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A new ground-coupled heat pump system integrated with a multi-mode air-source heat compensator to eliminate thermal imbalance in cold regions

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ABSTRACT

A ground-coupled heat pump (GCHP) is a clean and energy-saving approach to providing air conditioning and domestic hot water. For buildings with a dominant heating load, more heat is extracted from the soil and thermal imbalance becomes a crucial problem, in turn reducing efficiency and impeding the wide application of GCHP. Due to the disadvantages of the existing solutions, a multi-mode air-source heat compensator (AHC) integrated with a GCHP system to make a hybrid AHC-GCHP system is proposed in this paper. The principles and operating strategy of AHC-GCHP are illustrated in detail and its performance is simulated in the transient system simulation tool TRNSYS. AHC can not only compensate heat into the ground but also supply heat for space heating and domestic hot water in different modes through full use of the energy in the air with the average coefficient of performance (COP) ranging from 4.49 to 15.09. The AHC-GCHP system effectively keeps the soil thermal balance, and saves 23.86% energy compared with a traditional "boiler + split air conditioner" system, and costs less than half as much as a "hybrid GCHP assisted with solar collector" system. Consequently, the AHC-GCHP system is a potentially efficient and economic approach for buildings in cold regions.

1. Introduction

1.1. The applications of GCHP in the world and China

A GCHP uses a borehole drilled into the soil as a GHE to extract or reject heat from or through the soil. As the soil temperature in deep layers remains stable throughout the year [1,2], the soil is a great heat source or heat sink in the winter or summer, respectively, compared with the ambient air. Thus, a GCHP performs more efficiently than an air-source heat pump in high or low ambient air temperatures. In addition, a GCHP is driven by power to extract heat or cold from the free heat retainer (the ground), and thereby emits less pollutants [3,4]. Last but not least, a GCHP need not destroy the beautiful exterior of a building which is valued by architects.

All of these advantages mean that GCHPs are applied widely around the world [5–9]. In the United States, GCHP installations continue to increase steadily, mostly in the mid-western and eastern states from North Dakota to Florida. In Europe, most of the GCHPs that are applied are in Sweden and Switzerland for space heating [10]. In China, GCHPs were introduced in the 1980s and today elevates at a fast speed under the support of government [11]. Due to the low reliability of air source heat pumps under low ambient air temperatures, and the low energy efficiency and serious pollution of boilers, GCHPs continues to draw increasing attention in applications for space heating in cold climate regions.

1.2. Thermal imbalance and existing solutions

However, some failed projects have emerged in the process of the substantial application of GCHPs. The main cause of the failure of these projects has been soil thermal imbalance [12]. As more and more GCHPs are used for space heating in cold regions, soil thermal imbalance caused by large heat extraction is manifested and leads to cold accumulation in the soil. This in turn causes the soil temperature to decrease [13] and even system failure.

Abbreviations: AHC, air-source heat compensator; AHC-dc, AHC for direct heat compensation; AHC-pc, AHC combined with a heat pump for heat compensation; AHC-ph, AHC combined with a heat pump for space heating; AHC-pw, AHC combined with a heat pump for direct DHW; AHC-GCHP, ground-coupled heat pump integrated with air-source heat compensator; DHW, domestic hot water; GCHP, ground-coupled heat pump; GHE, ground heat exchanger; GCHP-HC unit, ground-coupled heat pump unit for space heating and cooling; GCHP-DHW unit, ground-coupled heat pump unit for DHW.

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Nomenclature

COP_{dc}	coefficient of performance of AHC for direct heat compensation
COP_{pc}	coefficient of performance of AHC and GCHP for heat compensation
COP_{ph}	coefficient of performance of AHC and GCHP for direct space heating
COP_{pw}	coefficient of performance of AHC and GCHP for direct DHW
c_a	specific heat capacity of air, kJ/(kg °C)
c_w	specific heat capacity of water, kJ/(kg °C)
F	heat transfer area of AHC, m^2
K	heat transfer coefficient of AHC, kW/(m^2·°C)
$LOAD_{heating}$	heating load, kW
$LOAD_{DHW}$	DHW load, kW
m_a	mass flow rate of air, kg/s
m_w	mass flow rate of water, kg/s
T_a	ambient air temperature, °C
T_{dc}	start temperature of the AHC-dc mode, °C
T_{pump}	start temperature of the AHC-pc/ph/pw mode, °C
$\bar{t}_a$	average air temperature, °C
t_{ai}	inlet temperature of the air side, °C
t_{ao}	outlet temperature of the air side, °C
t_{si}	inlet water temperature of soil-side heat exchanger of the GCHP unit, °C
t_{uo}	outlet water temperature of user-side heat exchanger of the GCHP unit, °C
$\bar{t}_w$	average water temperature, °C
t_{wo}	outlet temperature of the water side, °C
t_{wi}	inlet temperature of the water side, °C
$P_{GCHP,C}$	power consumption of the GCHP unit for space cooling, kW
$P_{GCHP,H}$	power consumption of the GCHP unit for space heating, kW
P_{fan}	power consumption of the fan of the AHC, kW
Q_{AHC}	heat capacity of the AHC, kW
$Q_{GCHP,C}$	heat capacity of the GCHP unit for space cooling, kW
$Q_{GCHP,H}$	heat capacity of the GCHP unit for space heating, kW
Q_{sup}	supplied heat from the AHC, kW

Therefore, the question of how to eliminate the soil thermal imbalance of GCHP in cold regions is urgent for the promotion of its reasonable application.

Increasing the number of boreholes by 20% or enlarging the borehole space is the common approach in practical design [14]. However, this increases the required investment and does not change the amount of heat transferred with the soil. As a result, the soil temperature decrease happens at a relatively slow speed but is not prevented. This approach cannot eliminate the central cause of soil thermal imbalance.

The absorption heat pump [15,16] was first introduced to use the soil as the heat source or link to eliminate soil thermal imbalance. Ground source absorption heat pumps extract less heat from the soil and reject more heat into it, which can reduce soil thermal imbalance in cold regions [17,18]. This solution is more suitable for cold regions when compared with common GCHPs driven by power.

Hybrid GCHPs [19–21], which add an auxiliary unit to the traditional GCHP system, are another approach to solving this problem. The auxiliary unit can compensate heat into the soil to increase annual heat rejection, or supply heat directly to the building to reduce annual heat extraction. Consequently, the soil retains its thermal balance throughout the year. A common auxiliary unit is

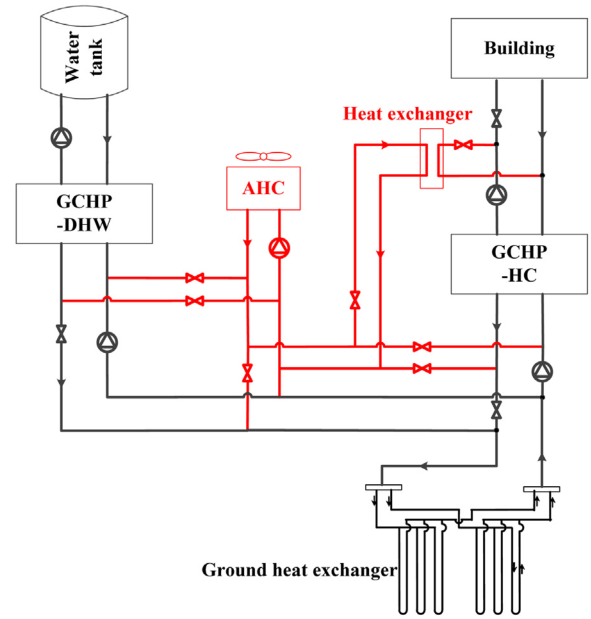

Fig. 1. Principle of the AHC-GCHP system.

a solar collector [22–25] or a boiler [26]. The solar collector, which uses sustainable energy, is popular but expensive and hard to maintain, and the boiler has low energy efficiency as well as causing some pollution. Due to these issues, a clean, energy-saving and economical solution needs to be investigated.

1.3. Objective

In order to eliminate the central cause of soil thermal imbalance with low additional energy consumption as well as low investment, a new hybrid system that adds a multi-mode AHC to a conventional GCHP system is proposed in this paper. AHC can transfer the heat in high temperature air during the non-heating season into the soil for heat compensation, effectively eliminating the soil thermal imbalance in cold regions. In addition, AHC can operate in other modes to supply heat directly for the building. An AHC is suitable for new projects or existing projects that need to be refitted due to its simple connection to the existing GCHP.

The principle of the proposed system will be demonstrated precisely in this paper. In addition, the dynamic performance of this system will be simulated, and the methodology and results will be illustrated.

2. A GCHP system integrated with a multi-mode AHC

2.1. Principle of the AHC-GCHP system

It can be seen from Fig. 1 that the AHC-GCHP system is composed of two parts: the conventional GCHP and the auxiliary AHC. For buildings that have a demand for space heating, space cooling, and DHW, GCHP-HC extracts heat from the soil for space heating in winter and rejects heat into the soil for space cooling in summer; GCHP-DHW is an another unit that extracts heat from the soil to produce DHW all year round, deteriorating soil thermal imbalance in cold regions.

The auxiliary AHC is an air–water heat exchanger in which the water flowing inside the tubes absorbs heat from the ambient air outside the tubes. As well as adding one heat exchanger, one pump, and some valves, an AHC can operate to realize different functions. Overall, when an AHC operates alone, it can compensate heat into