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Optimization of design and operation parameters for hybrid ground-source heat pump assisted with cooling tower

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ABSTRACT

Thermal imbalance is usually encountered in the application of ground-source heat pump (GSHP) in cooling or heating load dominated areas, which results in the performance degradation of the system. Hybrid ground-source heat pump (HGSHP) assisted with cooling tower has been developed to attemper the underground heat accumulation in cooling load dominated areas. Based on TRNSYS 16, the performances of parallel and serial HGSHP systems are, respectively, studied in this paper. Considering the ground temperature increase and the total power consumption in the 20-years running time, 50% of the auxiliary cooling ratio (ACR) is found to be the optimum for both parallel and serial HGSHP systems. A control strategy which is named fixed load ratio (FLR) is proposed for the parallel HGSHP system. 0.5 of the load ratio is the optimal FLR, which is concluded from the 20 years' performance simulation. The fixed entering temperature (FET) control strategy is studied for the serial HGSHP system, and the optimal temperatures that cooling water enters the heat pump to start up and shut down the cooling tower are 30 °C and 28 °C, respectively.

1. Introduction

Ground-source heat pump (GSHP) has been regarded as an energy efficient technology to meet the heating and cooling demands of a building simultaneously, so it has been widely used in the world to deal with the energy shortage and the environmental issues. With the development of GSHP, some problems are also encountered, one of which is the thermal imbalance. Usually, there inevitably exists some difference between the cooling and heating loads of a building, and this difference could become very large especially for the cooling or heating load dominated areas. In such conditions, the amount of cooling or heating will be accumulated under the ground after a long-time running of GSHP system. Therefore, the ground temperature will get decreased or increased due to the load imbalance between cooling and heating, and eventually the performance of GSHP system will get decreased because the ground temperaure is approaching far away from the originally designed value [1–5].

In order to attemper the accumulation of heat or cold in the ground, hybrid ground-source heat pump (HGSHP) is proposed, which is generally referred to GSHP with supplemental heat sink or source [6]. The advantages of HGSHP for reducing initial costs and ground area requirement compared with conventional GSHP has been discussed in ASHRAE manual [7]. Qi et al. provided an overview of the status and development of different types of HGSHP systems [4]. In cooling load dominated areas, the most common auxiliary heat rejecter of HGSHP is cooling tower. There are usually two connection modes between borehole heat exchanger (BHE) and cooling tower in HGSHP system, i.e. parallel and serial configurations, as shown in Fig. 1. For the parallel configuration of HGSHP, cooling tower and BHE are installed in two separated loops with two independent pumps. A closed-type cooling tower is adopted to prevent cooling water from contamination. For the serial configuration of HGSHP, cooling tower and BHE are connected serially by a plate heat exchanger, and an open-type cooling tower is used to enhance the heat transfer between the water and ambient air.

Some researches have been conducted on the performance of HGSHP system. Hackel and Pertzborn [8] studied three HGSHP systems including two cooling tower assisted systems. Considering the economic and enviromental performances of the HGSHP systems, some improved design and operation stratgies were proposed in their study. Hao and Luo [9] compared the system performances by experimental means and concluded that HGSHP with parallel configuration was superior to that with serial configuration in energy saving and operation management. Based on a series of experimental studies, Park, Lee and Kim [10–12] summarized

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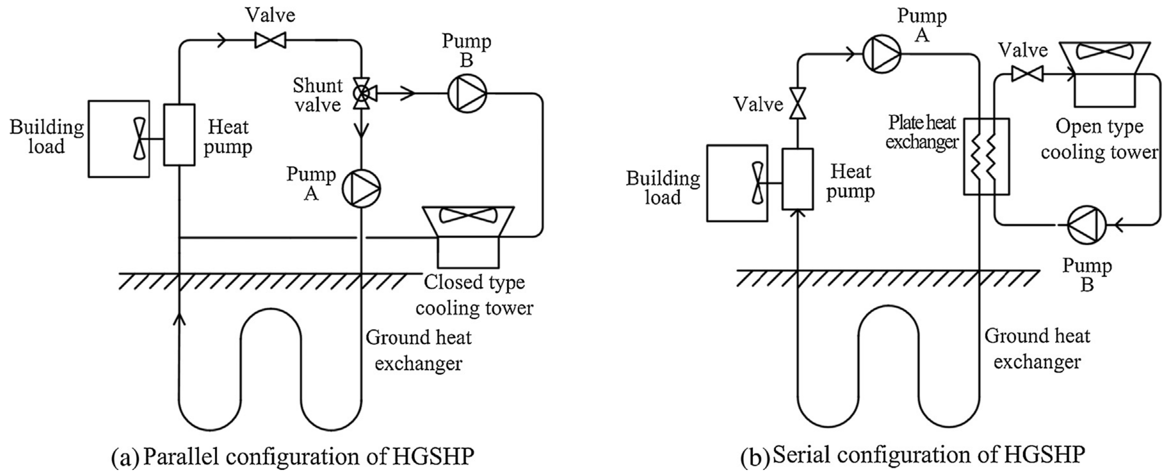

Fig. 1. Schematic diagrams of HGSHP systems.

that the coefficients of performance (COPs) of both parallel and serial HGSHP systems were higher than that of conventional GSHP system, which was concluded at the optimized conditions of the amount of refrigrent, fluid flow rate through ground loop, set-point temperature of hybrid operation, and etc. Man et al. [13] studied the performance of a HGSHP system installed in hot-weather areas with a practical hourly simulation model. Their simulation results showed that the HGSHP system could effectively solve the heat accumulation problem and reduce both initial and operating costs compared with conventional GSHP system. Furthermore, Sagia et al. [14] improved the design of cooling tower in a HGSHP system through the performance comparison among systems with different auxiliary cooling ratios (ACRs). Sayyadi and Nejatolahi [15] optimized thermodynamic and thermoeconomic performances of a HGSHP system in a multi-objective optimization process using the genetic algorithm.

Since cooling tower is an auxiliary heat rejecter for HGSHP, some control strategies are usually required to regulate the running of cooling tower, such as specifying the conditions for starting up and shutting down the cooling tower. The followings are the three control strategies usually used in HGSHP system:

(1) The fixed entering temperature (FET) control strategy: to activate cooling tower when the temperature that cooling water enters heat pump unit (HPU) exceeds a fixed temperature;
(2) The fixed temperature difference (FTD) control strategy: to activate cooling tower when the difference between the temperature that cooling water enters HPU and the dry-bulb (or wet-bulb) temperature of ambient air exceeds a certain value;
(3) The fixed running time (FRT) control strategy: to activate cooling tower at a predetermined point in time.

These control strategies can be used individually or combined with each other. Several papers have investigated these control strategies. Yavuzturk [16] investigated the advantages and disadvantages of these three control strategies in a HGSHP system by using an hourly system simulation model under different climatic conditions. A life-cycle cost analysis was conducted to compare each control strategy and determine the lowest-cost option for a given climate. Man et al. [17] compared the initial and operating costs of these control strategies. They inferred that the best control strategy for the studied HGSHP system was the FTD control strategy, i.e. cooling tower should be activated when the temperature that cooling water enters HPU was 3 °C higher than the wet-bulb temperature of ambient air. They also studied a combined control strategy of FET and FRT in another HGSHP system [13]. Fan et al. [18] also studied different combinations of these three control strategies. They came to the conclusion that the combination of FET and FTD (wet-bulb) control strategies had the lowest energy consumption. Yang et al. [19] combined FTD and FRT control strategies, and the optimal operating conditions that favored both energy consumption reduction and ground temperature recovery were found.

As mentioned above, most studies in literatures focus on the comparison of different system configurations or control strategies of HGSHP. The relevance between system configuration and control strategy is seldom clarified, and also these different configurations and control strategies are seldom considered for HGSHP projects with different properties. Actually, there may be only one suitable system configuration or control strategy for a specific HGSHP project. In cooling dominated areas, HGSHP is usually used in two cases: one is the newly-built HGSHP project that the thermal imbalance has already been considered in the design phase and the cooling tower has been constructed as one part of the system; the other is the renovated HGSHP project that used to be an existed conventional GSHP system, and cooling tower is introduced due to the performance degradation of GSHP system for the reason that the heat accumulation under the ground after several years of operation. In this paper, both the suitable system configuration and the best control strategy of these two cases are analyzed, and based on TRNSYS code the 20 years' performances of HGSHP systems are simulated to explore the optimal parameters of design and operation.

2. Building load and HGSHP models

2.1. Building description and load characteristics

The studied building is a multistoried building with an air conditioning zone of 3000 m^2 office area in the first and second floors located in Chongqing, China, where the climate is characterized by hot summer and cold winter. In order to evaluate the hourly load of the building, a simulation project for load calculation is established in TRNSYS, as shown in Fig. 2. TRNSYS is a modular simulation software which can be used to simulate and predict the behavior and performance of transient thermal systems. It was developed by Solar Energy Laboratory of the University of Wisconsin-Madison and improved by some research institutes in Europe [20].

In the above schematic diagram, the *Building* type represents the studied building which is generated from TRNBuild (a part of TRNSYS for simulating multi-zone buildings [21]) and the description of the building programmed in TRNBuild is shown in Table 1. Meteorological data of Chongqing are contained in the *Weather* type as shown in Fig. 2, which is extracted from the Chinese standard