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Numerical analysis of the efficiency of earth to air heat exchange systems in cold and hot-arid climates

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ABSTRACT

In order to examine and compare the efficiency of earth to air heat exchanger (EAHE) systems in hot-arid (Yazd) and cold (Hamadan) climates in Iran a steady state model was developed to evaluate the impact of various parameters including inlet air temperatures, pipe lengths and ground temperatures on the cooling and heating potential of EAHEs in both climates. The results demonstrated the ability of the system to not only improve the average temperature and decrease the temperature fluctuation of the outlet air temperature of EAHE, but also to trigger considerable energy saving. It was found that in both climates, the system is highly utilized for pre-heating, and its usage is unfeasible in certain periods throughout the year. In winter, EAHEs have the potential of increasing the air temperature in the range of 0.2–11.2 °C and 0.1–17.2 °C for Yazd and Hamadan, respectively. However, in summer, the system decreases the air temperature for the aforementioned cities in the range of 1.3–11.4 °C and 5.7–11.1 °C, respectively. The system ascertains to be more efficient in the hot-arid climate of Yazd, where it can be used on 294 days of the year, leading to 50.1–63.6% energy saving, when compared to the cold climate of Hamadan, where it can be used on 225 days of the year resulting in a reduction of energy consumption by 24.5–47.9%.

1. Introduction

In recent years, the building sector has been responsible for about 40% of the world energy consumption [1]. Buildings also contribute to more than 36% of the world total CO_2 emission [2]; a share which is predicted to surge with further population growth, industrial development, and the amelioration of residential thermal comfort [3]. In developed countries, approximately 10–20% of the total energy consumption in buildings is due to the use of HVAC systems, while this ratio reaches to about 50% in developing countries [4]. In Iran, approximately 34% of the total energy consumption is related to the building industry [5]. Additionally, the highest amount of energy demand in buildings is related to the HVAC systems with around 61% [6]. Thus, in order to reduce energy demand in buildings the need for further use of such methods as passive techniques, renewable energies and designing energy efficient buildings is growing [7].

Using ground cooling and heating is a well-known passive technique to reduce building energy consumption and increase thermal comfort [8] which optimizes the high thermal capacity of the soil and low-temperature fluctuations below the ground surface for cooling in summers and heating in winters [9]. This potential can be exploited through two main strategies: (i) Direct Contact, in which all or some part of the building envelope is built into the ground to reduce the heat exchange with the outside [10], and (ii) Indirect Contact, in which such fluids as air pass through buried pipes and exchange heat with the ground, and then pass through the building or HVAC systems to cool or heat the space and reduce the energy demand for the building [11]. The two methods are illustrated in Fig. 1.

The earth to air heat exchange is a method for indirect utilization of ground temperatures for reducing cooling/heating loads [12]. In this method, energy transfer between the air and soil augments the outlet air temperature in winter and decreases it in summer [13]. The amount of heat transfer between the air and ground, and the performance of the EAHE systems depends on several factors such as the thermal properties of the soil and pipes, the air flow rate, the inlet air temperature, the pipe length, dimeter and the depth of buried pipes [14].

Research has shown, the utilization of this system in office buildings has brought about up to a 20–30% improvement in the comfort conditions and up to a 22 °C reduction in the outlet air temperature [15], as well as up to a 74.6 kW h daily cooling capacity [16]. A numerical study on an EAHE system with a pipe length of 80 m in Mathura in India has shown that this system can create

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Nomenclature

$t_{a,out}$	outlet air temperate or temperature of air coming out of pipe (°C)
t_{ground}	ground temperature (°C)
$t_{a.in}$	I air temperate or temperature of air entering into the pipe (°C)
t_s	average temperature of the soil surface (°C)
t_{amp}	amplitude of the soil temperature (°C)
t_{amb}	ambient air temperature (°C)
m_{air}	rate of air mass flow through the EAHE pipe (kg/s)
C_{air}	air specific heat capacity at constant pressure (kJ/kg K)
L	horizontal EAHE pipe length (m)
R_{total}	total thermal pipe resistance (m^2 °C/W)
R_{conv}	thermal convective resistance between the airflow and the inner pipe surface (m^2 °C/W)
R_{cond}	thermal conductive resistance of the pipe (m^2 °C/W)
R_{ground}	thermal resistance between the outer pipe surface and the ground (m^2 °C/W)
$\mathrm{D}_{in,pipe}$	inner diameter of pipe (m)
$D_{out,pipe}$	outer diameter of pipe (m)
k_{pipe}	thermal conductivity of pipe (W/m °C)
k_{ground}	average ground thermal conductivity (W/m °C)
$d_{constant}$	distance between the pipe surface and the undisturbed ground (m)
h_c	convection coefficient of the airflow (W/m^2 °C)
Nu, Re, Pr	Nusselt, Reynolds and Prandtl numbers
λ_{air}	thermal conductivity of air (W/m °C)
r_i	inner radius of pipe (m)
$V_{a,p}$	air speed in the pipe (m/s)
ν_{air}	air kinematic viscosity (m^2/s)
μ_{air}	dynamic viscosity of air (kg/m s)
ρ_{air}	air density (kg/m^3)
C_{air}	heat capacity of air (J/kg °C)
ω	annual temperature frequency (rad/day)
ρ_{ground}	soil density (kg/m^3)
C_{ground}	specific heat capacity of soil (J/kg °C)
V	volume of air (m^3)
Q	cooling/heating potential by $t_{a,out}$ (kW h)
z	the depth from the surface in meters
α_s	soil thermal diffusivity (m^2/day)
n	the number of target day counting from 31 December
n_o	the number of the coldest day of the year counting from 31 December

456 kW h cooling potential in summer and 296 kW h heating potential in winter and maintain the indoor air temperature at about 27.65 °C [17]. Results showed that the use of EAHEs reduce the peak cooling load of the typical buildings by 30% in summer and cause indoor temperature reduction of 2.8 °C during peak hours in the hot-arid climate of Kuwait [18]. Ralegaonkar et al. [19] compared EAHEs with conventional cooling systems, were concluded that EAHEs save 90% electricity and 100% water in comparison with air conditioners and evaporative coolers, respectively. Mathur et al. [20] investigated EAHE performance for three different soil conditions, and concluded that higher thermal conductivity accompanies higher thermal performance. Ahmed et al. [21] examined the impact of different parameters such as pipe lengths, diameters, thicknesses, materials, depths, as well as air velocity on the thermal performance of EAHEs for the humid subtropical climate of Australia. Results showed, pipe with a smaller diameter and thickness leads to higher cooling performance. It is concluded that the EAHE with 60 m pipe length and 1.5 air velocity has maximum performance. Gallero et al. [22] proposed a new simple model to evaluate thermal behavior of single buried U-tube. The model validated against experimental data with 0.3% relative error.

The performance of EAHEs have been widely analyzed by numerical methods, experimental studies and simulations using computational software. Rodrigues et al. [23] used a numerical method to find the impact of different geometrical configurations on EAHE performance. It is found that an increase of duct number (complexity of geometry) leads to higher performance. Khabbaz et al. [24] carried out an experimental and numerical study on the cooling performance of EAHEs with three parallel PVC of 72 m length, as well as a pipe with 0.15 m inner diameter connected to a residential building in a hot-dry climate. Results showed that EAHEs have the potential for reducing cooling loads for one and three pipes 58 W/m^2 and 55 W/m^2, respectively. Misra et al. [25] examined EAHEs performance using Fluent software. The CFD method was used to simulate the air flow, heat transfer process and thermal conductivity of the soil in an EAHE system. The modeled EAHE decreased the air temperature under the steady state and transient condition by approximately 18.8 °C and 18.7–16.6 °C, respectively. Chel and Tiwari [26] studied EAHEs performance integrated with a masonry building. They employed MATLAB software to solve the heat balance equations of the building. It was concluded that the room air temperature during summer is lower than the ambient air temperature, and it is around 5–15 °C higher than during winter periods. Mihalakakou et al. [27] developed a numerical model inside TRNSYS to calculate the impact of the humidity variation on the soil and air.

To achieve a desirable efficiency, EAHEs can be coupled with other passive techniques. Bansal et al. [28] assisted EAHEs with

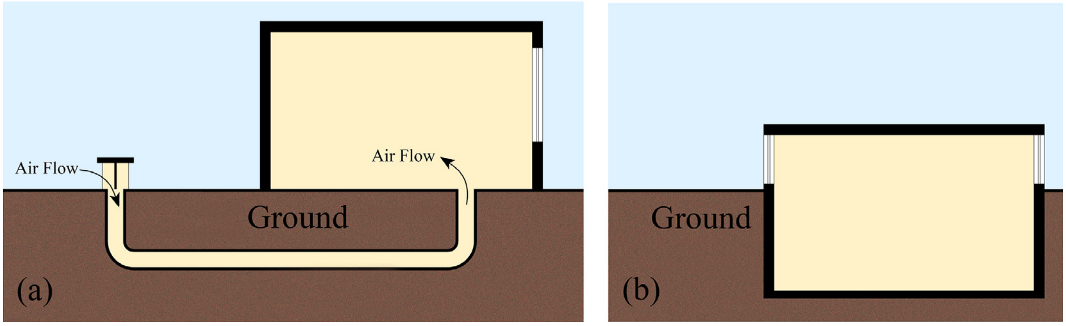

Fig. 1. Two strategies using earth temperatures. (a) Indirect contact. (b) Direct contact.