Performance Evaluation of a Mixed Earth-Air Heat Exchanger

Gerson Henrique dos Santos*, Anderson Lemes da Silva, Thiago Antonini Alves

Federal University of Technology – Parana (UTFPR)
Rua Doutor Washington Subtil Chueire, 330, Ponta Grossa, 84017-220, PR, Brazil;
gsantos@utfpr.edu.br

Abstract. Earth-Air Heat Exchangers (EAHE), also known as Ground-to-Air Heat Exchangers (GAHE), are sustainable and cost-effective systems designed to improve building energy efficiency by utilizing the thermal characteristics of the soil. The core principle behind EAHE is that the soil beneath the surface maintains a relatively constant temperature throughout the year, depending on the local climate and depth. This stability makes it an ideal medium for passive heat exchange, reducing the reliance on conventional heating and cooling systems. The system consists of underground pipes, arranged in horizontal or vertical configurations. During operation, air is drawn through these buried pipes, where it either gains heat from the warmer soil during winter or releases heat into the cooler soil during summer, effectively tempering the airflow before it enters the building. This process significantly reduces the energy needed for indoor climate control, leading to lower utility bills and a smaller environmental footprint. However, the performance of an EAHE depends heavily on the soil's hygrothermal properties, which influence heat and moisture transfer within the ground. Furthermore, in cold climates, the exchanger's performance can be increased by exposing part of the piping to solar radiation through a bypass. To address this, a 2D model was developed to analyze the exchanger's performance. A modification in the tube circuit is proposed to take advantage of the effects of solar radiation on air heating. Experimental validation was performed through a prototype built at the Federal University of Technology of Paraná (UTFPR).

Keywords: earth-air heat exchanger, passive air conditioning, solar radiation effects

1 Introduction

Earth–Air Heat Exchangers (EAHEs) are passive systems designed to improve energy efficiency in buildings by using the relatively constant temperature of the ground to precondition ventilation air. These systems consist of pipes buried at a certain depth through which ambient air is drawn. As air flows through the ducts, it exchanges heat with the surrounding soil, being cooled during hot periods and warmed during cold periods, thereby reducing the load on mechanical HVAC systems.

The effectiveness of an EAHE system depends on various factors, including soil thermal conductivity, pipe material and geometry, burial depth, air velocity, and local climatic conditions. The ground temperature at depths of 1.5 to 3 meters typically remains stable throughout the year, providing a favorable thermal gradient for energy exchange. The advantages of EAHEs include reduced energy consumption, lower operational costs, and decreased environmental impact. They have been successfully applied in residential buildings, schools, greenhouses, and livestock facilities. With increasing emphasis on sustainability and building energy performance, EAHEs present a viable solution for passive thermal conditioning. Advances in numerical modeling and field testing continue to refine their design and expand their applicability across different climates and building types.

Research into Earth–Air Heat Exchangers (EAHEs) has evolved over the past two decades, progressing from fundamental theoretical studies to sophisticated experimental and numerical investigations. Florides and Kalogirou [1] examined the fundamentals and modeling of ground-coupled systems, including EAHEs. They covered heat transfer mechanisms, experimental validation across climates, and summarized simulation and empirical data on system performance.

Peretti et al. [2] systematically analyzed global studies on EAHE systems, focusing on design parameters such as pipe length, depth, material, and configurations. The authors compared projects, proposed design suggestions, and evaluated environmental benefits and applicability across climates. Bisoniya [3] presented a one-dimensional simplified model incorporating correlations for friction factor, Nusselt number, and undisturbed ground temperature to estimate heat transfer, pressure drop, and optimal pipe dimensions. The study concluded that longer, smaller-diameter pipes at greater burial depths improve system performance.

Sakhri et al. [4] showed a 66 m EAHE at 1.5 m depth in an arid Algerian climate with forced ventilation. The authors analyzed temperature and humidity profiles along the duct, showing significant improvement in thermal comfort even under extreme ambient conditions. Kumar and Gupta [5] reviewed various EAHE designs, focusing on how soil thermal properties and pipe burial depth affect thermal performance. They summarized past investigative methods and emphasized enhancements to indoor comfort and energy savings.

Mihalakakou et al. [6] presented a holistic overview of EAHE research, analyzing experimental validation and parametrization of design variables like pipe length, burial depth, soil type, and coverage. The authors also included modeling classifications and guidance for hybrid system integration. Kouki et al. [7] analyzed EAHE performance across many experimental and modeling studies. They focused on the effects of soil thermal properties, climate, and airflow conditions on the heat exchanger effectiveness, offering insights for future design improvements.

H. Koshlak [8] presented a comprehensive review covering the fundamental principles and advanced Earth–Air Heat Exchangers (EAHE) applications. The paper is structured around three key aspects: thermal performance fundamentals, comparative analysis between experimental and simulated results, and integrating EAHEs with renewable energy systems such as solar and geothermal sources. The author emphasized the role of EAHEs in hybrid ventilation systems and evaluated their effectiveness in reducing building energy demand. The review also identified challenges related to soil properties, airflow design, and climate variability, while offering forward-looking perspectives on improving system efficiency through material and layout optimization.

As highlighted in the literature review, using an Earth–Air Heat Exchanger (EAHE) can significantly reduce the energy required for indoor climate control. However, its performance is strongly influenced by the soil's hygrothermal properties, which govern the ground's heat and moisture transfer processes. In cold climates, the system's efficiency can be enhanced by incorporating a bypass section where part of the duct is exposed to solar radiation. To investigate this, a two-dimensional model was developed to evaluate the exchanger's performance. A modification to the pipe layout is proposed to harness the benefits of solar radiation for air preheating.

2 Experimental Procedure

The experimental setup was developed at the Federal University of Technology – Paraná (UTFPR), Ponta Grossa Campus. Figure 1 shows the location where the EAHE system was installed. The exchanger consists of 100 mm diameter polyvinyl chloride (PVC) pipes arranged in a serpentine configuration and buried 1.5 meters below the surface. The individual pipe sections have an average length of 5.15 meters, with 0.50-meter spacing between them, totaling 50.65 meters of piping. 14 K-type thermocouples were installed along the pipeline to measure the air temperature. The first five thermocouples are distributed along the initial 4.85 meters (first pass), while the remaining ones are placed at intervals of 5.60 meters.



Figure 1: Location where the EAHE was installed at UTFPR.

3 Mathematical Model

The model for the porous soil domain has been elaborated considering the differential governing equations for moisture, air, and energy balances. The transient terms of each governing equation have been written in terms of the driving potentials to take more advantage of the MTDMA [9] solution algorithm that simultaneously solves the three sets of equations. A fully-implicit central-difference scheme has been considered for discretization using the finite-volume method [10].

The moisture content conservation equation for porous soil can be written as:

$$\frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial P_v}\frac{\partial P_v}{\partial t}+\frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial T}\frac{\partial T}{\partial t}=\nabla.\left[-K\frac{\partial P_{suc}}{\partial T}\nabla T-\left(K\frac{\partial P_{suc}}{\partial P_v}-\delta_v\right)\nabla P_v+\rho_v\frac{kk_{rg}}{\mu_g}\nabla P_g+K\rho_l\mathbf{g}\right], \tag{1}$$

Where is the liquid water permeability (s), t, the time (s), ∅, the relative humidity (-), P_{suc}, the suction pressure (Pa), ρ_l, the liquid water density (kg/m³), $\mathbf{g}$, the gravity (m/s²), δ_v is the vapor diffusive permeability (s), P_v, the partial water vapor pressure (Pa), ρ_v, the water vapor density (kg/m³), k, the absolute permeability (m²), k_{rg}, the gas relative permeability, μ_g, the dynamic viscosity (Pa.s) and, P_g, the gas pressure, T, temperature (K), and w, the moisture content (kg/m³).

The dry air transport can be described as a function of the partial gas and vapor pressure driving potentials so that the air balance can be written as:

$$\frac{\partial \rho_a}{\partial P_g}\frac{\partial P_g}{\partial t}+\frac{\partial \rho_a}{\partial P_v}\frac{\partial P_v}{\partial t}+\frac{\partial \rho_a}{\partial T}\frac{\partial T}{\partial t}=\nabla.\left(-\delta_v\nabla P_v+\rho_a\frac{kk_{rg}}{\mu_g}\nabla P_g\right), \tag{2}$$

Where ρ_a is the density of dry air (kg/m³).

Assuming 0 °C as the reference temperature, the energy conservation equation is:

$$c_m\rho_0\frac{\partial T}{\partial t}=\nabla.\left(\begin{array}{l}\left(\lambda-K\frac{\partial P_{suc}}{\partial T}c_{pl}T\right)\nabla T-\left(K\frac{\partial P_{suc}}{\partial P_v}c_{pl}T+\delta_v c_{pa}T-\delta_v\left(L+c_{pv}T\right)\right)\nabla P_v+\\ \left(\rho_a\frac{kk_{rg}}{\mu_g}c_{pa}T+\rho_v\frac{kk_{rg}}{\mu_g}\left(L+c_{pv}T\right)\right)\nabla P_g+K\rho_l c_{pl}T\mathbf{g}\end{array}\right), \tag{3}$$

Where λ is the thermal conductivity (W/mK), c_{pa}, the specific heat capacity at constant pressure of the dry air (J/kgK), c_{pl}, the specific heat capacity of the water liquid (J/kgK), c_{pv}, the specific heat capacity at constant pressure of the vapor (J/kgK) and, L, the vaporization latent heat (J/kg), c_m is the specific heat capacity of the structure (J/kgK) and ρ_0, the density of the dry material (kg/m³)..

3.1 Boundary Conditions And Earth-Air Heat Exchanger Model

A two-dimensional reduced model was employed to represent both the soil and heat exchanger domains in the simulations. The soil domain extended 0.5 meters to the north and south from the centerline of the heat exchanger serpentine. For the governing equations of dry-air transport, moisture transport, and energy conservation, Dirichlet boundary conditions were applied at the top and bottom surfaces, prescribing values for gas pressure, partial vapor pressure, and temperature.

Figure 2 illustrates the boundary conditions adopted in the simulations. The thermal resistance of the tube wall was neglected; however, the wall was assumed to be impermeable to moisture transfer.

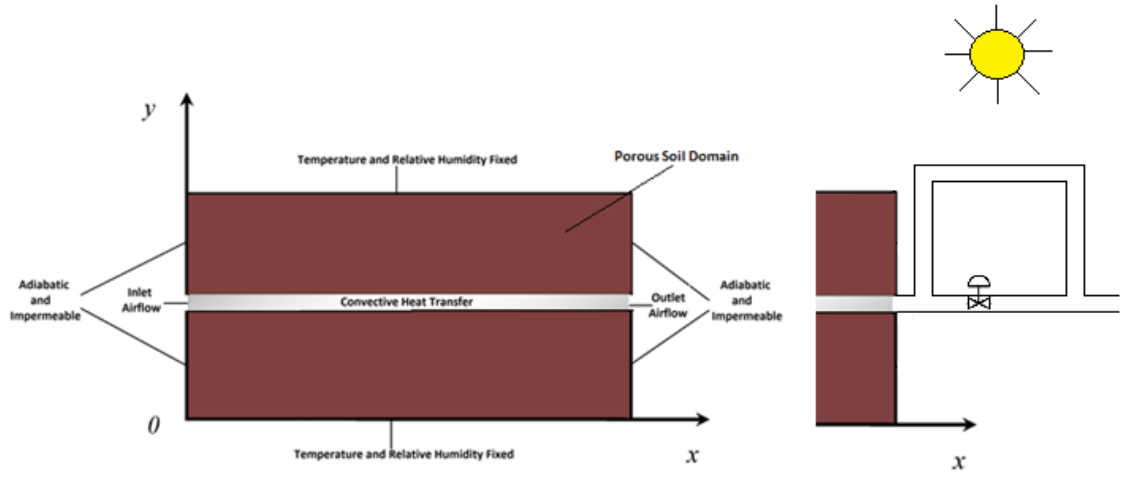


Figure 2. Boundary conditions for the porous soils.

The mathematical model utilized for the Earth-Air Heat Exchanger was proposed by Niu et al. [11]. The control volume method was employed in the energy balance for each small volume within the system, as depicted in Figure 3. In this model, only sensible heat transfer was considered for the air.

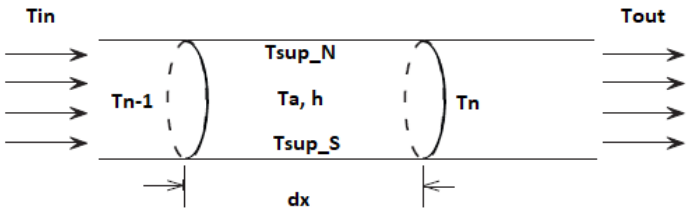


Figure 3. Energy balance in each control volume.

The energy governing equation for each control volume can be written as:

$$\dot{m}C\mathrm{d}T_a = Ph_{int}(T_S - T_a)\mathrm{d}x \tag{4}$$

Where $\dot{m}$ is the mass flow rate of air (kg/s), C, the air specific heat (J/kg K), P, the perimeter (m), and h_{int}, the heat transfer coefficient (W/m² K).

The homogeneous ordinary differential equation can be solved analytically as:

$$T_a[i] = T_{avg} - (T_{avg} - T_a[i-1])\exp(-dx/a)\ , \tag{5}$$

Where $T_a[i]$ is the air temperature for each control volume, T_{avg}, the average superficial temperature of tube, and $a = \frac{\dot{m}\,\mathrm{C}}{\mathrm{P\,h_{int}}}$.

The heat transfer coefficient (h_{int}) has been obtained using the Nusselt number (Nu), which was calculated following the Dittus-Boelter equation, valid for turbulent and fully-developed flows through smooth circular pipes.

In the case where a tube was installed through a bypass, subjected to the effects of solar radiation, the term h_{int} was replaced by the overall heat transfer coefficient U, and the sun-air temperature T_{s-a} replaced the term T_{avg}:

$$T_{s-a} = \frac{(\propto Q_r - Q_{ir})}{h_{ext}} + T_{ext}, \tag{6}$$

Where $\propto$ is the solar absorptivity, Q_r is the global solar radiation (W/m²), Q_{ir} is the infrared radiation (W/m²), $\mathrm{h_{ext}}$ is the external heat transfer coefficient (W/m² K), and T_{ext} is the air external temperature (K). The external heat transfer coefficient was calculated using the empirical correlation of R. Hilpert to the Nusselt number.

4 Simulation Procedure

In order to optimize the numerical analysis of EAHE, a 2D reduced model for the soil and heat exchanger domains was tested. The soil domain extending 0.5 m in north and south directions from the heat exchanger serpentine was considered.

The air temperature values obtained were compared with experimental data from an EAHE at the Federal University of Technology—Parana, Ponta Grossa/Brazil (25.1° South, 50.16° West) to validate the computational model [12]. The results are shown at noon on January 23 and 24, 2022 (summer condition).

Constant temperatures of 24 °C and 23.5 °C (summer condition), 19.7 °C and 19.3 °C (winter condition) and 50% of relative humidity were imposed on the upper and lower surfaces of the soil domain, which were also obtained experimentally at a depth of 1.5 m for the day 01/23-24/2022 and 07/29/2022, respectivaly. An air inlet velocity of 0.774 m/s was also used. The hygrothermal properties of sandy clay (installation site soil) were acquired from Oliveira and Freitas [13]. Climate data were obtained in [14] as observed in Figure 4.

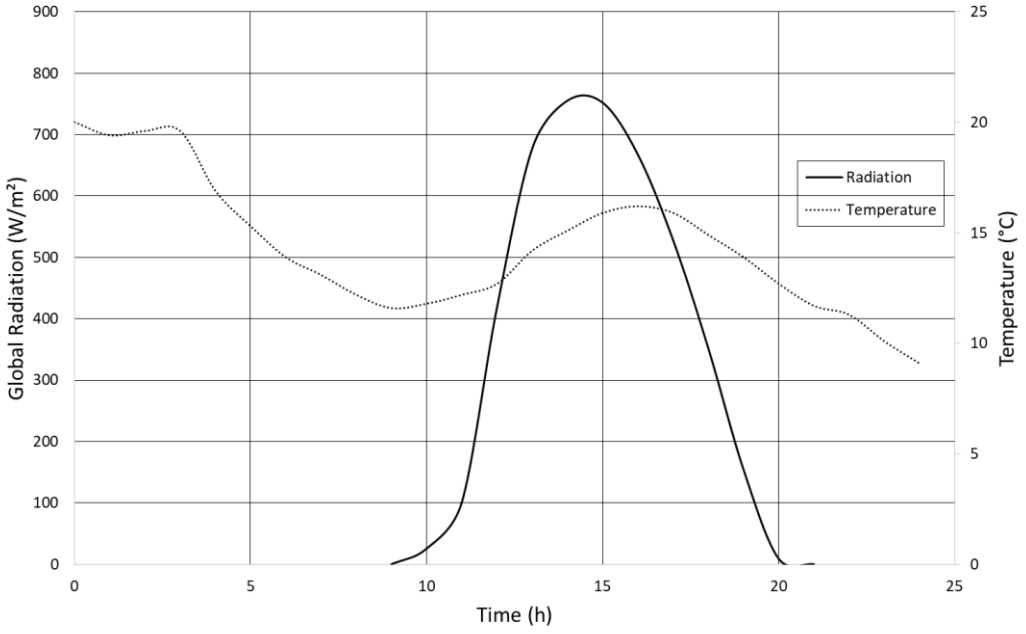


Figure 4. Global radiation and temperature values on 29 July 2022.

5 Results and Discussions

Figure 5 illustrates the temperature distribution along the EAHE obtained from experimental measurements and numerical simulations on January 23 and 24, 2022. The maximum deviation observed at the EAHE outlet is 0.8 °C for both cases (January 23 and 24), demonstrating strong agreement between the experimental and simulated results despite using a simplified soil and heat exchanger representation. In summer, the EAHE offered an air outlet temperature that could provide a thermal comfort condition for the conditioned environment.

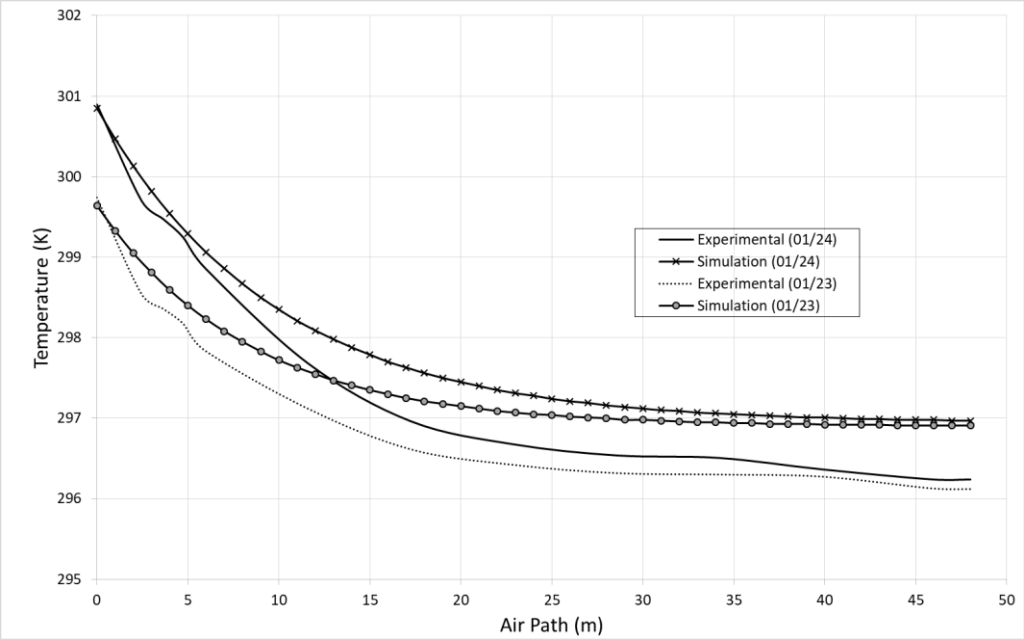


Figure 5. Temperature values on January 23 and 24, 2022, at noon.

Figure 6 shows the EAHE outlet temperatures on a typical winter day for Ponta Grossa, Brazil. In this case, the system directed all of the EAHE air flow through the bypass to the tube exposed to solar radiation.

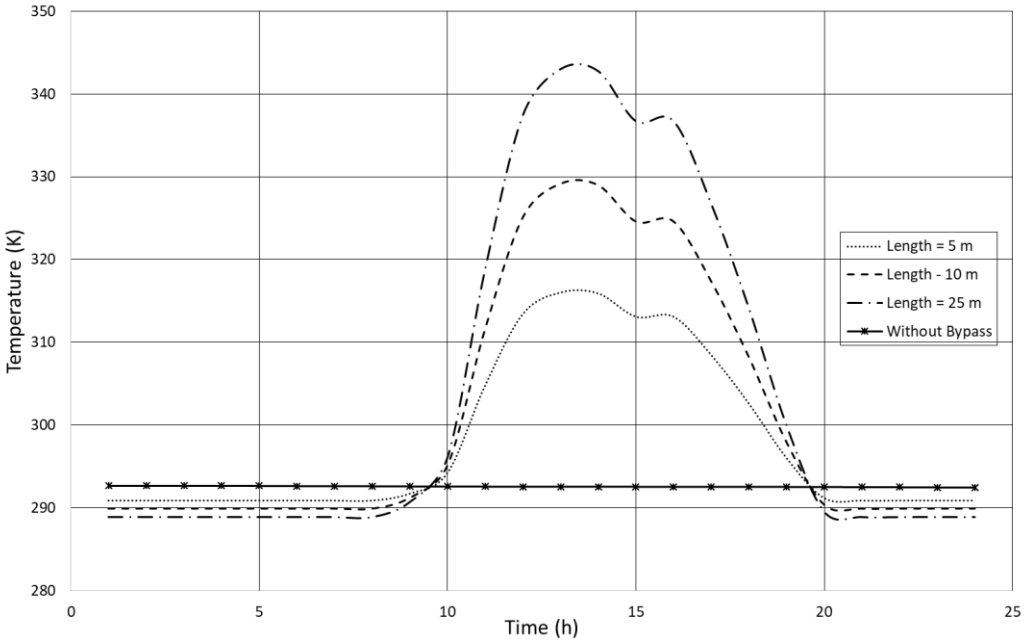


Figure 6. EAHE air outlet temperature on 29 July 2022.

All tubes exposed to solar radiation (5 m, 10 m, and 25 m) show a noticeable increase in outlet temperature starting around 9 a.m., peaking between 2 p.m. and 3 p.m., and returning to near baseline after 7 p.m. This indicates a strong correlation between solar radiation exposure and the heating of the exchanger, with the peak temperatures aligning with typical solar noon. The longest exchanger (25 m) shows the highest outlet temperature peak, reaching approximately 345 K, followed by the 10 m and 5 m cases, which peak progressively lower. The "Without Bypass" configuration, which is not subjected to solar radiation, maintains a nearly constant outlet temperature throughout the day, around 293 K. This shows that the EAHE would not provide adequate thermal comfort conditions for Ponta Grossa, Brazil, during winter. However, by exposing a portion of the piping to solar radiation, the exchanger could easily achieve comfort conditions by mixing two air streams, without thermal resistance (electrical energy consumption) during the day. On days with high cloud cover, the exchanger outlet temperature could also provide adequate comfort conditions due to the effects of diffuse solar radiation.

6 Conclusions

This study evaluated the performance of a mixed Earth-Air Heat Exchanger (EAHE) through the development and validation of a two-dimensional numerical model, supported by experimental data obtained from a prototype installed at UTFPR. The model effectively accounted for the hygrothermal behavior of the soil and accurately predicted the air outlet temperatures under both summer and winter conditions.

In summer, the EAHE provided outlet air temperatures that align with thermal comfort requirements, confirming its potential for passive cooling applications. During winter, however, conventional configurations failed to deliver adequate heating. To address this, a modified configuration was proposed in which part of the piping is exposed to solar radiation via a bypass. Simulation results demonstrated that this modification significantly enhances thermal performance during cold periods, enabling outlet temperatures sufficient to meet comfort conditions without requiring auxiliary energy input.

The results confirm that incorporating solar-assisted sections in the EAHE design improves system effectiveness, especially in climates with significant seasonal variation. Future research should include long-term performance monitoring and further optimization of the bypass configuration to ensure year-round energy efficiency.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] G. A. Florides and S. A. Kalogirou, "Ground heat exchangers—A review of systems, models and applications," *Renewable Energy*, vol. 32, no. 15, pp. 2461–2478, 2007.
[2] C. Peretti, A. Zarrella, M. De Carli, and R. Zecchin, "The design and environmental evaluation of earth-to-air heat exchangers (EAHE): A literature review," *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 107–116, 2013.
[3] T. S. Bisoniya, "Design of earth–air heat exchanger system," *Geothermal Energy*, vol. 3, no. 1, pp. 1–12, 2015.
[4] N. Sakhri, Y. Menni, A. J. Chamkha, G. Lorenzini, N. Kaid, H. Ameur, and M. Bensafi, "Study of heat and mass transfer through an earth to air heat exchanger equipped with fan in South West of Algeria," *International Journal of Heat and Technology*, vol. 37, no. 3, pp. 689–695, 2019.
[5] N. Kumar and U. Gupta, "A review on earth-air heat exchanger systems," *Recent Trends in Fluid Mechanics*, vol. 7, no. 1, pp. 9–14, 2020.
[6] G. Mihalakakou, M. Souliotis, M. Papadaki, G. Halkos, J. Paravantis, S. Makridis, and S. Papaefthimiou, "Applications of earth-to-air heat exchangers: A holistic review," *Renewable and Sustainable Energy Reviews*, vol. 155, 2022.
[7] N. Kouki, D. D'Agostino, and A. Vityi, "Properties of Earth-to-Air Heat Exchangers (EAHE): Insights and perspectives based on system performance," *Energies*, vol. 18, no. 7, pp. 1–20, 2025.
[8] H. Koshlak, "A review of Earth-Air Heat Exchangers: From fundamental principles to hybrid systems with renewable energy integration," *Energies*, vol. 18, no. 5, 2025.
[9] N. Mendes, P.C. Philippi, R. Lamberts, "A new mathematical method to solve highly coupled equations of heat and mass transfer in porous media", International Journal of Heat and Mass Transfer, vol. 45, no. 3, pp. 509–518, 2002.
[10] S. V. Patankar, Numerical heat transfer and fluid flow. Series in Computational Methods in Mechanics and Thermal Sciences, CRC Press, Boca Raton, FL, USA., 2009.

[11] F. Niu, Y. Yu, D. Yu, H. Li, "Heat and mass transfer performance analysis and cooling capacity prediction of earth to air heat exchanger". Applied Energy, vol. 137, pp. 211–221, 2015.
[12] C. H. Diedrich, G. H. Santos, G. C. Carraro, V. V. Dimbarre, T. A. Alves, "Numerical and Experimental Analysis of an Earth-Air Heat Exchanger" *Atmosphere*, vol. 14, 2023.
[13] A. A. J. Oliveira, D. S. Freitas, "Influência do Meio nas Difusividades do Modelo de Phillip e Vries". Research Report, UFSC, 1993.
[14] Climate archives of Brazilian cities. INMET – Instituto Nacional de Meteorologia: https://portal.inmet.gov.br/dadoshistoricos