 1. The absorption heat pump is powered by the driving heat source, extracts low-grade heat from the underground soil and then heats the returned water from the users to the required temperature in the absorber and condenser. The detailed operation principle and mathematical model of the single-stage absorption