Techno-economic analysis and energy performance of a geothermal earth-to-air heat exchanger (EAHE) system in residential buildings: A case study

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Abstract

Natural air ventilation in the hot-dry regions plays a key role to decrease indoor air temperature in hot season, also to improve thermal comfort during the cold season. One of the most common ways to take advantage of natural ventilation is using wind catcher with an underground tunnel. In this method, the tower catches the airflow and directs it to the underground tunnel to decrease the air temperature by transferring heat to the ground, which is cooler in the summer and warmer in the winter. Earth-to-air heat exchanger (EAHE) is a modern form of wind catcher with underground tunnel. In this method, air after passing through buried pipes exchanges heat with the ground, and its temperature increases in the winter and decreases during the summer. This study analyzes the energy performance and cost-effectiveness of earth-to-air heat exchanger to be utilized in a residential building in climate condition of the province of Kermanin Iran. In this regard, 9 different configurations of the EAHE are investigated to find the optimized EAHE. The system performance
1 | INTRODUCTION

The critical environment challenge for the human being is of great climate warm effects due to the increasing global carbon dioxide emission. To greatly cut down the emission has been considered as an important international development policy. United Nations Environment Program (UNEP) revealed that the building energy consumption has a ratio of 30%-40% to the total energy consumption and its greenhouse gas emissions will reach up to around 30% by 2030. The biggest consumption produces from the space heating, and air conditioning systems is a proportional to 20% of total consumption. Thus, to save energy and reduce gas emission by means of optimal design of the building energy system, it is required to reduce energy demand and negative environment impact caused by the building.

Traditionally, the building sector’s substantial fossil fuel energy consumption has been a major cause of greenhouse gas emission, and a major contributor to global warming and climate change. However, in recent years, the use of air conditioners to provide thermal comfort in residential units has seen a substantial upsurge. Residential space heating and cooling consume nearly 10%-20% of total energy in developed countries and 50% in developing countries. The effective use of renewables like solar and clean energy sources can result in major positive outcomes in terms of fossil fuel consumption and greenhouse gas emission, energy cost, and security.

Geothermal energy is one of the important renewable energies that can be used to decrease the building’s heating and cooling energy consumption and thereby mitigates the environmental impact of fossil fuels typically used for this purpose. One method of utilizing geothermal energy to reduce the building’s energy consumption is the use of Earth-to-Air Heat Exchanger (EAHE). In this method, depending on the season and climate, air temperature is increased or decreased by the passage of air through the pipes buried deep in the ground.

Building air conditioning in buildings consumes 20%-40% of energy consumption. Geothermal as a clean renewable energy for Heating, Ventilating, and Air Conditioning (HVAC) systems can be applied considering an EAHX system. D’Agostino analyzed an air conditioning plant by fan-coil units and primary air in a building. They found that best results were for a duct length of 100 m for Ottawa (warm-summer humid continental climate, 65% capacity reduction), and the worst belonged to Rio de Janeiro (tropical wet and dry climate, maximum 24% reduction).

Integration of EAHE to buildings can be accomplished in two ways:

- Open-loop design, where air passes through the buried pipe, exchanges heat with the ground and then enters the indoor space, thereby lowering or raising the indoor temperature,
- Closed-loop design, which has a similar mechanism, except that the outbound air, is redirected toward the buried pipes (with the help of fans) to undergo another cycle of heat exchange.

Figure 1 shows a schematic diagram of open-loop and closed-loop EAHE systems.

The effectiveness of EAHE systems depends upon key parameters including the air velocity in the pipe, the length and diameter of buried pipes, and the thermal properties of soil.

EAHE in three different fields was analyzed as follows:

- Evaluation of heat transfer of the system and outlet air temperature for different length and depth;
- Impact of the EAHE on annual cooling/heating load reduction for a common building in hot-dry climate in Iran; and
- Evaluation of life cycle cost (LCC) and payback period for an earth-to-air heat exchanger integrated in a residential building.
World demand for energy declined almost by 3.8% in the first quarter of 2020, which most of its impact was in March. World demand for coal declined by almost 8% in 2020 compared with the first quarter of 2019. Reasons for this high decrease are as follows: COVID-19 problem in China; low price of gas and continued rapid use of renewables; and finally mild weather also capped coal use. Demand for oil also was hit by nearly 5% in the first quarter of 2020, mostly by mobility and airlines, which account for almost 60% of world demand for oil. By the end of March 2020, world road transportation activities were almost 50% lower than 2019, and air transportation was 60% below.22

Renewable energies in general were the only source that had growth rate in demand, driven by more installation capacities. Demand for electricity has also been significantly reduced because of lockdown measures in many countries too. Electricity demand has been reduced by almost 20% for full lockdown period in many countries. Reducing demand has lifted the share of renewable energies in the supply of electricity, as the output is mainly unaffected by demand.22

Global installed capacity for geothermal has increased over the last decade, reaching 13.93 gigawatts in 2019. Implementation of geothermal technologies is among the rapidly growing renewable energy trend occurring in the world. Figure 2 illustrates geothermal energy capacity from 2009 to 2019 in the globe which has increasing trend from 2009.23

Advantages and disadvantages of EAHE in geothermal energy are as follows24:

**Advantages:**
Simple design and installation;

- Adapting to different kinds of soil properties;
- For fully buried EAHE, the air outlet temperature depends only the inlet air temperature and the subsoil temperature;
- Air is used as a working fluid;
- No need for energy for operation while high wind speeds occurs;
- Low maintenance and operational cost
- Pollution free because of no combustion.
Disadvantages:
Despite these advantages, the technique has the following disadvantages:

- High initial investment;
- Possibility for development of micro-organisms that reduces indoor air quality, because of condensing phenomenon inside of the tubes;
- Outlet temperature of air is nonuniform;
- Dependency to local climatic conditions in the presence of upper parts of tube which is above ground.

Notwithstanding, several types of researches have been done in different areas of Iran to evaluate energy reduction via utilizing renewable energy sources. Hence, this study aims to close this existing gap in Iran via scrutinizing the potential of Kerman province as a case study regarding using geothermal energy for cooling and heating buildings. Another novelty of this work is use of both payback period (PBP) and Life Cycle Cost (LCC) together, also a thorough economic evaluation by considering initial cost, and operation and maintenance cost.

The rest of this paper is structured as follows: Section 2 investigates literature reviews. Section 3 describes the geographical characteristic of Kerman city. In Section 4, the methodology is discussed. The mathematical model to evaluate the energy performance of EAHEs is validated in Section 5. Energy performance for different configurations of EAHE is presented in Section 6. Economic evaluation and life cycle costs are discussed in Section 7. Finally, conclusions are drawn in Section 8.

2 | LITERATURE REVIEWS

There have been numerous research studies in the literature which related subjects are presented for this study.

Amanowicz and Wojtkowiak investigated characteristics of flow for multi-pipe EAHE for thermal analysis under variable conditions of airflow. It was concluded that calculated one year heat and cool gains for real airflows were up to 20% lower than the calculated maximum possible gains assuming ideally uniform airflow distribution between parallel branch-pipes. Misra et al investigated thermal characteristic and performance of four different hybrid earth air tunnel heat exchanger (EATHE). It was found that power consumption of conventional 1.5 TR window type air conditioner was reduced by 18.1% in a condition that cold air from EATHE was completely used for condenser cooling of the air conditioner.

Amanowicz and Wojtkowiak investigated thermal performance for multi-pipe EAHE by considering nonuniform distribution of air between parallel pipes. It was found that measured thermal performance of EAHEs, for a pipe with length and diameter of \( L = 76 \text{d} \), was 28% lower than for ideal (uniform) distribution of air in an analogous exchanger. It was found that thermal performance was also improved with different size of lengths and diameters too. Hsu et al investigated performance of EAHE for a building in subtropical monsoon climate in Taiwan. They performed an experimental research work to examine long-term effect of EAHE for providing ventilation for a building. Results were compared with previous studies for clarifying the effect of different climates and design conditions on application of EAHE. It was found that by implementing uncontrollable soil temperatures condition, the use of low surface area was suitable for cooling demand in a hot and humid climate. However, the design was on maximizing the heat transfer rate rather than a higher temperature difference. Minaei and Safikhani analyzed a transit model for EAHE. They investigated thermal diffusion into soil after 6 hours and 120 hours of continuous operation. It was found that for fluid velocity of 5 m/s, after 6 and 120 hours of continuous operation, heat diffused up to 10 cm and 50 cm distance from pipe axis, respectively. Research has shown that when EAHE is used in building’s design, the system can perform with higher energy efficiency.

Hollmuller developed an analytical solution for heat diffusion of EAHE system with a harmonic inlet air temperature, cylindrical pipe, and adiabatic or isothermal boundary condition. The influence of soil moisture, type, and thermal properties demonstrated on heat transfer of buried vertical pipes by Li et al. The effect of Reynolds number, form factor, and pipe depth on the outlet air temperature was investigated by Sehli et al Misra et al and Bansal et al studied the impact of soil thermal conductivity, and the duration of continuous operation of the EAHE.

Niu et al investigated effects of pipe length, diameter, air temperature, relative humidity, and airflow velocity on the performance of EAHE system were reported by a number of investigations that have sought EAHE performance through experimental and numerical modeling. Krarti and Kreider used an analytical model to determine the efficiency of an underground air tunnel for cooling and heating and the air temperature fluctuations along the tunnel length. Badescu proposed an exact numerical model for predicting the EAHE system’s efficiency and concluded that EAHE system’s energy exchange depends on the depth, diameter, and material of buried pipes.

Gan investigated the effect of atmospheric condition and also interactions between the heat exchanger and its environment on the system's efficiency. Al-Ajmi et al developed a numerical model to determine the EAHE system's efficiency for residential units located in a hot and dry climate of Kuwait. Their results showed that in summer, this system decreased the cooling load by 1700 W and reduced the indoor air temperature by 2.8°C. Breesch et al compared the cooling performance of EAHE system against natural ventilation
for an office building in Belgium. The results showed that both systems reduced the building’s cooling load, but natural ventilation could increase thermal comfort more efficiently. Kaushik and Kumar\(^43\) studied the heating efficiency of EAHE system and reported that increasing the length of the air channel and air volume enhanced the system’s heating potential.

Sodha et al\(^42\) investigated the effect of EAHE system on heating and cooling energy consumption in a hospital in India. They concluded that a system with pipe length of 80 m, sectional area of 0.528 m\(^2\), and airflow velocity of 4.89 m/s saved 512 kWh of cooling and 269 kWh of heating loads. CFD analysis of Wu et al\(^45\) on the efficiency of EAHE system showed that this system had an average daily cooling potential of 74.6 kWh. Ahmed et al\(^44\) studied the efficiency of an EAHE system in the humid subtropical climate of Australia. They reported that for a 27.23 m\(^3\) room, the studied system could reduce air temperature by 2°C, thereby making an 866.54 kWh (8.82%) reduction in annual energy consumption. The study of Dubey et al\(^45\) on the efficiency of an EAHE system with parallel piping showed that increasing the airflow velocity in the pipe from 4.16 to 11.2 meters per second decreased the COP (coefficient of performance) from 5.7 to 2.6.

According to the study of Rodrigues et al,\(^46\) combining the EAHE system with PCM (phase change material) reduces the room temperature fluctuations by 47%. Raleganorkar et al\(^47\) showed that using EAHE system, instead of a conventional air conditioner system, reduced the electricity consumption by 90%, and instead of an evaporative cooler, reduced the water consumption by 100%. Khalajzadeh et al\(^48\) integrated an EAHE system with an evaporative cooler to enhance efficiency. Their results showed that the combined system provided better cooling efficiency than the standalone system.

Bojic et al\(^49\) performed an economic analysis of EAHE system and reported that this system could effectively decrease the daily heating and cooling load. Their economic analysis showed this system was more cost-effective in summer than in winter. Thiers and Peuportier\(^50\) showed that the use of EAHE systems in residential buildings in France led to a measurable reduction in building’s energy consumption and reduced CO\(_2\) footprints. Esen et al\(^51\) made a comparative cost analysis on the ground-coupled heat pump (GCHP) and air-coupled heat pump (ACHP) systems. Results of their analysis showed that when used for cooling, GCHP was more efficient than ACHP. Chel and Tiwari\(^52\) investigated the economic feasibility and efficiency of EAHE system for an adobe house in India and found that this system was more efficient for heating. In addition, their LCC analysis showed that such a system would have a payback period of fewer than two years.

Following research works were performed in Iran:

Faridi et al\(^53\) designed an EAHE converter in Iran for heating and cooling a commercial greenhouse. They developed an one-dimensional model for EAHE system for evaluating the effects of main parameters like fan power and system efficiency, air flow rate, and length. It was found that effects of the parameters can easily be assessed without any waste of time, energy, and complexity. Jamshidi and Sadafi\(^54\) investigated the spiral coiled tube AEHE in Tehran, Iran. Effects of factors like absorbed thermal load by heat exchanger, depth of buried heat exchanger in soil, and finally speed and temperature of inlet air on the exhaust air temperature were analyzed. It was shown that the spiral heat exchanger was able to increase up to 15°C of the air inlet temperature for buildings during winter. Mirahmadi Golrodbari et al\(^55\) analyzed a new model for EAHE. Parametric analysis and feasibility for this system in city of Tehran in Iran were performed using the model for summer season with two different input temperatures. They found that the system was capable to supply thermal comfort in different environmental conditions like continuous summer operation for cities with cold climate and low annual average temperature. Atabi et al\(^56\) performed calculations for air conditioning and thermal load for a 4-story 12-unit building in east of Tehran, Iran. It was concluded by implementing geothermal heat pumps, the total emission of pollutants for 10 years would save 67 000 gigajoules of natural gas fuel consumption. Discussion and Conclusion: Based on land condition, soil property, and climatic conditions of building, the system can be used instead of the boiler. This finding leads to a significant reduction of electricity, and also a lower payback period (PBP).

There have been numerous research studies in Iran related to EAHE, but there has not been serious effort for construction of this system mainly because of the economic sanctions and lack of investors.

3 GEOGRAPHIC CHARACTERISTIC OF CASE STUDY

The city of Kerman is located at 30.29N and 57.06E, and its latitude is 1756 m above mean sea level. According to the Köppen-Geiger classification, the climate of this city falls into the hot-dry category and the fluctuations of air temperatures between summer and winter, and through days and nights are high and variable.\(^57\) Figure 3 illustrates the map of Iran including Kerman province, also Kerman city.

The average air temperature for the province is around 16.9°C throughout the year with the maximum temperature in July (36.8°C) and the minimum in January (−3.2°C). The main meteorological parameters of Kerman from 2007 to 2011 are presented in Table 1.

For sandy-loam soil, the thermal conductivity of soil with 5% humidity, 1925 (kg/m\(^3\)) density, and 1285 (J/kg °C) specific heat capacity is 1.2 (W/m °C). Figure 4 illustrates ground temperature for this city at depths of 1.0, 2.0, and 3.0 m, in respect.\(^59,60\)
4 | MATERIALS AND METHODS

To evaluate the efficiency, energy consumption, and cost-effectiveness of EAHE system in hot-dry climate, EAHE system are designed with three different pipe lengths and three different pipe burial depths. After investigating the system efficiency and determining the best pipe burial depth, we examine the air-soil energy exchange rate and its effect on the inlet air temperature and outlet air temperature, fluctuations relative to ambient temperature. Next, a one-story building with an area of 100 square meters is modeled, and its energy consumption with and without EAHE system is investigated. The building was constructed with the materials typically available in Iran. Lastly, the total energy-saving value of EAHE system and the costs due to construction, operation, maintenance, and energy loss over a 30-year period are calculated. A schematic sketch of the model is presented in Figure 5.

4.1 | Energy conservation model of EAHE system

Earth's soil can be assuming disototropic with homogeneous thermal conductivity. The modeled EAHE is an open-loop system at the steady-state condition. The pipe with a uniform circular cross section made up of Polyvinyl chloride (PVC) is buried at three different depths including 1, 2, and 3 m. The inner diameter of the pipe is 0.3 m with buried length of 25, 50, and 75 m. The air from the ambient with constant velocity and pressure is forced through the buried pipe with a velocity of 2 m/s.
The heat transfer between air and ground is divided into two coupled thermal processes: (1) heat transfer between air and the inner surface of the pipe by convection; (2) heat transfer between the outer surface of the pipe and surrounding soil by conduction. The energy balance for circulating fluid and soil is given by the following equation:\(^{39}\):

$$d\theta = -m_f \times C_f dT_f (x)$$ \hspace{1cm} (1)

or

$$d\theta = \mu_{soil} dT_{soil} (x)$$ \hspace{1cm} (2)

where \(\mu_{soil} = M_{soil} \times C_{soil}\). The heat flux can be expressed as:

$$d\theta = U (T_f (x) - T_{soil} (x)) \, dx$$ \hspace{1cm} (3)

where \(U\) is the overall coefficient of heat transfer between ground and the air in the pipe. Using Equations (1)-(3) gives fluid and soil temperature variation by the following equation:\(^{39}\):

$$\begin{cases} \frac{dT_f (x)}{dx} = -\frac{U}{m_f \times C_f} [T_f (x) - T_{soil} (x)] \\ \frac{dT_{soil} (x)}{dx} = \frac{U}{\mu_{soil}} [T_f (x) - T_{soil} (x)] \end{cases}$$ \hspace{1cm} (4)

The subtraction of two energy balances gives:\(^{58}\):

$$\frac{dT_f (x)}{dx} - \frac{dT_{soil} (x)}{dx} = U \left( \frac{1}{m_f \times C_f} + \frac{1}{\mu_{soil}} \right) [T_f (x) - T_{soil} (x)]$$ \hspace{1cm} (5)

Applying the boundary condition at \(x = 0\) and \(x = L\) for pipe and \(x = z\) for surrounding soil gives:\(^{58}\):

$$\begin{cases} \text{if } x = 0 \text{ then } T_f (0) = T_{inlet} \\ \text{if } x = L \text{ then } T_f (L) = T_{outlet} \\ \text{if } x = z \text{ then } T_{soil} (z) = T_{soil} \end{cases}$$ \hspace{1cm} (6)

The solution of Equation (5) gives the outlet air temperature:\(^{58}\):

$$T_{outlet} = T_{soil} + (T_{inlet} - T_{soil}) \times e^{-\frac{U \times 2\pi z}{\mu_{soil} \times C_f}}$$ \hspace{1cm} (7)

where \(U\) is obtained from Equation (8).

$$U = \frac{1}{R_{total}}$$ \hspace{1cm} (8)

where \(R_{total}\) is the total thermal resistance between air and soil, which is obtained from following equation:\(^{39}\):

$$R_{total} = R_{p,g} + R_p + R_{f,p}$$ \hspace{1cm} (9)

To calculate \(R_{p,g}\) and \(R_{a,p}\), Equations (10) and (11) are used:\(^{39}\)

$$R_{p,g} = \frac{\ln (r_f / r)}{2\pi \cdot L \cdot k_{soil}}$$ \hspace{1cm} (10)

$$R_{f,p} = \frac{1}{2\pi \cdot r_f \cdot L \cdot h_c}$$ \hspace{1cm} (11)

where \(h_c\) is convective film coefficient in W/m\(^2\)°C that is obtained from Equation (12).

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**FIGURE 4** Mean monthly dry bulb temperature and ground temperature at depth of 1.0, 2.0, and 3.0 m\(^{39}\)

**FIGURE 5** Schematic sketch of the modeled building with open-loop EAHE
where $k_f$ is the thermal conductivity of air, and the Nu is the Nusselt number for air flow in the pipe with a circular cross section. Nu can be expressed by following equation $^62$:

$$Nu = 0.023Re^{0.8} \times Pr^{0.4}$$  \hspace{1cm} (13)$$

$Re$ and $Pr$ can be calculated by the following equation $^62$:

$$Re = \frac{p_f \times V_{f,p} \times 2r}{\mu_f} = \frac{(V_{f,p} \times 2r)}{V_{f,p}}$$  \hspace{1cm} (14)$$

$$Pr = \frac{(C_f \times \mu_f)}{k_f}$$  \hspace{1cm} (15)$$

To determine the total heat transferred between air and ground along the pipe, and cooling/heating potential of the system, Equation (16) can be applied $^62$:

$$Q_{EAHE} = m_f \times C_f \times \Delta t \rightarrow Q_{EAHE} = m_f \times C_f \times (t_{outlet} - t_{inlet}) \hspace{1cm} (16)$$

According to a physiologically equivalent temperature (PET) study in Iran, the thermal comfort zone is 18-23°C. $^63$ To calculate the energy-saving potential for the EAHE, the following equations are used:

For cooling:

If $T_{outlet} < T_{inlet}$ and $T_{inlet} > 23 \rightarrow Q_{saving} = m_f \times C_f \times (t_{outlet} - t_{inlet}) \hspace{1cm} (17)$

For heating:

If $T_{outlet} > T_{inlet}$ and $T_{inlet} < 18 \rightarrow Q_{saving} = m_f \times C_f \times (t_{outlet} - t_{inlet}) \hspace{1cm} (18)$

and

If $18 \leq T_{inlet} \leq 23$ or $T_{outlet} = T_{inlet} \rightarrow Q_{saving} = 0 \hspace{1cm} (19)$

where $m_{air}$ is the air mass flow rate, $C_{air}$ is the specific heat at constant pressure of air, and $p_{air}$ is the air density. $T_{inlet}$ is equal to the ambient temperature, and $T_{outlet}$ is the outlet air temperature of the EAHE. The main properties of the EAHE are listed in Table 2.

| TABLE 2 Major parameters of modeled EAHEs |
|------------------------------------------|
| **Properties**                           | **Value** |
| Ground temperature at certain depth      |           |
| 1.0 m                                    | Figure 2  |
| 2.0 m                                    |           |
| 3.0 m                                    |           |
| Pipe diameter (m)                        | 0.30      |
| Pipe length (m)                          | 25, 50, 75|
| Buried depth of pipes (m)                | 1.0, 2.0, 3.0|
| Radius of pipe (m)                       | 0.15      |
| Thermal resistance of the pipe (m² °C/W) | 0.14      |
| Thickness of the soil annulus (m)        | 0.30      |
| Reynolds number                          | 39 709    |
| Nusselt number                           | 95.78     |
| Prandtl number                           | 0.71      |
| Thermal resistance between air and pipe (m² °C/W) |          |
| 25 m                                     | 0.14      |
| 50 m                                     | 0.07      |
| 75 m                                     | 0.05      |
| Thermal resistance between pipe and ground (m² °C/W) |          |
| 25 m                                     | 0.18      |
| 50 m                                     | 0.09      |
| 75 m                                     | 0.06      |
| Convective film coefficient (W/m² °C)    | 0.305     |
| Thermal conductivity of air (W/m °C)     | 0.025     |
| Specific heat capacity of air (J/kg °C)  | 1005      |
| Mass flow rate of air (kg/s)             | 0.17      |
| Air velocity (m/s)                       | 2.0       |
| Air density (kg/m³)                      | 1.205     |
| Kinematic viscosity of air (m²/s)        | $1.511 \times 10^{-5}$ |
| Dynamic viscosity of air (kg/ms)         | $1.846 \times 10^{-5}$ |
| Soil density (kg/m³)                     | 1925      |
| Thermal conductivity of soil (W/m °C)    | 1.2       |
| Specific heat capacity of soil (J/kg °C) | 1285      |
| Thermal diffusivity of soil (m²/d)       | 0.06      |

4.2 | Energy conservation model of building

A building with 100 m² is studied to investigate an open-loop EAHE impact on energy saving of a building by common materials used in Kerman city. The building dimensions are 10 m × 10 m × 4 m (width × length × height). The south side of the building has a window with dimensions 1.8 m × 2.0 m (width × height) and a door with dimensions 1.5 m × 2.2 m (width × height). The north side of the building has a window with dimensions 1.2 m × 2.0 m (width × height). It is assumed that all walls, windows, and doors vertical, and the roofs are horizontal. For the modeled building, the outdoor temperature is equal to sol-air temperature. The intensity of long-wave radiation from the black body for horizontal surfaces is zero for horizontal surfaces and 60 W/m² for vertical surfaces. $^52$ The floor temperature is assumed equals to mean annual temperature of the ground, and the air penetration is one time per hour. The main specifications of building components are presented in Table 3.
The rate of heat gain and loss for nonconditioned building can be written as follows:

\[ Q_{\text{total}} = Q_{\text{loss}} - Q_{\text{gain}} \]  

\[ Q_{\text{loss}} = Q_{\text{env}} + Q_{\text{ihg}} + Q_{\text{inf}} \]  

\[ Q_{\text{gain}} = Q_{\text{iso}} + Q_{\text{EAHE}} \]  

where \( Q_{\text{env}} \) is the rate of heat loss through building envelope by convection, conduction, and radiation. \( Q_{\text{ihg}} \) and \( Q_{\text{inf}} \) can be written as follows:

\[ Q_{\text{inf}} = \frac{n \cdot \rho_{\text{air}} \cdot c_{\text{air}} \cdot V \cdot (T_{s,a} - T_{i,a})}{3600} \]  

\[ Q_{\text{env}} = (A_{\text{wall}})(t_{s,a} - t_{i,a}) + (A_{\text{wall}})(t_{f,a} - t_{i,a}) + (A_{\text{roof}})(t_{s,a} - t_{i,a}) + \frac{n \cdot \rho_{\text{air}} \cdot c_{\text{air}} \cdot V \cdot (T_{s,a} - T_{i,a})}{3600} - Q_{\text{EAHE}} \]  

So, the total heat loss and gain for the modeled building can be written as follow:

\[ Q_{\text{total}} = Q_{\text{wall}} + Q_{\text{win}} + Q_{\text{door}} + Q_{\text{floor}} + Q_{\text{roof}} + Q_{\text{inf}} - Q_{\text{EAHE}} \]

or

\[ Q_{\text{total}} = \sum (U_{\text{env}}A_{\text{wall}})(t_{s,a} - t_{i,a}) + \sum (U_{\text{env}}A_{\text{wall}})(t_{f,a} - t_{i,a}) + (U_{\text{env}}A_{\text{roof}})(t_{s,a} - t_{i,a}) + \frac{n \cdot \rho_{\text{air}} \cdot c_{\text{air}} \cdot V \cdot (T_{s,a} - T_{i,a})}{3600} - Q_{\text{EAHE}} \]

where \( T_{s,a} \) is the soil-air temperature of building components and can be written as follows:

\[ T_{s,a} = T_{g,a} + \frac{1}{h_o} \times (\alpha I_T - \varepsilon I_l) \]

Table 3 presents the major thermal specifications of the modeled building.

| Component   | Description                                                                 | Area (m²) | \( \frac{1}{h_o} \) (m² kW⁻¹) | \( \tau \) | \( \alpha \) | \( \varepsilon \) | \( u \)-value (W/m² k) |
|-------------|-----------------------------------------------------------------------------|-----------|--------------------------------|------------|------------|-------------|----------------------|
| Window      | External wood window with two-layer glass (12 mm air gap)                   | 6.0       | 0.08                           | 0.6        | 0.32       | 0.84        | 2.80                 |
| Door        | 38 mm thick external wood door                                             | 3.3       | 0.07                           | -          | 0.6        | 0.9         | 2.00                 |
| Wall        | 2 cm brick, 3 cm mortar cement, 10 cm concrete panel, 3 cm mortar gypsum, 2 cm gypsum finishing | 150.7     | 0.05                           | -          | 0.6        | 0.9         | 2.20                 |
| Roof        | 15 cm thick concrete with asphalt, coating and 2.5 cm insulation            | 100.0     | 0.05                           | -          | 0.9        | 0.88        | 1.00                 |

Table 4 presents the input parameters for four comparative validations.

| System                  | Experimental data of Bansal et al.⁶⁴ | Experimental data of Dhaliwal et al.⁶³ | Theoretical data of Al-Ajmi et al.⁵⁸ | Theoretical data of Barakat et al.⁶⁵ |
|-------------------------|--------------------------------------|---------------------------------------|--------------------------------------|-------------------------------------|
| Pipe diameter (cm)      | 0.15                                 | 0.3                                   | 0.3                                  | 0.15                                |
| Pipe length (m)         | 23.42                                | 25.00                                 | 24.7                                 | 23.42                               |
| Air velocity (m/s)      | 2, 3, 4 and 5                       | 1.5                                   | 1.5                                  | 2, 3, 4 and 5                       |
| Soil temperature (°C)   | 26.7                                 | 18.89                                 | 18.89                                | 26.7                                |
| Pipe depth (m)          | -                                    | 2.13                                  | 2.13                                 | -                                   |
| Soil thermal conductivity (W/m°C) | 0.52                             | 1.16                                  | 1.16                                 | 0.52                                |
| Soil thermal diffusivity (m²/h) | -                                  | 0.00232                               | 0.00232                              | -                                   |
by both experimental data and theoretical method which carried out by data reported by Dhaliwal et al.\textsuperscript{68} and cases that reported by Al-Ajmi et al.\textsuperscript{39} in the hot-dry region in Kuwait. Both studies were conducted under the configuration of the buried pipe at a depth of 1.7 m with 24.7 m length and 0.3 m inner diameter. The model was also validated against experimental data reported by Bansal et al.\textsuperscript{69} and theoretical data reported by Barakat et al.\textsuperscript{70} for different inlet air velocities. The main parameters of the four studies are presented in Table 4.

| Axial distance from the pipe inlet (m) | Experimental data of Dhaliwal et al.\textsuperscript{68} | Theoretical data of Al-Ajmi et al.\textsuperscript{39} | Results of present model |
|--------------------------------------|-------------------------------------------------|-------------------------------------------------|--------------------------|
| 3.35                                 | 25.0                                            | 24.94                                           | 24.91                     |
| 6.40                                 | 24.4                                            | 24.43                                           | 24.37                     |
| 9.95                                 | 25.0                                            | 23.97                                           | 23.80                     |
| 12.50                                | 24.4                                            | 23.54                                           | 23.43                     |
| 15.55                                | 23.8                                            | 23.15                                           | 23.03                     |
| 24.70                                | 23.8                                            | 22.16                                           | 22.01                     |

**Table 4** Results of outlet air temperature for the present model at different axial distance from the pipe inlet compared against both the experimental\textsuperscript{68} and the theoretical values of Dhaliwal et al.\textsuperscript{68} and Al-Ajmi\textsuperscript{39}.

As shown in Table 5, there is a good agreement between reported experimental and theoretical data and outlet air temperature prediction by the present model. The maximum difference between predicted outlet air temperature and reported data is 1.7°C for 24.7 m pipe length. The slight difference between theoretical and experimental data may be due to differences on solar radiation, soil humidity, and wind speed. Table 6 illustrates results of outlet air temperature for the present model at various inlet air velocity compared with both the experimental\textsuperscript{69} and the theoretical data.\textsuperscript{70}

| Inlet air velocity (m/s) | Inlet air temperature(°C) | Experimental data of Bansal et al.\textsuperscript{69} | Theoretical data of Barakat et al.\textsuperscript{70} | Results of present model |
|--------------------------|---------------------------|-------------------------------------------------|-------------------------------------------------|--------------------------|
|                          |                           | $T_{\text{out}}$(°C) Relative error % | $T_{\text{out}}$(°C) Relative error % | $T_{\text{out}}$(°C) Relative error % |
| 2                        | 43.4                      | 29.3                                           | 11.48                                           | 31.23 5.65              |
| 3                        | 42.5                      | 29.7                                           | 10.27                                           | 32.36 2.24              |
| 4                        | 42.3                      | 30.6                                           | 8.65                                            | 33.35 0.45              |
| 5                        | 42.2                      | 31.1                                           | 9.06                                            | 34.16 0.12              |

**Table 5** Results of outlet air temperature for the present model at various inlet air velocity compared with both the experimental\textsuperscript{69} and the theoretical data\textsuperscript{70}.

As can be seen in Table 5, there is a good agreement between reported experimental and theoretical data and outlet air temperature prediction by the present model. The maximum difference between predicted outlet air temperature and reported data is 1.7°C for 24.7 m pipe length. The slight difference between theoretical and experimental data may be due to differences on solar radiation, soil humidity, and wind speed. Table 6 illustrates results of outlet air temperature for the present model at various inlet air velocity compared with both the experimental\textsuperscript{69} and the theoretical data.\textsuperscript{70}

### 6 | ENERGY SAVINGS AND PERFORMANCE

#### 6.1 | EAHE system

To evaluate the EAHE system’s energy-saving potential in the hot-dry climate, the air temperature improvements in summer and winter are investigated. The effect of pipe length and soil temperature around the pipe on the air temperature within the pipe is calculated by the use of Equations (1)-(15) and Table 2. In the model, three ground temperatures (GT) are studied, that is, 18, 22, and 26°C and the constant inlet air temperature is assumed 30°C.

The results show that the systems’ cooling performance increases with the pipe length. For the modeled EAHE system, highest efficiency (1.4-11.6°C decrease in air temperature) is achieved with pipe lengths of 25-75 m and the lowest efficiency (0.2-2.9°C decrease in air temperature) is achieved with pipe lengths of 5-25 m. The results also show that increasing the pipe length to more than 75 m has not a significant effect on air temperature reduction. For example, increasing the pipe length from 75 m to 100 m lowers the air temperature by just 0.1–0.2°C. Figure 6 illustrates the effect of pipe length and soil temperature at pipe burial depth on variation of the outlet air temperature.

As shown in Figure 6, the highest air-soil energy exchange occurs in pipe lengths of 25-75 m. Considering the soil temperature at various depths, the effects of pipe burial depths of 1, 2, and 3 m on the efficiency of EAHE system with pipe lengths of 25, 50, and 75 m are also investigated (see Figure 2). It should be noted that the weather data used in this study belong to Kerman’s synoptic stations and pertain to year 2014. Figure 7A-C demonstrate the effect of pipe length and pipe burial depth on the system efficiency. The results show that the modeled EAHE system is least efficient
when pipes are buried at the depth of 1 m and is most efficient when pipes are buried at the depth of 3 m. As shown in Figure 7, the passage of air through the pipes increases its temperature in winter and decreases its temperature in summer. Thus, in hot and dry climates, EAHE system can be used for both heating and cooling purposes.

Results show the EAHE system exhibits the highest heating efficiency in January and December and exhibits the highest cooling efficiency in June and July. In June and July, EAHE systems with pipe lengths of 25, 50, and 75 m decrease the inlet temperature by 0.5-3.6°C, 1.2-8.4°C, and 1.4-9.9°C, respectively; and in January and December, these systems increase the air temperature by, 0.9-4.0°C, 2.2-9.4°C, and 2.5-11.2°C, respectively.

As shown in Figure 7, an increase in a pipe burial depth from 1 to 3 m has increased the system's heating and cooling efficiency. Figure 7A shows that for EAHE system with pipe length of 25 m, increasing the pipe burial depth from 1 to 3 m leads to 52.7% increase in cooling potential and 18.5% increase in heating potential. For EAHE system with a pipe length of 50 m, a similar change in pipe burial depth increases the cooling potential by 85.8% and heating potential by 38% (Figure 7B), and for EAHE system with a pipe length of 75 m, this change leads to 48.9% increase in cooling potential and 100% increase in heating potential (Figure 7C). These figures indicate that in the presence of sufficient supply of airflow, system’s outlet air temperature will be within the range of comfort and there would not be any need for additional cooling energy consumption.

EAHE system's energy-saving potential can be obtained by the use of Equations (16)-(19). Naturally, in the periods when the ambient temperature is within the range of thermal comfort (18-23°C), the use of EAHE system will be pointless as it either does not make any change in air temperature, or disrupts the thermal comfort and causes extra heating or cooling load. Table 7 shows the number of days when EAHE system can be utilized to reduce the building’s cooling/heat- ing load and the total monthly energy-saving potential of the systems with pipe lengths of 25, 50, and 75 m and pipe burial depths of 1, 2, and 3 m. It should be mentioned that the reported energy saving excludes the days when the system is inapplicable. Comparing the outlet and inlet temperatures computed for Kerman indicates that during a year, the EAHE
| Length of pipe | Depth of buried pipe | Month                  |
|---------------|----------------------|------------------------|
|               |                      | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 25 m          | 1.0 m                | 173 | 45  | 5   | 043 | 222 | 165 | 95  | 40  | 5   | 149 | 269 | 238 |
| No. Day       | 26                   | 9   | 3   | 5   | 20  | 26  | 24  | 13  | 3   | 15  | 28  | 29  |     |
| 2.0 m         | 043                  | 390 | 131 | 18  | 334 | 391 | 331 | 127 | 21  | 178 | 439 | 478 |     |
| No. Day       | 31                   | 19  | 7   | 4   | 20  | 29  | 31  | 27  | 8   | 15  | 30  | 31  |     |
| 3.0 m         | 043                  | 564 | 254 | 54  | 505 | 505 | 505 | 282 | 59  | 165 | 502 | 620 |     |
| No. Day       | 31                   | 26  | 13  | 4   | 20  | 29  | 31  | 31  | 15  | 15  | 30  | 31  |     |
| 50 m          | 1.0 m                | 402 | 104 | 23  | 096 | 517 | 389 | 219 | 44  | 13  | 347 | 629 | 547 |
| No. Day       | 25                   | 10  | 5   | 4   | 20  | 29  | 24  | 9   | 4   | 15  | 28  | 28  |     |
| 2.0 m         | 043                  | 910 | 306 | 42  | 100 | 779 | 911 | 771 | 297 | 48  | 415 | 1022| 1115|
| No. Day       | 31                   | 20  | 7   | 4   | 20  | 29  | 31  | 27  | 8   | 15  | 30  | 31  |     |
| 3.0 m         | 043                  | 1315| 594 | 127 | 101 | 876 | 1219| 1176| 658 | 138 | 384 | 1169| 1444|
| No. Day       | 31                   | 27  | 14  | 4   | 20  | 29  | 31  | 31  | 15  | 15  | 30  | 31  |     |
| 75 m          | 1.0 m                | 466 | 123 | 15  | 1.19| 613 | 457 | 268 | 2072| 15  | 412 | 757 | 649 |
| No. Day       | 23                   | 10  | 3   | 5   | 20  | 28  | 25  | 8   | 4   | 15  | 29  | 27  |     |
| 2.0 m         | 043                  | 1079| 360 | 51  | 119 | 924 | 1081| 915 | 358 | 53  | 492 | 1213| 1323|
| No. Day       | 31                   | 18  | 8   | 4   | 20  | 29  | 31  | 28  | 7   | 15  | 30  | 31  |     |
| 3.0 m         | 043                  | 1560| 696 | 150 | 119 | 1040| 1446| 1396| 780 | 163 | 455 | 1387| 1713|
| No. Day       | 31                   | 26  | 13  | 4   | 20  | 29  | 31  | 31  | 15  | 15  | 30  | 31  |     |
systems with pipe lengths of 25 and 50 m could be used in 113–150 days for heating and in 88–128 days for cooling purpose. Furthermore, the EAHE system with pipe length of 75 m could be used in 108–148 days for heating and in 87–128 days for cooling application. The results show that the annual cooling energy savings of the systems with pipe lengths of 25, 50, and 75 m are, respectively, 563–1783 kWh, 1269–4156 kWh, and 1505–4931 kWh. The annual heating energy savings of the systems with pipe lengths of 25, 50, and 75 m are calculated to 885–2164 kWh, 2061–5045 kWh, and 2439–5975 kWh, respectively. As the results show, in a hot and dry climate, this system is more efficient in heating than in cooling.

The total annual energy saving of the EAHE systems with different pipe lengths and with the pipe burial depths of 1, 2, and 3 m is shown in Table 8. The results show that the system with pipe length of 75 m length and pipe burial depth of 3 m has the highest efficiency for the studied region (Kerman).

### Table 8

| Length of buried pipe | Depth of buried pipes | Energy Saving (kWh) |
|-----------------------|-----------------------|---------------------|
|                       | 1.0 m                 | 2.0 m               |
| 25 m                  | 1448                  | 2881                |
| 50 m                  | 3330                  | 6717                |
| 75 m                  | 3944                  | 7969                |

#### 6.2 Building integrated with EAHE

To study the effect of EAHE system on the heating and cooling load of the building, one should first determine the building’s energy loss through its envelope and via infiltration. The building’s energy loss via conduction, convection, radiation, and infiltration is obtained by the use of Equations (20)-(28) and Table 3. The total monthly energy losses obtained for the studied building are shown in Figure 6 (Indoor air temperature is assumed 22°C).

The results show that heating energy loss in winter is greater than cooling energy loss in summer. As Figure 8 shows, the greatest cooling energy loss is 6857 kWh occurring in July and the greatest heating energy losses are 9169 kWh in December and 8753 kWh in January.

The walls account for 7515 kWh of annual energy loss per year, which is about 50% of the building’s total annual energy loss. After the walls, the elements responsible for the highest annual energy loss are the roof (3621 kWh), infiltration (2602 kWh), windows (1260 kWh), and the door (179 kWh). Figure 9 illustrates the contribution of each element to the building’s total energy loss.

As determined in Section 4.1, EAHE system with the pipe buried at a depth of 3 m produces the best results for the studied climate. The effect of EAHE system on the buildings’ cooling and heating load can be evaluated with the help of Equations (20)-(28). Figure 10 shows the potential of the EAHE system with a pipe burial depth of 3 m in reducing the building’s daily energy consumption. The results show that the EAHE system with pipe length of 25 m has a cooling...
load reduction potential of 1.25% and heating load reduction potential of 1.34% for the studied building. For the EAHE system with pipe length of 50 m, these values are 2.60% and 2.75%, respectively. As expected, the greatest energy savings, namely 3.97% cooling load reduction, and 3.96% heating load reduction are achieved by the EAHE system with the pipe length of 75 m.

7 ECONOMIC EVALUATION

To decide whether EAHE system is sufficiently cost-effective to be used as a passive energy-saving method, the life cycle costs must be compared with the total value of energy saving by the system over a period of 30 years. For this purpose, the initial, operation, maintenance, and disposal costs of the EAHE system for a 1-year period and a 30-year period are calculated. The system's energy cost saving is then compared with its total annual cost to determine the payback period. Initial cost of EAHE system includes all expenses due to design, construction, and installation; its operation cost is the value of the energy needed to operate the system; maintenance cost includes all expenses due to regular inspections, repairs, and replacement of parts over the course of its lifetime; and disposal cost includes the depreciation of its value over its lifetime and the cost of final dismantling. All costs of EAHE system over its lifetime are illustrated in Figure 11.

Building the EAHE system with pipe lengths of 25, 50, and 75 m requires about 20, 40, and 60 m³ of excavation, respectively. To ensure better and uniform performance, after installing the pipes at the depth of 3 m, the removed soil will be replaced with isotropic soil with homogeneous

![Figure 11](https://example.com/figure11.png)

**Figure 11** The main parameters for life cycle cost estimation of the EAHE
thermal conductivity. It is assumed that buried PVC pipes are connected to each other by 10–18 bends. It is also assumed the air is blown into the pipe at a constant velocity of 2 m/s, using a blower that can be turned on or off by an electrical switch. In some months of the year, the EAHE system will have no effect on the building’s cooling and heating load, so the system is assumed equipped with an air valve with digital sensor and thermometer, which is capable of cutting off the airflow when the system is not needed. To protect indoor space against dust and pollution, PVC pipe outlet is assumed equipped with an air filter. Table 9 lists the costs related to construction, operation, and maintenance of the EAHE systems with pipe lengths of 25, 50, and 75 m for a 1-year period. It should be noted that the costs provided in this table are specific to Iran and the currency exchange rate is assumed to be 38000IRR = 1USD.

The initial, operation, maintenance, and disposal cost of this system for a 1-year period and for the duration of its lifetime (here, considered 30 years) are calculated. Electricity consumption of a 1500 W blower working 276 days a year will be 9936 kWh. Considering the price of electricity in Iran, which is 0.012$ per kWh, the annual cost of the blower’s electricity consumption will be 119.2$. The maintenance cost of EAHE system with any pipe length (25, 50, or 75 m) is assumed to be 133$ per year. Disposal cost accounts for the devaluation of system parts at the end of its lifetime. In addition, at the end of the system lifetime, equipment and pipes buried in the ground should be removed to reduce environmental damage. The cost of excavation and dismantling the systems with pipe lengths of 25, 50, and 75 m will be 165, 270, and 365 $. At the end of the system lifetime (after 30 years), most of the EAHE system equipment will have no value, and the value of blower and air valve will be reduced by 80%. The costs of EAHE systems with pipe lengths of 25, 50, and 75 m and pipe burial depth of 3 m are shown in Table 10. As can be seen, over a 30-year period, maintenance expenses constitute the largest fraction (42.9%-46.8%) and disposal expenses constitute the smallest fraction (1.7%-3.9%) of total costs of EAHE system.

The payback periods calculated for the modeled EAHE systems are shown in Figure 12. Assuming that the cost of energy in Iran is $ 0.00007 (3IRR) per kWh, the systems with pipe lengths of 25, 50, and 75 m will have annual energy savings of $ 311.6, $ 726.4, and $ 861, respectively. As the figure shows, the systems with pipe length of 25 m have a payback period of 16 years, but those with pipe lengths of 50 and 75 m have a payback period of 30 years.

In Figure 13, the costs of EAHE system with pipe lengths of 25, 50, 75 m, and pipe burial depth of 3 m over a 30-year period are shown.
period are compared with the value of energy to be saved by these systems. The results show that for the EAHE system with a pipe length of 25 m, life cycle cost is about 90.9% of energy-saving cost, but for the systems with pipe lengths of 50 and 75 m, this ratio is 40.8% and 35.9%, respectively.

8 | CONCLUSIONS

The energy efficiency and cost-effectiveness of an EAHE system in residential buildings were investigated in a hot-dry climate of province of Kerman in Iran. For this, different scenarios including different pipe lengths of 25, 50, and 75 m and pipe burial depths of 1, 2, and 3 m were considered to examine the cooling/heating potentials of the system. Moreover, the amount of energy saved in a year due to utilizing the system and its life cycle cost over a period of 30 years was estimated. The main findings of the study are shown in the following:

- The more the length of pipe and the depth of pipe burial are, the more the efficiency of the EAHE system will be. Using pipe with a length between 25 and 75 m resulted in the highest efficiency. In other words, utilizing a pipe fewer than 25 m has no considerable impact on inlet air temperature, and a pipe of more than 75 m cannot substantially increase the energy exchange between soil and air.
- The findings indicated that in hot and dry climate, the studied system was by far more suitable for heating purposes, while it could be employed for both cooling and heating in buildings. It was estimated that the system with a pipe length of 25 m is capable of saving almost 563–1783 kWh of cooling energy and 2439–5975 kWh of heating energy in a year. Furthermore, cooling energy saving of 1269–4156 kWh and heating energy saving of 2061–5045 kWh were estimated via using the system with the pipe length of 50 m. Finally, the pipe length of 75 m can result in saving 1505–4931 kWh of cooling energy and 2439–5975 kWh of heating energy.
- The study showed that utilizing conventional air conditioning along with the system was necessary for a building with an area of 100 m². An EAHE system containing 25 m of piping buried at the depth of 3 m could decrease the cooling load by 1.25% and the heating load by 1.34%. In the next scenarios, with pipe lengths of 50 m and 75 m, cooling load reductions were 2.60% and 3.97% and heating load reductions were estimated to be 2.75% and 3.96%, respectively.
- With regard to the economic aspect, it was found that the system is cost-effective in a region with hot-dry climate. The scenario with a pipe length of 25 m was determined as the one with longest payback periods of 16 years, but EAHE systems with pipe lengths of 50 and 75 m were found to have higher efficiency, and therefore, a much
shorter payback period of almost 3 years was required. The lifecycle costs of EAHE systems with pipe lengths of 25, 50, and 75 m were found to be, respectively, 90.9%, 40.8%, and 35.9% of their respective energy-saving values.

- Traditionally, wind catchers with an underground tunnel were used for cooling purposes. But the designed EAHE can be deployed for both cooling and heating. Results show that the EAHE system could be a reliable integration part of wind catchers with an underground tunnel which were used for many years in Kerman. Moreover, the system has enough heating performance to be used in the winter.

Nomenclature

- $Q$: heat transfer (kWh)
- $C$: heat capacity (J/kg °C)
- $A$: area of surface (m²)
- $Pr$: Prandtl number
- $Nu$: Nusselt number
- $Re$: Reynolds number
- $m$: mass fluid (g)
- $M$: mass (m³)
- $L$: length of buried pipe (m)
- $k$: thermal conductivity (W/m °C)
- $V$: volume of room air (m³)
- $U$: heat transfer coefficient (W/m² °C)
- $t$: temperature (°C)
- $r$: radius (m)
- $R$: thermal resistance (m² °C/W)
- $I_T$: direct and diffuse solar radiation on the surface (W/m²)
- $I_i$: intensity of long-wave radiation from the black body at temperature (w/m²)
- $1/h_o$: convective heat resistance of outer thin air layer (m² °C/W)
- $h_c$: convection coefficient of the airflow (W/m² °C)

Acronyms

- eahe: earth-to-air heat exchanger
- $n$: number of air change per hour
- $p, g$: between outer pipe surface and ground
- $i, a$: indoor air
- $o, a$: outdoor air
- $s, a$: solar-air
- $f, p$: between airflow and inner pipe surface

Greek symbols

- $d$: the heat flux transferred between ground and fluid
- $\alpha$: solar absorptivity
- $\varepsilon$: solar emissivity of surface
- $\mu$: dynamic viscosity (kg/ms)
- $\rho$: density (kg/m³)
- $\tau$: transmissivity of transparent surface
- $\nu$: kinematic viscosity (m²/s)

Subscripts

- $p$: Pipe
- $g$: Ground
- $s$: Solar
- $a$: Air
- $inlet$: inlet air
- $outlet$: outlet air
- $env$: building envelop
- $r$: room
- $iso$: isothermal mass
- $inf$: infiltration
- $ihg$: internal heat gain
- $f$: fluid
- $ven$: ventilation
- $win$: window

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