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Research on cooling performance of phase change material-filled earth-air heat exchanger

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ABSTRACT

As a passive energy technology, the earth-air heat exchanger (EAHE) can greatly contribute to reducing the energy consumption of heating, ventilating, and air-conditioning (HVAC) systems. In a traditional EAHE, the cooling/heating effect is achieved through the charging/discharging process of soil sensible heat. However, this process is detrimental to fully develop its potential. Considering that the phase change-based thermal energy storage technology has outstanding advantages in this regard, a new system named phase change material (PCM)-filled EAHE is proposed to overcome this deficiency. To study the cooling performance of this new system, a three-dimensional numerical model based on the effective heat capacity method has been built in ANSYS FLUENT and validated using an indoor test rig, which was filled with some laboratory-prepared shape-stabilized PCM. Then comparative studies between the PCM-filled EAHEs and the traditional one are conducted under Chongqing (China) summer condition. The results indicate that, at the daily maximum outdoor temperature, the outlet temperature of the PCM-filled EAHE, which employs the laboratory-prepared shape-stabilized PCM, is approximately 0.83 °C lower than that of the traditional EAHE. Therefore, this PCM-filled EAHE can achieve an improvement of 20.24% in cooling capacity compared to the traditional one.

1. Introduction

As the largest developing country, China has been exerting considerable effort in reducing the emission of greenhouse gases (GHGs). In 2015, we announced internationally that, compared to 2005, CO_2 emissions per unit of GDP will be reduced by 40% to 45% in 2020 and by 60% to 65% in 2030 [1]. It is an enormous challenge to achieve this goal, especially for the construction industry, which constitutes 44.9% (24.9% for construction, 20% for operation) of the total social energy consumption [2]. Among all operational energy consumption, heating, ventilating, and air conditioning (HVAC) systems are the largest energy consumers. Fortunately, research shows that an effective integration of passive features into buildings can remarkably reduce or even eliminate the energy consumption for HVAC systems while maintaining thermal comfort [3]. An example is the earth-air heat exchanger (EAHE), an ancient technique mainly composed of shallowly buried air pipes. The current urgent situation and the arduous task of reducing the GHG emissions have imposed new aims for this technique, and re-innovation is imperative.

A comprehensive investigation of sub-soil temperature distribution is the priority work in studying an EAHE system. Related studies indicate that the soil temperature follows a periodic sine function of time and depth, which experiences amplitude attenuates and phase delays with the increasing depth, but remains stable after reaching a certain depth [4,5]. These are the features supporting the fresh air being heated/cooled through a meticulously located EAHE.

In the 1930 s, studies by the United States Bureau of Mines reported that underground tunnels reduced the temperature fluctuations of fresh air flowing into mines [6]. To explore the capacity of heating/cooling of earth air tunnels in India, Bansal et al. [7] and Sodha et al. [8] provided a simple theoretical model to predict the temperature variation of air flow through a tunnel, and validated it by experimental data of an EAHE system at St. Methodist Hospital, Mathura. In this model, the interaction between air and soil was ignored, which means the temperature of the tunnel surface is constant. Nevertheless, Gan [9] suggested that neglecting the interactions between air and soil will introduce significant deviations in predicting the heat transfer rate and air temperature in long-term operation. This deficiency has been overcome by more accurate quasi-two-dimensional computer models developed by Dhaliwal and Goswami [10] and Liu et al. [11]. Moreover, the latter model considered the variation in air humidity along the tunnel, which means that condensation can be predicted as well.

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Nomenclature

Symbols

A_{gs}	annual amplitude of temperature variation at ground surface (°C)
C	specific heat (J/(kg. °C))
C_{eff}	effective specific heat of phase change material (J/(kg. °C))
$C_{1\varepsilon}$,$C_{2\varepsilon}$,C_{μ}	constants
G_k	the generation of turbulence kinetic energy due to the mean velocity gradients
I	total solar radiation incident on surface (W/m^2)
$I_{diffuse}$	diffuse radiation intensity at the ground surface (W/m^2)
L	latent heat of fusion (J/kg)
p	pressure (Pa)
Q	heat flux (W/m^2)
T	temperature (°C)
T_{gs}	ground surface temperature (°C)
T_{ms}	annual mean temperature of deep soil (°C)
$T_{sol-air}$	sol-air temperature (°C)
T_y	annual period (s)
ΔR	difference between the long-wave radiation incident on the surface from the sky and surroundings and radiation emitted by a blackbody at outdoor air temperature (W/m^2)
a_0	the absorptivity of solar radiation at ground surface
f_l	liquid fraction of phase change material
h_{gs}	convectional heat transfer coefficient at ground surface (W/(m^2. °C))
k	turbulent kinetic energy (m^2/s^2)
t	time (s)
u	fluid velocity (m/s)
x	length component (m)
y	depth in sub-soil (m)

Greek symbols

α_s	thermal diffusivity of soil (m^2/s)
α_k	inverse effective Prandtl numbers for k
α_{ε}	inverse effective Prandtl numbers for ε
ε	the rate of dissipation of turbulent energy (m^2/s^3)
ε_s	long-wave emissivity of the ground surface
φ_{y0}	phase constant of the ground surface (rad)
λ	thermal conductivity (W/(m.°C))
ρ	density (kg/m^3)
μ_a	dynamic viscosity of air (kg/(m.s))
μ_t	turbulent viscosity of air (kg/(m.s))
ω_y	annual fluctuating frequency (s^{-1})
β,η_0	constants

Subscripts

1	solid phase
2	liquid phase
a	air
p	phase change material
s	soil
c	convection
e/c	evaporation/condensation
rs	solar radiation
rl	long wave radiation
i,j	coordinate direction

Abbreviations

EAHE	earth-air heat exchanger
HVAC	heating, ventilation, and air-conditioning
PCM	phase change material
PCM-EAHE	phase change material-filled earth-air heat exchanger
SSPCM	shape stabilized-phase change material
TMY	typical meteorological year

However, these models are not suitable for shallowly buried EAHEs, because ignoring the temperature disturbance from the ground surface will result in an erroneous prediction of the vertical temperature gradient in soil. This has been confirmed by a comparison between the theoretical calculation and experimental result from the study by Dhaliwal and Goswami [10]. Fortunately, these imperfections have been supplemented by an elaborate three-dimensional numerical model presented by Gan [9]. More specifically, the processes of transient heat and moisture transfer in air and soil, the heat and moisture interactions between the tunnel, soil and air, as well as the heat and moisture disturbance from soil surface due to radiation, convection, evaporation/condensation, and precipitation, are considered.

As a promising energy conservation technique, the true value of the EAHE system is its potential to further reduce or even eliminate the energy consumption of building HVAC systems by formulating appropriate methods that can improve its cooling/heating capacity. A parametric study cannot be more suitable to perform such works. The literature review shows that factors affecting the thermal performance of EAHE can be divided into four categories: geometric parameters, thermophysical parameters, operating parameters (or operating strategies), and meteorological condition.

For geometric parameters, the most focused are depth, diameter and length, as well as the spacing for multi-tube arrangements. Studies revealed that the cooling capacity can be improved by increasing the buried depth of EAHE pipes, but this improvement becomes less significant beyond a certain depth [12–15]. For a pipe of smaller diameter, the per unit volume air has a larger heat transfer area, and therefore more heat can be transferred to the soil under the same condition. Or an increase in pipe diameter decreases the difference between the ambient outdoor air temperature and outlet air temperature [14,16]. But increasing the pipe diameter is conducive to improve the total cooling capacity, since the air flow rate increases when the average air velocity remains unchanged [13,17]. Increasing the length of pipes can reduce the outlet air temperature in summer [13–15]. However, it should be decided discreetly, because there is little improvement in the cooling capacity when the pipe exceeds some length [7]. Additionally, if a multi-tube EAHE is employed, the spacing should be designed appropriately to minimize thermal interaction, and it is important to note that a large spacing does not necessarily mean an extra benefit [18].

The soil composition, pipe material, and soil surface treatments, considered as thermophysical parameters, will affect the thermal performance of EAHEs as well. Simulation results of Mathur et al. [19] showed that high thermal conductivity soils are conducive to improving the thermal performance of EAHEs. Meanwhile, the fitting results of the relationship between soil thermal conductivity and moisture in the experimental test of Cao et al. [20] suggested that higher water content means higher thermal conductivity. Thus, it is reasonable to deduce that soil with high water content helps to improve EAHE's thermal performance. This argument can be confirmed by a comparative study on the effect of different soil typologies on EAHE's thermal performance [21]. Owing to the small thickness of tubes, materials such as concrete, plastic and metal lead to a similar thermal performance [21,22]. Furthermore, research on different earth surface treatments shows that a wet and shaded earth surface leads to high cooling potential, and a