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Investigation of a coupled geothermal cooling system with earth tube and solar chimney

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HIGHLIGHTS

- We investigated a coupled geothermal system with earth tube and solar chimney.
- Three experiment tests were conducted in a sequence as passive, active, and passive.
- We analyzed indoor air condition, cooling capacity, and soil temperature.
- The system is feasible to provide cooling for free and supply a high airflow rate.
- Preliminary control and soil saturation and recovering should be considered.

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ABSTRACT

We present a systematic study of a coupled geothermal cooling system with an earth-to-air heat exchanger and a solar collector enhanced solar chimney. Experiments were conducted with an existing test facility in summer to evaluate the performance of the system, in terms of passive cooling capability, active cooling capability, and soil thermal capability. Correspondingly, three different tests were carried out in 43 days in a sequence, from a passive cooling mode to an active cooling mode, and then back to a passive cooling mode. The results show that the coupled geothermal system is feasible to provide cooling to the facility in natural operation mode free without using any electricity. The solar collector enhanced solar chimney can provide more airflow to the system during the daytime with a stronger solar intensity. The thermal sensation analysis based on predicted mean vote and predicted percent of dissatisfied people indicates that the indoor air condition under the natural airflow stage was more acceptable in terms of thermal comfort than that of the forced airflow stage. The cooling capacity of the coupled system drops quickly after the one week forced airflow test due to the underground soil temperature increase. It takes the soil over two weeks to fully recover from the thermal saturation after the forced air test. In addition, the underground soil temperature test results indicate that the underground heat dissipation in the horizontal level was greater than that in the vertical level. The findings suggest that a minimum level of control on the system and consideration on soil saturation is needed to further improve the overall performance.

1. Introduction

The utilization of geothermal energy can be an open system with direct water exchange [1–3] or a closed system with a medium circulating in the heat exchangers [4,5]. A ground-coupled heat exchanger (GCHX) is an underground heat exchanger that can capture heat from and/or dissipate heat to the ground. They use the earth' near constant subterranean temperature to warm or cool air or other fluids for residential, agricultural or industrial uses. Among the different types of GCHXs, an earth-to-air heat exchanger (EAHE) is such a ground-coupled device that conditions the ambient air for various cooling, heating and ventilation purposes. EAHEs have been applied in agricultural facilities and greenhouses in the United States over the past several decades [6].

In the ambit of bioclimatic architecture, where a building has a direct connection with nature, EAHEs have been assigned an increasingly important role in cooling primary air free for buildings during hot weather [7]. Air passing through the buried pipes in an EAHE system can be either from outdoor air or circulation air. To assess the performance of EAHEs, Krarti and Kreider [8] proposed a simplified analytical model. The enthalpy transfer problem was treated as a transient heat transfer problem without condensation, assuming a periodic variation of both air source and ground

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Nomenclature

Roman letter symbols

fcl	ratio of clothed body surface area to nude body surface area
h	enthalpy, kJ/kg
h_c	convectional heat transfer coefficient, W/m^2 K
M	metabolism, W/m^2
Pa	partial water vapor pressure, Pa
Q	rate of heat transfer, kW
T	temperature, °C
V	volume flow rate of air flow, m^3/s
W	external work, W/m^2

Subscripts/acronyms

air, a	air
cooling	cooling
cl	cloth
mrt	mean radiant temperature
system	system
t	total
ACP	above cooling pipe
EAHE	earth to air heat exchanger
GCHX	ground-coupled heat exchanger
HR	humidity ratio
NCP	next to cooling pipe
OA	outdoor air
OAT	outdoor air temperature
PMV	predicted mean vote
PPD	predicted percent of dissatisfied people
RA	room air
RAT	room air temperature
SA	supply air
SAT	supply air temperature

Greek letters

ρ	specific density, kg/m^3

temperatures. They validated the model against measured data and applied it for parametric analysis on cooling capacity and air temperature with the pipe diameter and air velocity.

Without considering the moisture transfer in the air, EAHE is like the other GCHXs, where the tubes and eventually soil are utilized as a heat sink/source. The heat transfer rate of a GCHX is critical since it determines the overall performance of a system that couples a GCHX [9–11]. Akpinar and Hepbasli [9,10] and Hepbasli et al. [10] investigated the performance of a GCHX coupled heat pump system. They concluded the heat extraction rate of the system was impacted by a GCHX in terms of the depth below grad, pipe size, spacing, and soil type beside other system parameters. Nam et al. [11] developed a numerical model to predict heat exchange rates of a GCHX in a coupled heat pump system. It was later applied to find the optimum design for an office building in Tokyo, Japan. Zeng et al. [12] utilized a quasi-three-dimensional model for the vertical GCHX heat transfer analysis. By comparing the single U-tube with double ones, they concluded that the borehole with double U-tubes is superior to the single U-tube regarding the heat transfer rate.

Understanding the soil temperature field underground can guide the reasonable operation of a GCHX coupled system and avoid the low performance due to the heat transfer attenuation. During the last decade, investigations about the soil temperature field and heat transfer have been conducted by researchers [13,14]. Some researchers obtained the soil temperature distribution under the nature condition and intermittent operation, analyzed the variation of the soil temperature and heat balance of the system, and put forward the method of calculation of the temperature for heat extraction or injection utilizing the numerical and experimental method [15–17].

Just like other GCHXs, an EAHE is a passive device that provides a thermal coupling between the medium fluid and the soil. Additional components are needed to provide the driving force for the medium fluid. In a pure passive design of an EAHE conditioning system, a solar chimney may be used to pull the air through the tubes. A solar chimney is a vertical or inclined air channel where its bottom end is connected to the building to be cooled and ventilated [18]. This air channel generates air movement by buoyancy forces and stack ventilation, drawing cooler air through the building in a continuous cycle in which hot air rises and exits from the top of the chimney [19]. In other words, a solar chimney is a natural draft device which utilizes energy produced by solar radiation to build up stack pressure, consequently, driving airflow through the chimney [20]. As the solar chimney problem involves both fluid movement as well as heat transfer, it was found that the computation fluid dynamics (CFD) is a good tool to describe the system numerically [21,22]. Other techniques have also been used beside the CFD to simulate the solar chimney systems. Two-dimensional conservation equations for mass, momentum and energy were used to describe the system. The conservation equations were then solved by finite difference-control volume numerical method [23]. When a solar chimney is used in conjunction with EAHE, free cooling and heating with natural airflow can be obtained.

Despite the research findings, very few experimental studies have been carried out to systematically evaluate the performance of an EAHE-solar chimney coupled geothermal system in natural and forced airflow conditions. In addition, research about the soil temperature saturation and recovering of such a system, which could strongly impact the operation and performance, was not reported. This research conducted three field tests and systematic analysis of an EAHE-solar chimney coupled geothermal system. The paper starts with a brief introduction of the test facility followed by a description on the experimental procedure. After that, the room air condition, thermal comfort, cooling capacity, and soil thermal capability are discussed. The paper concludes with a discussion on the findings and future research directions.

2. The test facility

2.1. Introduction of the test facility

A test facility for an EAHE-solar chimney coupled geothermal system was constructed in Omaha, Nebraska, USA. The design of

Table 1
Main design calculated values.

Design component	Calculated value	Unit
Total cooling load	2.8	kW
Sensible cooling load	1.6	kW
Latent cooling load	1.2	kW