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Performance improvements of a ground sink direct cooling system under intermittent operations

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ABSTRACT

Ground heat exchangers (GHEs) present declining performance during continuous running. The purpose of this paper is to study the effects of intermittent operations on improving the heat transfer of GHEs in a ground sink direct cooling system (GSDCS), and then optimize the on-time and off-time durations of the intermittent cycles. A numerical model of a GHE was developed with experimental validation. The influences of different flow rates and ground temperatures on the GHE performance were studied in direct cooling mode. Different operation modes were adopted to investigate the intermittent performance of the GHE and analyze the recovery mechanism of the surrounding ground temperature. The results reveal that lower flow rate of the GHE is preferred to decrease the outlet water temperature in direct cooling. Intermittent operations can effectively raise the heat transfer rate of the GHE and slower the increase of its outlet water temperature. The length of on-time and off-time shows significant influence on the ground temperature recovery. Shorter on-time contributes to quicker recovery for next off period. Prolonging off-time enables ground temperature to recover more sufficiently, however, overlong time leads to inefficient process. The proper length of intermittent durations is provided in the study for better utilization of the system.

1. Introduction

The increasing consumption of building energy has brought great challenges to energy shortages and climate changes. Utilizing renewable energy has been regarded as an effective approach to relieve the problems [1]. In last decades, vertical ground heat exchangers have been widely used to utilize geothermal energy, since the ground is a good heat reservoir for buildings to exchange heat [2]. However, the performance of GHEs decreases with time during continuous running, because earlier heat transfer has changed the surrounding ground temperature. The phenomenon leads to lower system efficiency and more GHE investments [3].

The heat transfer of GHEs has great effects on application of different geothermal energy systems. It is common to couple GHEs to heat pumps as a system, which is known as ground source heat pump system (GSHPS). It is also feasible to use standalone GHEs in some areas to extract underground cold energy to cool indoor environment directly, which is called ground sink direct cooling system (GSDCS) [4]. The outlet water temperature of this system is much higher in comparison with the GSHPS, and this system has no function in dehumidification. However, the GSDCS consumes much less operating energy. For the GSHPS, the declining GHE performance would decrease the efficiency of the whole system. For the GSDCS, the declining GHE performance could even fail the normal system utilization, when the outlet water temperature of GHEs increases over the extreme value [5]. It has been found that operating GHEs intermittently can improve their heat transfer.

A number of experimental and numerical researches have been conducted to study the heat transfer of GHEs [6–11]. Arif et al. analyzed the daily variations of the inlet and outlet water temperature of a GHE, and concluded the heat transfer rate of the GHE decreases in general [12]. Mustafa et al. [13,14] studied the ground temperature variation around a GHE during operations of a GSHPS, and pointed out the ground temperature deterioration reduces the system performance coefficient significantly. Several studies have focused on discontinuous operations of GHEs to alleviate these problems. Stevens [15,16] calculated the intermittent heat transfer rates for a GHE with different intermittent factors through a finite difference model. The average heat transfer rates of running periods under the intermittent modes were found to be always higher than under the continuous mode. Fang et al. [17] developed a modified line-source model to study the discontinuous

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operation of a GHE and pointed out the intensity and duration of the discontinuous load are significant to the GHE performance. Cui et al. [18] developed a finite element numerical model, and proved discontinuous and alternative operations could effectively raise the performance coefficient of a GSHPS. Gao et al. [19] conducted experimental and numerical studies to analyze ground temperature variations around a GHE under intermittent operations. It was found the intermittence could prolong the heat transfer before ground temperature reaches the extreme value. Shang et al. [20] studied the ground temperature variations and their different influencing factors for intermittently operated GHEs with a validated numerical model. Jalaluddin et al. [21] simulated the heat transfer of a GHE under different operation modes and concluded the heat transfer rate is apparently higher under alternative and intermittent modes in comparison of under the continuous mode. Most of these studies focused on studying the effects of intermittent operations and the variation of surrounding ground temperature for the GHEs in GSHPS. More specific mechanism of heat transfer under intermittent operations has not been studied.

This research focuses on improving the performance of GHEs through intermittent operations. A validated numerical model was developed to study the performance of a GHE in direct cooling mode. The outlet water temperatures and the heat transfer rates of the GHE under different intermittent modes were investigated, and the ground temperature recovery was also analyzed. Additionally, the same GHE working under a typical running condition of GSHPS was also simulated in order to compare the ground temperature recovery between GHEs with different heat transfer rates. The length of intermittent durations was studied for designing a more efficient operation mode for the GSDCS.

Nomenclature

C, C_1, C_2	empirical constants
E	energy (J)
g	acceleration of gravity
G_k	produce item from the kinetic energy
G_r	Guerra Akio number
h	convection coefficient (W/m^2 K)
I	the unit tensor
l	characteristic length (m)
Nu	Nusselt-number
p	pressure of the flowing fluid (Pa)
P_r	Prandtl-number
S_R	additional source term (W/m^3)
T	temperature (K)
u	velocity vector of the flowing fluid (m/s)

Greek symbols

λ	conduction coefficient (W/K)
μ	dynamic viscosity (Pa s)
μ_t	turbulent viscosity (Pa s)
κ	kinetic energy
ε	turbulent dissipation rate
σ_T	turbulent Prandtl number
σ_k, σ_s	Prandtl number of κ and ε
ν	kinematic viscosity (m^2/s)
ρ	density of the flowing fluid (kg/m^3)

2. Description of the GSDCS

2.1. System description

The GSDCS was set up in Huazhong University of Science and Technology, Wuhan (latitude 30.57° N, longitude 114.30° E), China, in 2010. The schematic diagram of the system is showed in Fig. 1, and it mainly consists as follows: (1) 8 vertical GHEs, (2) 2 water buffers, (3) 10 indoor fan coils, (4) 2 water pumps, (5) some auxiliary equipment, such as water collectors, separators and some valves. The GSDCS is connected to a low energy student workroom, extracting underground cold energy for indoor cooling during summer. The workroom was designed and constructed as an energy efficient building, which was added at the roof of an existing three-floor building. The workroom adopted the technologies of ventilated façade and underfloor air ventilation, which contributes to a small air-conditioning load.

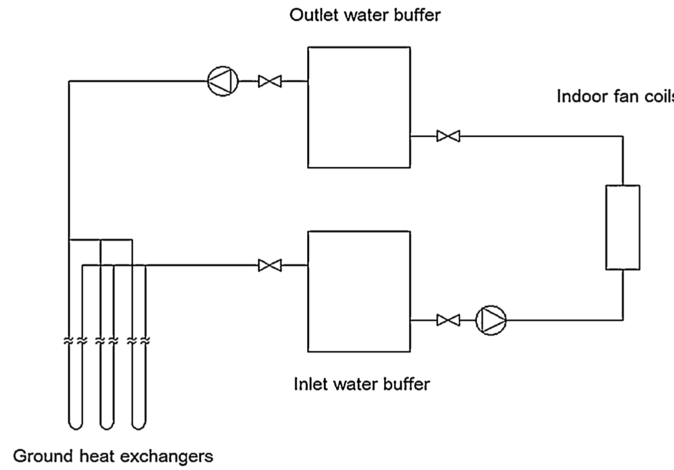

Fig. 1. Schematic diagram of the GSDCS.

The GSDCS pumps water through the GHEs to store underground cool energy in the water buffers, and then indoor fan coils extract the water stored for daytime cooling. The GHEs consist of 8 vertical U tubes which are buried 12 m away from the existing building, and the space between the tubes is 4.5 m. These tubes have an outer diameter of 32 mm, a tube thickness of 5 mm and a length of 50 m. The central distance between the two legs of the U tube is 70 mm.

The water buffers work as a thermal energy storage system which enables the GHEs run intermittently during the whole day. Therefore, the buffers could make the supply water temperature more stable for fan coils, instead of being influenced by the heat transfer of GHEs directly. The intermittent operations of GHEs have 3 main functions, which are as follows: (1) increasing the heat transfer efficiency of the GHEs which is beneficial to control the outlet water temperature in acceptable range, (2) lengthening the running time of the GHEs during a whole day which could decrease the required amount of the GHEs, (3) reducing the operating electricity cost of the system through being able to shift part of the running time from peak to off-peak periods.

2.2. Ground and climate characteristics

Ground temperature has a direct effect on determining the feasibility and performance of a GSDCS. The annual ground temperature at different depths in Wuhan is calculated based on measurement data, as shown in Fig. 2. The local daily average ambient temperature is also presented.

The cooling season of Wuhan is from June to September. The *x*-axis in Fig. 2 starts at the end of July, which is the hottest period. It can be seen the ground temperature below the depth of 10 m keeps approximately 18 °C for the whole year. The daily average ambient temperature of the cooling season is mainly in the range of 22.5–35 °C. The temperature difference between the moderate ground and the hot outdoor ambient makes it capable to utilize GSDCS. However, the ground temperature increasing during the