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Technical article

A Passive Decarbonisation Approach for Hot-Arid Residential Structures: CFD Study of a Courtyard Earth-Air Heat Exchanger in Baghdad Assisted by Thermal Thrust

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A B S T R A C T

One of the biggest contributors to the world's energy consumption and carbon emissions is the building industry, especially in hot and dry countries where the yearly building energy use is dominated by the need for cooling. Passive cooling techniques that can lessen reliance on traditional air conditioning systems are desperately needed in Iraq due to the country's severe summer heat and ongoing electricity problems. The effectiveness of a thermal thrust-assisted courtyard earth-air heat exchanger (EAHE) as a passive cooling option for residential structures in Baghdad is examined in this study. Using ANSYS Fluent, a three-dimensional computational fluid dynamics (CFD) model was created to simulate heat transfer and airflow in an underground pipe system under typical local soil and climate conditions. The impacts of pipe diameter (0.2–0.4 m), pipe length (30–80 m), pipe burial depth (1–5 m), and inlet air velocity (1–5 m/s) were methodically assessed. According to simulation results, an ideal balance between thermal performance and pressure losses is achieved with a burial depth of roughly 3 m, pipe length of 60 m, and pipe diameter of 0.25 m. At an intake velocity of 1 m/s, the suggested system was able to reduce the air temperature by up to 20.75 °C during the hottest summer months. Passive airflow and cooling performance are greatly improved when thermal buoyancy (stack effect) is integrated with a courtyard-based EAHE. The findings show that the suggested solution can help hot, dry residential buildings lower their cooling energy consumption and related carbon emissions. These results show how low-carbon building design in Iraq and other climates can be supported by combining contemporary passive cooling technologies with traditional courtyard architecture.

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1. INTRODUCTION

Approximately one-third of the world's carbon dioxide emissions and over 40% of all energy usage are attributed to the building sector. The heating and cooling systems needed to ensure indoor thermal comfort

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account for a significant amount of this energy requirement. Cooling demand accounts for the majority of building energy use in hot and dry locations, especially in the summer. As a result, increasing building energy efficiency and putting passive cooling techniques into practice have emerged as crucial elements of international decarbonisation initiatives.

Iraq has among of the Middle East's highest summertime temperatures, often rising above 45 °C. Due to the widespread usage of mechanical air conditioning systems, these harsh weather conditions result in a significant increase in the demand for electricity. However, there are serious problems with the country's electrical infrastructure, which leads to frequent power outages and an unstable energy supply in the summer. Therefore, it is now crucial to develop passive cooling technologies that can lower cooling demands in residential structures.

In the Middle East, passive environmental techniques, including interior courtyards, shading devices, thick walls, and natural ventilation, have long been part of traditional architectural approaches. By offering shade, encouraging air circulation, and lowering solar heat gains, courtyard buildings in particular have been crucial in controlling microclimatic conditions. Even if they work well, there is still a dearth of modern technical solutions combined with old passive design techniques in Iraqi residential buildings (Fakoush & Rama 2012).

The earth-air heat exchanger (EAHE), one of several passive cooling systems, has drawn more interest since it can pre-cool incoming air by using the comparatively steady temperature of underground soil. This technique involves passing ambient air through subterranean pipes where heat exchange takes place between the surrounding earth and the airflow. EAHE systems can successfully lower the temperature of incoming ventilation air before it enters the building since soil temperatures at depths of around 2-4 meters stay much lower than ambient air temperatures during the summer (Baglivo et al. 2018) & (Zhao et al. 2023).

Thermal buoyancy, commonly referred to as the stack effect, can improve natural airflow in addition to geothermal cooling effects. Warmer air rises and cooler air descends due to thermal buoyancy, which happens when temperature differences cause density fluctuations in the air column. This phenomenon can greatly improve passive ventilation and cooling performance without requiring mechanical energy input when combined with architectural features like courtyards (Myroniuk et al. 2026).

EAHE systems have the ability to lower cooling loads in a variety of climatic zones, according to recent studies. Nevertheless, the majority of current research concentrates on classic horizontal buried pipe layouts without taking into account how they might be integrated with conventional architectural elements like courtyards. The combined impacts of courtyard-based EAHE systems and thermal buoyancy in hot, dry areas have also not been thoroughly studied.

As a result, this study suggests an integrated passive cooling approach that combines thermal buoyancy-assisted airflow with an under-courtyard earth-air heat exchanger. The method was created especially for residential buildings in Baghdad, where courtyard architecture is still relevant both architecturally and culturally. The thermal and fluid dynamic performance of the suggested system is assessed under typical climate conditions using computational fluid dynamics (CFD) simulations.

The study's findings are intended to offer design recommendations for incorporating passive geothermal cooling systems into residential buildings with courtyards in hot, dry areas. The suggested strategy helps to improve building energy efficiency and facilitate the shift to low-carbon and climate-responsive architecture by lowering reliance on mechanical cooling systems.

1.1. RESEARCH GAP

Even though earth-air heat exchanger systems have been extensively studied as passive cooling technologies, their integration with conventional courtyard architecture and buoyancy-driven airflow has not received enough attention, especially in hot and dry regions like Iraq. The majority of earlier research has been on horizontal EAHE designs without taking courtyard shading and thermal thrust effects into account. Furthermore, only a small amount of study has assessed the combined effects of geometric features and airflow characteristics of courtyard-based EAHE systems in Baghdad's unique climate.

1.2. RESEARCH OBJECTIVES

The main objectives of this study are:

1. To investigate the thermal and airflow performance of a thermal thrust–assisted courtyard earth–air heat exchanger system using computational fluid dynamics (CFD).

2. To assess how important design factors, such as pipe burial depth, pipe length, pipe diameter, and inlet air velocity, affect cooling performance.
3. To determine the best design arrangement that minimises pressure losses and maximises temperature reduction.
4. To evaluate the suggested system's potential as a passive decarbonisation method for homes in hot, dry regions.

1.3. NOVELTY AND CONTRIBUTION OF THE STUDY

The under-courtyard earth-air heat exchanger, courtyard-based architectural shade, and thermal buoyancy (stack effect)-driven airflow are the three main passive cooling techniques that this study integrates into a single system. Although earth-air heat exchangers have been studied as stand-alone systems in the past, little research has been done on how they may be integrated with buoyancy-driven ventilation and traditional courtyard architecture, especially given Iraq's climate.

Additionally, this work offers a thorough CFD-based parametric analysis of system performance taking into account pipe shape and airflow conditions, which has not been thoroughly covered in previous studies for hot-arid locations. The efficiency of the suggested integrated design is demonstrated by the obtained temperature reduction of up to 20.75 °C, which likewise surpasses values reported in various prior research.

2. LITERATURE REVIEW

2.1. PASSIVE COOLING TECHNIQUES FOR HOT, DRY CLIMATES

In order to lower building energy consumption and mitigate greenhouse gas emissions related to mechanical cooling systems, passive cooling techniques have grown in significance. Conventional air conditioning systems account for a large amount of building energy consumption in hot-arid locations where summer temperatures often surpass 40 °C. As a result, including passive cooling methods in building design is seen to be a crucial strategy for raising energy efficiency and lowering carbon emissions (Ascione et al. 2018).

In hot areas, a number of passive design techniques, such as shading systems, natural ventilation, thermal mass, evaporative cooling, and underground heat exchange systems, have been extensively researched. Passive cooling systems, which make use of natural environmental resources including solar radiation, airflow, and ground temperature, have a significant potential to lower building energy usage (Soni et al. 2024).

In many Middle Eastern and Mediterranean structures, courtyard design has long been a key component of passive environmental control. Through improved natural ventilation, controlled solar exposure, and shading, interior courtyards can produce microclimatic conditions that increase thermal comfort. Prior research has shown that courtyard shape, orientation, and opening arrangement have a major impact on building thermal performance and airflow patterns.

Parsons' research showed that the size of courtyards and the placement of openings affect how airflow behaves within them. Similarly, Sharples and Bensalem used wind tunnel experiments to study airflow patterns in courtyard buildings and discovered that ventilation efficiency and thermal comfort are strongly influenced by the presence and arrangement of openings (Mustapha et al. 2024; Sharples & Bensalem 2001; Parsons 1993).

2.2. EARTH-AIR HEAT EXCHANGERS FOR COOLING STRUCTURES

One of the most promising passive cooling solutions for buildings is earth-air heat exchangers (EAHE), sometimes referred to as ground-air heat exchangers. In order to facilitate heat exchange with the surrounding earth, these systems work by moving ambient air through subterranean pipes. EAHE systems may successfully lower air temperature in the summer and raise it in the winter since soil temperature stays comparatively constant at depths of two to four meters throughout the year (Yildiz et al. 2023).

The thermal performance of EAHE systems in various climatic locations has been the subject of numerous studies. In a thorough analysis of EAHE applications, Bisoniya et al. found that, depending on soil characteristics, pipe shape, and airflow conditions, temperature reductions of 10 to 18 °C are possible (Bisoniya et al. 2021). In a similar vein, Baglivo et al. showed that when combined with passive design techniques, EAHE systems can dramatically lower cooling demands in residential structures (Baglivo et al. 2018).

A number of design factors, such as pipe diameter, length, burial depth, soil thermal conductivity, and airflow velocity, affect how successful EAHE systems are. Heat exchange between the airflow and the soil is normally improved by longer pipes; however, overly lengthy pipes may cause greater pressure losses. Similarly, burial depth affects thermal stability since temperature changes are less pronounced in deeper soil layers (Al-Husseini & Yousri 2013).

Even though EAHE systems have been thoroughly studied in a variety of climates, the majority of research concentrates on traditional buried pipe layouts without taking into account how they integrate with architectural elements like courtyards.

2.3. THERMAL BUOYANCY AND STACK-DRIVEN VENTILATION

Density variations between warm and cool air create thermal buoyancy, also known as the stack effect, which is a natural ventilation mechanism. Warm air rises and escapes through upper apertures when indoor air is warmer than outdoor air due to buoyancy forces, while cooler air enters through lower openings. Natural airflow produced by this occurrence can greatly enhance building ventilation and thermal comfort (Al-Wattar 2013).

In passive building design, stack-driven ventilation has been employed extensively, especially in wind tower systems, solar chimneys, and atrium buildings. Bahadori showed that by utilising buoyant forces and pressure differences, conventional wind towers may successfully improve natural ventilation in hot areas (Bahadori 1985).

Thermal buoyancy can further improve passive airflow without the requirement for mechanical ventilation systems when paired with subterranean cooling systems like EAHEs. This combination strategy can reduce energy usage and increase cooling efficiency.

2.4. RECENT DEVELOPMENTS IN PASSIVE COOLING TECHNOLOGIES

Significant advancements in building energy efficiency in hot areas have been demonstrated by recent research on passive cooling solutions. Advanced techniques like solar-assisted cooling, earth-air heat exchangers, and hybrid ventilation systems have been extensively studied. According to recent research, including passive cooling with architectural features like courtyards and shading devices can greatly lower the energy required for cooling and enhance indoor thermal comfort. These advancements emphasise how crucial it is to improve system performance by fusing conventional design techniques with cutting-edge simulation technologies (Trzaski & Zawada 2011; Raheem et al. 2024; Riffat et al. 2026).

The increasing significance of incorporating passive cooling techniques into urban residential structures to lower carbon emissions has been emphasised by recent studies published in journals with a focus on sustainability and climate change. Passive technologies, such as earth-air heat exchangers, can significantly lower cooling energy demand and improve environmental performance, according to research in fields including sustainable cities, climate-responsive architecture, and energy-efficient building systems. In order to develop low-carbon building solutions in hot, dry locations, these studies highlight the necessity of fusing traditional architectural aspects with contemporary engineering techniques (Kong et al. 2017; Raheem & Raheem 2026; Lin et al. 2022; Raheem et al. 2026b).

2.5. RESEARCH GAP AND THE CURRENT STUDY'S CONTRIBUTION

Few studies have examined the integration of earth-air heat exchangers with courtyard-based ventilation systems and thermal buoyancy effects, despite the expanding corpus of research on EAHE systems and passive cooling technologies. The majority of current research concentrates on standalone EAHE systems without taking into account how they interact with building design techniques that can improve cooling and airflow.

Additionally, relatively few studies have looked at the use of such integrated systems in Iraq's unique climate, where passive cooling technologies are especially useful due to the country's severe summer heat and lack of energy.

Thus, by examining a thermal thrust-assisted courtyard earth-air heat exchanger system created especially for residential buildings in Baghdad, this study seeks to close this research gap. The suggested method is a unique passive cooling technique that can help lower building energy consumption and carbon emissions in hot, dry areas by fusing geothermal cooling with buoyancy-driven ventilation and conventional courtyard construction.

The powerful cooling potential of earth-air heat exchanger systems in hot regions has been validated by recent computational and experimental investigations. Depending on pipe layout, soil characteristics, and airflow, reported temperature drops usually fall between 10 and 18 °C. Furthermore, when combined with building ventilation systems, large-scale EAHE implementations have shown notable energy savings and carbon emission reductions. These results demonstrate the potential of EAHE technology as a crucial part of low-carbon building passive cooling methods.

EAHE systems have great promise as passive cooling systems, as evidenced by recent numerical simulations that suggest they can achieve temperature decreases between roughly 14 °C and 18 °C depending on airflow and soil conditions.

EAHE systems can dramatically lower indoor temperatures and increase energy efficiency in buildings situated in hot climes, according to experimental and numerical studies.

3. METHODOLOGY

3.1. RESEARCH APPROACH

The thermal and airflow performance of a courtyard-integrated earth-air heat exchanger system supported by thermal buoyancy is assessed in this study using a numerical simulation method. In order to investigate airflow patterns and heat transfer characteristics within the buried pipe system under representative climate conditions in Baghdad, Iraq, computational fluid dynamics (CFD) simulations were carried out.

CFD modelling is a potent technique for assessing passive cooling systems in buildings prior to actual deployment since it enables in-depth examination of fluid flow and heat transfer processes.

3.2. AN EXPLANATION OF THE SYSTEM UNDER CONSIDERATION

The suggested system is a subterranean air pipe placed under a residential building's shaded interior patio. Through an inlet opening, ambient air enters the pipe and passes through the subterranean portion, where heat exchange takes place between the airflow and the surrounding earth. Indoor areas are then supplied with the cooled air.

In the system, the courtyard serves two purposes. In the first place, it offers shade, which lowers the soil's surface temperature above the buried pipe. Second, buoyancy-driven ventilation, which is produced by temperature variations between inside and outside air, improves natural circulation.

The system may run mostly on passive forces thanks to this combination mechanism, greatly lowering the requirement for mechanical cooling systems.

Figure 1 shows the conceptual setup of the suggested passive cooling system. Through an intake close to the courtyard wall, ambient air enters the system and travels through an aluminium pipe that is buried beneath the courtyard at a depth of around three meters. Heat exchange between the airflow and the surrounding soil happens as the air passes through the pipe, keeping the temperature comparatively constant all year round.

The cooled air then enters the building interior, contributing to indoor thermal comfort. By offering shade that lowers ground surface heating and by encouraging buoyancy-driven airflow through thermal thrust effects, the courtyard improves system performance. The system may function mostly through passive mechanisms thanks to this integrated structure, reducing the requirement for mechanical cooling systems.

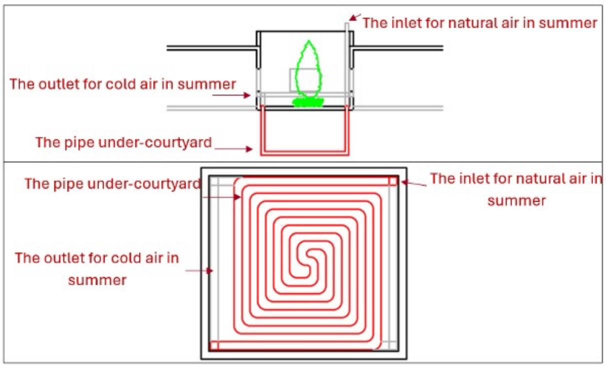

Figure 1. An illustration of the courtyard earth-air heat exchanger system with thermal thrust assistance.

Adopting passive design techniques that lessen reliance on energy-intensive cooling systems is necessary for the shift to low-carbon buildings. Passive cooling technologies, such earth-air heat exchangers, present a viable approach to lower energy use and related carbon emissions while preserving indoor thermal comfort in hot and dry areas.

3.3. GOVERNING PHYSICAL PRINCIPLES

The concepts of fluid dynamics and heat transfer control the system's airflow. The following is an expression for the buoyancy-induced pressure differential brought on by thermal thrust (Hasbullah et al. 2022):

$$\Delta P = \rho g H \left(\frac{T_i - T_o}{T_i} \right) \tag{1}$$

Where:
ρ is air density (kg/m³).
g is gravitational acceleration (9.81 m/s²).
H is the vertical height between inlet and outlet (m).
T_i and T_o are the indoor and outdoor air temperatures (K), respectively.
The building's ventilation is improved by the natural airflow created by this pressure differential.

3.4. CFD MODEL

A computational model of the buried pipe and surrounding soil domain was developed using ANSYS Fluent.

The following assumptions were adopted:

- It is believed that airflow is incompressible.
- It is anticipated that turbulent flow conditions.
- The characteristics of the soil are uniform and isotropic.
- Heat is transferred by convection in the wind and conduction in the soil.

Because of its ability to accurately forecast interior turbulent fluxes and heat transport, the Realisable k–ε turbulence model was chosen.

3.5 GOVERNING EQUATIONS

The basic conservation equations of fluid flow and energy control the airflow and heat transfer in the suggested system. ANSYS Fluent was used to solve the following equations:

Continuity equation:

$$\nabla \cdot (\rho \vec{V}) = 0 \tag{2}$$

Momentum equation:

$$\rho(\vec{V} \cdot \nabla \vec{V}) = -\nabla p + \mu \nabla^2 \vec{V} \tag{3}$$

Energy equation:

$$\rho c_p(\vec{V} \cdot \nabla T) = k\nabla^2 T \quad (4)$$

Where:
ρ = air density (kg/m³)
V = velocity vector (m/s)
p = pressure (Pa)
μ = dynamic viscosity (Pa·s)
c_p = specific heat capacity (J/kg·K)
k = thermal conductivity (W/m·K)
T = temperature (K)

Because the Realisable k–ε turbulence model is reliable in forecasting internal flow and heat transfer properties, it was used to simulate turbulent airflow. (Lin et al. 2022; Kong et al. 2017; Trzaski & Zawada 2011; Raheem et al. 2026a).

3.6. BOUNDARY CONDITIONS

The boundary conditions listed below were utilised:

- Inlet. The input velocity ranges from 1 to 5 m/s, and the ambient air temperature corresponds to Baghdad's peak summer temperatures.
- Outlet. Pressure outlet with a 0 Pa gauge pressure.
- Pipe wall. Heat transfer between the pipe wall and air is linked with a no-slip boundary condition.
- Soil domain. Regardless of burial depth, the constant far-field soil temperature ranges from 22 to 25 °C.

3.7. SOIL THERMAL PROPERTIES

The provided values for typical Iraqi soil conditions served as the basis for the thermal characteristics of the soil employed in the simulations:

- Thermal conductivity (k): 1.2–1.5 W/m·K
- Density (ρ): 1800 kg/m³
- Specific heat capacity (Cp): 800 J/kg·K (Al-Ajmi 2010)

3.8. INTEGRATION OF EAHE WITH BUILDING COOLING SYSTEM

By delivering pre-cooled fresh air straight into interior spaces, the suggested earth-air heat exchanger system integrates with the building's ventilation and cooling system. While warmer indoor air is released through high-level apertures made possible by thermal buoyancy (stack effect), the cooled air leaving the subterranean pipe is brought into the dwelling areas through low-level openings.

This arrangement lowers the cooling burden on traditional air conditioning systems by lowering the temperature of incoming air before it enters the conditioned space. Consequently, the EAHE system serves as a pre-cooling stage that lowers energy usage and improves indoor thermal comfort.

3.9. PRACTICAL IMPLEMENTATION IN A TYPICAL BAGHDAD COURTYARD HOUSE

The design was conceptually linked with a typical courtyard house in Baghdad to increase the system's practical applicability. These homes are distinguished by an open courtyard in the middle that is encircled by living spaces, offering natural ventilation and shade.

The earth-air heat exchanger pipes are positioned beneath the courtyard area at a depth of about three meters in the suggested layout. By acting as a shaded area, the courtyard lowers solar heat gain on the ground's surface and enhances the soil's thermal stability.

Ambient air can enter the subterranean pipe system through low-level air intake apertures near the courtyard perimeter. A buoyancy-driven airflow cycle is created when warmer air leaves through higher apertures and cooler air is delivered to interior regions.

This setup shows how the suggested system can be incorporated into actual residential buildings in

Baghdad, improving energy efficiency and passive cooling performance.

From a construction standpoint, typical excavation methods can be used to install the hidden pipes beneath the courtyard floor. To reduce heat loss, the pipes' entry and departure points should be adequately insulated. Vegetation, shading devices, or architectural features like arcades can all improve courtyard shade.

To maximise airflow distribution and improve the stack effect, air input and outlet holes should be positioned properly. These pragmatic factors enhance the suggested system's viability and practicality.

4. RESULTS AND DISCUSSION

The under-courtyard structure is especially appropriate for dense urban residential situations in Iraq because it offers architectural shading and lower surface heat losses when compared to normal horizontal EAHE systems (figures 2, 3, 4, 5, 6, 7, and 8).

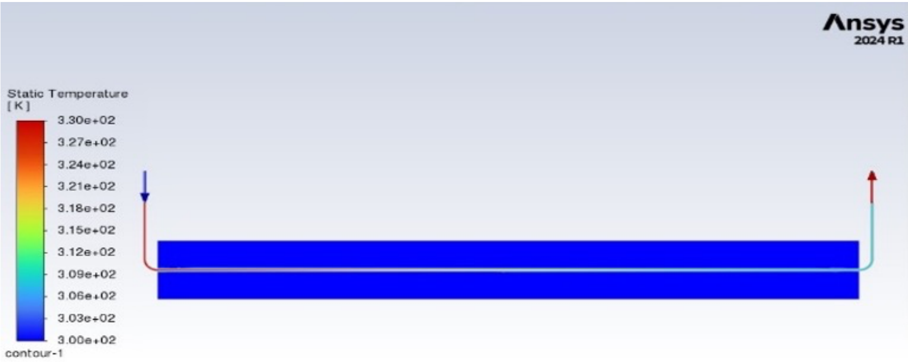

Figure 2. The temperature difference between the intake and outflow at a speed of one metre per second is depicted by the static temperature contours.

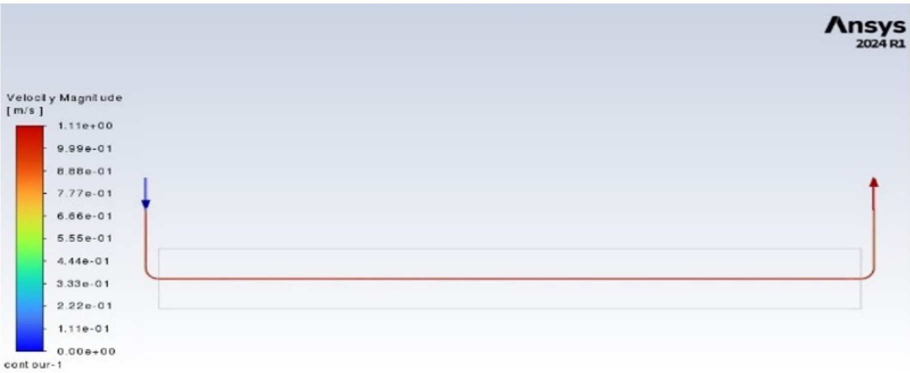

Figure 3. The velocity magnitude contours at a speed of one metre per second.

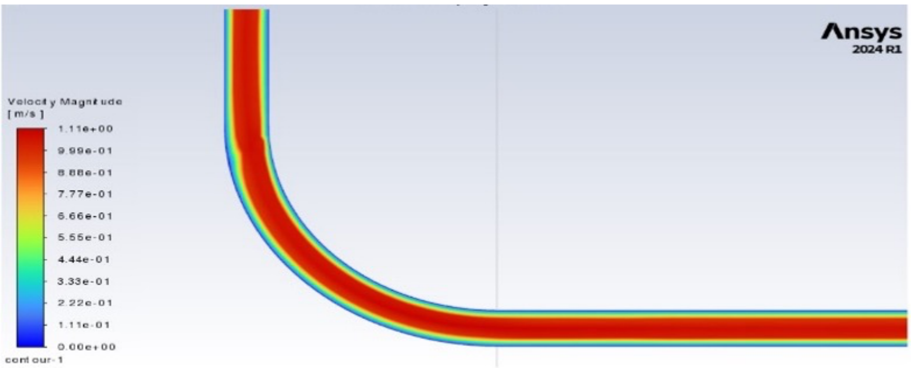

Figure 4. At a speed of one metre per second, focus on the outlines of a velocity magnitude.

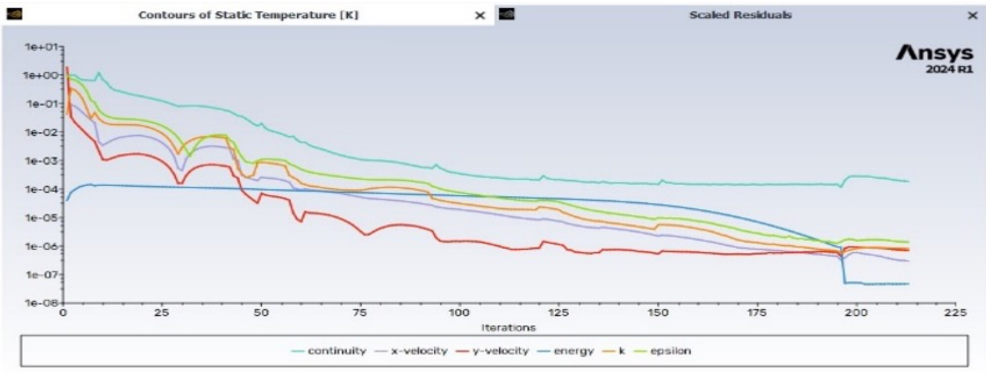

Figure 5. Two hundred iterations of scaled residuals.

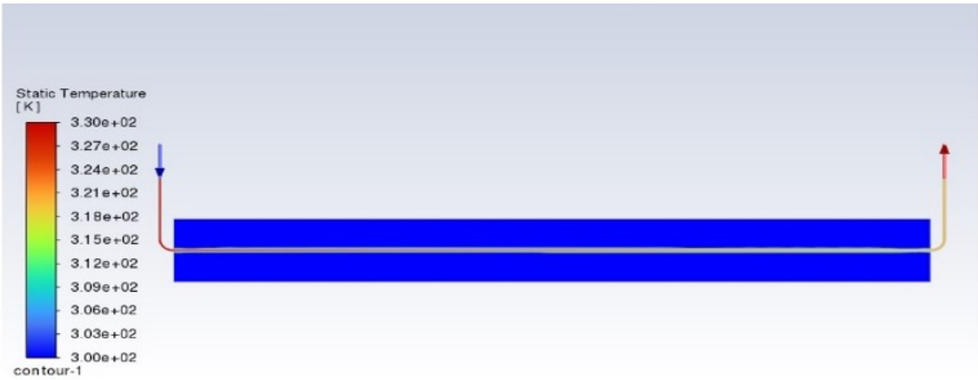

Figure 6. At a speed of 5 m/s, the static temperature contours show how the intake and output temperatures vary from one another.

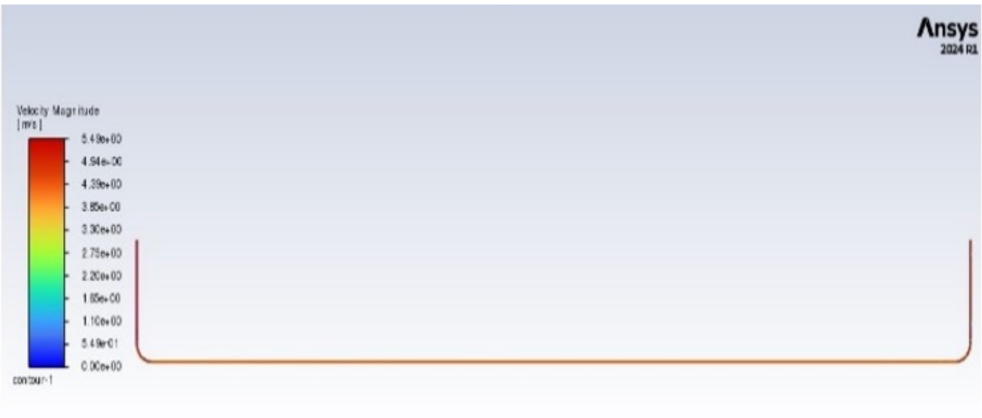

Figure 7. The velocity magnitude contours at a speed of five meters per second.

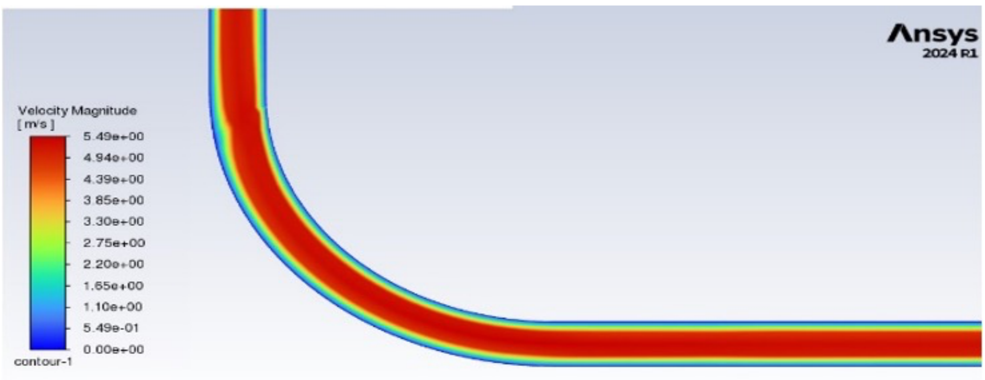

Figure 8. Focus on the velocity magnitude contours at a speed of five meters per second.

4.1. THE COURTYARD EARTH-AIR HEAT EXCHANGER'S THERMAL PERFORMANCE

The suggested courtyard-integrated earth-air heat exchanger (EAHE) greatly enhances the cooling effectiveness of entering ventilation air under Baghdad's climate, according to the CFD simulations. The technology can lower the temperature of incoming air before it reaches the building during the hottest summer months, when external air temperatures usually surpass 45 °C.

The findings show that courtyard shading and subterranean heat exchange work together to produce ideal thermal conditions for passive cooling. Heat is transferred between the surrounding earth and the airflow as it passes through the subterranean pipe system, keeping the temperature comparatively constant all year round. The air temperature at the pipe exit is significantly lowered as a result of this thermal interaction.

The suggested system demonstrated the great cooling capability of EAHE systems in hot, dry areas by achieving a maximum air temperature drop of about 20.75 °C under ideal circumstances.

4.2. THE IMPACT OF PIPE BURIAL DEPTH

The earth-air heat exchanger's efficacy is significantly influenced by the depth of burial. As depth increases, soil temperature swings become much smaller, creating more stable thermal conditions for heat exchange.

According to the modelling results, cooling effectiveness is much improved when the burial depth is increased from 1 to 3 meters. Surface temperature fluctuations have a significant impact on soil temperatures at shallow depths, which lowers the system's cooling efficiency.

However, there are only slight gains in temperature decrease when burial depth is increased above 3–4 m. At these depths, the temperature of the soil becomes comparatively constant, which explains this behaviour. As a result, more excavation raises building expenses without offering appreciable thermal advantages.

As a result, a burial depth of roughly 3 m offers the best compromise between construction viability and thermal performance.

4.3. THE IMPACT OF PIPE LENGTH

The length of the pipe has a direct impact on how long the air stays in the buried heat exchanger. Longer pipes reduce temperature more because they give the surrounding soil and airflow more time to transfer heat.

According to the simulation results, cooling performance is much enhanced when pipe length is increased from 30 to 60 meters. Nevertheless, rises over 60 m result in greater pressure losses and only slightly more temperature reduction.

Long pipes can also lower airflow efficiency and raise installation expenses. As a result, the ideal configuration for the suggested system was found to be a pipe length of roughly 60 meters.

4.4. THE IMPACT OF PIPE DIAMETER

In the EAHE system, pipe diameter influences both the heat transfer coefficient and airflow velocity. Stronger convective heat transfer between air and pipe walls is encouraged by smaller pipe sizes, which also enhance airflow velocity. On the other hand, overly small diameters could lead to increased pressure losses.

According to the simulation results, a pipe diameter of about 0.25 m offers the optimum balance between thermal performance and airflow efficiency. While smaller diameters increase system pressure losses, larger diameters decrease airflow velocity and heat transfer efficiency.

4.5. THE IMPACT OF AIR VELOCITY

Because air velocity controls how long air stays in the buried pipe, it has a major impact on the thermal performance of the EAHE system.

More heat exchange with the surrounding soil is possible with lower intake velocities because the airflow stays inside the pipe for a longer period of time. Lower air velocities thus result in greater temperature drops.

According to the calculations, the best cooling performance was obtained at an inlet air velocity of 1 m/s, which led to a temperature drop of 20.75 °C. Due to a shorter heat exchange period, the temperature drop dropped to about 10.95 °C when the air velocity rose to 5 m/s.

This result emphasises how crucial it is to maximise airflow velocity in order to strike a compromise between thermal performance and ventilation rate.

4.6. AIRFLOW CHARACTERISTICS AND PRESSURE LOSSES

The EAHE system's pressure losses rise with pipe length and airflow velocity. Stronger frictional forces along the pipe walls are produced by higher velocities, increasing the pressure drop.

Higher airflow velocities increase ventilation rates, but excessive pressure losses would necessitate the use of fans or other mechanical aids, which would lessen the system's passive nature. In order to guarantee that the system functions mostly by natural airflow mechanisms, it is crucial to maintain moderate airflow velocities.

The findings show that an adequate compromise between cooling performance and pressure losses is provided by the ideal arrangement (3 m depth, 60 m pipe length, 0.25 m diameter, and 1 m/s velocity).

4.7. POTENTIAL FOR ENERGY SAVING AND CARBON REDUCTION

The promise of passive cooling technologies to lower building energy consumption and related carbon emissions is one of the primary drivers behind their implementation.

In Iraqi traditional residential buildings, air conditioning systems use a significant amount of electricity in the summer. When operating, typical air conditioners use between 3 and 5 kW of electricity (Al-Masry 2013).

The suggested EAHE system can greatly lessen the cooling demand on mechanical air conditioning systems by pre-cooling ventilation air before it reaches the building. It is projected that the system might cut cooling energy demand by roughly 30–50% during peak summer months based on the obtained temperature reductions.

This decrease in cooling demand can result in a considerable drop in carbon dioxide emissions, assuming that fossil fuels are the primary source of energy generation in Iraq. As a result, the suggested technique is a workable passive decarbonisation method for homes in hot, dry regions.

4.8. EFFECT OF AMBIENT TEMPERATURE

The ambient air temperature has a significant impact on the EAHE system's performance. Simulations were run for various input air temperatures (35 °C, 40 °C, and 45 °C) that mimic normal summer conditions in Baghdad in order to assess this effect, but the research concentrated on the maximum temperature in Baghdad at 47 °C.

Because of the larger temperature differential between the surrounding soil and the air, the results show that higher ambient temperatures result in greater temperature reduction. Nevertheless, the soil temperature, which functions as a thermal sink, continues to limit the output air temperature.

This indicates that the EAHE system performs better in harsh weather, which makes it especially appropriate for hot, dry regions like Iraq.

Table 1. Fixed pipe diameter, modified other variables and altered the pipe's length and depth.

Experiment no.	Pipe diameter (m)	Pipe length (m)	Pipe depth (m)	Velocity of inlet air (m/s)	Temperature of inlet air (°C)	Temperature of outlet air (°C)
1	0.25	30	1	1	47	44.30
2	0.25	30	2	1	47	40.90
3	0.25	30	3	1	47	36.80
4	0.25	30	4	1	47	34.40
5	0.25	30	5	1	47	33.90
6	0.25	40	1	1	47	41.10
7	0.25	40	2	1	47	38.20
8	0.25	40	3	1	47	34.10
9	0.25	40	4	1	47	32.30
10	0.25	40	5	1	47	31.90
11	0.25	50	1	1	47	38.90
12	0.25	50	2	1	47	34.80
13	0.25	50	3	1	47	30.90
14	0.25	50	4	1	47	27.10
15	0.25	50	5	1	47	26.70
16	0.25	60	1	1	47	35.90

Experiment no.	Pipe diameter (m)	Pipe length (m)	Pipe depth (m)	Velocity of inlet air (m/s)	Temperature of inlet air (°C)	Temperature of outlet air (°C)
17	0.25	60	2	1	47	30.50
18	0.25	60	3	1	47	26.25
19	0.25	60	4	1	47	25.30
20	0.25	60	5	1	47	25.10
21	0.25	70	1	1	47	34.80
22	0.25	70	2	1	47	30.10
23	0.25	70	3	1	47	26.10
24	0.25	70	4	1	47	25.20
25	0.25	70	5	1	47	25.05
26	0.25	80	1	1	47	34.50
27	0.25	80	2	1	47	29.85
28	0.25	80	3	1	47	26.00
29	0.25	80	4	1	47	25.10
30	0.25	80	5	1	47	25.00

The table above shows that a pipe with a diameter of 0.25 m, a length of 60 m at a depth of 3 m, and an air velocity of 1 m/s can reach the desired temperature. Nonetheless, we will alter the air velocity and fix the other variables in the following table:

Table 2. Adjusted the inlet air velocity and set other parameters to reach the desired temperature.

Experiment no.	Pipe diameter (m)	Pipe length (m)	Pipe depth (m)	Velocity of inlet air (m/s)	Temperature of inlet air (°C)	Temperature of outlet air (°C)
1	0.25	60	3	2	47	26.95
2	0.25	60	3	3	47	27.55
3	0.25	60	3	4	47	28.40
4	0.25	60	3	5	47	29.20

It is evident that cooling performance is much improved by raising the burial depth to 3 m, after which the benefits reduce.

Increasing the burial depth from 1 to 3 meters greatly improves temperature decrease, but further increases yield decreasing returns. This illustrates the impact of pipe depth on cooling performance.

4.9. PERFORMANCE IN HOT–HUMID CLIMATES

While the suggested technique performs well in hot, dry climates like Baghdad, its efficacy might be diminished in hot, humid areas. High air moisture content in humid climates limits the cooling potential of earth-air heat exchangers, which lowers sensible cooling efficiency and may cause condensation inside the underground pipes.

Furthermore, even when the air temperature is lowered, high humidity levels can still have an impact on indoor thermal comfort. To maintain suitable indoor conditions in such circumstances, further dehumidification techniques could be needed. As a result, even if the suggested system works very well in arid conditions, more research and possible system changes would be necessary to improve its performance in humid settings.

4.10. COMPARISON WITH PREVIOUS STUDIES

The findings from earlier studies on EAHE systems in hot climates are in line with the conclusions of this investigation. Temperature drops of 10 to 18 °C have been seen in earlier research, depending on soil conditions, pipe design, and airflow characteristics.

This study's greatest temperature reduction of 20.75 °C is marginally more than several previously published findings. The combined effects of courtyard shade and subterranean heat exchange, which improve thermal performance, are responsible for this enhancement.

Additionally, the suggested system's incorporation of thermal buoyancy effects encourages natural airflow and lessens reliance on artificial ventilation. This potential strategy for enhancing passive cooling performance in hot, dry residential buildings combines engineering technology and architectural design.

The collected data were compared with findings from earlier research on earth-air heat exchanger systems carried out in various climatic locations in order to assess the performance of the suggested system.

Table 3. Comparison between previous studies.

Study	Location	Burial Depth	Pipe Length	Temperature Reduction
(Baglivo et al. 2018)	Italy	2.5 m	40 m	10–14 °C
(Bisoniya et al. 2021)	India	3 m	50 m	12–15 °C
Present Study	Baghdad, Iraq	3 m	60 m	20.75 °C

The findings show that the current study's temperature reduction is marginally greater than many previously published numbers. Thermal buoyancy-driven airflow, courtyard shading, and subterranean heat exchange all contribute to this improvement.

The integration of these three mechanisms enhances passive cooling performance and demonstrates the potential of combining traditional architectural strategies with modern engineering technologies.

The success of combining architectural and engineering approaches is demonstrated by the greater temperature reduction attained in this study when compared to earlier research. The suggested system gains from courtyard shading and thermal buoyancy, which improve heat exchange and airflow, in contrast to traditional EAHE systems that function independently. Compared to conventional designs documented in the literature, this integrated design is a major improvement.

4.11. REDUCTION OF CARBON EMISSIONS POSSIBILITY

The capacity of passive cooling systems to lower power use and related carbon emissions is one of its most significant benefits. Fossil fuel-based power facilities, which emit large amounts of carbon dioxide, are the main source of electricity in Iraq.

During peak summer operation, mechanical air conditioning systems in Baghdad's traditional residential structures usually use 3 to 5 kW of electricity. During the summer, a household's total electricity consumption for cooling might be between 24 and 40 kWh per day, assuming an average daily operation of 8 hours (GhaffarianHoseini et al. 2015).

The cooling demand of mechanical air conditioning systems can be greatly decreased by pre-cooling incoming ventilation air using the suggested earth-air heat exchanger system. The EAHE system can lower interior cooling demand by roughly 30–50%, depending on operation conditions and building attributes, according to the simulation results reported in this study.

The daily electricity savings per home might be between 8 and 14 kWh, assuming a 35% average reduction. Given that fossil fuel-based systems generate power with an average carbon emission factor of about 0.45 kg CO_2 per kWh, the suggested system might cut carbon emissions by about: 3.6–6.3 kg CO_2 per household per day during summer operation.

When applied widely in residential neighbourhoods, this results in a substantial annual decrease in carbon emissions. Thus, in hot and dry locations, incorporating courtyard-based EAHE systems into building design can make a significant contribution to passive decarbonisation efforts.

5. CONCLUSIONS

5.1. MAIN FINDINGS

Using computational fluid dynamics (CFD) simulations, this study examined the effectiveness of a thermal thrust-assisted courtyard earth-air heat exchanger as a passive cooling method for residential structures in Baghdad.

The findings show that in hot, dry climates, the suggested approach can considerably lower the temperature of entering ventilation air. The study's primary conclusions can be summed up as follows:

1. During the hottest summer months, the earth-air heat exchanger system reduced the air temperature by a high of about 20.75 °C.
2. The ideal compromise between thermal stability and construction viability is found at a burial depth

of 3 m.

3. A 60-meter pipe length prevents excessive pressure losses and permits adequate heat exchange.
4. A 0.25 m pipe diameter provides a good balance between heat transfer performance and airflow efficiency.
5. By lengthening the airflow's residence time inside the pipe, lower air velocities improve thermal performance.
6. The suggested solution might cut residential buildings' cooling energy requirements by 30 to 50%, which would lessen power use and carbon emissions.

By showcasing the efficiency of integrating earth-air heat exchangers with courtyard architecture and thermal buoyancy, this study adds to the body of knowledge by offering a novel passive cooling approach for hot, dry residential buildings.

5.2. CONSEQUENCES FOR DESIGNING LOW-CARBON STRUCTURES

The results of this study demonstrate how energy-efficient and climate-responsive residential buildings can be produced by combining contemporary passive cooling technologies with traditional courtyard architecture. In hot, dry areas with limited electricity supplies and high cooling needs, the suggested approach provides a workable method for lowering cooling energy demand.

The technology can help lower carbon emissions related to the production of electricity by lowering reliance on traditional air conditioning systems. As a result, the incorporation of courtyard-based EAHE systems could be crucial in helping Iraq and other hot-arid climates make the shift to low-carbon and sustainable building design.

5.3. LIMITATIONS AND FUTURE RESEARCH

Despite the encouraging outcomes, there are a few things to keep in mind. Seasonal fluctuations in soil temperature and moisture content are not taken into consideration in this study, which assumes constant soil thermal characteristics. Furthermore, no research was done on the long-term thermal interactions between the pipe and the surrounding soil.

Experimental validation of the suggested system in actual climate circumstances should be the main focus of future study. Evaluation of seasonal performance and possible effects of soil thermal saturation might also be aided by long-term monitoring studies. Additionally, life-cycle analyses and economic feasibility studies are advised to facilitate the widespread installation of EAHE systems in residential structures.

AUTHOR CONTRIBUTIONS

Mazin Ismael Raheem: Contributed to all aspects of the study, including conceptualisation, methodology, analysis, and manuscript preparation; read and approved the final version of the manuscript. **Xiaofeng Zheng**: Contributed to all aspects of the study, including conceptualisation, methodology, analysis, and manuscript preparation; read and approved the final version of the manuscript. **Christopher Wood**: Contributed to all aspects of the study, including conceptualisation, methodology, analysis, and manuscript preparation; read and approved the final version of the manuscript.

COMPETING INTERESTS

The authors have no competing interests to declare.

DATA ACCESSIBILITY

The data supporting the findings of this study are available within the article. Additional simulation data can be provided by the corresponding author upon reasonable request.

ETHICAL APPROVAL

This study does not involve human participants or animals, and therefore, ethical approval was not required.

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