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Research paper

Hybrid ground source absorption heat pump in cold regions: Thermal balance keeping and borehole number reduction

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HIGHLIGHTS

- Hybrid ground source absorption heat pump (HGSAHP) with cooling tower is proposed.
- HGSAHP maintains soil thermal balance and reduces borehole number in cold regions.
- Borehole number and land areas are reduced by 37–52% and 20–38% by various cycles.
- The annual primary energy efficiency can be 17.5% higher than conventional GSHP.
- Lifecycle cost of HGSAHP over 20 years can be advantageous over conventional GSHP.

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ABSTRACT

Thermal imbalance of ground source electrical heat pump (GSEHP) leads to cold accumulation in cold regions. Ground source absorption heat pump (GSAHP) can relieve the thermal imbalance, but may cause heat accumulation in the warmer parts of cold regions. Hybrid GSAHP (HGSAHP) integrated with a cooling tower is proposed to solve this problem. Hourly simulations of single-effect HGSAHP and generator absorber heat exchange (GAX) cycle HGSAHP are conducted, and are compared with hybrid GSEHP (HGSEHP). Results show that the thermal balance can be well kept by HGSAHP, with imbalance ratio reduced from 60–80% to within 20%, and soil temperature variation staying within 3 °C after 20 years' operation. Moreover, HGSAHPs are advantageous in heating mode and inferior to HGSEHP in cooling mode. The annual performance of GAX-cycle HGSAHP is very close to that of HGSEHP in Beijing, while being 17.5% higher than that of HGSEHP in colder regions like Shenyang. Compared with HGSEHP, the required borehole number and occupied land areas can be reduced by 37–52% by single-effect HGSAHP and reduced by 20–38% by GAX-cycle HGSAHP. Additionally, the lifecycle cost of GAX-cycle HGSAHP (coal) is the lowest, while GAX-cycle HGSAHP (gas) is cheaper than conventional HGSEHP (gas) assisted by an auxiliary boiler.

1. Introduction

1.1. Problems of ground source heat pump (GSHP) in cold regions

GSHPs are widely used for space heating, air conditioning, and domestic hot water due to the advantages of energy saving and emission reduction, as well as the incentives from the government [1–4]. In 2012, GSHP installation reached an estimated 50 GW of capacity; China had the biggest market share and continued to increase at about 10% annually [5]. Under the severe circumstance of hazy weather in China, the urgent necessity of reducing the pollutant emissions of the conventional heating systems offers great opportunities for the clean heating technologies, with GSHP as one of the potential alternatives. Therefore, the GSHP systems are predicted to be more and more popular in the future.

However, the large-scale application of GSHP systems brings about three major problems:

(1) The conventional heating systems in northern China are mainly based on the burning of fossil fuel because of the coal-dominated energy structure [6,7]. A massive replacement with electricity-based heating systems will bring serious pressure on electricity generation and transmission, and also, it is a big waste of the existing system investment. It

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Nomenclature

COP_c	coefficient of performance in cooling mode
COP_h	coefficient of performance in heating mode
C_{annual}	annual operation cost, CNY
$C_{initial}$	initial investment of the system, CNY
$C_{20\,years}$	lifecycle total cost over 20 years, CNY
c_p	specific heat, kJ/(kg °C)
e_i	hourly electricity consumption, kW
H_{fuel}	lower heat value of fuel, kJ/kg for coal and kJ/Nm^3 for gas
$m_{b,i}$	fluid mass flow rate inside the ground heat exchanger, kg/s
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_{AHE}	accumulated heat extraction during heating season, kWh
$Q_{AHE,hybrid}$	accumulated heat extraction from soil for hybrid system during heating season, kWh
Q_{AHR}	accumulated heat rejection during cooling season, kWh
$Q_{AHR,hybrid}$	accumulated heat rejection into soil for hybrid system during cooling season, kWh
Q_c	cooling capacity, kW
Q_h	heating capacity, kW
$q_{boiler,i}$	hourly heating load supplied by the auxiliary boiler, kW
q_i	hourly heating or cooling load, kW
R_{GHX}	ratio of ground heat exchanger rejection to total heat rejection
R_{HP}	ratio of heat pump heating to total heating
$t_{bin,i}$	hourly borehole inlet fluid temperature, °C
$t_{bout,i}$	hourly borehole outlet fluid temperature, °C
$t_{c,in}$	condenser inlet fluid temperature, °C
$t_{e,in}$	evaporator inlet fluid temperature, °C
η_{boiler}	boiler efficiency, %
$\eta_{driving}$	driving source efficiency of GSHP
η_{power}	power generation efficiency, %

Abbreviations

APEE	annual primary energy efficiency
COP	coefficient of performance
CPEE	cooling seasonal primary energy efficiency
CT	cooling tower
GAX	generator absorber heat exchange
GHX	ground heat exchanger
GSAHP	ground source absorption heat pump
GSEHP	ground source electrical heat pump
GSHP	ground source heat pump
HGSAHP	hybrid ground source absorption heat pump
HGSEHP	hybrid ground source electrical heat pump
HGSHP	hybrid ground source heat pump
HPEE	heating seasonal primary energy efficiency
IR	imbalance ratio
PEE	primary energy efficiency

may be more practically reasonable to improve energy efficiency and reduce the pollutant emission of the present heating systems, rather than completely replace them with other heating systems attached with new problems.

(2) The imbalance between heat extraction and heat rejection will lead to the cold accumulation in heating-dominated buildings [8,9] or heat accumulation in cooling-dominated buildings [10,11]. Cold accumulation is very common in cold regions; the soil temperature will gradually decrease after long-term operation, since the temperature recovery ability of soil is limited, which finally leads to the deterioration of heating performance [12]. Measures to solve the above problems mainly include increasing borehole spacing, depth, and numbers, installing auxiliary heat sources, and utilizing thermal energy storage [13,14]. Among these solutions, increasing borehole spacing or numbers will increase the occupied land and initial investment, besides the disability of fundamentally eliminating the thermal imbalance. Utilizing an auxiliary heat source like a boiler or solar collector will either reduce the energy saving (auxiliary boiler) or increase the initial investment and installation space (auxiliary collector), while thermal energy storage also requires large auxiliary storage devices and high investment [15,16].

(3) The large amount of required boreholes and occupied land is always a major issue that requires the designers to give up GSHP regretfully in their decision-making. A lot of measures have been carried out to reduce the required borehole number and occupied areas, such as increasing the borehole heat exchange rate [17], integrating auxiliary equipment [18], and utilizing a pile-pipe heat exchanger [19]. Among these solutions, the improvement of the heat exchange rate is usually limited; using auxiliary equipment will reduce the energy saving or increase initial investment and installation space, while for the pile-pipe heat exchanger, the influence of thermal stress on a building foundation is still unknown.

1.2. Progress of ground source absorption heat pump (GSAHP)

To reduce the thermal imbalance of conventional ground source electrical heat pump (GSEHP) systems used in cold regions, a heating/cooling system based on GSAHP was proposed [20]. Compared with GSEHP, GSAHP has lower heating and cooling COP, so it extracts less heat from the soil during the heating season and rejects more heat into the soil during the cooling season, which can effectively reduce the year-round thermal imbalance. Analysis has shown that GSAHP systems have advantageous primary energy efficiency (PEE) over GSEHP systems in heating applications, considering the power generation efficiency of GSEHP [20]. Case studies have indicated that the soil temperature of GSAHP can remain stable in northern parts of northern China (severely cold), but it may increase after long-term operation in southern parts of northern China (cold). In these cases, GSEHP leads to cold accumulation underground, whereas GSAHP will cause heat accumulation.

To further reduce the thermal imbalance in this specific region, a combined heating/cooling/domestic hot water system based on GSAHP with heat recovery was put forward. GSAHP with different cycles applied in different regions were simulated comparatively in terms of the thermal imbalance, soil temperature, heat recovery, and energy efficiency [21]. The results showed that GSAHP with a generator absorber heat exchange (GAX) cycle is suitable for Beijing, and GSAHP with a single-effect cycle is suitable for Shenyang. The imbalance ratio can be reduced to −14.8% and 6.0% respectively, with an annual soil temperature variation of only 0.5 °C and