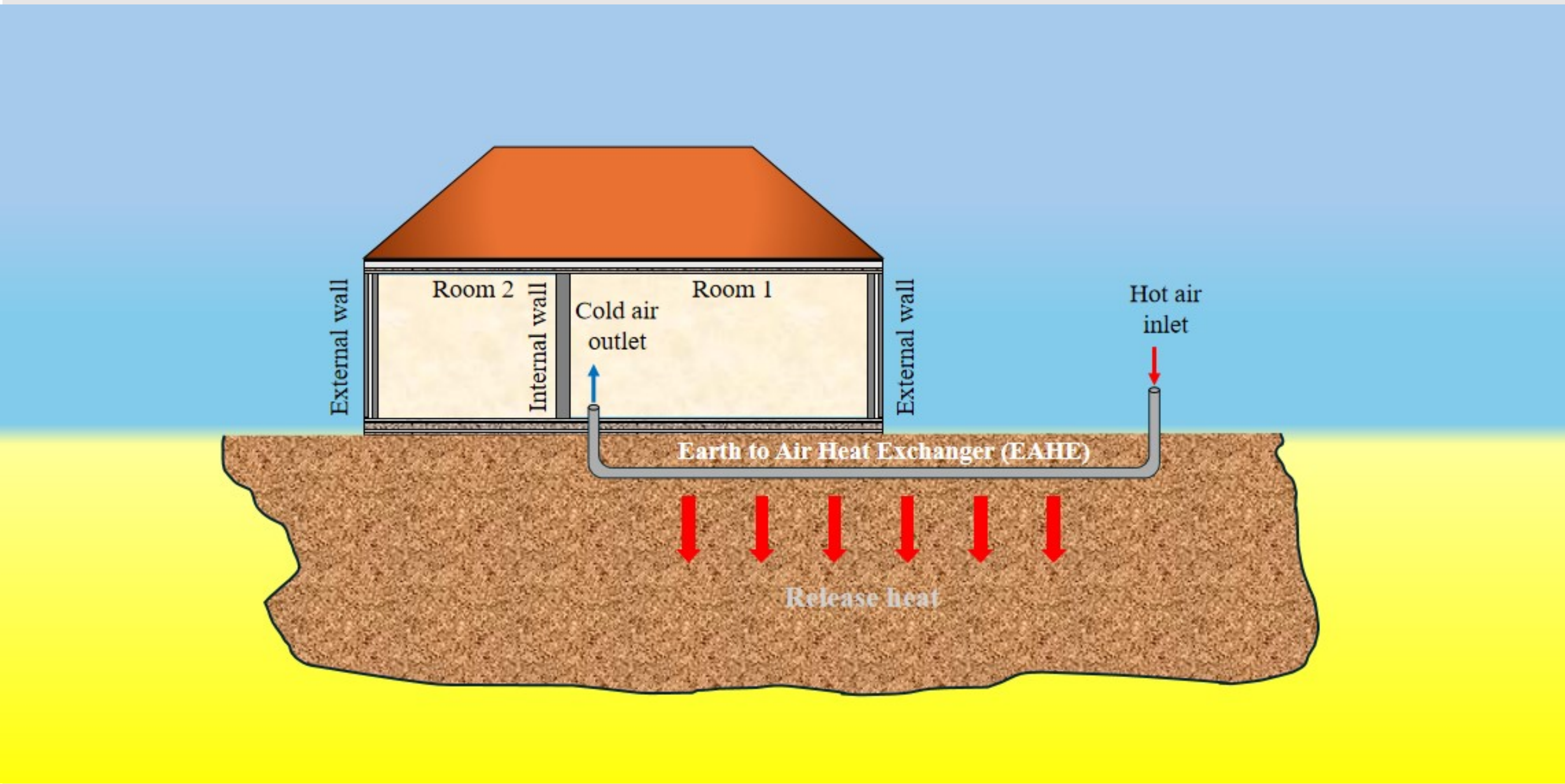
UNIVERSITAT ROVIRA i VIRGILI

PASSIVE COOLING IN BUILDINGS USING EARTH–AIR HEAT EXCHANGERS

NATALIIA TRON



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PASSIVE COOLING IN BUILDINGS USING EARTH–AIR HEAT EXCHANGERS

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DECLARATION

We STATE that the present Master's Thesis, entitled "PASSIVE COOLING IN BUILDINGS USING EARTH–AIR HEAT EXCHANGERS" by Nataliia Tron, has been carried out under our supervision at the CREVER Research Group, Mechanical Engineering Department, Universitat Rovira i Virgili, Tarragona (Spain).

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ABSTRACT

This thesis investigates the application of Earth–Air Heat Exchangers (EAHEs) as a passive cooling technology, with a focus on the climatic and soil conditions of the Tarragona and Poltava regions. The study combines a comprehensive literature review of international research. Numerical simulations are conducted using COMSOL Multiphysics to model transient heat transfer in underground pipes under local soil and temperature profiles. Parametric studies are performed to evaluate the influence of pipe length, diameter, burial depth, and air velocity on cooling performance. Results demonstrate that EAHEs can reduce indoor air temperatures by up to 8°C during summer peaks, with optimal performance achieved at pipe depths around 3.5-4.5 m and diameters of 10–20 cm, balancing thermal efficiency and pressure losses. The findings confirm that EAHEs can serve as a viable component of low-energy cooling strategies in temperate continental climates, offering a practical pathway to reduce reliance on mechanical air-conditioning and contributing to building energy efficiency and resilience in the face of climate change.

Keywords: Earth-Air Heat Exchanger; passive cooling; building energy efficiency; thermal performance; Comsol Multiphysics.

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INTRODUCTION

The rising demand for energy-efficient and environmentally friendly solutions in the building sector has driven increasing interest in passive thermal systems. Heating and cooling loads represent a major portion of energy consumption in residential buildings, especially in regions with extreme climate conditions.

Conventional Heating, Ventilation, and Air Conditioning (HVAC) systems, while effective, are often energy-intensive and contribute significantly to greenhouse gas emissions. In response to these challenges, Earth-Air Heat Exchangers (EAHEs) have emerged as a sustainable alternative that uses the thermal inertia of the soil to condition incoming air before it enters the building [1]. These systems exploit the relatively stable underground temperature to either cool or heat the air, depending on seasonal requirements, thereby reducing the building's reliance on conventional systems and lowering its energy footprint.

Recent global analyses confirm that the building sector remains a principal driver of energy consumption and emissions. In 2023, buildings accounted for approximately 34% of global final energy demand and 34% of energy-related CO_2 emissions, underscoring their central role in decarbonization efforts. Building energy intensity averaged just over 130 kWh/m^2 per year, and while aggregate demand decreased for the first time in a decade-primarily due to milder winter temperatures-efficiency improvements have proceeded slowly. For Spain, the building stock consumed 31.3% of total final energy consumption in 2022, and buildings were responsible for over 64% of national electricity use - a proportion that exceeds the European average. Total electricity demand for Spain in 2023 stood at 254.1 TWh. Spain has made notable progress in renewable adoption, with PV generation reaching 46.6 TWh in 2023, covering 18.3% of total electricity consumption.

In Ukraine, the residential building sector has historically constituted about 28% of the country's total final energy consumption. Average energy use in multi-family residential buildings is 130–180 kWh/m^2 per year, and despite recent policy efforts to improve national energy efficiency with the introduction of nearly-zero energy building standards substantial inefficiencies persist in both the public and private building stock.

These data underscore the profound impact of building energy consumption worldwide, as well as the significant opportunity particularly in Spain and Ukraine to realize energy savings and emissions reductions through the adoption of passive technologies such as Earth–Air Heat Exchangers [2].

The EAHE consists of pipes buried underground through which outside air is drawn. As air passes through these pipes, it exchanges heat with the surrounding soil, which has a more constant temperature compared to the air temperature at the surface.

During the summer, the relatively cooler soil absorbs heat from the incoming warm air, reducing its temperature before it enters the building. In contrast, during the winter, the comparatively warmer soil transfers heat to the colder ambient air, thereby naturally preheating it before it reaches the interior space.

The system's performance depends on a variety of factors including pipe material, diameter, length, burial depth, soil properties, air velocity, and climatic conditions. Understanding how these variables interact is crucial for the efficient design and implementation of EAHE systems.

This thesis aims to evaluate the thermal performance of EAHE systems through a combined bibliometric, physical, and numerical modelling approach. The research is divided into four chapters, each contributing a key component to the overall investigation. The work is structured into four interdependent chapters:

Chapter 1: State of the art

This chapter presents a comprehensive analysis of the current research status on EAHE systems. It begins with a bibliometric analysis conducted using Scopus database, aimed at identifying global publication trends, leading countries, and dominant themes in EAHE research. The analysis is visualized through publication evolution charts, a global contribution map, and keyword co-occurrence networks, helping to contextualize the rising interest in this technology. The chapter also includes an in-depth literature review that summarizes experimental and numerical studies on EAHE systems, highlighting key findings, different modelling approaches, system parameters, and gaps in current knowledge.

Chapter 2: Physical model of the Earth-Air Heat Exchanger (EAHE)

In this chapter, the physical configuration and operating principles of the EAHE are described. The system consists of a buried air duct through which ambient air is drawn before entering the room. The heat transfer phenomena occurring in the soil, inside the pipe, and within the indoor air of the building are discussed, covering conduction in the soil, forced convection inside the pipe, and natural/forced convection within the building. The model also considers the thermal characteristics of the building envelope, including multilayer walls. This chapter provides the foundational understanding of working principle of the EAHE systems.

Chapter 3: Numerical modelling of the EAHE

This chapter details the development of a two-dimensional (2D) numerical model using COMSOL Multiphysics software, which applies the finite element method (FEM) to solve heat transfer equations. The chapter describes the governing equations (mass conservation, momentum conservation, and energy conservation), initial and boundary conditions, and the assumptions made to simplify the complex thermal environment. The 2D geometry includes the soil domain, the house structure, and the buried pipe. The meshing strategy, modeling approach, and parameter variations (pipe diameter, pipe length, burial depth, and inlet air velocity) are systematically presented through a simulation matrix.

Chapter 4: Results and discussion

The fourth chapter presents the results of the numerical simulations. It focuses on the temperature distribution inside the house and evaluates the influence of various EAHE parameters on indoor air conditions. Results are illustrated through temperature contours and graphs. Additionally, a comparison of the simulation in the case of the Tarragona region (Spain) and the Poltava region (Ukraine) is presented.

Chapter 5: Conclusions

Finally, the last chapter presents the main conclusions drawn from this study, summarizing the key findings and providing recommendations for future research.

CHAPTER 1. STATE OF THE ART

1.1 Bibliometric analysis of EAHE research

To explore the scientific landscape and research trends related to Earth-Air Heat Exchangers (EAHEs), a bibliometric analysis was conducted following a structured and reproducible methodology. The objective of this analysis was to identify the most prominent research themes, their interrelations, and how they have evolved over time.

1.1.1 Methodology

The bibliometric analysis methodology outlines a systematic process for analyzing bibliographic data, incorporating specific tools and steps as shown in Figure 1.1:

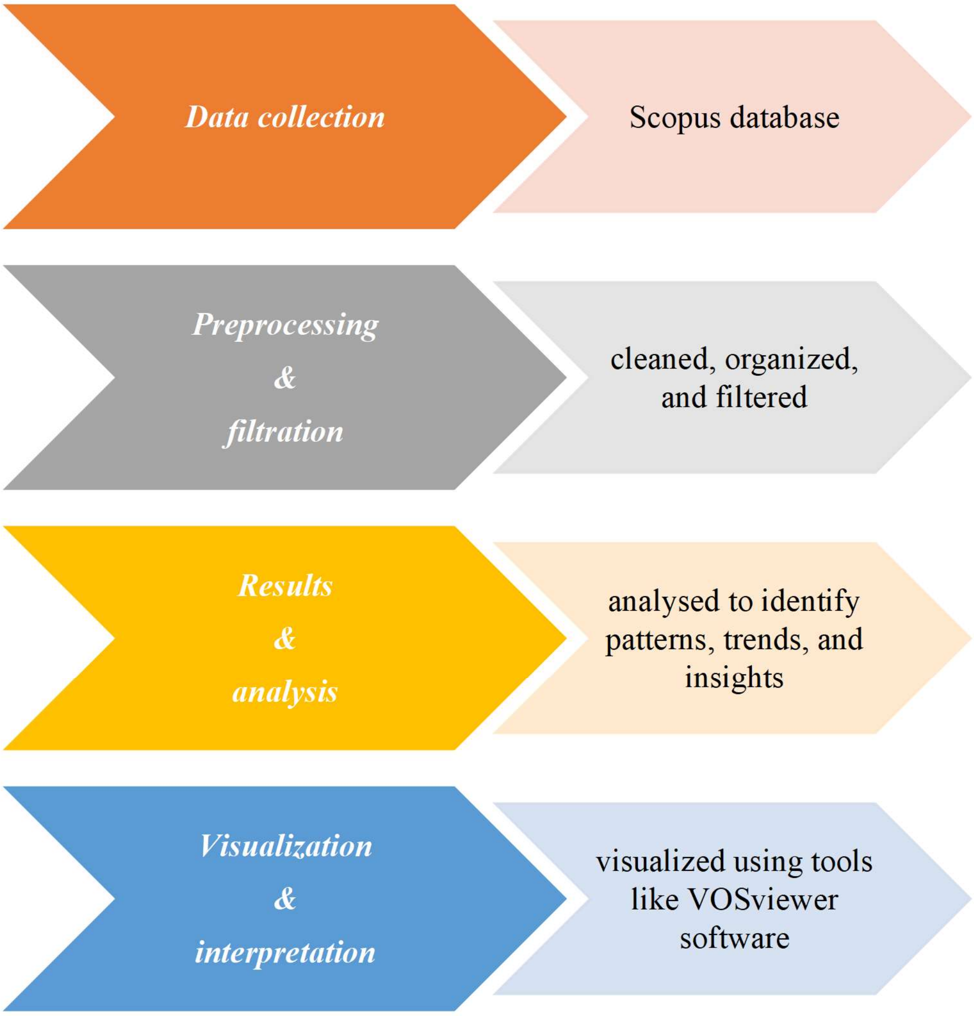


Figure 1.1. The bibliometric analysis methodology.

Data collection: Relevant data is gathered from academic databases, such as the Scopus database, using a targeted query to retrieve publications that align with the research objectives. Scopus provides comprehensive coverage of peer-reviewed literature, ensuring a robust dataset.

Pre-processing & filtration: The collected data is cleaned, organized, and filtered to ensure quality and relevance. This involves removing duplicates, correcting inconsistencies, and refining the dataset based on criteria like publication type, time frame, or subject area.

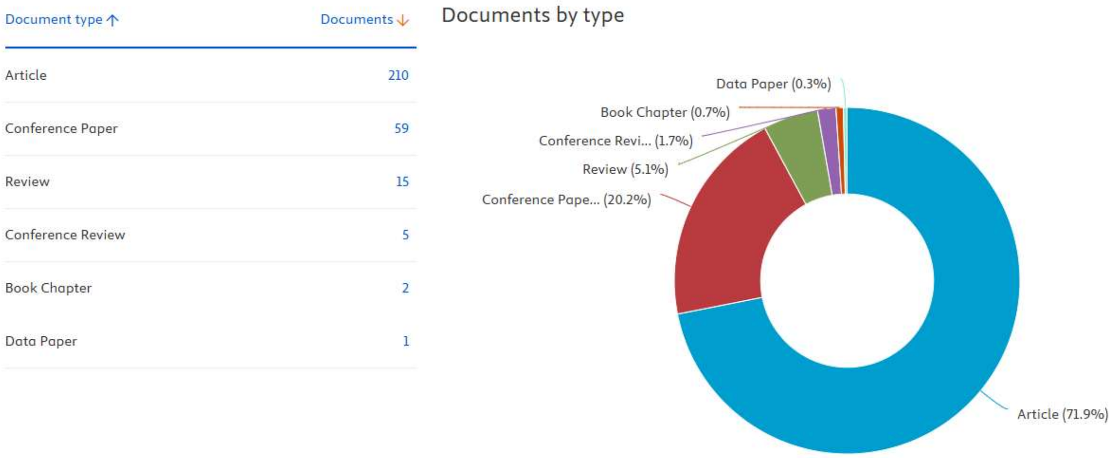
Results & analysis: The pre-processed data is analyzed to identify patterns, trends, and insights, such as citation networks, author collaborations, or keyword co-occurrences. Statistical methods and metrics, like citation counts or h-index, are applied to derive meaningful results.

Visualization & interpretation: The analyzed results are visualized using tools like VOSviewer software, which creates intuitive maps to illustrate relationships, such as co-authorship or keyword networks.

1.1.2 Scopus Database

The query used to retrieve and assess the relevant literature from the Scopus database is focused on Earth-Air Heat Exchangers (EAHEs). The first part of the query targeted core EAHE terminology as (“earth air heat exchanger”, “ground-coupled heat exchanger”, “EAHE system”), ensuring broad inclusion of related studies. The second part refined the search by incorporating technical and performance related terms such as (“pipe diameter”, “thermal conductivity”, “soil moisture”, and “energy efficiency”), linking system design with real world applications in building cooling. Finally, a publication date filter (2005–2024) was applied to capture recent advancements and evolving research trends, producing a robust dataset suitable for bibliometric analysis.

1.1.3 World map and documents number



Document type ↑	Documents ↓
Article	210
Conference Paper	59
Review	15
Conference Review	5
Book Chapter	2
Data Paper	1

Figure 1.2. Classification documents by type of the bibliometric analysis.

The bibliometric analysis using the query mentioned above on the Scopus database identified a total of 292 documents, forming a robust foundation for detailed examination. Among these, articles constitute the majority with 210 entries, highlighting their role as the main source of peer-reviewed research. Conference papers make up 59 documents, reflecting active scholarly engagement through academic events. The dataset also includes 15 reviews, 5 conference reviews, 2 book chapters, and 1 data paper.

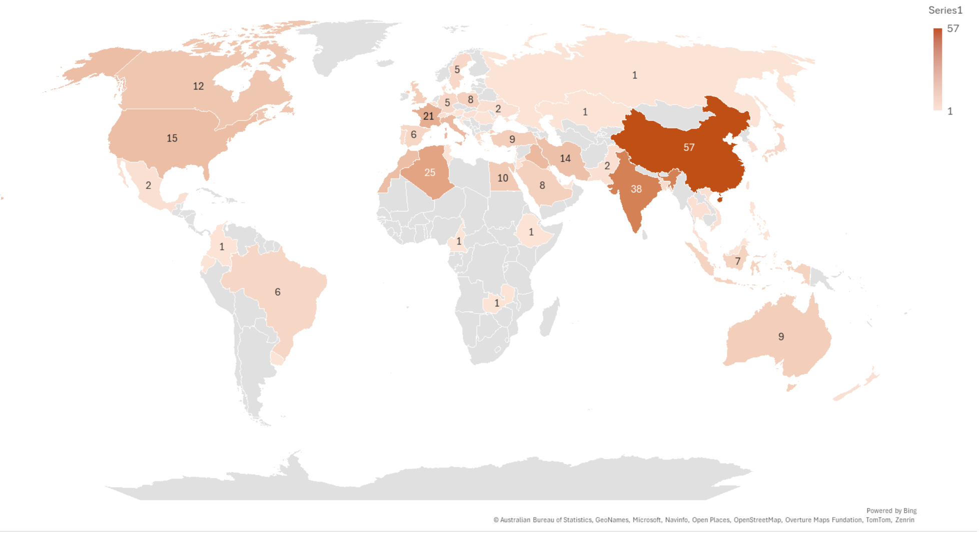


Figure 1.3. The world map visualizes the number of documents by country.

The world map visualizes the number of documents by country, with a colour gradient ranging from light pink (1 document) to dark red (57 documents) Figure 1.3. It can be seen that China leads with the highest contribution of 57 documents, indicating a significant research presence, followed by India with 38 documents. Algeria ranks third with a notable number of documents of 25 documents, positioning it as a key contributor after China and India. Other notable contributors include France (21 document), Italy (17 documents), the United States (15 documents), Australia (9 documents), and other regions in Europe and the Middle East, suggesting a diverse global research landscape.

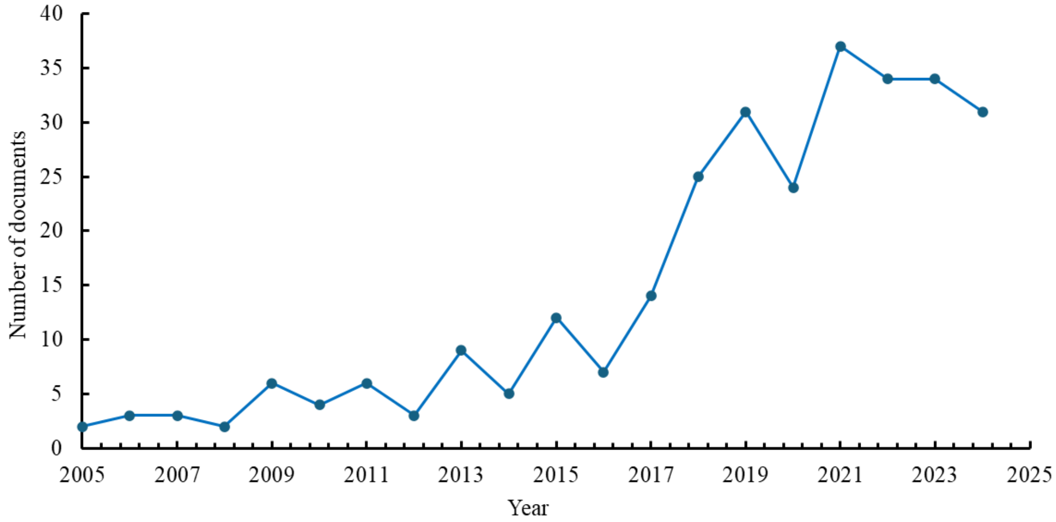


Figure 1.4. The line graph of the figure tracks the number of documents.

The line graph of the figure tracks the number of documents published annually from 2005 to 2025. The trend shows a gradual increase, with minimal activity (0-5 documents) until around 2011. A noticeable rise begins post 2015, peaking at approximately 35-40 documents around 2021-2022, followed by a slight decline toward 2025. This pattern reflects growing research interest over time, with a potential maturation or shift in focus in recent years, aligning with the global distribution where established research hubs as China.

Table 1.1. The 10 most cited papers in the field of EAHE.

№	Paper	Authors	Year	Country	Citation number
1	Energy and geotechnical behaviour of energy piles for different design solutions [3]	Batini et al.	2015	Switzerland Italy	188
2	An intense review on the latest advancements of Earth Air Heat Exchangers [4]	Bordoloi et al.	2018	India	180
3	Earth-to-air heat exchangers for Italian climates [5]	Ascione et al.	2011	Italy	170
4	Modeling and parametric studies for thermal performance of an earth to air	Ghosal and Tiwari	2005	India	154

	heat exchanger integrated with a greenhouse [6]				
5	Heat and mass transfer performance analysis and cooling capacity prediction of earth to air heat exchanger [7]	Niu et al.	2015	USA	135
6	Performance evaluation and life cycle cost analysis of earth to air heat exchanger integrated with adobe building for New Delhi composite climate [8]	Chel and Tiwari	2009	India	134
7	A practical approach to predict soil temperature variations for geothermal (ground) heat exchangers applications [9]	Ozgener et al.	2013	Turkey, USA	128
8	Parametric study on thermal performance of earth-to-air heat exchanger used for cooling of buildings [10]	Benhammou and Draoui	2015	Algeria	126
9	A review of solar chimney integrated systems for space heating and cooling application [11]	Monghasemi and Vadiee	2018	Iran	123
10	Experimental and numerical study of an earth-to-air heat exchanger for air cooling in a residential building in hot semi-arid climate [12]	Khabbaz et al.	2016	Switzerland, France, Morocco	121

1.1.4 Summary of the most cited papers in the field of EAHE

Batini et al. [3] investigated energy piles with various design configurations, highlighting their dual role in supporting structural loads and providing geothermal energy exchange.

Results showed that energy piles could reduce building heating and cooling loads significantly, with performance depending on pile geometry and soil properties.

Bordoloi et al. [4] presented a comprehensive review of Earth–Air Heat Exchangers that revealed advances in design, materials, and hybrid systems. The paper emphasized the crucial role of soil thermal conductivity and system configuration, underscoring EAHE potential in reducing HVAC energy consumption by up to 40%.

Ascione et al. [5] focused on Italian climates, this study showed EAHE systems could reduce summer indoor temperatures by 2–5°C, improving occupant comfort while lowering cooling energy demand, particularly when integrated with appropriate ventilation strategies.

Ghosal and Tiwari [6] modelled an earth-to-air heat exchanger integrated into greenhouses, demonstrating that optimal pipe length and airflow rates could enhance thermal performance, achieving temperature reductions of up to 6°C and improving plant growth conditions.

Niu et al. [7] analyzed heat and mass transfer in EAHEs, predicting cooling capacities accurately and indicating that moisture in soil significantly influences thermal performance by affecting heat exchange efficiency.

Chel and Tiwari [8] described the evaluation of EAHE integrated with adobe buildings in New Delhi showed life cycle energy savings up to 29% and cost benefits, especially when system parameters were optimized for local climate and building design.

Ozgener et al. [9] developed a practical model to predict soil temperature variations relevant for ground heat exchangers, essential for accurate simulation of EAHE performance under varying climatic conditions.

Benhammou and Draoui [10] conducted a parametric study highlighting that increased pipe length and soil thermal conductivity improved EAHE thermal performance, while high airflow velocity could reduce cooling effectiveness.

Monghasemi and Vadiee [11] reviewed solar chimney systems, noting that integrating solar chimneys with EAHEs further enhances natural ventilation and passive cooling by improving air movement and reducing indoor temperatures.

Khabbaz et al. [12] Experimental and numerical studies in a hot semi-arid climate showed that EAHEs effectively decreased indoor air temperatures by up to 4°C, confirming their suitability for harsh environments and their contribution to reducing building cooling loads.

1.1.5 Keyword co-occurrence

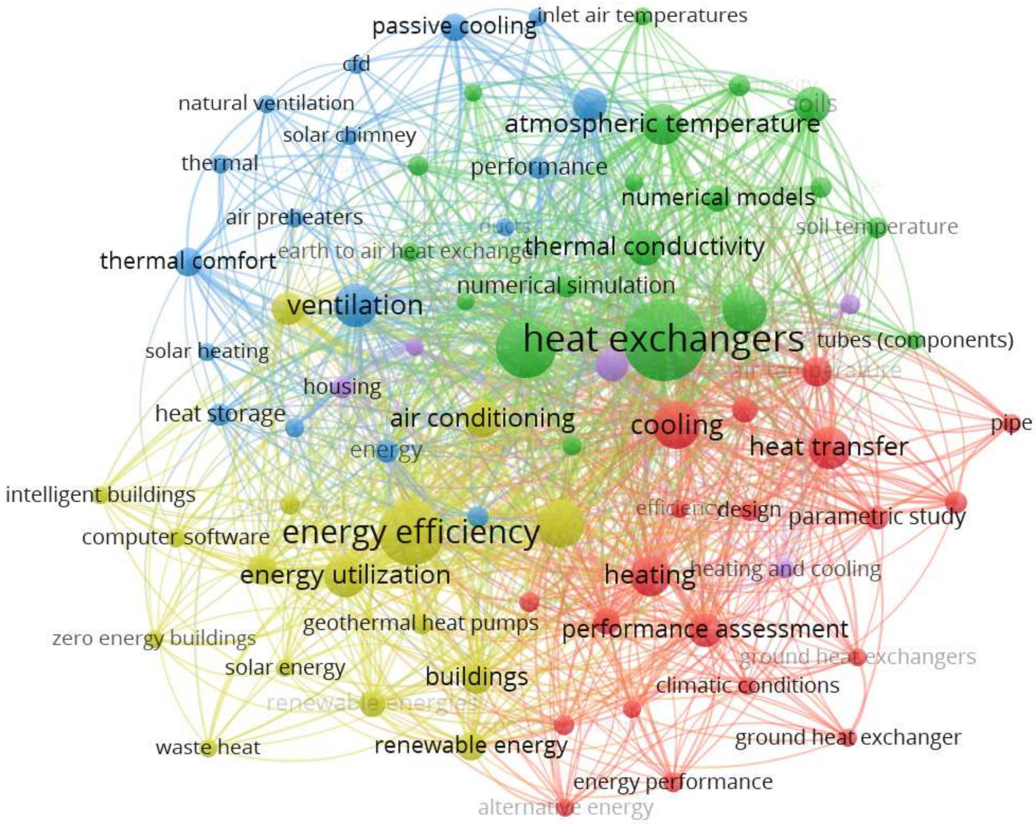


Figure 1.5. Keyword co-occurrence map of Earth-to-Air Heat Exchangers (EAHEs).

The bibliometric keyword co-occurrence map illustrates the intellectual structure and thematic organization of research related to EAHEs. This visualization reveals five major keyword clusters, each representing a specific focus within the broader field. The green cluster, which dominates the central region of the map, centres around keywords such as *heat exchangers*, *thermal conductivity*, *numerical models*, *numerical simulation*, and *atmospheric temperature*. This cluster reflects a strong emphasis on the technical and modelling aspects of EAHEs, particularly the use of numerical simulations to predict thermal behaviour and optimize exchanger design under varying soil and atmospheric conditions. Closely connected to this is the red cluster, which groups terms like *heat transfer*, *cooling*, *heating*, *performance assessment*, *parametric study*, and *pipe*. This indicates a significant research focus on evaluating system performance, thermal efficiency, and design variables through both experimental and computational studies. These two clusters (green and red) collectively highlight the engineering and thermodynamic core of EAHE research, dealing with physical modelling, performance analysis, and optimization techniques.

Moving toward the yellow cluster, keywords such as *energy efficiency*, *renewable energy*, *energy utilization*, *buildings*, *geothermal heat pumps*, and *solar energy* suggest a broader sustainability-oriented research perspective. This group of studies emphasizes the integration of EAHEs into low-energy or zero-energy building strategies, showcasing their role in reducing energy consumption and promoting the use of renewable sources. The blue cluster, which includes terms like *ventilation*, *thermal comfort*, *natural ventilation*, *solar chimney*, and *passive cooling*, highlights the architectural and environmental aspects of EAHE applications. Here, research is more focused on indoor environmental quality, occupant comfort, and the role of passive design strategies in reducing mechanical ventilation needs. The map also reveals cross-linkages between this cluster and others, indicating a growing interdisciplinary approach that merges architecture, engineering, and environmental science.

Finally, smaller nodes such as *soil temperature*, *tubes (components)*, *inlet air temperatures*, and *intelligent buildings* which bridge several clusters show the emergence of niche but increasingly important topics such as smart building integration, microclimatic influences, and component-level innovations. The central position of *earth-to-air heat exchanger* in the map, closely linked to almost all major themes, confirms its multidisciplinary nature and the pivotal role it plays across technical, environmental, and building performance research domains. Overall, this co-occurrence analysis demonstrates that while the field is heavily rooted in thermal modelling and performance assessment, it is progressively expanding toward sustainable building applications and occupant-centric design paradigms, revealing a maturing and diversifying research landscape.

1.2 Literature review

The increasing demand for sustainable and energy-efficient solutions in the building sector has led to a growing interest in passive cooling systems. Among these, Earth–Air Heat Exchangers (EAHEs) have emerged as an effective and environmentally friendly approach to regulate indoor temperatures, especially in regions with hot or extreme climates.

In this literature review the development, theoretical background, experimental investigations, numerical simulations, and practical applications of EAHE systems were analyzed. The focus is given not only to their performance in temperate climates but also in regions characterized by hot or arid conditions.

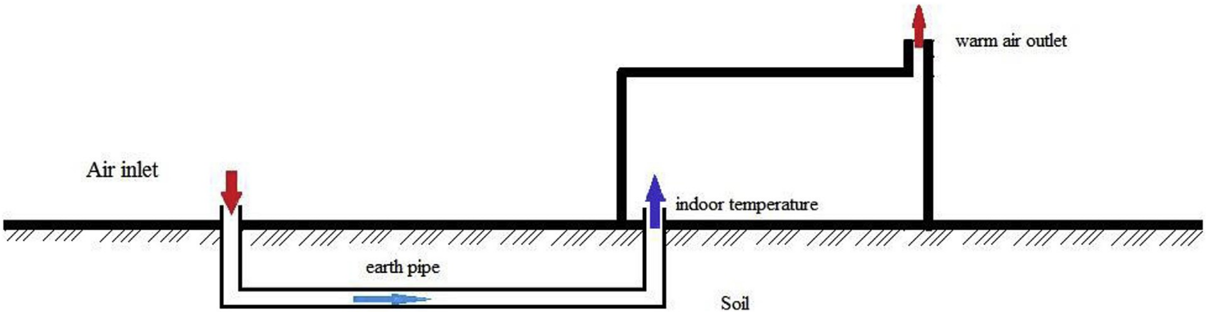


Figure 1.6. Schematic diagram of a passive air-conditioning system using earth air heat exchanger [13].

EAHEs utilize the thermal inertia of the ground to pre-cool or pre-heat ambient air before it is introduced into the building, thereby reducing the load on active HVAC systems [1,14].

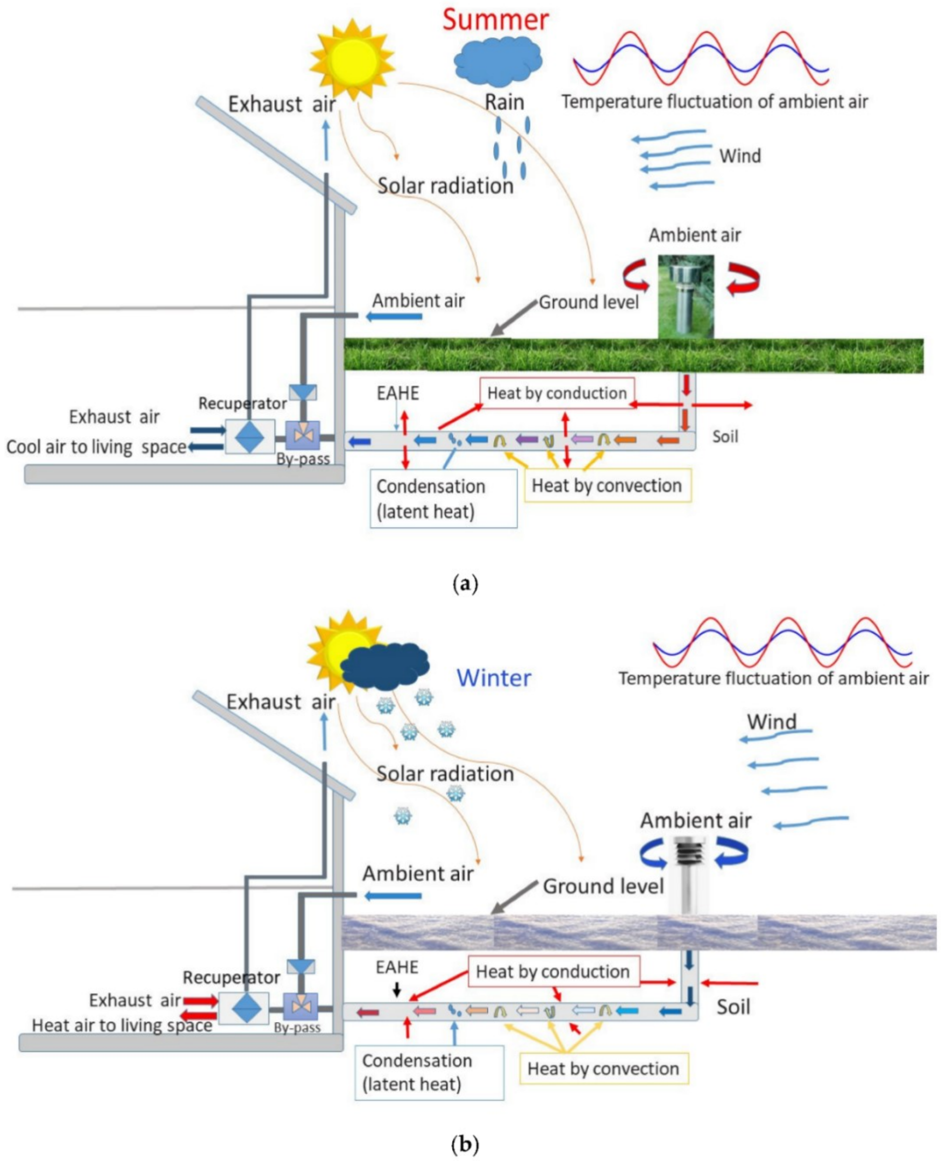
1.2.1 Historical development and technological evolution

The use of subterranean air channels for thermal regulation has been practiced for centuries in various forms. Traditional systems, such as qanats and wind catchers in Persia, utilized similar principles to cool buildings in desert climates. The modern EAHE system has evolved significantly, incorporating standardized materials like PVC (Polyvinyl Chloride) and HDPE (High-Density Polyethylene) pipes, along with advanced simulation techniques for optimization.

H. Koshlak [1] provided a comprehensive overview of the historical trajectory and the recent integration of EAHEs with renewable energy technologies such as photovoltaic panels and solar chimneys. The hybridization of EAHEs with solar-assisted ventilation systems has further improved their efficiency and applicability in zero-energy building designs.

1.2.2 Fundamental principles of Earth–Air Heat Exchangers

EAHEs are based on the principle of heat transfer between the air and the surrounding soil through buried pipes. Air drawn from the outside atmosphere passes through these underground pipes and either gains or loses heat depending on the temperature differential between the air and the ground [1]. This process enables the air to be cooled in summer or warmed in winter before it enters the building’s air handling unit or directly into the occupied space.



(a)

(b)

Figure 1.7. Working Principle of earth-air heat exchangers (EAHE) coupled with heat recovery units: (a) in summer; (b) in winter [1].

The governing equations for heat transfer in EAHEs incorporate the principles of conduction through the soil, convection between the pipe wall and the airflow, and the influence of soil moisture content and thermal diffusivity. The thermal performance of an EAHE depends on multiple design and environmental factors, including:

- soil type and thermal conductivity,
- depth and length of the pipe,
- pipe material and diameter,
- airflow velocity and turbulence,
- seasonal soil temperature variation [14,15].

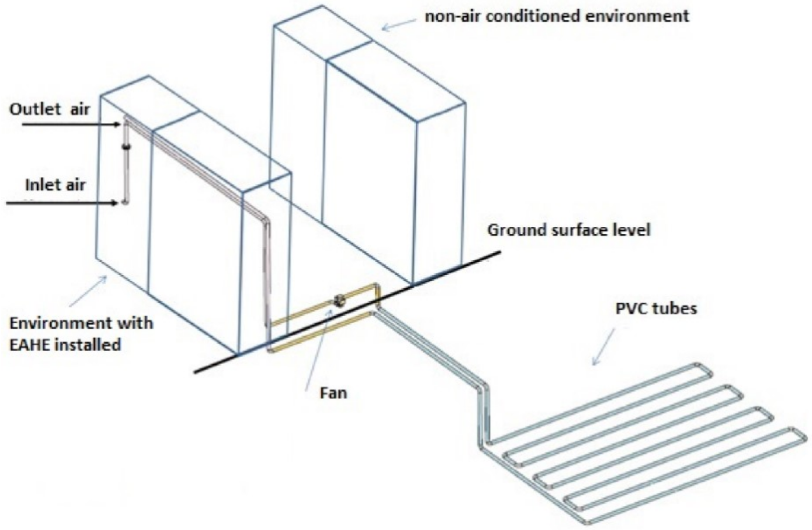


Figure 1.8. Indoor environments of the Graduate Program in Mechanical Engineering building [15].

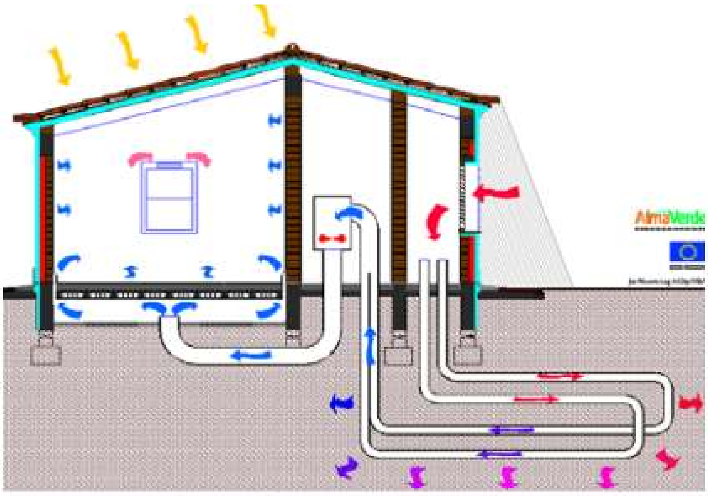


Figure 1.9. Schematic diagram of the indoor house and EAHE [14].

The review by Soares et al. [16] presented a comprehensive analysis of recent advancements in both standalone and hybrid EAHE systems, focusing on design parameters, performance metrics, and integration with other renewable energy technologies.

The authors conducted an extensive literature review, analyzing a wide range of studies related to EAHE systems. The review encompasses various configurations, operational strategies, and integration methods with other systems such as photovoltaic panels, heat pumps, and solar chimneys. The selection criteria for the literature included relevance to EAHE technology, innovation in design or application, and empirical validation of performance.

The performance of standalone EAHE systems is influenced by several factors, including soil thermal properties, pipe material and geometry, burial depth, and airflow rate. Properly designed EAHEs can significantly reduce indoor temperature fluctuations and enhance thermal comfort. However, challenges such as soil moisture variability and potential condensation within pipes necessitate careful design considerations.

Integrating EAHEs with other renewable energy systems has shown promising results in improving overall energy efficiency. For instance, coupling EAHEs with photovoltaic panels can aid in cooling the panels, thereby enhancing their electrical efficiency. Similarly, integration with air-source heat pumps can lead to better thermal management and reduced energy consumption. These hybrid systems demonstrate the potential for synergistic benefits, but they also introduce complexity in system design and control.

The review highlights the versatility of EAHE systems in various climatic conditions and building types. While standalone systems offer simplicity and passive operation, hybrid configurations can achieve higher efficiency and adaptability. Nevertheless, the lack of standardized design guidelines and the need for site-specific customization remain barriers to widespread adoption. Future research should focus on developing predictive models and control strategies to optimize the performance of EAHE systems.

1.2.3 Experimental and numerical investigations

Experimental and numerical studies play a pivotal role in evaluating the performance of EAHEs under real and simulated climatic conditions. Vaz et al. [15] conducted a combined experimental and numerical analysis of an EAHE system in Brazil, emphasizing the effect of pipe geometry and soil properties on the cooling capacity. Their findings demonstrated that pipe length and airflow rate significantly influence the thermal efficiency of the system.

Computational Fluid Dynamics (CFD) tools have been widely used to simulate airflow and heat exchange phenomena inside the pipes. These models allow for the prediction of outlet air temperature, pressure drops, and seasonal variation in performance. Belatrache et al. [13] utilized numerical simulations to assess the efficiency of EAHE systems in arid regions, such as southern Algeria. Their study found that despite the dry and hot conditions, EAHEs can maintain stable performance, particularly when buried deeper than 2.5 meters in soil with favorable thermal properties.

One of the significant studies analyzing the effectiveness of earth-to-air heat exchangers (EAHE) in Southern European conditions is the work by Ascione et al. [5]. The authors investigated the feasibility of integrating EAHE systems in buildings located in various Italian climate zones, taking into account both cooling and heating seasonal needs. Through detailed simulations based on soil and outdoor air temperature data, they evaluated the thermal efficiency of the system and its potential for energy savings.

Particular attention was given to the influence of the heat exchanger's geometry (length, burial depth, and pipe diameter), as well as soil thermal properties, on system performance. The results demonstrated that under Italian climatic conditions, EAHEs can reduce supply air temperatures by 4–6 °C during summer [5]. This highlights the system's suitability for passive cooling in buildings located in regions with mild or moderately hot climates. Therefore, this study emphasizes the importance of considering regional climatic and geological conditions when designing EAHEs, and it confirms their high effectiveness in Mediterranean and similar environments.

A notable contribution to the field of passive and hybrid cooling strategies is presented by Qi et al. [17], who conducted both theoretical modeling and experimental validation of a combined EAHE system integrated with a return air circulation loop. The study was designed to enhance thermal performance and energy efficiency in building ventilation, particularly during hot seasons. This hybrid system configuration allows for the simultaneous use of cool air from underground soil layers and partially conditioned indoor return air, offering a dynamic control strategy based on outdoor and indoor temperature fluctuations. The authors developed a coupled heat and mass transfer model to simulate the thermal behavior of the EAHE, considering soil thermal conductivity, air velocity, pipe depth, and seasonal variations.

Field experiments were performed under real climate conditions, showing that the hybrid system achieved substantial cooling potential and could reduce the supply air temperature by more than 7°C compared to outdoor ambient air during peak summer periods. Moreover, the study highlighted that the hybrid approach mitigates some of the limitations of traditional EAHE systems, such as excessive cooling or reduced effectiveness under low soil-air temperature differentials. Importantly, the authors emphasized the energy-saving potential of this system, demonstrating its capacity to reduce the load on mechanical air conditioning systems while maintaining thermal comfort. The research is particularly relevant in the context of increasing interest in sustainable HVAC solutions and underscores the potential of EAHE systems coupled with intelligent hybrid configurations for energy-efficient building design.

The study conducted by Khabbaz et al. [12] contributes to this field by examining both the experimental performance and numerical modeling of an EAHE system integrated into a residential building located in a hot semi-arid region of Morocco. The research focuses on assessing the cooling potential of the system and validating a computational model to support broader applications.

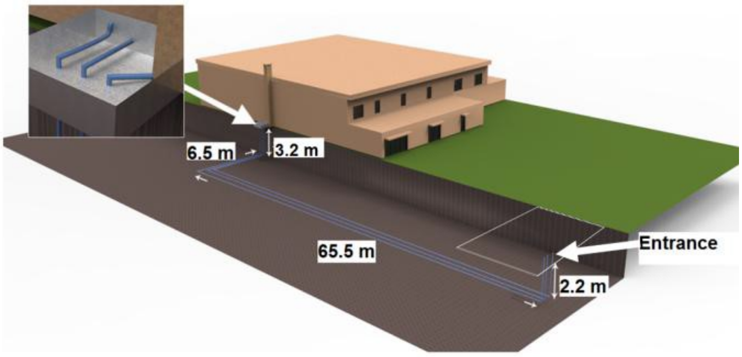


Figure 1.10. Schematic diagram of the EAHX [12].

The study adopts a dual methodology:

Experimental approach: A full-scale EAHE system was installed at a site in Ouarzazate, Morocco. The system was composed of a horizontal pipe buried at a depth of 2.5 m and designed to allow ambient air to flow through and be cooled by the surrounding soil mass.

Numerical simulation: A transient numerical model was developed using COMSOL Multiphysics. The model incorporated detailed thermophysical soil and air properties, and boundary conditions that reflect actual climatic conditions. It was calibrated using experimental data to ensure high predictive accuracy.

The study was carried out over a summer period, with measurements taken of inlet and outlet air temperatures, air velocity, soil temperature profiles, and thermal exchange rates.

The experimental results demonstrated that the EAHE system effectively reduced indoor air temperature by up to 11°C during peak afternoon hours. The system provided an average cooling power of 420 W, with peak performance exceeding 800 W. The average thermal efficiency was calculated at 45%, which is significant for passive systems in arid conditions.

Validation of model: The numerical model showed strong agreement with experimental data, with an average root mean square error (RMSE) of less than 1°C between simulated and measured air temperatures.

These findings confirm that EAHE systems can be highly effective in regions with high diurnal temperature variation and low soil moisture.

The study highlights the following implications:

Climatic suitability: The hot semi-arid climate of southern Morocco, characterized by hot days and cool nights, enhances the performance of the EAHE by enabling heat dissipation during the night.

Design considerations: The optimal pipe length and diameter, burial depth, and airflow rate are critical for system performance. The authors suggest the use of parametric simulations to optimize design for other climates.

Energy savings potential: By reducing the need for mechanical air conditioning, EAHE systems can contribute to significant energy savings in residential buildings in similar climates.

The study also points to challenges, such as ensuring soil thermal stability over prolonged operation and mitigating pipe condensation effects.

1.2.4 Applications in arid and hot climates

EAHEs have proven particularly beneficial in hot and arid climates, where active cooling demands are high. Santamouris [14] emphasizes the role of passive systems like EAHEs in reducing peak electricity loads and enhancing indoor thermal comfort. In Iraq, for instance, systems have been developed that combine EAHEs with night ventilation or solar chimneys to counteract extreme daytime temperatures.

Belatrache et al. [13] reported that the performance of EAHEs in Saharan environments could be optimized by adjusting the pipe depth and length, as well as using insulating coatings to reduce external heat gain. Similarly, Moroccan studies revealed that coupling EAHEs with green roofs could further improve cooling efficiency.

1.3 Integration with renewable systems

Koshlak [1] discusses the integration of EAHEs with photovoltaic (PV) panels, solar chimneys, and thermal storage units. These hybrid systems can regulate building microclimates while also reducing reliance on fossil fuel-based HVAC systems. For example, combining EAHEs with PV-powered fans allows for autonomous operation in off-grid settings, which is particularly useful in rural and remote areas.

1.4 EAHE in the case of the Poltava region, Ukraine

Passive cooling of buildings in Poltava (Ukraine) using Earth-Air Heat Exchangers (EAHE) has received growing attention due to the region’s pronounced seasonal temperature fluctuations and the increasing necessity for sustainable climate control solutions. Recent literature and experimental studies by Ukrainian institutions have systematically analyzed the operational characteristics of EAHEs under local soil and climate conditions. EAHE systems exploit the relatively stable subsurface ground temperature to pre-cool or pre-heat ventilation air for improving overall building energy efficiency.

So, several recent studies have addressed the applicability of EAHEs in temperate continental climates. Koshlak [1] analyzes both the thermodynamic performance and economic feasibility of EAHEs. Her research shows that seasonal temperature variations in continental climate like Ukraine allow EAHEs to be effective both in summer and during mild winters, especially when integrated into passive house design standards.

1.5 Conclusions

The literature on Earth–Air Heat Exchangers (EAHEs) reflects the growing importance of passive cooling strategies in the face of global climate challenges and rising energy demands. Fundamental studies have established the thermodynamic behavior of EAHEs and highlighted the importance of parameters such as pipe geometry, soil thermal properties, burial depth, and air velocity.

Research [1] provided a foundation for regional adaptation in countries like Ukraine, showing promising potential for integration with renewable energy systems. Vaz et al. [15] and Belatrache et al. [13] offer valuable insights into experimental and numerical performance evaluations in both temperate and arid climates, while Santamouris [14] emphasizes the role of EAHEs in sustainable building design and urban cooling strategies.

Studies from Ukraine and hot-climate countries like Iraq, Algeria, and Morocco further underscore the versatility and adaptability of EAHE systems across different geographical zones. Despite the progress, critical research gaps remain regarding long-term system efficiency, integration with smart energy systems, and economic feasibility in various building types.

This review serves as a conceptual and technical basis for the modelling and design process in subsequent chapters, particularly focusing on the climatic and soil conditions of the Tarragona region, Spain. As well as comparable case of study in the Poltava region, Ukraine.

EAHE systems, both standalone and hybrid, present viable solutions for sustainable building climate control. Their ability to leverage stable ground temperatures can lead to significant energy savings and improved indoor comfort. However, to fully realize their potential, further research is needed to address design challenges, develop integration strategies with other renewable systems, and establish comprehensive guidelines for implementation.

The integrated experimental and numerical approach adopted by Khabbaz et al. [12] provides robust validation of EAHE technology for passive cooling applications in hot semi-arid climates. The system's high efficiency, low environmental impact, and compatibility with existing building structures make it a promising option for sustainable building design. The results further emphasize the importance of climate-adaptive passive technologies in achieving energy-efficient architecture.

CHAPTER 2. PHYSICAL MODEL OF THE EARTH-AIR HEAT EXCHANGER (EAHE)

2.1 Introduction

In this chapter, a comprehensive physical model is developed to represent the functioning of an Earth-Air Heat Exchanger (EAHE) system integrated into a residential building. The EAHE consists of a buried pipe network through which ambient air is drawn and thermally conditioned via heat exchange with the surrounding soil before being introduced into the interior space. This passive system capitalizes on the relatively stable subsurface temperatures to provide heating in winter and cooling in summer, significantly reducing the energy demand for conventional HVAC systems

2.2 Working principle of an EAHE

The EAHE is a passive energy system that utilizes the relatively stable thermal properties of the ground to precondition incoming air for heating or cooling purposes. It consists of a pipe system buried underground, where the temperature of the ground remains relatively stable throughout the year. As outdoor air flows through the buried pipe, it undergoes convective heat exchange with the inner pipe surface and conductive heat transfer through the pipe wall and from the surrounding soil.

In summer, when the air temperature is higher than the ground temperature, thermal energy from the air is transferred to the cooler soil, lowering the air's temperature before it enters the building. In winter, the process reverses, the warmer soil transfers heat to the colder incoming air as shown in Figure 2.1.

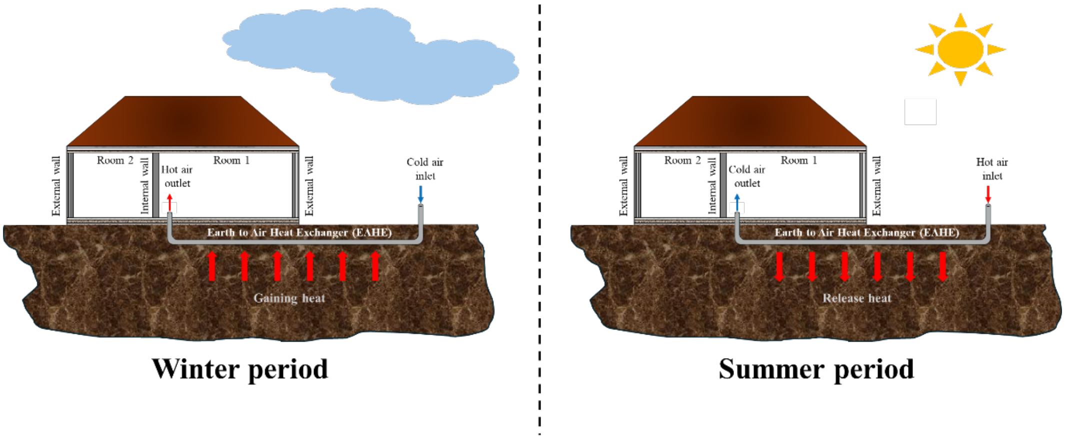


Figure 2.1. Schematic diagram of the EAHE model.

This passive preconditioning of ventilation air reduces the load on active HVAC systems and contributes to energy efficiency by utilizing the natural thermal inertia of the ground.

2.3 System configuration and geometry

The physical configuration under study consists of a simplified two-room residential structure (Figure 2.2) designed to evaluate the thermal performance of the EAHE system. Each room represents a thermally isolated zone, with different construction materials applied to the building envelope.

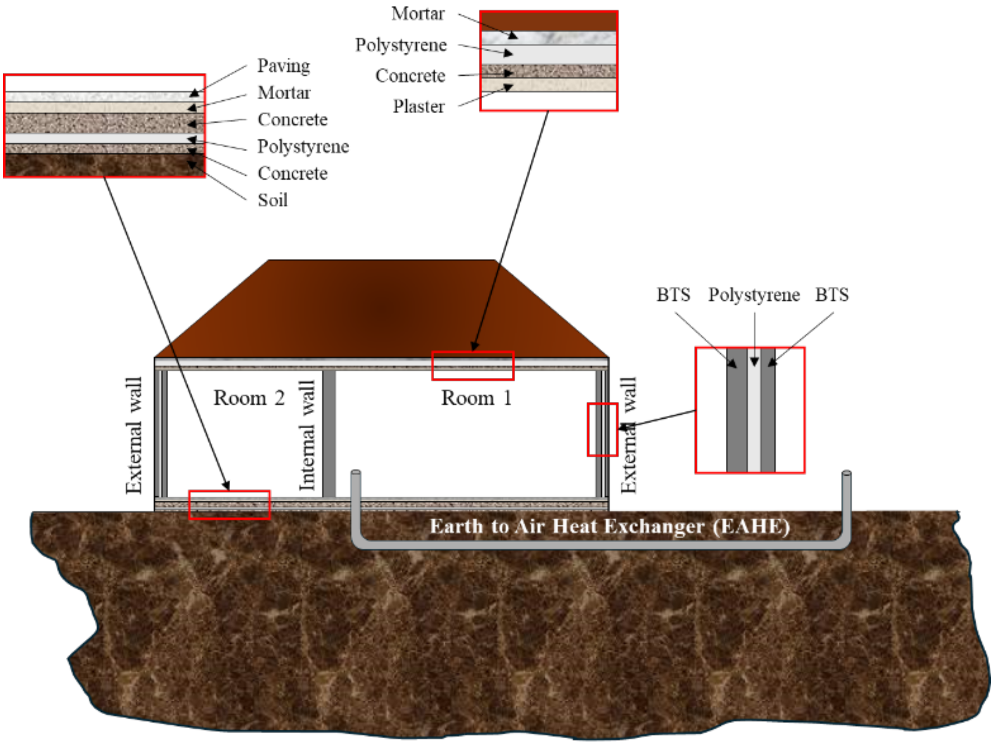


Figure 2.2. Description of the material used in the physical model.

The house walls are made from stabilized earth concrete (BTS), an eco-friendly material known for its moisture regulation, durability, and thermal storage capacity. Cement stabilizer is added at 3–6% volume to enhance longevity. The BTS walls have a density of approximately 1700 kg/m³, with a heat transfer coefficient of 3.6 W/m²·K for a 14 cm thickness and 2.54 W/m²·K for 29 cm. Additional insulation includes a 9 cm expanded polystyrene layer with a 1 mm polyethylene vapor barrier on external walls, 16 cm expanded polystyrene with vapor barrier on the ceiling, and 6 cm extruded polystyrene (XPS) insulation on the floor. This configuration ensures improved thermal resistance and optimal indoor thermal comfort aligned with passive cooling objectives [18].

The external walls, rooftop, and foundation of the house are insulated using different materials to reflect realistic construction variability, while the internal partition separating the two rooms is made of expanded polystyrene to provide partial thermal separation while allowing thermal influence from adjacent spaces. The dimensions of the building are shown in Figure 2.3.

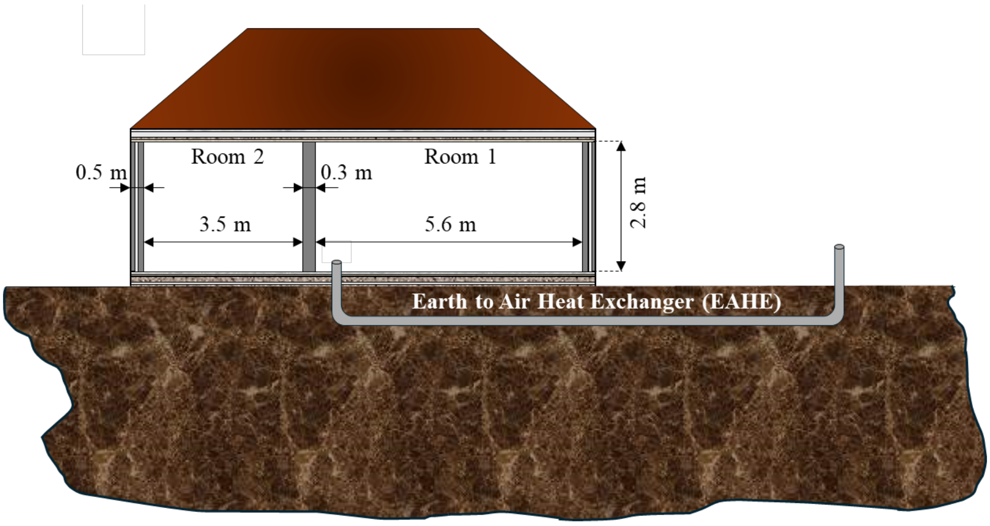


Figure 2.3. Dimensions of the system.

The EAHE system is implemented as a U-shaped buried pipe, with its air inlet located outside the building and its outlet positioned inside one of the Room 1. This specific arrangement is intended to analyse not only the direct impact of the EAHE on the room where the air is introduced, but also the secondary thermal influence it may have on the neighbouring space through indirect conduction or air diffusion.

The underground EAHE pipe is studied under a variety of design and operational parameters. These include variation in the pipe diameter (D) from 2 cm to 20 cm, the burial depth (z) ranging from 1.5 meter to 4.5 meters below the ground surface, to assess its influence on airflow and thermal exchange.

In addition, the total pipe length (L) measured from the air inlet outside the house to the internal outlet in Room 1 is varied from 7 meter to 20 meters to evaluate the extent of heat exchange over different soil contact surfaces and distances. This parameter is particularly important in determining the residence time of air within the buried section, and thus the level of thermal preconditioning achieved before entering the indoor environment.

The material selected for the pipe should be thermally conductive, corrosion-resistant, and mechanically durable suitable for long-term operation in harsh subsurface conditions and ensuring sustained heat transfer performance with minimal degradation over time.

Inside the building, the air outlet from the EAHE is placed in Room 1, without any mechanical air redistribution system, to analyse the natural dispersion of preconditioned air. This setup allows the study of passive indoor air diffusion and how the thermal influence propagates spatially from the EAHE outlet toward the adjacent room.

The physical model thus represents a controlled test case for examining how geometric, material, and operational parameters of the EAHE system interact with building thermal dynamics.

2.4 Heat transfer mechanisms in the EAHE system

The operation of an EAHE system relies fundamentally on the transfer of thermal energy between the ambient air flowing through a buried pipe and the surrounding soil. This heat exchange process is governed by a combination of convective, conductive, which act across different domains of the system as shown in Figure 2.4.

As air flows through the pipe, it undergoes forced convection, exchanging heat with the internal pipe wall. Simultaneously, the pipe wall conducts heat radially to or from the surrounding soil, which acts as a thermal reservoir. The efficiency and direction of this thermal exchange depend heavily on the temperature gradient, airflow characteristics, soil thermal properties, and pipe geometry.

To analyse the thermal behaviour in detail, the system is divided into three key zones: the air inside the pipe, the air inside the rooms and the soil domain. Each zone involves distinct heat transfer modes that are coupled through thermal resistances and boundary conditions.

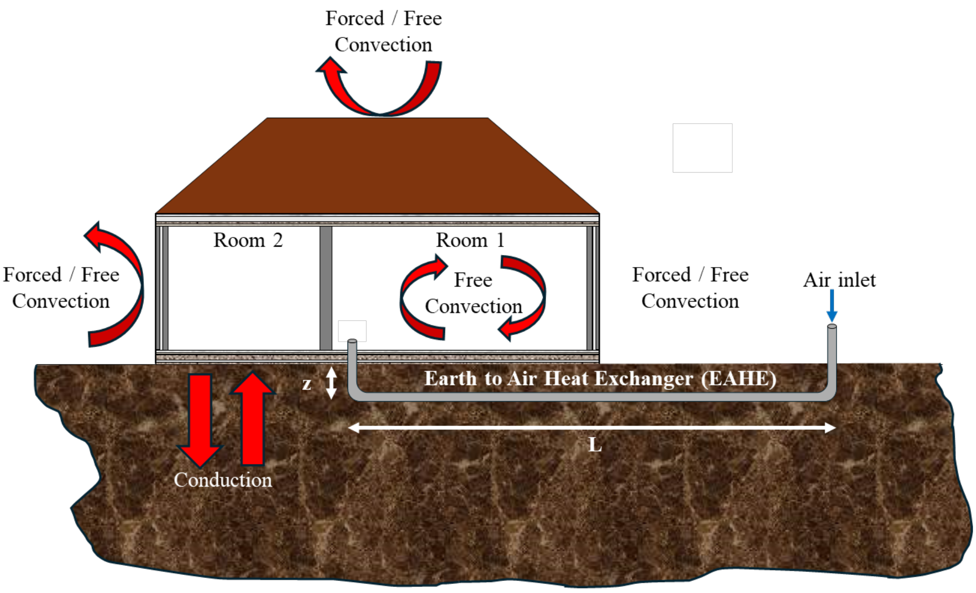


Figure 2.4. Heat transfer modes within the system.

2.4.1 Heat transfer inside the pipe

Within the buried pipe of the EAHE system, the primary mode of heat transfer between the air and the inner pipe surface is forced convection. As ambient air is drawn through the pipe it interacts thermally with the pipe walls, whose temperature is influenced by the surrounding soil. The nature of this convective heat transfer depends largely on the airflow velocity, pipe diameter, pipe length and thermal properties of air.

To characterize the convective behaviour, the flow regime is first determined using the Reynolds number and it is defined as:

$$Re = \frac{\rho v D}{\mu}$$

where:

ρ is the air density [kg/m^3],

v is the mean air velocity [m/s],

D is the pipe diameter [m],

μ is the dynamic viscosity of air [Pa·s].

For most EAHE applications, the airflow tends to be laminar (Re<2300) or transitional.

Based on the Reynolds number (Re), appropriate empirical correlations are used to estimate the Nusselt number (Nu), which relates convective to conductive heat transfer at the pipe surface. For fully developed laminar flow in a circular pipe with constant surface temperature, the Nusselt number is typically:

$$Nu = 3.66$$

For turbulent flow, the Dittus-Boelter equation is commonly applied:

$$Nu = 0.023\, Re^{0.8}\, Pr^{n}$$

where:

Pr is the Prandtl number,

Re is the Reynolds number,

$n = 0.3$ for cooling (air releasing heat), or $n = 0.4$ for heating (air gaining heat).

From the Nusselt number, the convective heat transfer coefficient h_{tube} is obtained using the following equation:

$$h_{tube} = \frac{Nu\, k}{D}$$

Where: k is the thermal conductivity of air [W/m·K].

The convective heat transfer rate q_{conv_tube} between the air and the pipe wall can then be calculated using Newton's law of cooling:

$$q_{conv\_tube} = h_{tube}\, A\, (T_{tube} - T_{air})$$

This heat exchange affects the temperature profile of the airflow along the pipe's length, leading to either cooling or heating depending on the season and the temperature difference between the air and the soil temperature.

2.4.2 Heat transfer through the pipe wall

The heat transfer through the pipe wall of an EAHE occurs primarily via radial conduction, bridging the thermal interaction between the air inside the pipe and the soil surrounding it. This stage serves as a critical thermal resistance path in the overall system, with the effectiveness of heat transmission largely governed by the thermal conductivity of the pipe material, wall thickness, and pipe geometry.

Assuming one-dimensional radial conduction in a cylindrical coordinate system, the heat flux through the pipe wall can be expressed using Fourier's law:

$$q_{cond\_tube} = \frac{2\,\pi\,L\,k_{tube}\,(T_{in} - T_{out})}{ln(r_o/r_i)}$$

Where:

q_{cond_tube} is the heat transfer rate [W],

L: pipe length [m],

k_{tube} is thermal conductivity of pipe material [W/m·K],

T_{in} and T_{out} are the inner and the outer pipe wall temperatures [°C],

r_i and r_o are the inner and the outer radii of the pipe [m].

2.4.3 Heat transfer in the surrounding soil

The soil around the buried pipe in an EAHE system plays a crucial role in heating or cooling the air. When air flows through the pipe, it gains or releases heat depending on the temperature difference between the air inside the pipe and the surrounding soil.

This heat transfer occurs mainly through conduction, which means the heat moves from warmer to cooler areas by direct contact through the soil particles.

The soil stores a large amount of heat and behaves like a thermal battery. During hot periods, it absorbs excess heat from the air inside the pipe and during cold periods, it releases stored heat to warm the incoming air.

The deeper the pipe is buried, the more stable the soil temperature becomes, which helps maintain a more reliable performance.

A simplified correlation often used for radial heat conduction into the soil is:

$$q_{cond\_soil} = \frac{2\,\pi\,L\,k_{soil}\,(T_{pipe} - T_{soil})}{ln\,(r_\infty/r_o)}$$

Where:

q_{cond_soil} is the heat transfer rate [W],

k_{soil} is the thermal conductivity of the soil [W/m·K],

L is the length of the pipe [m],

T_{pipe} is the outer surface temperature of the pipe [°C],

T_{soil} is the average temperature of the undisturbed soil [°C],

r_o is the outer radius of the pipe [m],

r_∞ represents a far distance where soil temperature remains constant [m].

2.4.4 Heat transfer inside the building

Once the preconditioned air exits the EAHE pipe and enters the indoor space (Room 1), it begins to mix with the indoor air and transfer heat to or from the room depending on the season. This occurs primarily through natural convective heat transfer driven by differences in temperature and air density

The heat transfer can be estimated using Fourier's law of convection and it is defined as:

$$q_{conv\_room} = h_{room}\, A\, (T_{room} - T_{air})$$

Where:

q_{conv_room} is the heat exchanged [W],

h_{room}: convective heat transfer coefficient [W/m²·K],

A: surface area involved in exchange [m²],

T_{air}: temperature of the EAHE air [°C],

T_{room}: temperature of indoor air [°C].

2.4.5 Heat transfer around the building

The interaction between the building's exterior surfaces and the surrounding environment greatly affects the indoor thermal comfort and the overall performance of the EAHE system.

$$q_{conv\_walls} = h_{wall}\, A_{wall}\, (T_{wall} - T_{air})$$

And

$$h_{wall} = \frac{Nu_H\, k}{H}$$

Where:

q_{conv_walls} is the heat exchanged [W],

h_{wall}: convective heat transfer coefficient [W/m²·K],

A_{wall}: surface area involved in exchange [m²],

T_{air}: temperature of the EAHE air [°C],

T_{wall}: temperature of indoor air [°C].

The heat transfer over the external walls of the building is strongly dependent of the shape, orientation of the walls and the wind velocity over the walls to determine the nature of the airflow and the heat transfer nature.

2.5 Model assumptions

To simplify the complex behaviour of the EAHE system and make the mathematical model tractable, several assumptions are adopted.

These assumptions are based on physical reasoning, typical boundary conditions, and standard practices in thermal-fluid modelling. They allow for efficient simulation while preserving the essential dynamics of airflow, heat transfer, and interaction with the surrounding environment.

The assumptions are grouped below into thematic categories:

2.5.1 Geometry and airflow

The airflow inside the buried pipe is assumed to be one-dimensional, meaning that air moves only along the pipe's axis from the inlet to the outlet, without significant radial or swirl components. The inlet air is considered to have a constant velocity profile. Inside the building, the air enters naturally into Room 1 without the aid of any mechanical redistribution system, allowing passive air diffusion to dominate the indoor air distribution.

2.5.2 Heat transfer behaviour

The model accounts for unsteady (transient) heat transfer, where temperatures within the air and pipe change over time. Radiative heat transfer is considered negligible. Additionally, there is no internal heat generation assumed within the system's materials (air, pipe, or soil).

2.5.3 Material and environmental properties

The soil is modeled as homogeneous and isotropic, meaning its thermal properties are constant in all directions and time. The thermophysical properties of air, pipe, and soil such as thermal conductivity, density, and specific heat are assumed constant and do not vary with temperature either with time.

Thermal contact between the pipe and the surrounding soil is considered perfect, implying no thermal resistance at the interface.

2.6 Integration of the Air Handling Unit (AHU) in EAHE systems

In practical applications of Earth-Air Heat Exchanger (EAHE) systems, the preconditioned air from the buried pipe does not typically enter the building directly. Instead, it first passes through an Air Handling Unit (AHU) a critical component in modern HVAC systems that conditions and distributes the air to ensure indoor comfort, air quality, and thermal efficiency. The AHU acts as an intermediary between the EAHE and the living spaces, refining the air and adjusting its properties to match indoor environmental needs more accurately.

2.6.1 Working principle of the AHU

The Air Handling Unit works by drawing the preconditioned air from the EAHE and further processing it before it is distributed into the rooms. Based on thermal comfort requirements and indoor air quality standards, the AHU may heat, cool, filter, humidify, or dehumidify the air. It operates by regulating these processes dynamically in response to external and internal environmental conditions. The unit typically works in closed-loop or open-loop systems, depending on whether it recirculates indoor air or continuously uses fresh outdoor air.

2.6.2 Main components of an AHU and their functions

An AHU consists of various components to deliver high quality air to the indoor space and are illustrated in the Table 2.1.

Table 2.1. Main components of an AHU and their functions.

Components	Function	Role
Air Filter	Removes dust, pollen, and other airborne particles from the air to improve indoor air quality and protect internal components of the system.	Ensures the air entering the house is clean and safe for occupants.

Fan / Blower	Moves the air through the system, from the EAHE to the AHU and then into the building.	Maintains airflow and pressure throughout the duct network.
Heating / Cooling Coil	Adjusts the temperature of the air using water or refrigerant coils, based on thermal requirements.	Provides additional heating in winter or cooling in summer when the EAHE alone is not sufficient.
Humidifier/ Dehumidifier	Adds or removes moisture from the air.	Maintains indoor humidity within comfort and health standards
Mixing Box	Mixes return indoor air with fresh air from the EAHE.	Enhances energy efficiency by reusing partially conditioned indoor air.
Control System	Monitors air quality, temperature, humidity, and pressure	Regulates operation of all AHU components to maintain optimal conditions.

2.6.3 Importance of AHU in EAHE systems

The AHU significantly enhances the overall performance of the EAHE by ensuring that the air delivered indoors is not only thermally conditioned but also clean, safe, and comfortable. It compensates for seasonal or hourly variations in outdoor climate and adds flexibility and control to the passive EAHE setup. This integration is especially valuable in climates with high humidity, pollution, or significant daily temperature swings.

CHAPTER 3. NUMERICAL MODELLING OF THE EAHE

3.1 Introduction

This chapter presents the numerical modelling of the Earth-Air Heat Exchanger system using COMSOL Multiphysics, based on the Finite Element Method (FEM).

The model is developed in 2D to simulate heat and airflow behaviour inside the buried pipe and its interaction with the surrounding soil and indoor environment.

The goal is to evaluate how changes in pipe diameter (2 to 20 cm), pipe length (7 to 20 m), burial depth (1.5 to 4.5 m), and inlet air velocity (0.5 to 2 m/s) affect the thermal performance of the system.

3.2 Numerical modelling

The numerical model of the Earth-Air Heat Exchanger system was developed using COMSOL Multiphysics, a multi-physics simulation software that applies the Finite Element Method (FEM) to solve coupled partial differential equations. The model integrates fluid flow and heat transfer processes to simulate how air flowing through a buried pipe, exchanges heat with the surrounding soil before entering a residential space.

A two-dimensional (2D) modelling approach is adopted to simplify the computational domain while maintaining sufficient accuracy in representing the heat and mass transfer mechanisms. The model consists of three primary regions: the airflow domain inside the pipe, the surrounding soil medium and a simplified indoor domain is included to observe the temperature distribution inside the residential room where the pipe discharges.

To ensure realistic representation, a conjugate heat transfer setup is used to couple the heat transfer between the air, pipe, and surrounding soil. The simulations are run in a transient (unsteady-state) mode to capture the time-dependent nature of thermal interactions and variations in outlet air temperature. A parametric study is performed to evaluate the impact of key variables on EAHE performance:

- pipe diameter (D), varied from 2 to 20 cm,

- pipe length (L), varied from 7 to 20 m,

- burial depth (z), varied from 1.5 to 4.5 m below the ground surface,

- inlet air velocity (V_{in}), changed from 0.5 to 2 m/s to assess its effect on heat transfer efficiency.

3.3 Model geometry description

A 2D numerical model was developed to simulate the thermal behaviour of a residential building integrated with an EAHE.

The geometry consists of three main domains: the soil, the EAHE pipe, and a building with two adjacent rooms. The building envelope is modelled with multilayer walls to account for material thermal properties and insulation.

The soil area around the house and the buried pipe is extended far enough to the sides and deep underground. This is done to make sure that the heat transfer between the pipe and the soil happens naturally, without being affected by the edges of the model. By making the soil domain large, we avoid errors that could happen if the boundaries were too close to the pipe or the house.

The EAHE is modelled as a single pipe, buried horizontally beneath the soil. The length (L) buried depth (z), and the diameter (D) are key design parameters analyzed to evaluate their effect on system performance. The model also considers varying inlet air velocities at the pipe entrance to study the dynamic influence of airflow rate on thermal performance.

The EAHE pipe is placed at a horizontal distance from the building and connects to the first room, where preconditioned air is released without any mechanical mixing system inside the building to allow the analysis of passive air diffusion.

3.4 Meshing strategy

The numerical domain is designed in two-dimensions (2D) to reduce computational complexity while accurately representing the physical configuration of the EAHE system. The modelled geometry consists of three main subdomains:

3.4.1 Air domain (pipe interior)

Represented as a horizontal o rectangular channel through which the air flows. The dimensions of this domain are varied based on the parametric study, particularly the pipe length (7–20 m) and pipe diameter (2–20 cm).

3.4.2 Soil domain

The soil domain is a rectangular soil block extending sufficiently in all directions to avoid boundary influence. The burial depth is varied from 1.5 m to 4.5 m in different cases.

3.4.3 Indoor zone

A simplified air region inside the house is placed at the outlet of the pipe to observe temperature behaviour due to the introduced preconditioned air. No mechanical ventilation is modelled to preserve the passive nature of the system.

A structured mesh with refinement near critical zones is used to ensure accuracy without excessive computation time as presented in Figure3.1.

- Finer mesh elements are applied around the pipe–soil interface and within the pipe to capture steep temperature and velocity gradients.

- Coarser elements are applied in the outer soil region where gradients are smaller.

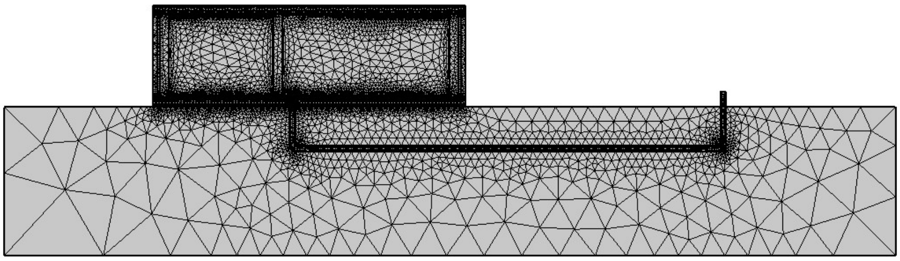


Figure 3.1. Mesh applied to the EAHE system using COMSOL Multiphysics.

3.5 Governing equations

The performance of an Earth-Air Heat Exchanger (EAHE) system is fundamentally governed by the principles of fluid flow and heat transfer. To accurately model the thermal and hydraulic behaviour of the air as it travels through underground pipes, a set of coupled governing equations is applied.

These include the conservation of mass, which ensures the continuity of air flow, the conservation of momentum, which accounts for the forces driving and resisting the airflow within the pipes, and the conservation of energy, which describes the temperature changes due to heat exchange between the air and the surrounding soil.

3.5.1 Mass conservation

The mass conservation equation ensures that the amount of air entering and leaving a control volume is balanced

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)=0$$

Where:

$\rho=\rho(x,y,t)$ is air density (kg/m^3),

$u=u(x,y,t)$ and $v=v(x,y,t)$ are velocity components in x and y directions respectively (m/s).

3.5.2 Momentum conservation (Navier-Stokes equations)

The momentum conservation equations describe the air slow motion inside the pipe and the house in x and y axes, based on pressure differences and friction with the walls.

x-momentum

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

y-momentum

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\rho g_y$$

Where:

$p=p(x,y,t)$ is pressure (Pa),

μ is dynamic viscosity (Pa·s),

g_x and g_y are components of gravitational acceleration along x and y axes (m/s^2).

3.5.3 Energy conservation

The energy equation tracks the heat transfer between the air and the surrounding soil, and air and the surrounding walls mainly through convection and conduction

$$\rho c_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)$$

Where:

$T = T(x, y, t)$ is air temperature (K),

c_p is specific heat capacity (J/kg·K),

k is thermal conductivity (W/m·K).

3.6 Boundary conditions

To ensure accurate representation of the physical processes within the EAHE system and the surrounding environment, boundary conditions were carefully defined for all components of the model. These boundary settings govern the behaviour of airflow and heat transfer in the pipe, soil, and building, and reflect realistic operating and environmental scenarios.

3.6.1 EAHE pipe inlet

Ambient air enters the system through the pipe inlet. The air is assumed to have a fixed inlet velocity, and the temperature is considered to be the surrounding ambient temperature as shown in Figure 3.2.

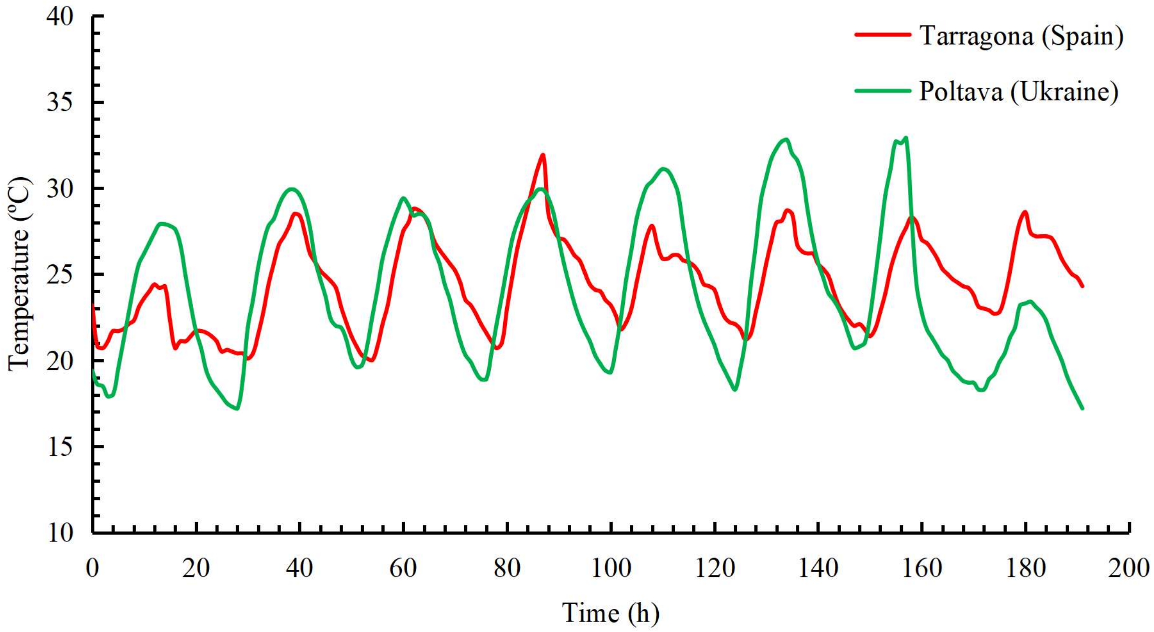


Figure 3.2. Ambient air temperature in Tarragona (Spain) and Poltava (Ukraine).

This boundary condition initiates the forced airflow through the buried pipe and determines the convective heat transfer between the moving air and the pipe wall.

3.6.2 EAHE pipe outlet (into Room 1)

The outlet of the EAHE is connected to Room 1 of the house. No additional mechanical fan or air redistribution system is used.

3.6.3 Soil domain boundaries

The depth should be sufficient to avoid interference with the heat exchange near the EAHE and prevent heat buildup or loss at the lower edge of the domain.

And the lateral extensions and the distance of the lateral walls of the soil domain in the numerical model should be large enough so the temperature gradient vanishes near the boundary. Soil temperature data as a function of depth, an essential factor for accurate EAHE modeling, were obtained from global and regional soil monitoring networks as well as scientific literature summarizing long-term soil thermal behavior in Spain and Ukraine.

Table 3.1. Average soil temperature in function of depth in Tarragona (Spain), and Poltava (Ukraine) [19].

Depth, m	Soil temperature, ºC	
	Tarragona (Spain)	Poltava (Ukraine)
1.5	17.0	9.5
2.5	16.5	9.0
3.5	16.0	8.5
4.5	15.5	8.0

3.6.4 Soil surface (top boundary)

The sol surface in contact with air is exposed to external climatic conditions. The heat transfer applied is external forced convective heat transfer. The solar radiation is neglected in this model.

3.6.5 Building envelope (walls, roof and floor)

The outer walls of the building are subjected to the surrounding climatic conditions. the parameters applied to the external walls are the ambient temperature as temperature and wind velocity to take into account force convective heat transfer around the external walls.

The internal walls of the building and the floor are considered solids, and the dominant heat transfer is conduction. Conductive heat transfer is also applied between the building's floor and the soil.

Table 3.2. Specific boundary conditions.

Domain	Position	Boundary	Condition
EAHE pipe inlet	Inlet	Velocity inlet	Inlet velocity = 0.5–2 m/s Ambient temperature
EAHE pipe outlet	Outlet (Room 1)	Pressure outlet	Atmospheric pressure
Soil domain	Bottom boundary	Temperature	Constant temperature
	Left & right sides	Adiabatic	q = 0 W/m²
	Top surface	Convective heat flux	Wind velocity Ambient temperature
Building	Outer walls & roof	Convective heat flux	Wind velocity Ambient temperature
	Floor	Heat conduction	Material thermal conductivity
	Internal Walls	Heat conduction	Material thermal conductivity

To accurately simulate the thermal behaviour of EAHE system and its interaction with the building and soil, specific boundary conditions were applied across different regions of the numerical model as illustrated in Table 3.2. The air enters the EAHE pipe through a velocity inlet where both velocity and temperature are predefined, simulating the influence of outdoor air conditions and ventilation control. At the outlet, the air discharges naturally into Room 1 under atmospheric pressure, allowing analysis of passive airflow distribution indoors. The soil domain is carefully defined with constant temperature conditions at the bottom, and insulated lateral edges, to prevent unrealistic thermal effects near the domain boundaries. A convective boundary is applied to the soil surface to model heat exchange with ambient air through natural convection.

The building envelope is represented with realistic assumptions: the roof and exterior walls experience convective heat transfer without wind influence, and the floor conducts heat from the soil to the interior. The walls are modelled as multilayered constructions, incorporating materials such as concrete, insulation, and plaster, to reflect actual thermal performance. Finally, the entire domain starts with a uniform initial temperature, forming the baseline for unsteady heat transfer analysis. These boundary settings together ensure a reliable, realistic simulation environment, allowing investigation of the EAHE's efficiency under varying geometric and operational conditions.

3.7 Detailed COMSOL model

The simulation of the EAHE system coupled with a conditioned room is structured within a single component in COMSOL Multiphysics to ensure full domain interaction and consistent Multiphysics coupling (Figure 3.3). The model begins with the Global Definitions, where all physical parameters are defined. These include dimensions, soil and wall material properties, air inlet conditions, and ambient temperature profiles. These parameters provide consistent input data for all physics and boundary conditions throughout the model.

All simulations in this thesis were performed using a detailed time-dependent framework, where input parameters such as ambient air and soil temperatures were dynamically set according to real meteorological records for each simulation hour. The entire data set analyzed corresponds to the period from July 24th, 2025, to July 31st, 2025, thereby capturing the actual thermal and climatic variations experienced during this specific summer week. Hourly values of ambient air temperature (Figure 3.2) for this time-frame were accessed via global climate data sources.

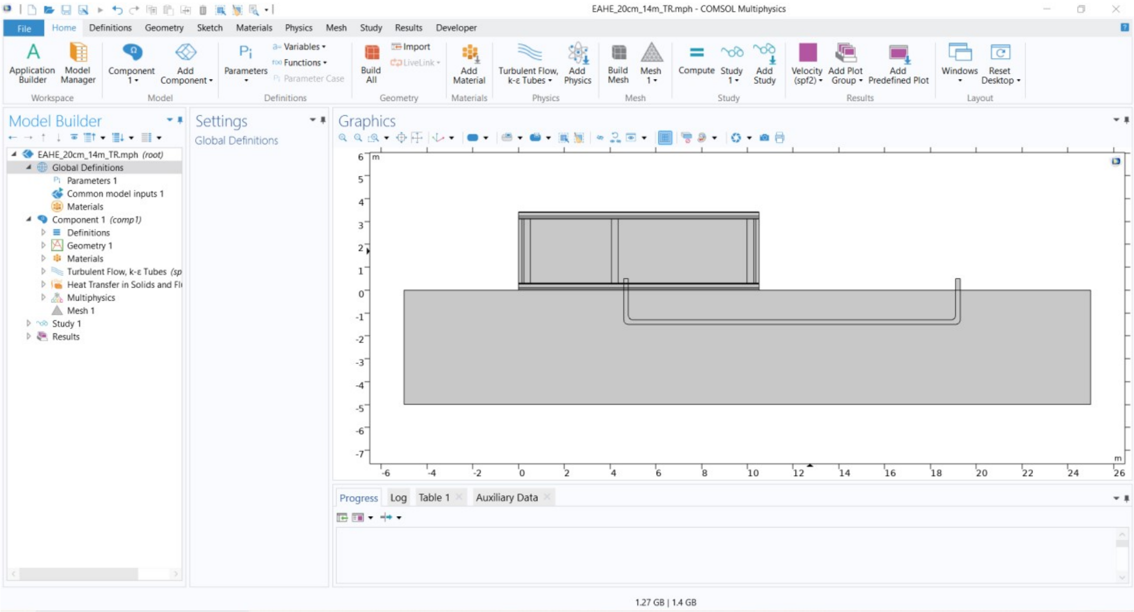


Figure 3.3. COMSOL Multiphysics interface.

Within Component 1, the entire geometry is constructed, incorporating the EAHE air domain (a cylindrical pipe), the surrounding soil block, the interior air domain of the rooms, and multilayered walls consisting of plaster, insulation, and concrete layers. The Materials node assigns the appropriate properties to each domain: air is used in both the pipe and rooms, while soil and solid building materials are assigned to their respective volumes.

The model incorporates several physics interfaces. The Laminar Flow / Turbulent Flow module is applied to both the EAHE pipe and the room to simulate low-Reynolds-number air movement forced convection in the pipe and free convection in the room.

The Heat Transfer in Fluids interface simulates convective and conductive heat transfer in the air domains, while the Heat Transfer in Solids module handles pure conduction in the soil and wall layers. These interfaces are coupled using the Non-Isothermal Flow Multiphysics node, which links the flow and temperature fields in the fluid regions, allowing for accurate modelling of temperature-dependent air density and viscosity effects.

The Mesh is structured to ensure sufficient resolution at critical areas. Finer meshing is applied at fluid-solid interfaces, such as the pipe-soil and air-wall contacts, and within wall layers to capture steep temperature gradients (Figure 3.1).

A Time Dependent Study is employed to simulate the transient behaviour of the system.

Finally, in the Results section, temperature and velocity fields are analyzed throughout the pipe, soil, and room domains. Key outputs include the temperature difference between inlet and outlet air in the EAHE, the heat flux exchanged with the soil, the indoor air temperature distribution, and the heat transmission through wall layers. These results allow for assessing the performance of the EAHE in conditioning indoor air and evaluating the building's overall thermal response.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the numerical results obtained from the simulation of an EAHE system under varying geometric and operating conditions. The objective is to evaluate the influence of key parameters as pipe length (7, 14 and 20 m), pipe diameter (2, 5, 10, 15 and 20 cm), and burial depth (1.5, 2.5, 3.5 and 4.5 m) as well as the inlet air velocity (0.5, 1, 1.5 and 2 m/s) on the system's thermal performance. The performance assessment is based on the analysis of the outlet air temperature, temperature reduction and the average air Room 1's temperature. A comparative analysis is carried out to identify how each parameter affects the cooling potential of the EAHE, highlighting interactions between geometry, depth, and inlet air velocity.

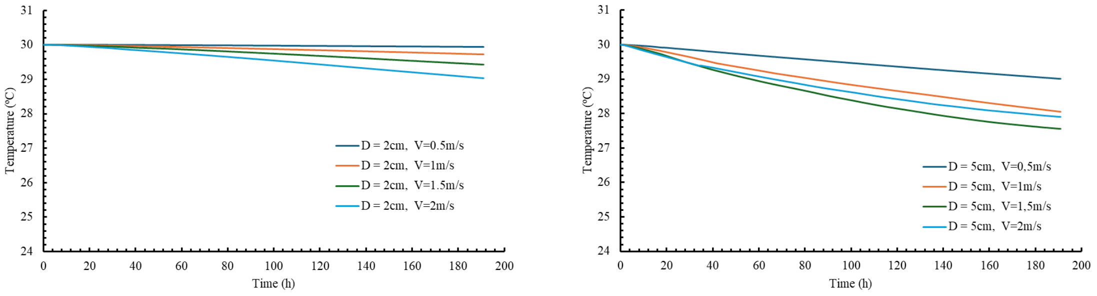
To thoroughly investigate the seasonal efficacy of EAHE systems, simulation periods were selected to represent summer extremes. In particular, one week from midsummer: July 24th to July 31st, 2025 was chosen as the primary case study for temperature-dependent modeling. This specific interval coincides with typical regional peak summer temperatures, thereby ensuring a realistic assessment of passive cooling system performance under maximum thermal load conditions. Selecting a full week allows for the capture of diurnal temperature cycles, short-term weather fluctuations, and the inherent lag in soil temperature response, providing a comprehensive and statistically relevant basis for evaluating EAHE behavior.

The simulations conducted for this research were explicitly designed to reflect the prevailing climatic conditions as defined by the Köppen-Geiger climate classification much of central and northern Ukraine is categorized as humid continental climate with warm summers and cold winters, featuring substantial annual and diurnal temperature amplitude. Spain generally falls under Mediterranean climate with hot or warm summers and mild winters [20].

4.2 Effect of pipe diameter

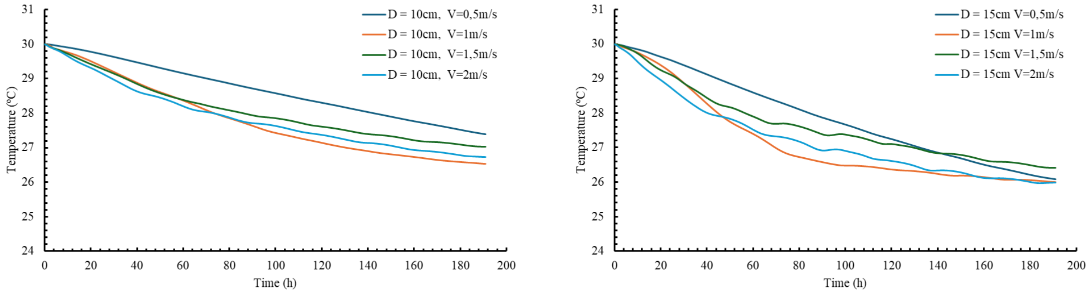
This sub-section evaluates the impact of pipe diameter on the thermal performance of the EAHE system under a constant pipe length (14 m) and a fixed burial depth of 1.5 m. The analysis considers diameters of 2, 5, 10, 15 and 20 cm while varying the inlet air velocity at 0.5, 1, 1.5 and 2 m/s. The objective is to examine how changes in diameter influence the air temperature behaviour.

4.2.1 Room 1’s temperature analysis



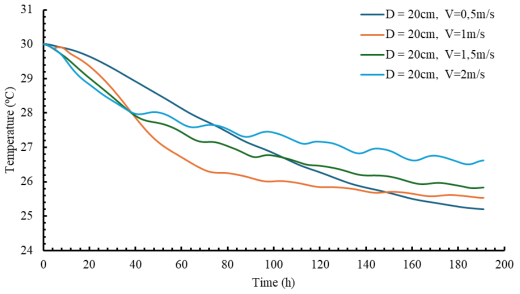
D=2 cm

D=5 cm



D=10 cm

D=15 cm



D=20 cm

Figure 4.1. Average temperature of the Room 1 in function of time for different inlet velocities and in function of different tube diameters.

Figure 4.1 presents the average temperature of Room 1 in function of time in the case of different diameters studied and also in function of different inlet air velocities. It can be seen that in all cases studied the temperature of the Room1 decreases with the increase of time. In the case of tube diameter of 2 cm the Room1’s temperature remains slightly the same as the initial temperature of 30 ºC especially in the case of inlet air velocity of 0.5 and 1 m/s. The extremely small diameter restricts airflow within the tube and reduces the interaction and consequently limits the heat transfer between the air and the tube wall and also it has small heat transfer area. As the tube diameter increases, the average Room 1’s temperature at the end of the simulation decreases and the average temperature of the Room 1 reaches the lowest value in the case of 1 m/s for tube diameter of 10 cm and 15 cm. In the case of tube diameter of 20 cm the temperature reaches a minimum value in the case of inlet air velocity of 0.5 m/s but the temperature evolution within the Room1 in the case of inlet air velocity of 1 m/s decreases rapidly because lower velocities allow cooler outlet temperature but supply less total air to the Room 1. Contrarily in the case of higher velocity, it allows cooler outlet temperature, and it supplies more total air to the Room 1.

Since the lowest temperature of the Room 1 at the end of the simulation resulted from the cases of inlet air velocity of 1 m/s in most tube diameter cases, this velocity is considered to compare all the tube diameters under the same inlet air velocity of 1 m/s. Figure 4.2 shows the average temperature evolution of Room 1 in function of time for all diameters studied. It can be seen from this figure that the temperature of the Room decreases with the increase of tube diameter, and it reaches the lowest value in the case of diameter of 20 cm. The largest diameter allows more surface area between the air the tube wall for better heat transfer, and it supplies more total cooler air to the Room 1.

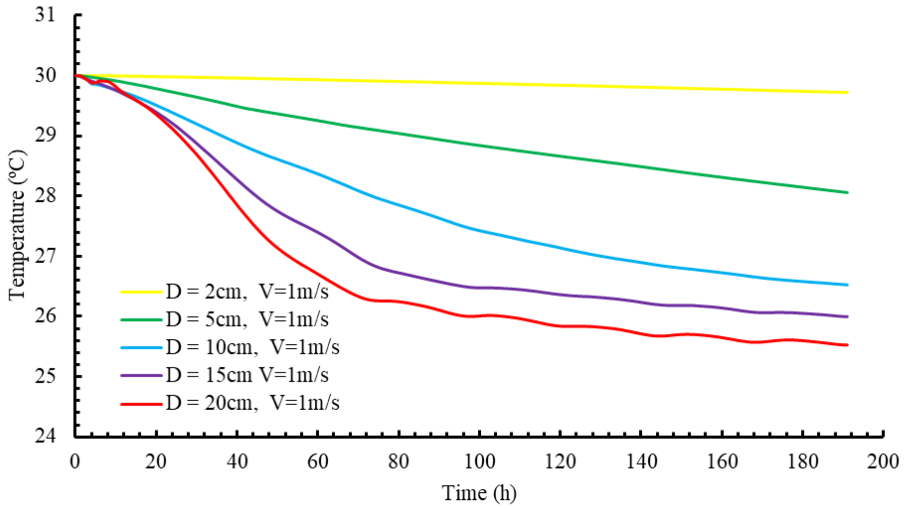
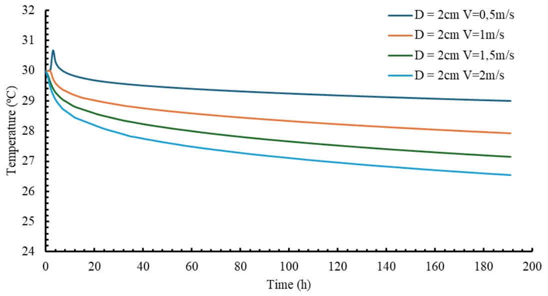
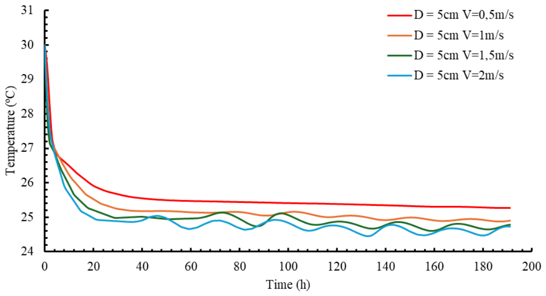


Figure 4.2. Average temperature of the Room 1 in function of time for different tube diameters in the case of inlet velocity of 1m/s.

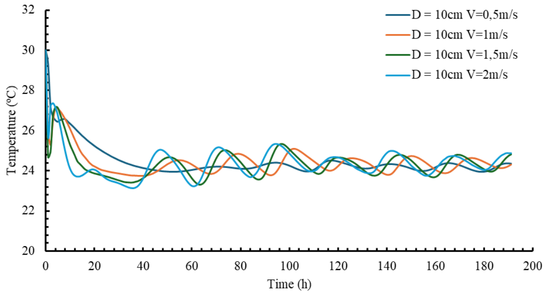
4.2.2 Outlet temperature analysis



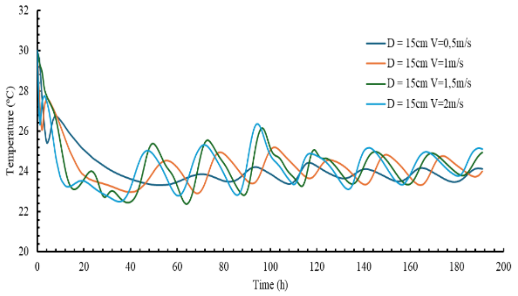
D=2 cm



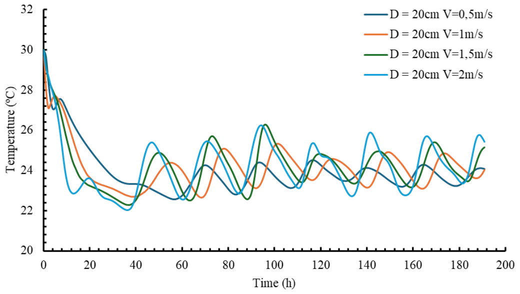
D=5 cm



D=10 cm



D=15 cm



D=20 cm

Figure 4.3. Outlet temperature of air in function of time for different inlet velocities and in function of tube diameter.

Figure 4.3 shows the temperature evolution of the air outlet in function of time for all the diameter studied and under the impact of inlet air velocities. It can be seen that the temperature at the outlet decreases with the increase of time in all cases in the beginning of the simulation and then it oscillates about an average temperature of 24 ºC because the temperature oscillation of the ambient temperature between the days and nights. In the beginning the temperature decreases sharply because of the large temperature difference between the air and the soil.

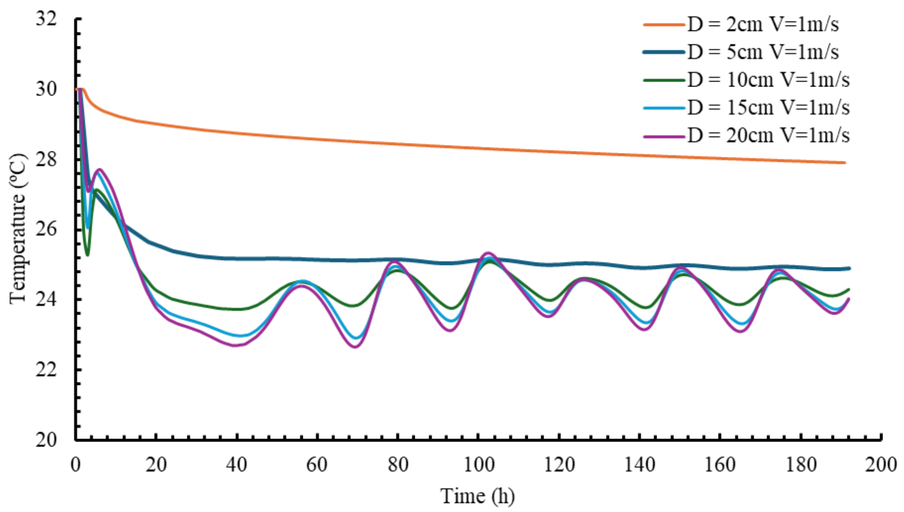
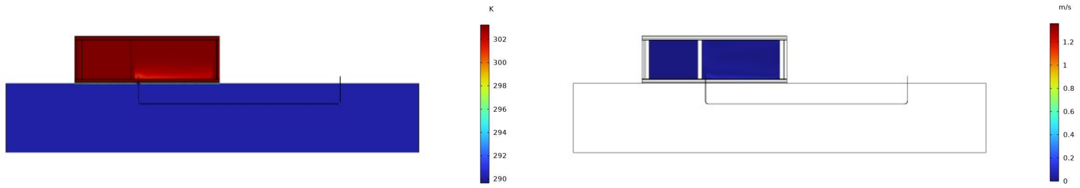


Figure 4.4. Outlet temperature of air in function of time for different tube diameters in the case of inlet velocity of 1m/s.

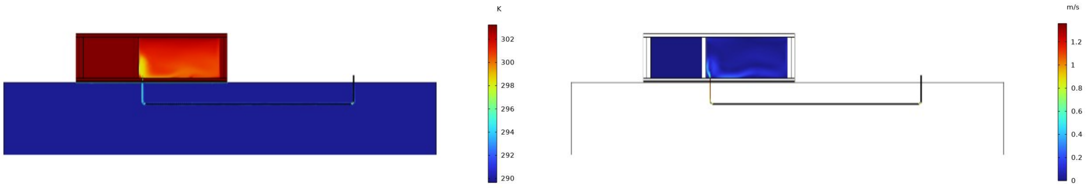
With time the soil temperature surrounding the tube increases which results small temperature difference. The oscillations in the outlet temperature are due to periodic fluctuations in inlet ambient temperature as shown in the Figure 4.4. In the case of tube diameter of 2 cm, the temperature remains significantly higher than the others, with a slower cooling rate and higher final temperature of about 28°C. This is due to the larger pressure drop, lower airflow area, and less contact surface for effective heat transfer. In the case of tube diameters of 5, 10 and 20 cm), the outlet air temperature drops quickly about 24°C and show more pronounced oscillations and achieve the lowest outlet temperatures of about 23°C, suggesting improved heat transfer due to greater airflow.

4.2.3 Temperature contours

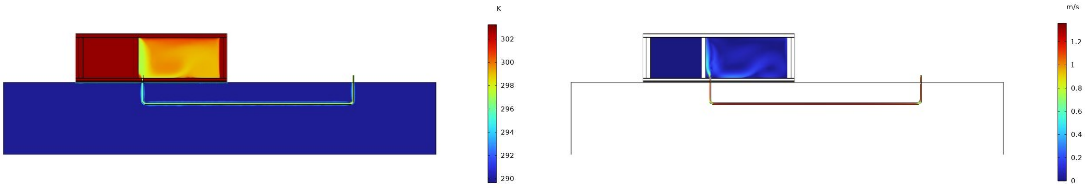
The temperature contours at the end of each simulation and in the case of air inlet velocity of 1m/s are presented to visualize the thermal evolution of the EAHE system.



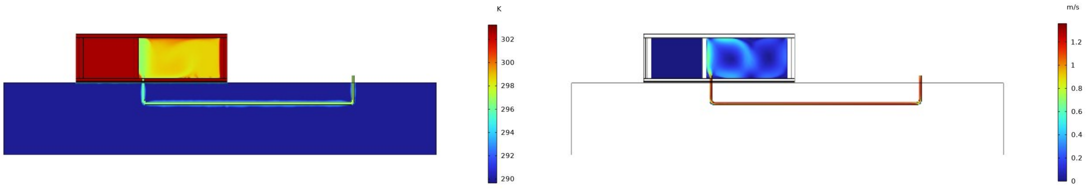
D=2 cm, L=14 m



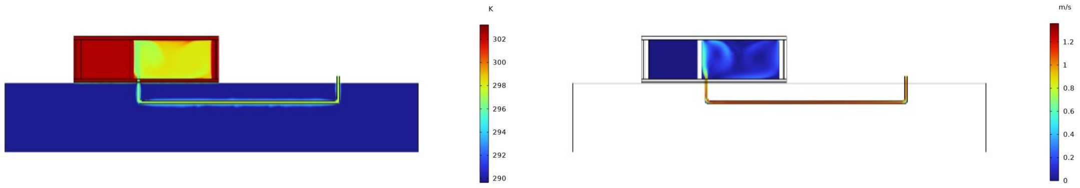
D=5 cm, L=14 m



D=10 cm, L=14 m



D=15 cm, L=14 m



D=20 cm, L=14 m

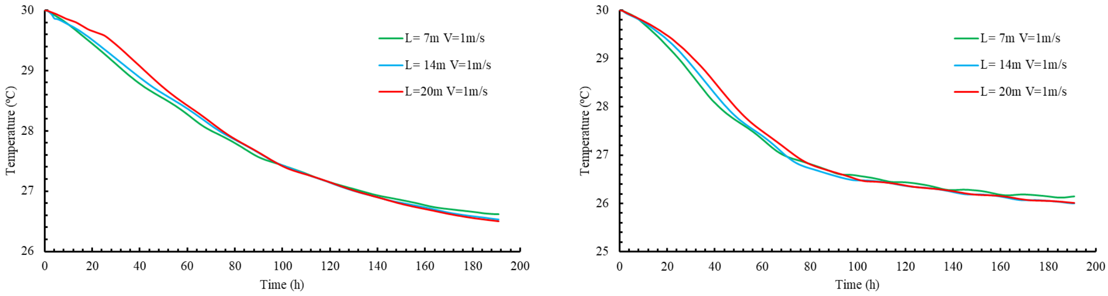
Figure 4.5. Temperature contours (left) and velocity contours (right) in function of tube diameter and in the case of inlet velocity of 1m/s.

Figure 4.5 shows the temperature contours on the left and the airflow behaviour on the right side for different tube diameter (2, 5, 10, 15 and 20 cm) in the case of pipe length of 14 m and a burial depth of 1.5 m. From this figure it can be seen clearly that the entering air exchanges heat with the soil and as it moves along the pipe, it cools down. When the air enters the Room 1, it is cooler than the initial air temperature, so the interior cools down also. For lower pipe diameters (2cm and 5 cm) the temperature of the whole Room 1 remains near the initial temperature of 30ºC, and as the pipe diameter increases the temperature within the Room 1 decreases. The temperature of the Room 1 is more homogeneous when the pipe diameter is 20 cm. And this is related to the airflow movement as shown on the right column of Figure 4.5, as the diameter increases the mixing inside Room 1 is higher resulting more homogenous temperature.

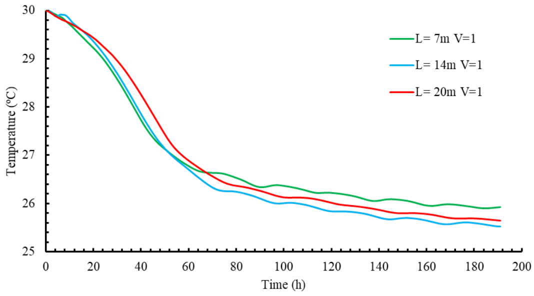
4.3 Effect of pipe length

This sub-section evaluates the impact of pipe length on the thermal performance of the EAHE system under different pipe diameters and a fixed burial depth of 1.5 m. The analysis considers lengths of 7, 14 and 20 m and an inlet air velocity at 1 m/s.

4.3.1 Room 1's temperature analysis



D=10 cm D=15 cm



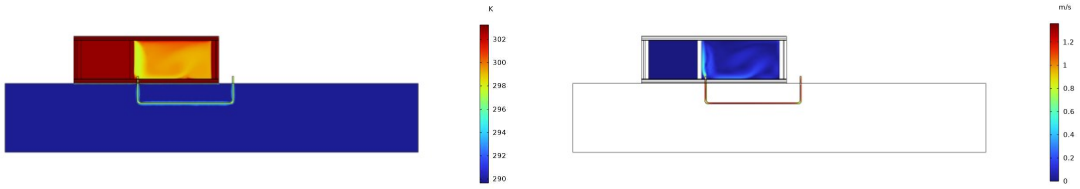
D=20 cm

Figure 4.6. Average temperature of the Room 1 in function of time for different tube lengths and in function of different tube diameters.

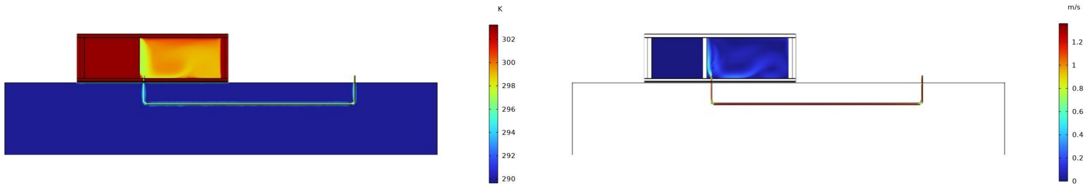
Figure 4.6 presents the average temperature of Room 1 in function of time in the case of different diameters studied and also in function of pipe length in the case of inlet air velocity of 1m/s. It can be seen that in all cases studied the temperature of the Room1 decreases with the increase of time.

In the case of tube diameters of (10 cm and 15 cm) the temperature evolution of the three pipe lengths studied is the same with a small deviation. In the other hand, in the case of tube diameter of 20 cm the air Room 1 temperature has a small difference between the tube lengths studied. For all three pipes lengths the air temperature decreases rapidly in the first-time steps, reflecting effective initial heat exchange with the soil.

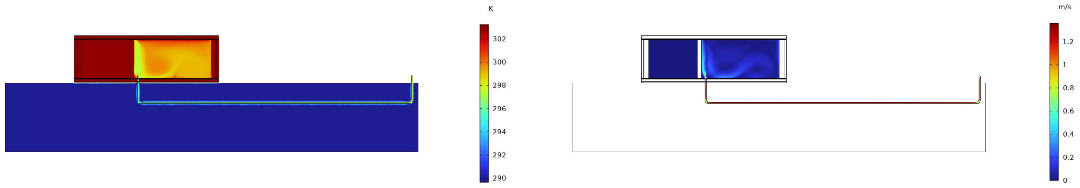
4.3.2 Temperature contours



L=7 m, D=10 cm

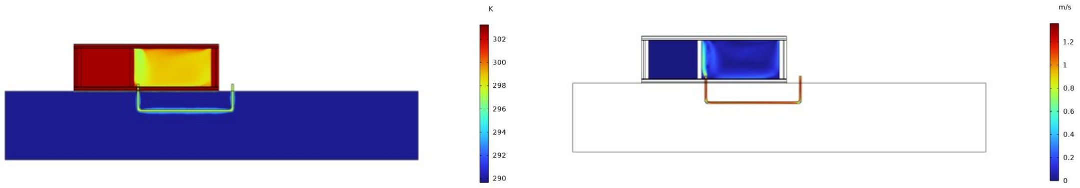


L=14 m, D=10 cm

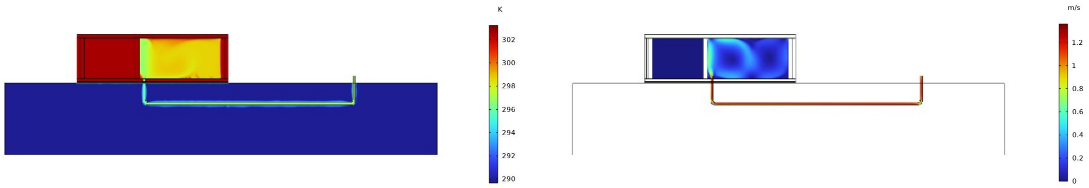


L=20 m, D=10 cm

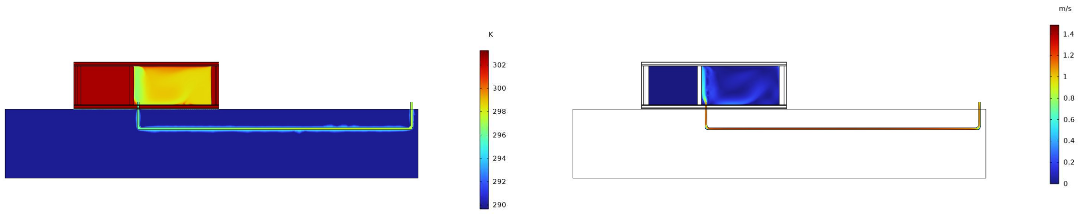
Figure 4.7. Temperature contours (left) and velocity contours (right) in function of tube length and in the case of inlet velocity of 1m/s and tube diameter of 10 cm.



L=7 m, D=15 cm

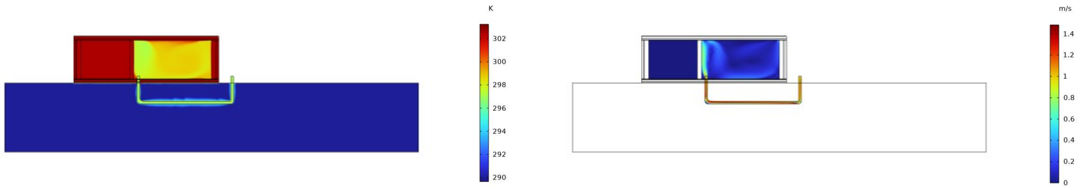


L=14 m, D=15 cm

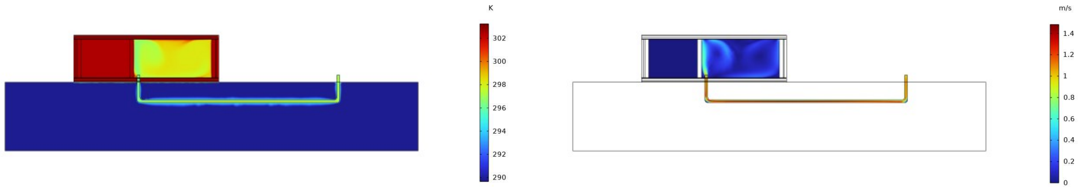


L=20 m, D=15 cm

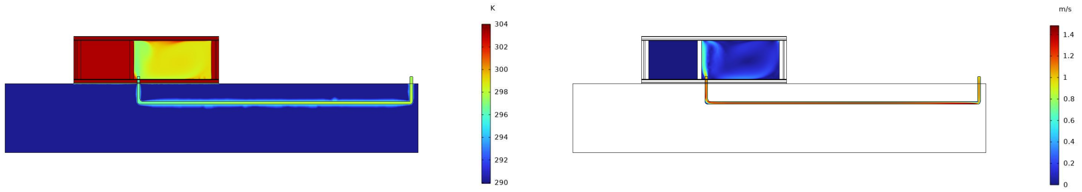
Figure 4.8. Temperature contours (left) and velocity contours (right) in function of tube length and in the case of inlet velocity of 1m/s and tube diameter of 15 cm.



L=7 m, D=20 cm



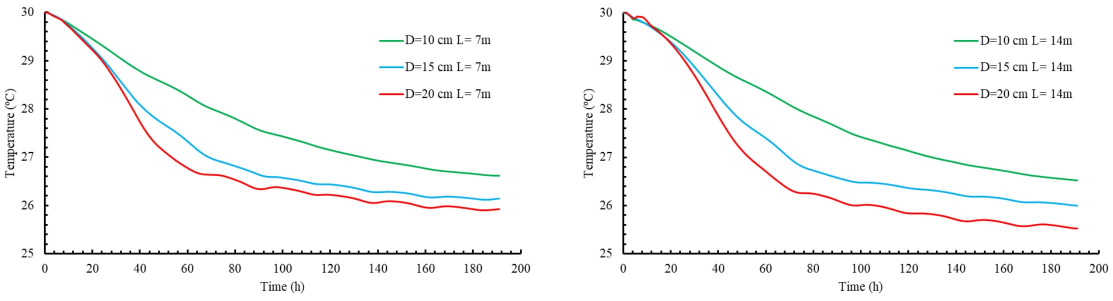
L=14 m, D=20 cm



L=20 m, D=20 cm

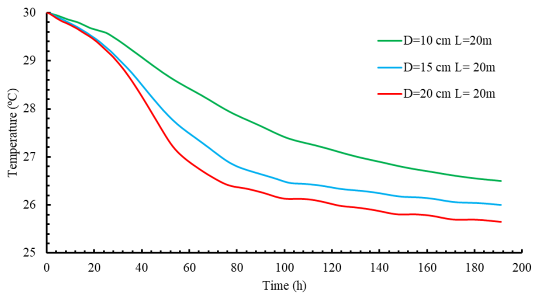
Figure 4.9. Temperature contours (left) and velocity contours (right) in function of tube length and in the case of inlet velocity of 1m/s and tube diameter of 20 cm.

Figures (4.7-4.9) show the temperature contours on the left and the airflow behaviour on the right side for different tube diameter (10, 15 and 20 cm) and different tube lengths (7, 14 and 20 m) in the case of a burial depth of 1.5 m and an inlet air velocity of 1 m/s. Comparing the temperature contours of all the cases presented, the average temperature of the Room 1 is slightly the same when fixing the diameter of the tube.



L=7 m

L=14 m



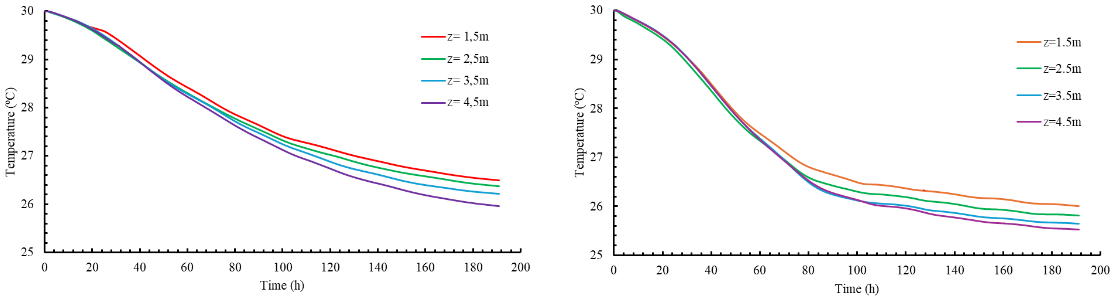
L=20 m

Figure 4.10. Average temperature of the Room 1 in function of time for different tube diameters and in function of different tube lengths.

Figure 4.10 presents the average Room 1 temperature in function of time for different tube diameters and in function of different tube lengths in the case of inlet air velocity of 1 m/s and the burial depth of 1.5m. It can be noticed that as the tube diameter increases, the average Room 1's temperature at the end of the simulation decreases and the average temperature of the Room 1 reaches the lowest value in the case of 1 m/s for tube diameter of 20 cm. Contrarily in the case of higher velocity, it allows cooler outlet temperature, and it supplies more total air to the Room 1.

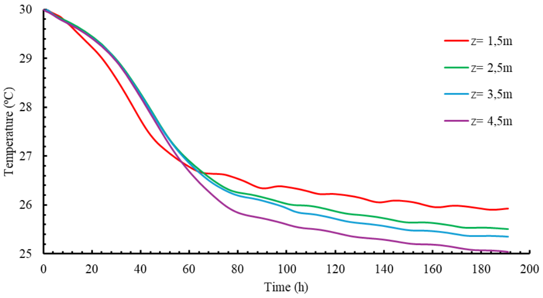
4.4 Effect of burial depth

4.4.1 Room 1's temperature analysis



D=10 cm, L=20 m

D=15 cm, L=20 m

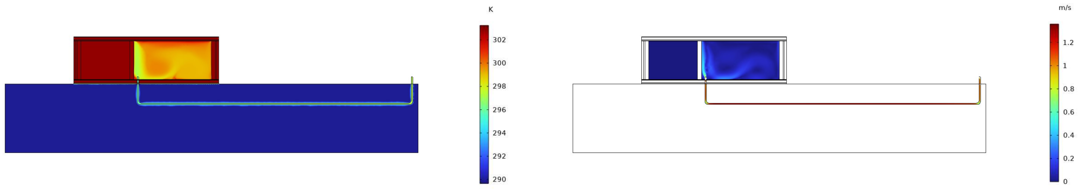


D=20 cm, L=20 m

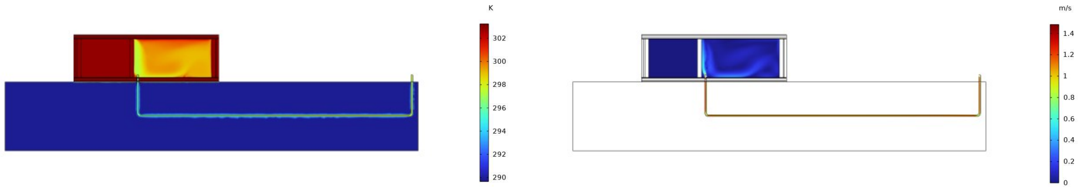
Figure 4.11. Average temperature of the Room 1 in function of time for different tube diameters and in function of burial depth in the case of inlet velocity of 1m/s and tube length of 20 m.

Figure 4.11 shows the average temperature of Room 1 in function of time in the case of different diameters studied and in function of burial depth in the case of inlet air velocity of 1m/s and tube length 20m. The air temperature decreases in the buried pipe strongly depends on the pipe depth in the ground, so the deeper the tube, the cooler the soil and average air Room 1 temperature is lower. At 4.5m of depth, air is cooled from 30ºC to 25ºC along 20m of buried pipe. So, the outlet average temperature drops for D=20 cm compared to D=10cm and D=15 cm at similar burial depth, suggesting improved cooling efficiency due to the large pipe surface area facilitating heat transfer.

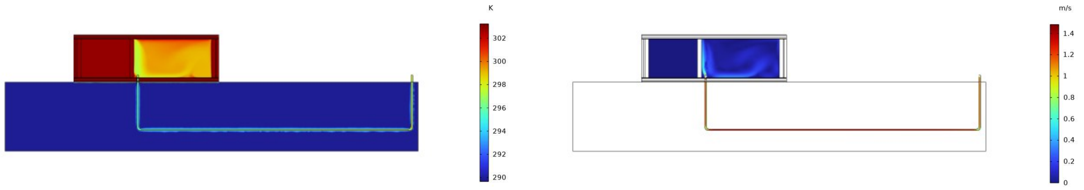
4.4.2 Temperature contours



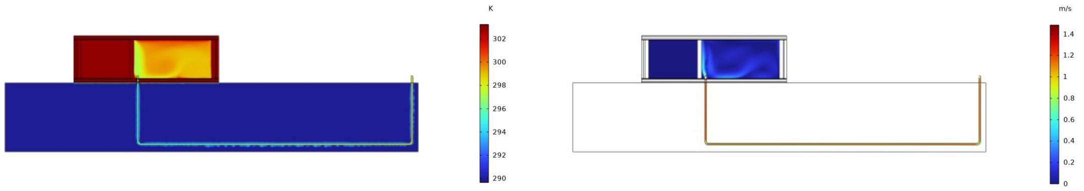
z=1.5 m, D=10 cm



z=2.5 m, D=10 cm

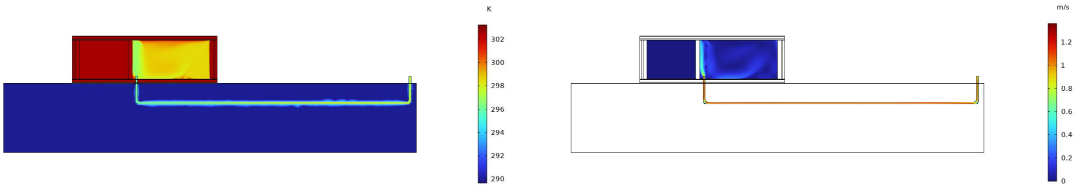


z=3.5 m, D=10 cm

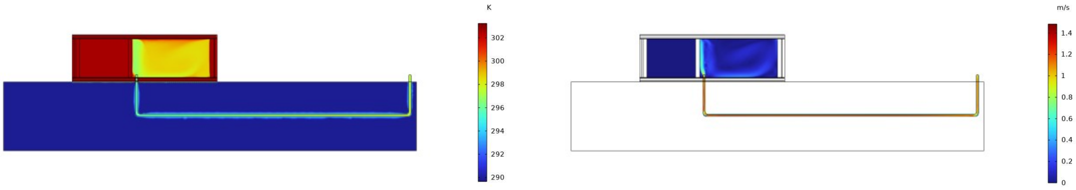


z=4.5 m, D=10 cm

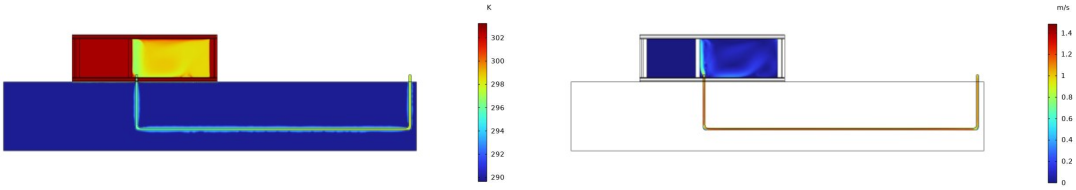
Figure 4.12. Temperature contours (left) and velocity contours (right) in function of burial depth and in the case of inlet velocity of 1m/s and tube length of 20 m and pipe diameter of 10 cm.



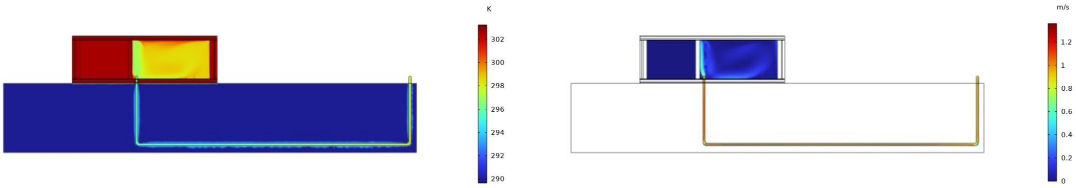
z=1.5 m, D=15 cm



z=2.5 m, D=15 cm

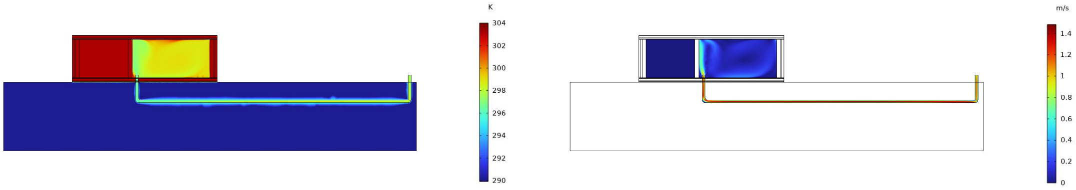


z=3.5 m, D=15 cm

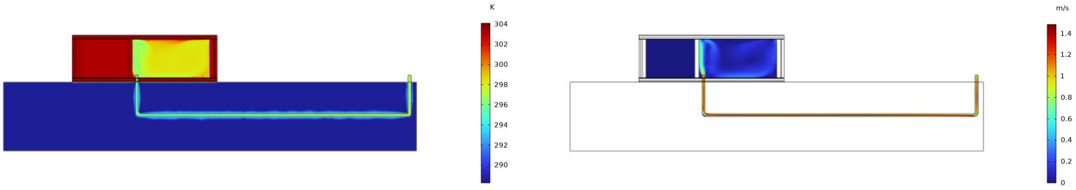


z=4.5 m, D=15 cm

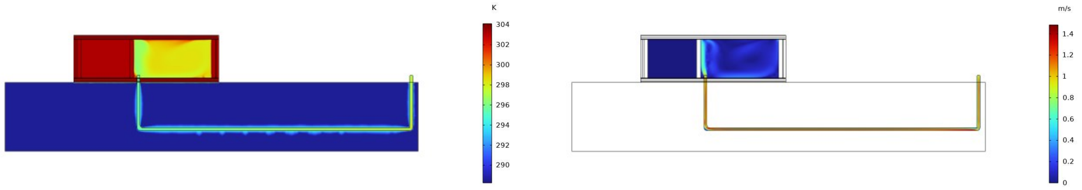
Figure 4.13. Temperature contours (left) and velocity contours (right) in function of burial depth and in the case of inlet velocity of 1m/s and tube length of 20 m and pipe diameter of 15 cm.



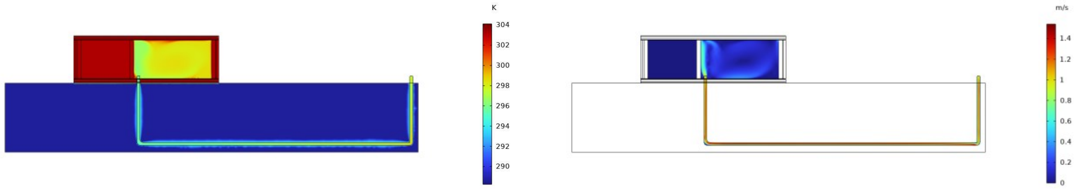
z=1.5 m, D=20 cm



z=2.5 m, D=20 cm



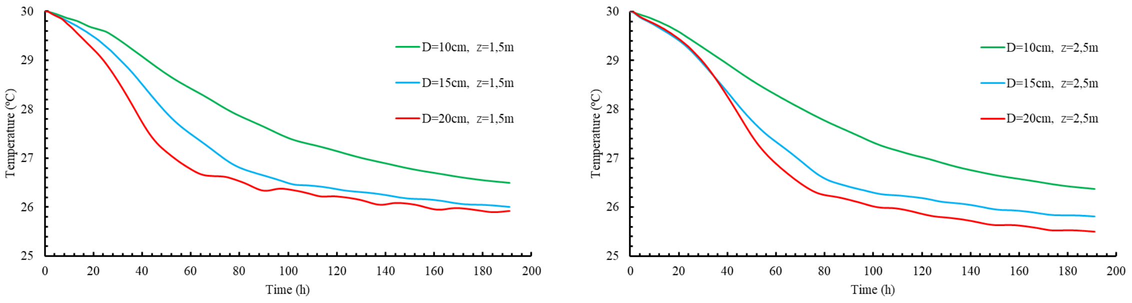
z=3.5 m, D=20 cm



z=4.5 m, D=20 cm

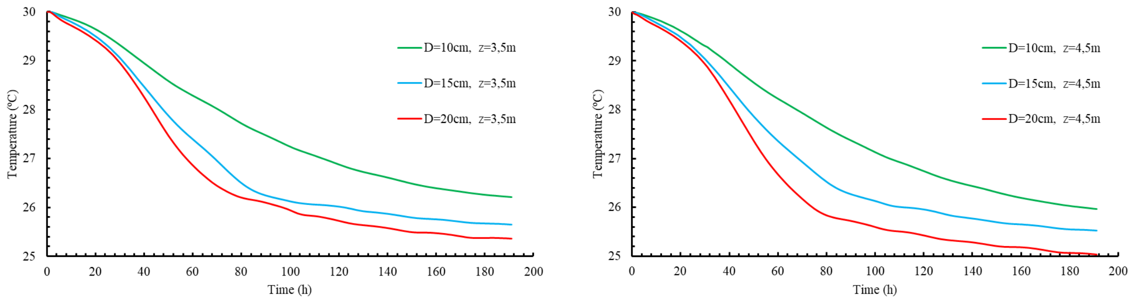
Figure 4.14. Temperature contours (left) and velocity contours (right) in function of burial depth and in the case of inlet velocity of 1m/s and tube length of 20 m and pipe diameter of 20 cm.

Figures (4.12-4.14) show the temperature contours on the left and the airflow behaviour on the right side for different tube diameter (10, 15 and 20 cm) and different tube lengths (7, 14 and 20 m) in the case of a burial depth of 1.5, 2.5, 3.5 and 4.5 m and an inlet air velocity of 1 m/s. Comparing the temperature contours of all the cases presented, the average temperature of the Room 1 is more and more homogenous when increasing the diameter of the tube and also when increasing the burial depth. From these figures it can be concluded that the average Room 1 temperature is highly affected by the burial depth of the tube inside the earth.



z=1.5 m, L=20 m

z=2.5 m, L=20 m



z=3.5 m, L=20 m

z=4.5 m, L=20 m

Figure 4.15. Average temperature of the Room 1 in function of time for different tube diameters and in the case of inlet velocity of 1m/s and tube length of 20 m.

Figure 4.15 presents the average Room 1 temperature in function of time and in function of tube diameter for different burial depths in the case of inlet air velocity of 1 m/s and the tube length of 20 m. It can be seen that as the depth increases, the average Room 1 temperature increases. Also, the average Room 1 temperature increases by increasing the tube diameter. Deeper soil layers have more stable and cooler temperature due to less influence from daily and seasonal surface temperature variations. The temperature difference between depths shows that even with a larger diameter, burial depth remains a critical design for maximizing cooling efficiency.

4.5 Optimal configuration

Based on the parametric study performed using COMSOL Multiphysics, the optimal configuration for an EAHE system in the Tarragona region during summer was identified as a pipe with a diameter of 20 cm, a length of 20 m, buried at a depth of 4.5 m, and an air velocity of 1 m/s. This combination delivers the most effective thermal performance because it maximizes the heat transfer surface area while ensuring sufficient residence time of air for heat exchange. The 20 cm diameter significantly reduces pressure losses compared to smaller diameters, resulting in lower fan energy consumption, while providing a higher flow capacity for ventilation. The 20 m pipe length ensures a sufficiently large heat transfer area. Additionally, the depth of 4.5 m places the pipe in a zone of stable and cool soil temperature, largely unaffected by daily fluctuations, which enhances cooling stability throughout the hottest periods. The selected velocity of 1 m/s represents an ideal trade-off between maximizing convective heat transfer and minimizing pumping energy, ensuring both performance and energy efficiency.

4.6 Case study

Based on simulations in COMSOL Multiphysics for an EAHE, the system was tested using a pipe with a diameter of 20 cm, a length of 20 m, and an air velocity of 1 m/s, with the initial temperature of Room 1 fixed at 30 °C. The goal was to compare the cooling effect in two locations with different soil temperatures: Tarragona, Spain (15.5 °C) and Poltava, Ukraine (8 °C). The results show that soil temperature strongly affects the cooling performance. In Tarragona, the room temperature decreased from 30 °C to 25,04°C, giving a cooling of about 5 °C. In Poltava, the room temperature dropped further, reaching 22,52°C, which is about 7.5 °C lower than the starting temperature.

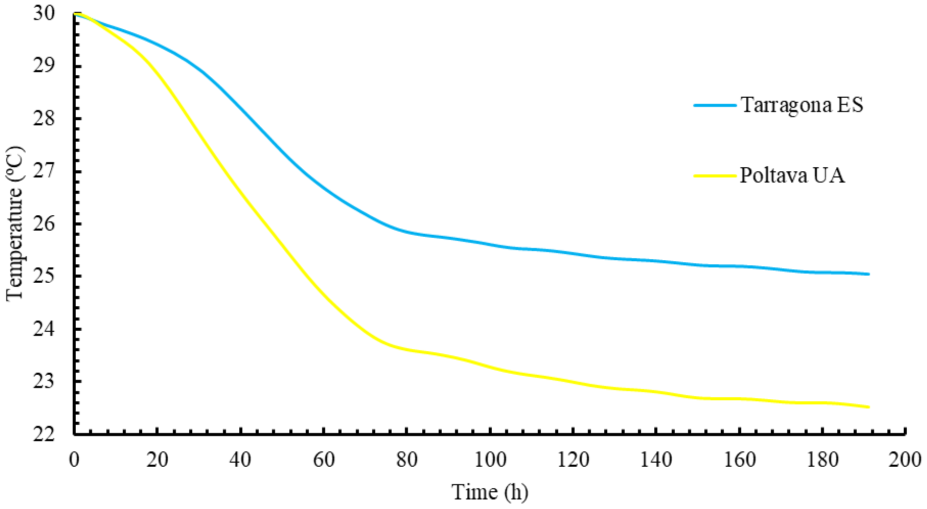


Figure 4.16. Average temperature of the Room 1 in function of time for different locations and in the case of inlet velocity of 1m/s, diameters of 20cm and tube length of 20 m.

The cooling process happens in two stages. At the beginning, the temperature drops quickly because the difference between the air and soil is large. Later, the cooling becomes slower because the temperature difference gets smaller. The pipe size and airflow speed were chosen to balance heat transfer and energy use. A larger diameter reduces pressure loss and makes airflow easier, while the 20 m length gives enough surface area for heat exchange without making the system too long.

The study shows that soil temperature is the main factor that decides how much cooling the EAHE can give. In a warmer soil like in Tarragona, the system can only cool down to around 25 °C unless the pipe is buried deeper or made longer. In colder soil, like in Poltava, the system performs better with the same design. These results are based on simplified conditions: constant soil properties, no groundwater movement, and a single straight pipe. For real applications, more detailed studies should include soil moisture, layered soil structure, seasonal changes, and multiple pipes to improve accuracy and optimize the system design.

4.7 Conclusions

This study aimed to evaluate the influence of geometric and operating parameters on the thermal performance of an EAHE system through numerical simulations carried out in COMSOL Multiphysics. The analysis focused on four main factors: pipe diameter, pipe length, burial depth, and airflow velocity, with the objective of identifying the configuration that maximizes cooling efficiency while maintaining practical feasibility. Once the optimal configuration was determined, it was applied to two different climatic contexts Tarragona, Spain, and Poltava, Ukraine in order to assess the effect of local soil temperature on system performance. According to the numerical simulations the following conclusions summarize the key findings of the parametric study and the comparative analysis between the two locations:

- increasing the pipe diameter significantly improves the cooling performance of the EAHE. Larger diameters reduce pressure losses, increase airflow capacity, and provide greater surface contact for heat exchange, while still maintaining sufficient residence time;
- longer pipes increase the total heat transfer surface and allow the air to approach more closely the soil temperature;
- deeper placement of pipes showed better reduction of average air temperature in the room and, accordingly, better cooling;
- lower velocities increase residence time and enhance heat exchange but reduce airflow delivery. Higher velocities increase flow but reduce thermal contact;
- the optimal EAHE configuration was found to be a 20 cm diameter pipe, 20 m long, buried at 4.5 m depth, with an airflow velocity of 1 m/s. The study confirms that while geometric and operating parameters strongly affect performance, the soil temperature at the site remains the dominant factor in determining the final cooling capacity of the EAHE;
- when applying the optimal configuration to two different sites, the soil temperature proved to be the key factor. In Tarragona, where the average soil temperature is 15.5 °C, the EAHE reduced the room temperature from 30 °C to about 25 °C. In Poltava, where the soil temperature is lower (8.0 °C), the system achieved a greater cooling effect, lowering the room temperature to approximately 22.5 °C. This comparison highlights that colder soil conditions strongly enhance EAHE performance.

CHAPTER 5. CONCLUSION

This chapter presents the conclusion of the work of this thesis. The comprehensive assessment of passive cooling with Earth–Air Heat Exchangers clearly demonstrates that this technology offers a reliable and energy-efficient means of maintaining comfortable indoor temperatures without reliance on conventional active air conditioning systems. EAHE systems leverage the thermal inertia of the earth: by drawing ambient air through underground pipes, the system pre-cools ventilation air during summer months and can provide thermal moderation year-round. Extensive research and simulation confirm that the performance of an EAHE is governed primarily by system design namely pipe length, burial depth, diameter, and airflow rate as well as the thermal properties and stability of the soil. Significant reductions in room air temperature depending on the design and local soil characteristics, have been consistently reported in both experimental and simulation-based studies.

Through a systematic review of international literature, numerical simulations, and parametric analyses, this thesis has elucidated the critical parameters affecting EAHE performance, such as pipe length, diameter, burial depth, soil temperature, and inlet air velocity. Both past studies and experimental campaigns in Ukraine and Mediterranean climatic zones have demonstrated that, when appropriately designed, EAHE systems can consistently reduce incoming air temperature by 5 to 8°C during peak summer periods, utilizing the stable subsurface soil temperature to buffer indoor environments against extreme heat events.

Integrating Earth-Air Heat Exchangers with other passive cooling strategies further enhances the effectiveness and resilience of building thermal management. Rational system design increasingly favors a hybrid approach, where EAHEs are combined with elements such as high thermal-mass structures, night ventilation, advanced shading systems, green walls, or solar chimneys to maximize overall passive cooling capacity and comfort.

In summary, the findings of this thesis establish that, when properly designed and adapted, EAHE systems are capable of substantially improving building energy performance, indoor thermal comfort, and environmental sustainability. Their ability to deliver reliable passive cooling with low operational input confirms their place as a central strategy for resilient and sustainable architectural design. The evidence from recent scientific literature, practical demonstration projects, and parametric thermal analyses all converge to reinforce the conclusion that EAHE technology is a vital tool for advancing the future of low-energy and environmentally responsible building practice.

FUTURE WORK

It is suggested that future studies should focus on refining the numerical model and broadening the analysis. More detailed investigations could include the influence of soil moisture variation, non-homogeneous thermal properties, and seasonal fluctuations. It is also recommended that the geometry of the buried tubes be modified by considering longer ducts, spiral configurations, and multiple parallel pipes, as these changes may enhance the heat transfer area and improve system efficiency. Further work could also explore alternative layouts such as branching networks and hybrid systems integrating EAHE with renewable energy sources. These enhancements are expected to provide a more accurate representation of EAHE performance and to support the development of optimized designs for different climatic and soil conditions. As well as coupling EAHEs with building information modeling (BIM) and smart control systems.

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