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Evaluation of the thermal performance of an earth-to-air heat exchanger (EAHE) in a harmonic thermal environment

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A B S T R A C T

The earth-to-air heat exchanger (EAHE) is a low-energy device used to improve the thermal condition of buildings, which is filled with the air directed from the outside and surrounded by the soil. The temperatures of both the air and soil are periodically fluctuating, leading to the EAHEs working in a harmonic thermal environment. However, most of the previous theoretical studies investigated the performance of EAHEs by ways of static and steady-state models, paying insufficient attention to the temperature phase shifting and fluctuation attenuation effects. The main purpose of this work is to develop an approach to predict the performance of EAHE subjected to harmonic thermal environments. The harmonic temperature signals transmitted from both the pipe inlet and the ground surface are incorporated in the model by means of the 'excess fluctuating temperature'. The amplitude dampening and phase-shifting of the EAHE air temperature for both annually and daily fluctuating cycles are derived as explicit expressions. The analytical results are validated against numerical simulations. The model is applied in a hot-summer/cold-winter region. Results indicate that a deep-buried EAHE pipe can reduce the air temperature by 7 °C on a summer day. The maximum cooling or heating capacities occur in spring/summer or autumn/winter transitional seasons. The use of an EAHE pipe can create a 3000-W cooling or heating capacity.

1. Introduction

Mankind constantly pursues a comfortable building environment. However, energy is essential in the process of maintaining comfortable indoor building environments. Currently, energy consumption of buildings accounts for 25–40% of the total energy consumption, of which, most of the energy is used for heating or air-conditioning and comes from non-renewable fossil fuels such as coal, oil and natural gas [1–3]. The requirement for sustainable development drives people to find alternative, renewable energy to regulate the indoor thermal environments. Scientists and engineers have undertaken many studies in this area, and in most cases, solar energy is directly or indirectly used [4–7].

The use of ground as a heat source or sink for passive heating or cooling of buildings has been used in ancient times [4,8], and this passive measure has attracted more and more attention in recent years. The ground receives solar radiation through its surface and acts as a large reservoir for solar energy. Because of the thermal inertia of the soil, the fluctuation amplitude of the soil temperature, with respect to the ambient air temperature, decreases exponentially as the depth increases. However, the phase shift between the soil temperature and ambient air temperature increases with depth. For this reason, at a sufficient depth, the soil is not as cold as the ambient environment during cold periods and is not as hot during hot periods [9,10]. These features provide a promising opportunity for the use of geothermal energy for passive regulation of building thermal environments. There are two prevalent types of techniques. One type is the ground source heat pump (GSHP), which typically includes a heat pump and a ground heat exchanger sub-system [11,12]. In the heating mode, the GSHP absorbs heat from the ground and uses it to heat buildings. In the cooling mode, the thermodynamic process is reversed and the heat is absorbed from the interior spaces of a building and released to the ground. GSHP systems have better energy efficiency compared to traditional air-conditioning and heating systems, leading to continued growth in applications. Earth-to-air heat exchangers (EAHEs) are simpler and typically cheaper devices, as also called ground air tubes or earth-air-tube ventilation systems [4,13–15]. It is unnecessary to use thermodynamic cycles for the conversion of

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Nomenclature

A	temperature fluctuation amplitude (K)
A'	temperature fluctuation amplitude combined with phase shift (K)
C_a	specific heat of air (J/kg K)
F	a combination of modified Bessel functions
h_1	heat transfer coefficient at the pipe inner wall (W/m^2 K)
I_n	first kind of modified Bessel functions of order n
K_n	second kind of modified Bessel functions of order n
Nu	Nusselt number
P	fluctuation period (s)
q	volume flow rate of ventilation air (m^3/s)
Q	heating or cooling capacity (W)
Q_L	reduction in heating or cooling load (W)
r	radial coordinate (m)
R	radius of an EAHE pipe (m)
Re	Reynolds number
T	temperature (K)
t	time (s)
V_a	velocity of pipe air (m/s)
x	pipe length (m)
z	burial depth of pipe (m)

Greek symbols

α_s	thermal diffusivity of the soil (m^2/s)
$\tilde{\theta}$	excess fluctuating temperature (K)
κ_g	normalized fluctuation amplitude of ground surface temperature with respect to the outdoor air temperature
κ_n	normalized fluctuation amplitude of pipe air temperature with respect to outdoor air
λ_s	thermal conductivity of soil (W/m K)
ρ_a	air density (kg/m^3)
φ_g	phase shift of ground surface temperature with respect to the outdoor air temperature (rad)
φ_n	phase shift of pipe air temperature with respect to outdoor air (rad)
ω	fluctuating frequency (s^{-1})

Superscripts

$-$	time-averaged value
$\sim$	time-dependent value
$\frown$	Laplace transformation

Subscripts

ini	initial condition
g	ground surface
n	earth-tube air
o	outdoor air
r	radius coordinate
s	soil
y; d	values of annual or daily fluctuation period
z	depth

geothermal energy in an EAHE, and thus the associated sub-system is omitted. The ventilation air is drawn through the pipes that are buried in the soil and exchanges heat with the soil directly. Thus, the air is pre-cooled in summer and pre-heated in winter before entering the interior building spaces, which could reduce both cooling and heating loads of buildings and in turn reduce electricity consumption. EAHEs have been applied in various climates. They are also applicable for several types of buildings, such as office buildings [16], commercial buildings [17], residential buildings [18] and agricultural greenhouses [15,19]. The combined systems that integrate EAHEs with other passive techniques, e.g., wind towers and solar chimneys [2,20], could provide both cooling or heating capacity and fresh air for the conditioned buildings with negligible fan energy consumption.

The growth in the applications of EAHEs requires tools for evaluating the thermal performance of EAHEs. The performance of EAHEs depends on various factors such as climate conditions, the configuration parameters of the pipes (e.g., length and radius), the buried depth of the pipes, the thermal physical parameters of the soil, etc. Various papers presented simplified models for predicting the thermal performance of EAHEs [21–24]. Sulaiman [22] studied the cooling effect of underground heat pipes theoretically. Malaysia and Kreider [23] calculated the energy performance of an underground air tunnel in a steady, periodic state using an analytical model. A detailed numerical model considering the effect of the thermal stratification in soil was presented by Mihalakakou, which was developed inside the TRNSYS simulation program [24]. Wu et al. [25] developed an implicit model based on numerical heat transfer and computational fluid dynamics (CFD) to predict the thermal performance and cooling capacity of earth-air pipe systems. Al-Ajmi et al. [26] developed a theoretical model for the outlet air temperature of an EAHE in a hot climate. Dehghan et al. [27] and Rashidi et al. [28] developed mathematical models for analyzing the local thermal non-equilibrium condition, heat transfer enhancement effects and pressure drop penalty for the tube heat exchangers embedded with porous media. However, most of the previous studies treated the EAHEs by ways of static and steady-state models, which cannot account for the phase-shifting effects induced by the transient heat transfer process. However, the ambient air temperature, as the inlet air temperature of an open-loop EAHE, periodically fluctuates throughout both annual and daily cycles. Meanwhile, the temperatures of the soil surrounding a pipe could also periodically fluctuate with dampened amplitudes and amplified phase shifts. The EAHE performance is thus strongly influenced by both the fluctuating characteristics of the ambient temperature and that of the soil temperatures. To quantify the contribution of EHAEs to the load reduction of buildings over the whole annual or daily cycles, it is necessary to obtain the transient air temperature profiles of the EAHE outlet. To date, very few studies provided explicit expressions for the phase shift and fluctuation amplitude of the outlet air temperature of an EAHE pipe. Although the Computational Fluid Dynamics (CFD) codes combined with numerical heat transfer simulations, such as Fluent, can be used for assisting the design of EAHEs, the numerical solutions are implicit. In addition, the computational cost of CFD even becomes unaffordable for simulating an annual fluctuation cycle. Hollmuller [29] derived analytical solutions for the heat diffusion of a cylindrical earth-air tube, which accounts for the periodic fluctuation of ambient air temperature, but his study does not account for the periodic fluctuation of soil. In Hollmuller's study, the penetration radius of heat diffusion inside the soil is specified as a constant. In a recent study, Yang et al. [30] proposed a method for determining the penetration radius of soil heat diffusion based on fluctuation frequency [30]. In the study of Yang et al., the effects of pipe air temperature fluctuation are considered, but the soil temperature fluctuation is excluded, reducing the accuracy for evaluating shallow-buried pipes.