Renewable Energy 84 (2015) 74–88

Contents lists available at ScienceDirect

Renewable Energy

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

Combining ground source absorption heat pump with ground source electrical heat pump for thermal balance, higher efficiency and better economy in cold regions

Wei Wu, Xianting Li*, Tian You, Baolong Wang, Wenxing Shi

Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 11 January 2015
Received in revised form
31 May 2015
Accepted 11 June 2015
Available online 23 June 2015

Keywords:
Ground source heat pump
Absorption heat pump
Hybrid
Thermal imbalance
Energy efficiency
Cold region

ABSTRACT

Ground source electrical heat pump (GSEHP) and ground source absorption heat pump (GSAHP) have opposite characteristics on thermal imbalance and primary energy efficiency (PEE) in cold regions: (1) GSEHP leads to cold accumulation while GSAHP may cause heat accumulation in the warmer part of cold regions; (2) GSEHP has higher PEEs in cooling mode while GSAHP has higher PEEs in heating mode. The hybrid GSAHP-GSEHP is proposed to counteract the disadvantages and combine the advantages. Different combinations of heating and cooling supply ratios contributed by GSAHP in a hybrid GSAHP-GSEHP can maintain good thermal balance with soil temperature variations within 0.2 °C/year. The influence of supply ratios on thermal imbalance ratio (IR), annual primary energy efficiency (APEE) and economy are investigated to select some preferred configurations of GSAHP-GSEHP, which will be modeled and dynamically simulated over 20 years. Results show that a bigger heating supply ratio of GSAHP and a more negative IR contribute to higher APEEs and fewer boreholes within acceptable IRs of ±20%. Compared with GSEHP, the APEE enhancement is 10.9–34.6%, the energy saving rate is 9.8–25.7%, the lifecycle cost (coal) reduction is 3.7–22.0%, and the lifecycle cost (gas) reduction is 4.1–12.1%. The GSAHP-GSEHP maintains good soil balance with high PEEs in cold regions.

1. Introduction

1.1. Status of ground source heat pump in cold regions

Building energy consumption accounts for about 20–40% of the total energy consumption in different countries [1]. China has become the largest energy consumer in the world, consuming about 3610 Mtce (million tons of standard coal equivalent) in 2012, of which the building energy consumption is 690 Mtce. China is facing severe challenges regarding energy saving and environment protection in the fast-developing economy, especially under the severe circumstance of hazy weather. Ground source heat pump (GSHP) systems, which are regarded as renewable and green technologies, and favorable to energy saving and emission reduction, are becoming more and more widely used for space heating, air conditioning, and domestic hot water all over the world [2–4]. It is reported that GSHP installation reached an estimated capacity of 50 GW in 2012, amounting to about three-quarters of the estimated total geothermal heat capacity [5]. China held the biggest market share of GSHP, and it continued to increase at about 10% annually [5]. GSHPs are predicted to be more and more popular in the future due to the low energy efficiency and heavy air pollution of the conventional heating systems [6].

In heating-dominated buildings, the annual heating load is much larger than cooling load, which will lead to a thermal imbalance between heat extraction from the soil in winter and heat rejection into the soil in summer [7]. The thermal imbalance will cause cold accumulation, so the soil temperature will gradually decrease after a long-term operation [8], which will finally lead to the deterioration of heating performance and reliability [9]. To solve this problem, the auxiliary heating sources are usually integrated with GSHPs to extract less heat from the soil or compensate additional heat into the soil [10,11].

For the hybrid GSHP system extracting less heat from the soil, a boiler is commonly used to undertake the peak heating load and GSHP provides the rest of heating load. Ni et al. [12] investigated the characteristics of GSHP assisted by a gas boiler, finding that a design heating load ratio of 60% for the GSHP and 40% for the gas

* Corresponding author.
E-mail address: xtingli@tsinghua.edu.cn (X. Li).

http://dx.doi.org/10.1016/j.renene.2015.06.025
0960-1481/

Nomenclature

$COP_{Ac,i}$	hourly cooling COP of GSAHP;
$COP_{Ah,i}$	hourly heating COP of GSAHP;
COP_c	COP in cooling mode;
$COP_{Ec,i}$	hourly cooling COP of GSEHP;
$COP_{Eh,i}$	hourly heating COP of GSEHP;
COP_h	COP in heating mode
C_{annual}	annual operation cost, CNY
$C_{initial}$	initial investment of the system, CNY
$C_{20\ years}$	lifecycle total cost in 20 years, CNY
c_p	specific heat, kJ/(kg °C)
H_{fuel}	lower heat value of fuel, kJ/kg for coal and kJ/Nm^3 for gas
h_{in}	inlet specific enthalpy, kJ/kg
h_{out}	outlet specific enthalpy, kJ/kg
L_{pump}	pump lift, m
m_f	mass flow rate of heat source or heat sink, kg/s
m_{in}	inlet mass flow rate, kg/s
m_{out}	outlet mass flow rate, kg/s
PE_c	total primary energy consumption in cooling season, kWh
PE_h	total primary energy consumption in heating season, kWh
p_i	hourly electricity consumption of the ground source pump, kW
P_{fuel}	unit price of fuel, CNY/kg for coal and CNY/Nm^3 for gas
$P_{electricity}$	unit price of electricity, CNY/kWh
Q	heat exchange rate of heat exchanger, kW
Q_{AHE}	accumulated heat extraction during heating season, kWh
Q_{AHR}	accumulated heat rejection during cooling season, kWh
Q_c	cooling capacity, kW
Q_h	heating capacity, kW
q_i	hourly heating or cooling load, kW
Rc_AHP	the distribution ratio of cooling load supplied by GSAHP
Rc_EHP	the distribution ratio of cooling load supplied by GSEHP
Rh_AHP	the distribution ratio of heating load supplied by GSAHP
Rh_EHP	the distribution ratio of heating load supplied by GSEHP
t_{in}	inlet fluid temperature of heat source or heat sink, °C
t_{out}	outlet fluid temperature of heat source or heat sink, °C
$t_{c,in}$	condenser inlet temperature, °C
$t_{e,in}$	evaporator inlet temperature, °C
UA	product of heat transfer coefficient and heat transfer area, kW/°C
V	volume flow rate, m^3/h
x_{in}	inlet solution concentration, kg/kg
x_{out}	outlet solution concentration, kg/kg
η_{boiler}	boiler efficiency, %
η_{power}	power generation efficiency, %
η_{pump}	pump efficiency, %

Abbreviations

APEE	annual primary energy efficiency
COP	coefficient of performance
DST	duct storage
GAX	generator absorber heat exchange
GSAHP	ground source absorption heat pump
GSEHP	ground source electrical heat pump
GSHP	ground source heat pump
IR	imbalance ratio
LMTD	logarithmic mean temperature difference
PEE	primary energy efficiency

boiler could achieve the best economy without any obvious increase in energy consumption. Alavy et al. [13] and Nguyen et al. [14] optimized the shave factor (portion of the peak demand supplied by GSHP) of GSHP assisted by a gas boiler. Sensitive analysis was performed to determine the effects that operating costs, inflation, geographical location and control strategy have on sizing hybrid GSHP systems. Mokhtar et al. [15] proposed an intelligent building management system to improve the control of GSHP integrated with a gas boiler. Simulations showed it could maximize the use of GSHP effectively by profiling, predicting and coordinating its usage with other energy resources.

As for the hybrid GSHP system compensating additional heat into the soil, energy storage techniques are commonly applied to store the natural energy underground, with solar energy storage being very popular at present [16]. Han et al. [17] investigated a solar-assisted GSHP with a latent heat storage tank, which made the system more flexible, effective and stable by the heat charge and discharge of the tank. Wang et al. [18] presented the experimental study of a solar-assisted GSHP system, with solar seasonal storage conducted throughout the non-heating seasons. A one-year operation revealed that the heat extracted from the soil accounted for 75.5% of the heat stored, and the excess heat raised the soil temperature to a higher level. Wang et al. [19] presented a hybrid solar-assisted GSHP system with two GSHP units, one used to supply the total cooling load and partial heating load, and the other coupled with a solar seasonal storage system to supply the rest heating load. Results showed that heat injection into the soil before heat extraction from the soil was favorable to the overall system coefficient of performance (COP). Rad et al. [20] studied solar-assisted GSHP systems in heating-dominated buildings, and found that the solar energy storage underground could reduce the ground heat exchanger length by 15%. The net present value of the hybrid GSHP system was estimated to be 3.7%–7.6% lower than the conventional GSHP system. Instead of only solar energy storage or only solar direct heating, the solar-assisted GSHP systems were preferred to be operated in multi-modes [21,22]: solar direct heating, solar heat pump heating, ground source heating, solar-coupled ground source heating, solar energy storage and recharging, as well as domestic hot water production. In addition, the seasonal energy storage of low-grade energy from the ambient air was also suggested to help maintain the soil balance of GSHP systems. You et al. [23,24] proposed a novel heat compensation unit with thermosyphon that combined an air-source thermosyphon with an air-source heat pump to transfer heat from the ambient air into the ground during the non-heating season. Dynamic simulations proved the ability to keep long-lasting efficiency without performance deterioration of GSHP systems. The COP of heat compensation in thermosyphon mode could reach 12.46, and a total energy saving rate of 15% could be obtained.

The existing solutions for thermal imbalance usually require auxiliary heating sources, at the price of additional investments and reduced energy savings. Apart from the conventional ground source electrical heat pump (GSEHP) systems, the novel ground source absorption heat pump (GSAHP) systems have recently been