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Numerical analysis of earth air heat exchangers at operating conditions in arid climates

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ABSTRACT

This paper presents the modeling and simulation of an earth air heat exchanger (EAHE), employed as an air-conditioning device for buildings in the climate conditions of the south of Algeria. The earth tubes buried in the ground can offer considerable advantages in terms of energy savings. The appropriate depth of the buried tubes was calculated taking into account the physical properties of the soil in the region under study and using a specific program developed by the authors. A parametric analysis was carried out taking into account the length and the radius of the pipe and the velocity of the air in the pipe. The results of performance and overall energy savings are presented. The maximum daily cooling capacity of the EAHE studied was 1.755 kWh. Results showed that a simple EAHE system can provide 246.815 kWh in a period of one year.

Introduction

An earth air heat exchanger (EAHE) consists of one or more pipes laid underground to supply air conditioning in buildings for cooling in summer and heating in winter. The ambient air is used for ventilation and also to reduce or partially replace the energy demand so as to maintain thermal comfort in buildings or houses [1,2]. EAHEs are characterized by their large potential for energy saving and low maintenance.

The physical phenomenon is simple and depends on the temperature difference between the soil and the ambient air. In summer, the soil temperature is lower than that of the ambient air. Soil temperature also remains almost constant throughout the year at a given depth below ground level. However, the soil temperature profile is a function of the depth involved and depends on other factors such as the physical properties of the soil and the climatic conditions [3].

To understand the thermal performance of EAHEs, several mathematical models, methods and computer tools were developed and used in the open literature. Krarti et al. [4] analyzed the heat transfer process in an EAHE and proposed an analytical model for the EAHE system. A physical model to simulate the EAHE was developed and validated by Mihalakakou et al. [5,6]. Benkert et al. [7] highlighted the lack of optimization criteria when analyzing EAHEs and developed a specific computer tool based on a physical model which was experimentally validated. Al-Ajmi et al. [8] developed an analytical model of an earth air heat exchanger to predict the air outlet temperature and the potential of these cooling devices in a hot arid climate. In their model, the thickness of the disturbed layer of the soil was taken as equal to the radius of

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Nomenclature

α	thermal diffusivity of the soil, m^2/day
Cp	specific heat capacity of the soil, J/kg K
λ	thermal conductivity of the soil, W/m K
ρ	density of the soil, kg/m^3
φ	heat flow, kJ
R_{conv}	thermal resistance of the convective heat exchange between the air and the pipe, m.K/W
R_{pipe}	thermal resistance of the buried pipe, m K/W
R_{soil}	thermal resistance of the soil, m K/W
r_i	inside radius of the buried pipe, m
r_e	outer radius of the buried pipe, m
ω	annual temperature frequency, rad/day
t	day of the year
t_0	day of maximum surface temperature (i.e. 198)
A_s	amplitude of the soil surface temperature variation, °C
T_{mean}	mean annual temperature, °C
Z	depth from the earth surface, m
D	pipe diameter, m
h	heat transfer coefficient, W/m^2 C
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, –
Pr	Prandtl number, –
Q	heat flow, W
Ra	Rayleigh number, –
Re	Reynolds number, –
T	temperature, °C
η	mean efficiency of the EAHE, %
Q_{cool}	average daily cooling potential, Wh

the underground pipe and the thermal resistance of the pipe material was neglected. After validation with other published works, the model was integrated into the TRNSYS environment to investigate the thermal performance of an EAHE in a residential house in Kuwait weather. It was found that the EAHE can provide 30% of the cooling energy demand in summer. A complete analytical solution for the heat diffusion of a cylindrical air/soil heat exchanger with isothermal boundary conditions was proposed by Hollmuller [9]. De Paepe and Janssens [10] proposed a 1-D model to analyze the influence of the design parameters of an earth air heat exchanger on the thermal hydraulic performance. Badescu [11] developed a simple and precise model of an earth air heat exchanger based on a 2-D numerical transient approach which allowed the calculation of the soil temperature at the surface and at different depths. The authors analyzed the potential of EAHEs for heating and cooling applications in domestic buildings under the climate conditions of Rhineland-Palatinate in Germany. Bansal et al. [12] evaluated the deterioration in the thermal performance of an earth air tunnel heat exchanger in a transient regime at climate conditions of Ajmer (India) using an experimental approach and CFD (computational fluid dynamics) modeling.

The objective of the present paper is to evaluate the impact of earth air heat exchangers on thermal comfort in domestic buildings in summer and hence the comfort of individuals. This work aims to demonstrate that a simple pipe placed underground and connected to a building can significantly regulate indoor thermal comfort and thus help in energy savings in hot arid climate conditions. The study was conducted in the month of July, in which the highest cooling demand is registered over a year, and the climatic conditions were those of the region of Adrar in the Algerian Sahara.

Mathematical modeling

An earth air heat exchanger (EAHE) consists mainly of a PVC (polyvinyl chloride) pipe buried in the ground. The geometric parameters of the buried pipe used in the thermal analysis are: length, inside diameter and thickness which is usually 4 mm.

The principle of operation of an earth air heat exchanger (EAHE) is such that the hot outdoor air is pumped into the underground buried pipe with the help of an adequate fan. The air is cooled by transferring heat to the soil which is at a lower temperature (Fig. 1). The cooled air is then injected into the building. The thermal and physical properties of air, soil and pipe used in this simulation are represented in Table 1, while the parameters of the earth air heat exchanger are summarized in Table 2.

The configuration described above can be further simplified by considering a uniform airflow inside the pipe. The surrounding soil is considered to have uniform and constant thermal properties, the dimensions and physical properties of the pipe are considered constant. The monthly maximum and minimum temperatures used in the simulation of the site under study are shown in Table 3.

The model is based on the energy balance equations when the soil temperature is constant. The equation that describes the variation in air temperature along the earth air heat exchanger takes into account the following parameters:

1. Outdoor temperature (ambient air).
2. Soil temperature at given depth taking into account the thermophysical properties of the soil.
3. Geometry and type of the pipe and air velocity.

Modeling of the soil temperature

The mathematical model of the soil temperature is based on the heat conduction theory applied to a semi-infinite homogenous solid. Heat conduction in the soil is given by Ref. [15]:

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{\alpha} \times \frac{\partial T}{\partial t} = 0 \quad (1)$$

$$T(0,t) = T_{mean} + A_s \times \cos(\omega(t - t_0)) \quad (2)$$

$$T(\infty,t) = T_{mean} \quad (3)$$

where the soil thermal diffusivity is given by: $\alpha = \frac{\lambda}{\rho \times Cp}$.

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