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Research and development of the hybrid ground-coupled heat pump technology in China

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ABSTRACT

The hybrid ground-coupled heat pump (HGCHP) systems with supplemental heat rejecter/supplier can effectively solve heat imbalance problems in the subsurface, and consequently improve the operation performance of the geothermal systems. For example, solar energy and/or industrial waste heat may be used as stable heat sources for underground heat storage in northern China with higher heating load, and cooling towers are installed to release heat into the air in southern China, where more cooling demand is needed. This paper reviews and discusses different HGCHP systems, which have been applied in China. And based on the heat transfer model of vertical borehole heat exchangers (BHE) for HGCHP systems, physical and mathematical models of multistage series circuits are developed to illustrate the heat transfer process of the underground thermal storage. A set of parameters, such as borehole spacing, heat recharging rate fractions and thermal properties of soils, which affect the thermal performance of the ground heat exchangers are analyzed, and the optimal solutions are discussed for engineering application.

1. Introduction

In recent decades, due to the support from the government, contributions of researchers and engineers and the growing concern about the air pollution from coal-fired boilers, ground-coupled heat pump (GCHP) technologies have improved dramatically and aroused more and more interest in China. According to national statistics, by the end of 2014, the completed GSHP systems which are used for space heating are applied for a total area of more than 300 million square meters [1], while the figure in 2009 was only 100 million. And by 2020, the total amount of used geothermal energy will equal to 50 million tons of standard coal [2].

There are five climate zones in China, therefore, the climate characteristics from different region vary widely. The buildings in the northern region have much more annual heating demand. If GCHP systems are applied to these buildings, the heat extracted from underground in winter is far greater than the heat injected in summer. The situation in the southern region is on the contrary. The imbalance between the cumulative amount of heat injection and extraction in the northern and southern regions restricts the wide application of GSHP systems. In order to solve heat imbalance problems in the subsurface, the HGCHP systems with supplemental heat rejecter/supplier were invented. The operation performance of the hybrid systems improves a lot, and therefore, they can be widely used across the country. For example, solar energy and industrial waste heat are used as supplemental heat sources for underground heat storage in northern region, and cooling towers are installed to release heat into the air in southern region.

According to the scale of the projects, the financial situation, and the heating/cooling loads of the buildings, HGCHP systems with cooling tower are generally connected in two configurations, namely in-parallel connection and in-series connection. In China, the research on HGCHP mainly focuses on the designing theories and methods, different system forms, performance analysis and control strategies etc. Man et al. discussed the feasibility of using HGCHP systems in regions with hot summers and warm winters [3], and they investigated the use of nocturnal radiation cooling as supplemental heat rejecter [4]. Guo et al. studied the optimization

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Nomenclature

a	ground thermal diffusivity (m^2/s)
c_p	fluid specific heat ($J/kg\ K$)
H	borehole depth (m)
k	ground thermal conductivity ($W/m\ K$)
M	mass flow rate of circulating fluid (kg/s)
q_l	heat flow per unit length of pipe (W/m)
r_b	borehole radius (m)
T_b	borehole wall temperature (°C)
T_f	fluid temperature (°C)

Greek symbols

β	recharging heat rate fraction
ε	borehole heat transfer efficiency
τ	time (s)
Θ	dimensionless fluid temperature

of underground loop systems with an objective of minimum investment [5]. Cui et al. simulated the performance of HGCHP system for domestic hot water supply [6]. Li et al. proposed a GCHP system using the absorption chiller, which can reduce the imbalance between heating and cooling load in cold climate region [7]. Hu et al. discussed the optimal intermittent operation strategies of HGCHP [8]. By using TRNSYS software, Fan et al. analyzed the impact of several important design parameters on a small HGCHP system performance [9]. Based on the study of artificial neural network, Wang et al. established a model for HGCHP system, and studied the control strategy [10]. In addition, there are a number of studies about experiments and simulations of solar energy assisted HGCHP system [11–14].

Different from the single GCHP system, the performance of hybrid system depends not only on long-term ground temperature evolution, but also the short-time high-frequency temperature response of BHEs. Li et al. proposed a composite-medium line-source model to simulate the high frequency temperature response of HGCHP systems [15–17], and they also established full-scale temperature response function for heat transfer from different time scales and proposed an entropy generation minimization method [18,19].

There are various types of industrial waste heat and solar energy collectors. In most industrial production processes, the industrial waste heat are generally featured by delivering thermal energy of over 50 °C and requiring a relatively lower return temperature, such as 20 °C. Obviously, the large temperature drop required by the production process cannot be implemented through the conventional parallel connection of boreholes which can mostly provide a maximum temperature difference of 5 °C [20–22]. Based on this, a novel borehole configuration of multistage-series circuits is proposed is this study, it could not only satisfy the requirement of the large temperature drop by the industrial process but also make full use of industrial waste heat. Previous studies mainly focus on the analysis of underground temperature distribution of boreholes with conventional parallel connection [23–30], while in this study, the heat transfer of a new borehole configuration of multistage-series circuits is analyzes. Fig. 1 illustrates the two different borehole connection configurations, i.e. the parallel connection for GCHP systems and the multistage-series connection for the seasonal thermal storage of industrial waste heat.

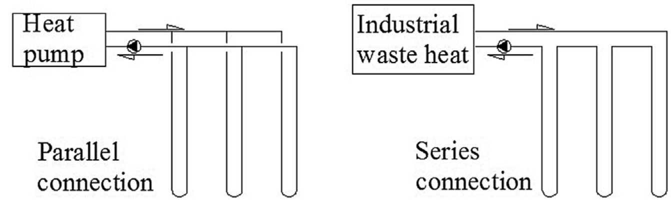

Fig. 1. Left: conventional GHE in parallel connection; right: multistage-series GHE for the thermal storage based on the industrial waste heat.

2. Solar energy assisted HGCHP systems

2.1. Heat transfer analysis of vertical BHE with multistage-series circuits

2.1.1. Assumptions for the heat transfer model

As for a single borehole, the heat transfer process can be directly analyzed by means of the same mathematical methods as the conventional vertical borehole in GCHP systems. The finite line source heat transfer model commonly used is employed in this study. To keep the problem analytically manageable, the theoretical model of the multistage-series GHE is based on the following simplified assumptions:

1) The ground is regarded as a homogeneous medium with a uniform initial temperature t_0, and its thermophysical properties do not change with temperature.
2) The heat transfer in the ground is assumed to be carried out solely by conduction with the neglect of groundwater advection, using an effective ground thermal conductivity. The moisture migration in the ground is also negligible.
3) Each circuit is composed of a number of individual boreholes connected in parallel with the same geometric parameters and thermal properties.
4) During the entire heat storage and extraction period, the heat flow rate and continuous time vary, but the total heat content remains the same. And for large thermal storage system, with the help of heat pumps, the amount of extracted heat equals to the storage amount.

2.1.2. Heat transfer model for heat storage and its solution

For a given GHE configuration with multistage series, the main objective of the thermal analysis is to determine the optimal heat injection/extraction rate (Q_i) of each independent circuit and to consequently obtain the inlet/outlet temperatures (t_i', t_i'') of the circulating fluid of each circuit. Fig. 2 describes the physical model of the multistage series, where, R_{bi} and t_i are the borehole thermal resistance and the fluid temperature of the *ith* circuit, respectively.

Based on the energy conservation law, the injection heat rate to the surrounding ground by *ith* circuit is equivalent to the heat rate

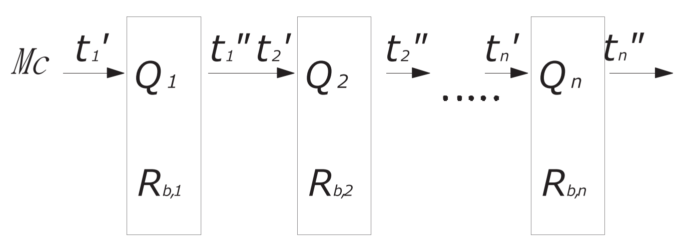

Fig. 2. The physical model of multistage series.