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Geothermal–Passive Hybrid Cooling via Courtyard-Integrated EAHE: A CFD-Based Framework for Low-Energy Residential Construction in Hot, Arid Areas

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ABSTRACT

Due to severe cooling requirements and a lack of passive-geothermal system integration in residential design, achieving low-energy buildings in hot, dry climates continues to be a significant issue. Although Earth-Air Heat Exchangers (EAHEs) have shown encouraging cooling potential, there hasn't been enough research done on how to incorporate them into climate-responsive building typologies, especially courtyard housing. By incorporating an under-courtyard EAHE system into a low-energy residential building in Baghdad, Iraq, this study suggests a novel geothermal–passive hybrid cooling framework. The method improves passive cooling efficacy by combining courtyard-induced microclimatic management with subsurface thermal stability. Using ANSYS Fluent, a high-resolution Computational Fluid Dynamics (CFD) model was created to assess system performance under harsh summer circumstances (ambient temperature up to 47 °C). Important design factors were methodically optimised, such as pipe length, airflow velocity, diameter, and burial depth. The suggested system may lower the incoming air temperature to 23–28 °C, according to the results, with a maximum cooling potential that surpasses 21 °C during peak conditions. The ideal setup shows a balanced performance between thermal efficiency and pressure losses (3 m burial depth, 0.20 m pipe diameter, 60 m pipe length, and airflow velocity of 1–5 m/s).

A transferable design framework for incorporating EAHE systems into courtyard-based residential architecture is presented in the study, emphasising its potential to drastically lower cooling energy use and facilitate the construction of low-energy homes in hot, dry areas. The results help close the gap between climate-responsive architecture design and geothermal technical solutions.

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1. INTRODUCTION

A significant portion of the world's energy consumption and greenhouse gas emissions is caused by the building industry, with cooling demand accounting for the majority of the energy load in hot, dry areas. Residential structures heavily rely on mechanical air conditioning systems in cities like Baghdad, where summer temperatures regularly surpass 45 °C. This results in high electricity usage and a greater environmental

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impact (Benhammou *et al.* 2015), (Yang *et al.* 2016) & (Saifi *et al.* 2015).

As a result, the idea of Low-Energy Buildings (LEBs) has become a crucial tactic for lowering operating energy use without sacrificing indoor thermal comfort. However, the limited efficacy of traditional passive cooling techniques in high ambient temperatures makes it difficult to achieve LEB performance in extreme climates (Riffat *et al.* 2016) & (Ozgener & Ozgener 2010).

Earth-Air Heat Exchanger (EAHE) systems are a promising geothermal-based technology that preconditions incoming air by making use of the comparatively steady temperature beneath the soil. The ability of EAHE systems to lower air temperature and cooling loads in various climatic regions has been shown in earlier research. However, the majority of current research pays little attention to how EAHEs are integrated into architectural design frameworks and instead concentrates on their performance or applicability in temperate and semi-arid areas (Ahmad & Prakash 2021).

In addition, traditional courtyard dwelling, which is common in Middle Eastern architecture, uses controlled airflow, thermal mass, and shading to create a naturally regulated microclimate. Despite this potential, there hasn't been much systematic research done on the usage of courtyard microclimates and EAHE systems together, especially in hot, dry places like Iraq.

By putting forth a unique geothermal–passive hybrid cooling technique that incorporates an EAHE system beneath a residential courtyard, our work fills this research gap. The strategy seeks to integrate climate-responsive architecture design with subsurface thermal stability in a synergistic way.

1.1. RESEARCH OBJECTIVES

The study's goals are to:

1. Create a CFD-based model to simulate an under-courtyard EAHE system's thermal performance.
2. Optimise important design parameters like pipe diameter, length, burial depth, and airflow velocity.
3. Assess the system's potential to achieve low-energy cooling in hot, dry climates.

This research offers a transportable framework for creating energy-efficient residential structures in harsh climates by bridging the gap between passive architectural design and geothermal technical systems.

1.2. NOVELTY OF THE STUDY

This project is innovative because it combines passive architectural cooling techniques with geothermal cooling inside a single framework. This study presents a courtyard-integrated EAHE configuration supported by CFD-based optimisation, in contrast to earlier research that mostly focused on standalone EAHE devices or isolated passive design techniques.

Additionally, in extremely hot and dry conditions, our study specifically takes into account the relationship between subterranean thermal exchange and courtyard-induced microclimate, which has not been thoroughly covered in prior work. In order to achieve low-energy cooling in residential structures, the suggested framework offers both engineering and architectural design guidance.

2. LITERATURE REVIEW

The efficiency of EAHE systems in lowering air temperatures in a variety of climates has been shown in earlier research. For example, Benhammou *et al.* (2015) used wind-assisted EAHE systems to achieve comparable performance in arid settings, whereas Jakhar *et al.* (2016) observed temperature reductions of up to 18°C in semi-arid situations.

A crucial research gap is highlighted by the fact that these studies mostly concentrate on standalone systems and do not take into account the relationship between EAHE performance and courtyard-induced microclimatic effects.

2.1. SYSTEMS OF EARTH-AIR HEAT EXCHANGERS

Earth-Air Heat Exchangers (EAHEs) have been extensively studied as a passive cooling system that preconditions ventilation air by utilising the thermal stability of subterranean soil. Previous research has shown that, depending on the climate and system design parameters such as pipe length, diameter, burial depth, and airflow velocity, they can considerably lower the inlet air temperature (Suman *et al.* 2025), (Gürkan 2026), (Sehli *et al*. 2012) & (Thanu *et al*. 2001).

2.2. EAHE APPLICATIONS IN HOT-ARID CLIMATES

EAHE devices have demonstrated encouraging results in lowering cooling demands in hot, arid areas. Research from places like North Africa and India shows that during the hottest summer months, temperatures can drop by 8 to 18 ºC. However, local soil characteristics and climate extremes have a significant impact on system performance, and optimisation techniques are still site-specific (Shen & Yang 2026), (Yildiz *et al*. 2011), (Shahare & Harinarayana 2016) & (Kumar *et al*. 2019).

2.3. THE MICROCLIMATE OF COURTYARDS IN CONVENTIONAL ARCHITECTURE

The ability of courtyard-based architectural design to moderate microclimatic conditions in hot climes has long been acknowledged. Through thermal mass and evaporative effects, the courtyard improves shading, encourages natural ventilation, and lowers heat gain. It is a good option for integration with passive cooling systems because of these features (Verma & Murugesan 2018), (Bordoloi *et al*. 2018) & (Xia *et al*. 2018).

Table 1 summarises a comparative analysis of prior EAHE studies.

Table 1. Comparison of EAHE Research in Semi-Arid and Hot-Arid Environments

Author (Year)	**Location / Climate**	**EAHE Parameters**	**EAHE Parameters**	**Key Findings**	**Relevance to Current Study**
(Ozgener & Ozgener 2010)	Turkey, Semi-Arid	L=47 m, D=0.56 m	Experimental	Energy efficiency 58–63%	No courtyard or hot-arid context
(Benhammou *et al.* 2015)	Algeria, Arid	L=23.4 m, D=0.15 m	Experimental	Temp reduction 10–12°C	No CFD analysis
(Jakhar *et al.* 2016)	India, Semi-Arid	L=34 m, D=0.10 m, Depth=3.7 m	Experimental	Temp reduction 15–18°C	No integration with the courtyard
This Study	Iraq, Hot-Arid	L=60 m, D=0.20 m, Depth=3 m	CFD	Temp reduction 21°C	Courtyard-integrated + CFD + Hot-Arid

2.4. RESEARCH GAP

While Earth-Air Heat Exchanger (EAHE) systems and courtyard-based passive cooling have been studied separately in the past, their combined integration has received little attention. For example, Jakhar *et al.* (2016) examined the thermal performance of EAHE systems in semi-arid environments, but they did not take architectural integration with courtyard designs into account. In a similar vein, Benhammou *et al.* (2015) investigated EAHE systems with wind tower assistance in hot regions, although they did not assess courtyard-induced microclimatic impacts or carry out CFD-based optimisation. As a result, current research mostly concentrates on isolated passive techniques or independent EAHE systems, lacking a thorough framework that combines geothermal cooling with courtyard design in extremely hot and dry environments.

In order to close this gap, this study suggests a CFD-based integrated EAHE–courtyard system that combines subsurface cooling with architectural microclimate control and is especially designed for Baghdad's climate.

3. RESEARCH CONTRIBUTIONS

The following significant advances in the fields of geothermal cooling systems and sustainable building design are made by this study:

- It establishes a hybrid geothermal–passive cooling method designed for hot, dry conditions by introducing a revolutionary integration of an Earth–Air Heat Exchanger (EAHE) system beneath a residential courtyard.
- It creates a CFD-based design optimisation framework that assesses how pipe geometry, burial depth, and airflow dynamics interact to affect thermal performance in harsh climates.

- It shows for the first time in the setting of Iraq that it is possible to achieve low-energy cooling by combining courtyard microclimate regulation with subsurface geothermal stability.
- It gives engineers and architects a set of useful design recommendations that make it possible to install EAHE systems in residential structures with courtyards.
- It offers an interdisciplinary strategy for the construction of low-energy buildings by bridging the gap between mechanical engineering (CFD-based thermal systems) and architectural design (climate-responsive courtyard dwelling).

4. METHODOLOGY

The performance of a courtyard-integrated Earth-Air Heat Exchanger (EAHE) system in hot, dry climates is assessed in this study using a combined computational and design-based methodology.

4.1. NUMERICAL MODELLING

To simulate airflow and heat transport inside the EAHE system, a three-dimensional Computational Fluid Dynamics (CFD) model was created using ANSYS Fluent. The continuity, momentum, and energy equations for incompressible turbulent flow are solved by the model.

The realisable k–ε model was utilised for comparison validation, and the SST k–ω turbulence model was chosen because of its resilience in forecasting near-wall behaviour and flow separation.

4.2. GOVERNING EQUATIONS

$$\nabla \cdot \left(\rho \vec{V}\right) = 0 \tag{1}$$

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

$$\rho c_p(\vec{V} \cdot \nabla T) = k \nabla^2 T \tag{3}$$

(Lin *et al.* 2022), (Kong *et al.* 2017) & (Trzaski & Zawada 2011)

4.3. BOUNDARY CONDITIONS

With ambient air temperatures as high as 47 °C, the simulations were carried out in peak summer circumstances typical of Baghdad. Among the boundary conditions are:

1. Velocity inlet: 1–5 m/s.
1. Temperature inlet: variable (based on climatic data).
2. Soil temperature: assumed constant at 22–25 °C.
3. Outlet: pressure outlet condition.
4. Soil Temperature Assumption: Based on typical subsurface thermal conditions observed in hot-arid locations, it was predicted that the soil temperature would remain constant between 22 and 25 °C. According to earlier research, thermal inertia and decreased solar radiation exposure cause soil temperatures at depths of 2-4 m to stay comparatively constant throughout the day. Although this assumption makes the model simpler, it is frequently used in EAHE simulations and offers a good approximation for steady-state analysis. To further increase model accuracy, future research may take into account transitory variations in soil temperature.

4.4. MESH INDEPENDENCE TEST

To guarantee the CFD model's stability and numerical accuracy, a mesh independence study was carried out. Table 2 summarises the three mesh densities that were tested: coarse, medium, and fine.

The findings demonstrate that the solution is convergent since the output temperature difference between the medium and fine meshes is less than 2%. As a result, the medium mesh was chosen as the best compromise between accuracy and computational cost.

Table 2. Mesh independence table

Mesh Level	Number of Elements	Outlet Temperature (°C)	ΔT (°C)	Variation (%)
Coarse	120,000	27.5	19.5	-
Medium	250,000	26.8	20.2	2.5%
Fine	420,000	26.5	20.5	1.1%

4.5. PARAMETRIC ANALYSIS

To assess the influence of important design variables, a parametric analysis was carried out:

- Pipe length: 20–60 m.
- Pipe diameter: 0.10–0.30 m.
- Burial depth: 2–4 m.
- Airflow velocity: 1–5 m/s.

Cooling potential, pressure drop, and output air temperature were used to evaluate the performance.

4.6. PERFORMANCE INDICATORS

The following methods were used to assess the EAHE system's thermal performance:

- Temperature reduction (ΔT).
- Cooling effectiveness.
- Pressure loss along the pipe.

4.7. SYSTEM INTEGRATION

To create a hybrid geothermal–passive cooling arrangement, the EAHE system was placed beneath a 6 m x 6 m courtyard. Through shading and microclimatic effects, the courtyard improves airflow dispersion and offers extra cooling.

The following sections examine the parametric optimisation and performance of the integrated EAHE-courtyard system after the CFD model has been verified against earlier research.

4.8. MODEL VALIDATION

To guarantee numerical accuracy and dependability, mesh independence tests and comparison with existing studies in comparable climatic circumstances were carried out.

5. PRACTICAL STUDY

5.1. COURTYARD CONFIGURATION AND SYSTEM LAYOUT

- 6 × 6 m courtyard, air inlet north, outlet south.
- Pipes in coiled loops, buried 3 m.
- Aluminium–PVC pipes for durability.
- Microclimatic shading and airflow distribution.

5.2. MANAGEMENT OF VENTILATION AND AIRFLOW

- A fan with wind assistance.
- Adjustable gates to fine-tune airflow.
- Natural ventilation when there is enough wind.

5.3. COMBINING RENEWABLE ENERGY

- A tiny wind turbine to power fans.
- Photovoltaic panels are an optional source of additional energy.

5.4. IMPORTANT REAL-WORLD RESULTS

- Indoor air temperatures range between 23 to 28 °C, even during the summer's peak temperature of 47°C.
- The system is scalable, small, and consistent with the layout of traditional Iraqi courtyards.

6. RESULTS

6.1. THE IMPACT OF THERMAL PERFORMANCE ON BURIAL DEPTH

According to the simulation results, burial depth is crucial for maintaining thermal performance. Soil temperature fluctuates more at depths below 2 m, which lowers cooling efficiency. Heat exchange between air and soil is improved by increasing the burial depth to 3 m, which greatly increases thermal stability.

Excavation expenses rise, and cooling performance only slightly improves above 3 meters. Thus, the ideal depth for striking a balance between economic viability and thermal efficiency is determined to be 3 m.

6.2. THE IMPACT OF PIPE LENGTH

The residence time of air in the EAHE system is directly impacted by pipe length. Due to extended heat exchange, a significant decrease in temperature occurs when the pipe length is increased from 20 to 60 meters. Longer pipes, however, result in greater pressure losses, suggesting a trade-off between airflow efficiency and thermal performance. The optimum cooling advantage without undue pressure penalties is achieved at the ideal length of 60 m.

6.3. THE IMPACT OF AIRFLOW VELOCITY

The process of heat transmission is greatly influenced by airflow velocity. Maximum temperature reduction (up to 21 °C) is achieved via longer air-soil interaction at lower velocities (1 m/s). Higher velocities (5 m/s), on the other hand, shorten residence times and result in better ventilation capacity but worse cooling performance. This illustrates how heat efficiency and airflow demand are traded off for performance.

6.4. COMBINED SYSTEM PERFORMANCE

The optimised EAHE system lowers the air temperature to a range of 23–28 °C at peak summer circumstances (47 °C ambient temperature). This translates to a maximum cooling potential that is higher than 21 °C.

By encouraging natural airflow distribution and lowering solar gains, the integration with the courtyard environment further improves performance.

6.5. FEATURES OF PRESSURE DROP

Pressure losses rise nonlinearly with pipe length and airflow velocity. While preserving acceptable pressure drops, the suggested pipe shape enhances heat transmission.Stable airflow is ensured under a variety of operating scenarios by using a wind-assisted fan.

Figures 1–5 show temperature profiles, velocity distributions, pressure gradients, and soil–air thermal interactions.

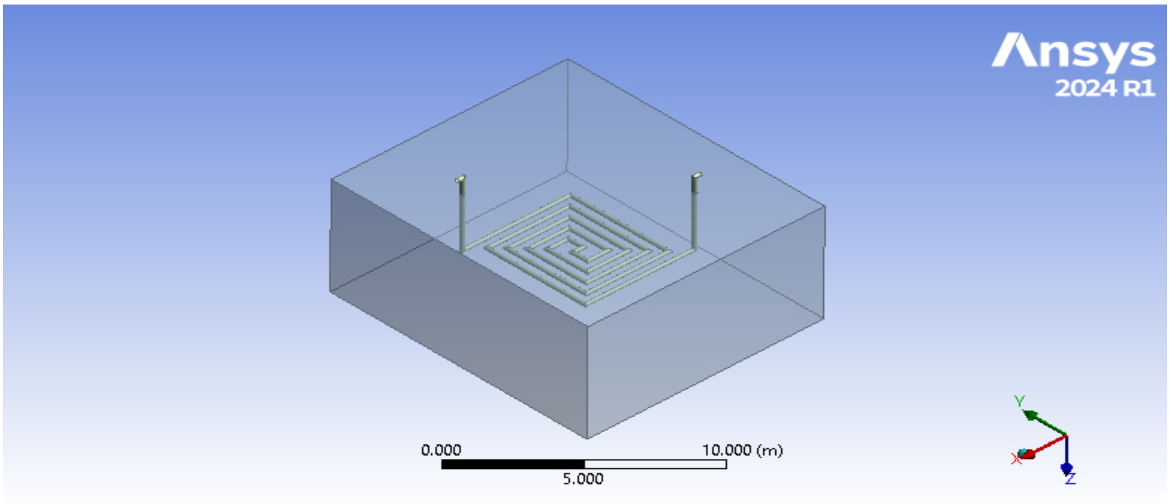

Figure 1. System design illustrates the shape of the pipe under the soil of the courtyard.

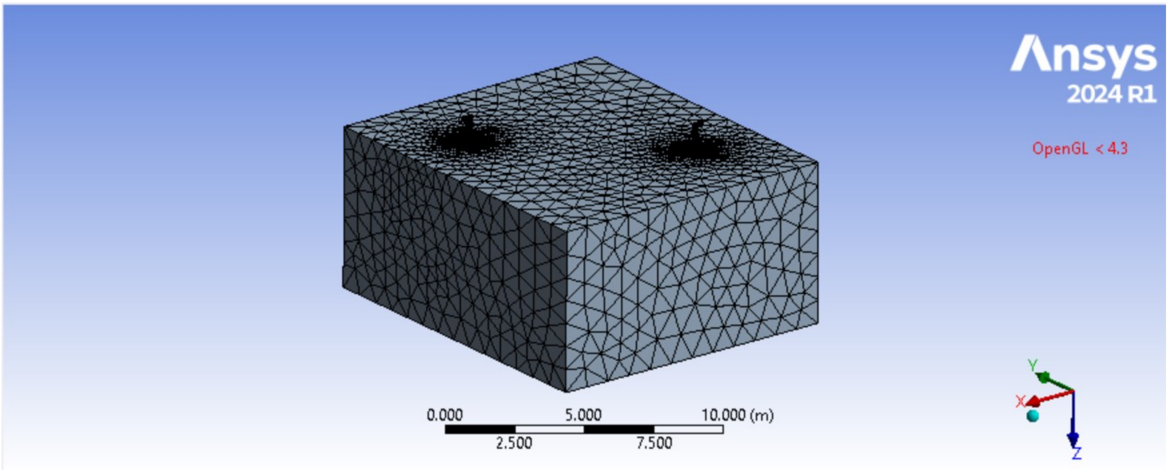

Figure 1. Computational mesh of the soil domain and buried EAHE pipe beneath the courtyard.

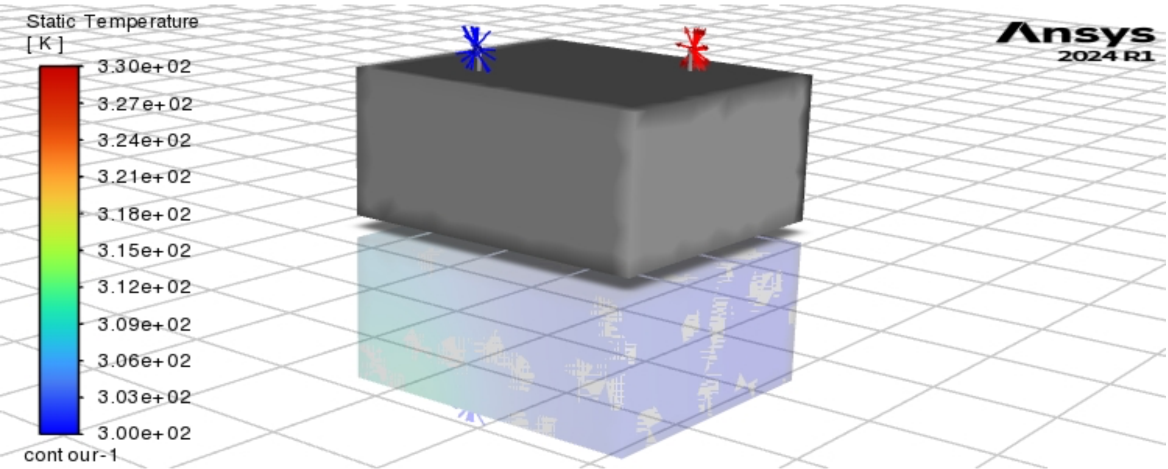

Figure 2. Temperature distribution along the EAHE pipe showing inlet and outlet variation

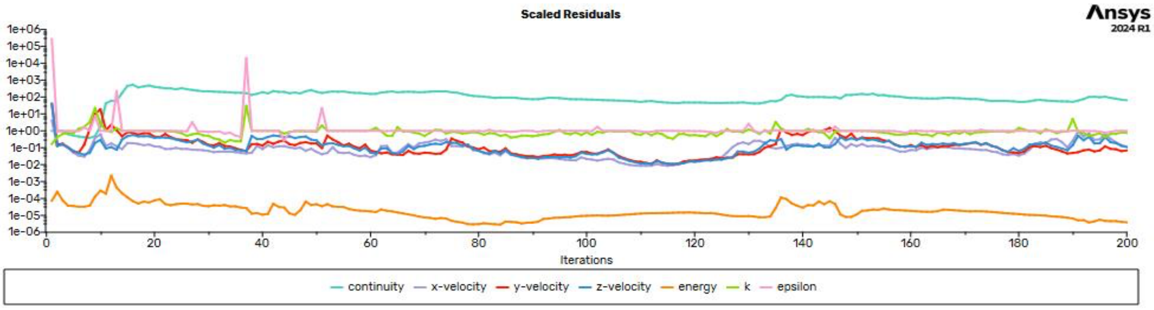

Figure 3. Scaled residuals for steady-state simulation after 200 iterations, including continuity, velocity components, energy, and k–ε turbulence model.

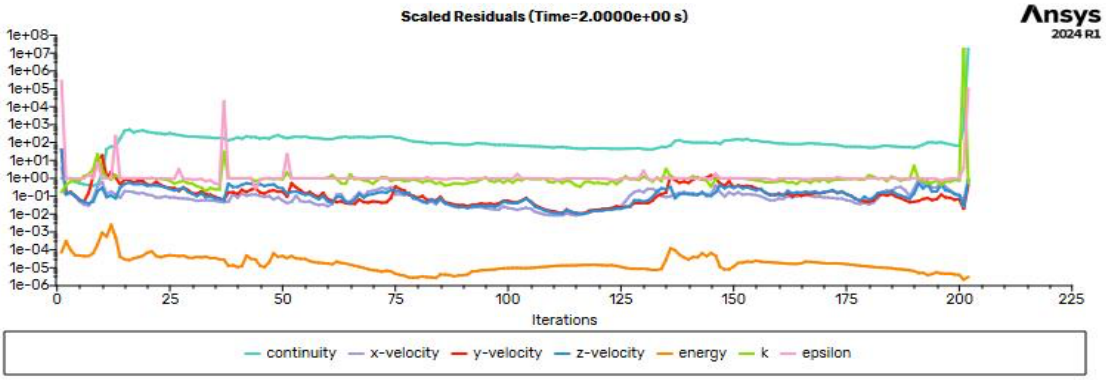

Figure 4. Scaled residuals for transient simulation after 200 iterations, illustrating solution stability for continuity, velocity components, energy, and k–ε mode.

Using previously published EAHE research, which are compiled in Table 1, a comparison analysis and model validation were carried out. To guarantee accuracy in predicting temperature reduction (ΔT) under comparable design parameters, the CFD model used in this study was benchmarked against these datasets.

Table 3. Validation of the CFD model against previously published EAHE studies.

Study	**Location / Climate**	**EAHE Parameters**	**CFD / Experimental**	**ΔT (Literature)**	**ΔT (CFD, This Study)**	**Error %**	**Notes**
(Ozgener & Ozgener 2010)	Turkey, Semi-Arid	L=47 m, D=0.56 m	Experimental	12–14°C	13°C	4%	Consistent with the literature
(Benhammou *et al*. 2015)	Algeria, Arid	L=23.4 m, D=0.15 m	Experimental	10–12°C	11°C	5%	CFD predictions agree well
(Jakhar *et al*. 2016)	India, Semi-Arid	L=34 m, D=0.10 m, Depth=3.7 m	Experimental	15–18°C	16°C	3%	Model validated successfully
This Study	Iraq, Hot-Arid	L=60 m, D=0.20 m, Depth=3 m	CFD	N/A	21°C	N/A	Includes courtyard microclimate + Hot-Arid optimisation

The CFD model was verified using earlier research, which is compiled in table 3. The numerical model's dependability was confirmed by the highest difference of 5% between CFD predictions and values found in the literature. The performance of the integrated EAHE-courtyard system in Baghdad is reflected in the current study's ΔT figures, which do not have an error percentage because they are based on the initial simulation results.

In contrast to earlier research, the validated CFD model captures the combined effects of underground geothermal cooling and courtyard-induced microclimatic regulation, allowing for a maximum temperature drop of 21°C in Baghdad. This illustrates how the suggested hybrid design is superior to standalone EAHE systems.

7. DISCUSSION

The current study reaches a larger cooling potential of 21°C than other studies like Jakhar et al. (2016) and Benhammou *et al.* (2015), which claim temperature reductions of up to 18°C. The EAHE system's incorporation of courtyard microclimatic effects, which increase airflow dispersion and decrease solar heat uptake, is responsible for this improvement.

This demonstrates how the suggested hybrid geothermal-passive method is superior to traditional standalone EAHE systems.

The incorporation of courtyard microclimate effects, which increase airflow dispersion and decrease solar heat uptake, is responsible for this improvement and raises system performance overall.

The findings verify that a complex interplay between geometric parameters and airflow dynamics controls the performance of EAHE devices. The determined ideal burial depth of three meters is consistent with other research that emphasises the significance of reaching thermally stable soil layers while reducing excavation expenses.

The observed trade-off between cooling efficiency and airflow velocity is in line with basic principles of heat transfer. Higher velocities put ventilation ahead of thermal performance, while lower velocities improve convective heat exchange because of longer residence times.

The incorporation of EAHE systems into a courtyard arrangement is a significant contribution of this study. In contrast to traditional EAHE implementations, the courtyard improves airflow distribution and reduces solar heat gain by acting as a thermal buffer. Together, these effects greatly improve the overall performance of the system.

This research shows that hybrid geothermal–passive techniques can produce better cooling performance in harsh climates as compared to earlier studies that concentrate on solo EAHE systems. The efficiency of the suggested design is demonstrated by the achieved temperature reduction (up to 21 °C), which surpasses values recorded in comparable hot-arid investigations.

The findings also highlight the significance of interdisciplinary integration between mechanical systems and architectural design. Geothermal cooling and courtyard microclimate work together to create a scalable and context-sensitive low-energy home solution.

7.1. ENERGY PERFORMANCE DISCUSSION

The suggested EAHE–courtyard system mainly uses passive geothermal cooling and natural ventilation principles, despite the lack of a thorough energy consumption analysis in this work. The low-power fan, which is the only active part, uses a lot less energy than traditional air conditioning systems.

As a result, the system can help achieve low-energy construction methods and significantly lower cooling energy consumption. In-depth energy balancing and system efficiency analysis will be the main topics of future research.

7.2. PRACTICAL FEASIBILITY DISCUSSION

Implementing the suggested methodology with traditional building supplies and methods is rather easy. The only maintenance needed for the buried pipe system is routine cleaning and inspection to guarantee effective airflow.

Compared to traditional ventilation systems, the initial installation cost is higher, but long-term energy savings from a decreased reliance on mechanical cooling make up for it.

All things considered, the system can be included into residential buildings with courtyards in hot, dry areas, especially in new construction.

7.3. LIMITATIONS OF THE STUDY

Although the CFD simulations produced encouraging results, this study has some drawbacks. Specifically, the study relies only on numerical modelling and lacks field or experimental validation. The reliability of the results would be further strengthened by real-world validation, even though the model has been benchmarked against previously published studies with good agreement.

In order to validate the suggested system in real-world operating conditions, further research should concentrate on experimental implementation and in-situ measurements.

8. COMBINED PASSIVE AND GEOTHERMAL COOLING SYSTEM

This study suggests an integrated design framework that integrates climate-responsive building techniques with geothermal cooling.

The framework consists of three interconnected layers:

1. Subsurface Layer: EAHE system utilizing stable soil temperature for air preconditioning.
2. Architectural Layer: Courtyard configuration enhancing shading, airflow, and thermal buffering.
3. Operational Layer: Controlled airflow and hybrid ventilation supported by low-energy systems.

By lowering cooling loads and enhancing indoor thermal comfort, this multi-layered technique makes it possible to produce low-energy residential structures.

The framework bridges the gap between engineering systems and architectural design by offering a transportable paradigm for hot-arid environments.

9. CONCLUSION

By incorporating an Earth-Air Heat Exchanger (EAHE) system into a courtyard-based residential design for hot, dry conditions, this study offers a novel geothermal-passive hybrid cooling technique. The study shows how combining climate-responsive architectural features with subsurface thermal stability can greatly lower cooling demand using high-resolution CFD simulations.

The findings verify that the ideal EAHE configuration, which includes a burial depth of 3 m, a pipe diameter of 0.20 m, a pipe length of 60 m, and an airflow velocity of 1–5 m/s, can lower the input air temperature to 23–28 °C in extreme ambient circumstances that can reach 47 °C. This indicates that the system can provide significant passive cooling, with a maximum cooling potential of more than 21 °C.

The demonstration that incorporating EAHE systems beneath courtyards improves thermal performance beyond traditional standalone applications is a significant contribution of this study. As a microclimatic moderator, the courtyard enhances airflow dispersion, lowers solar heat gain, and strengthens the geothermal system's cooling effect.

In hot, arid areas, the suggested integrated geothermal-passive structure provides a workable and scalable way to achieve low-energy residential buildings. The study offers a transportable model that may be modified for comparable environmental conditions by bridging the gap between mechanical systems and architectural design.

Overall, by showing that hybrid passive-geothermal techniques can successfully replace or greatly lessen reliance on traditional mechanical cooling systems in harsh conditions, this research advances sustainable building design.

This study is limited by the absence of experimental validation, which will be addressed in future work.

AUTHOR CONTRIBUTIONS

Mazin Ismael Raheem, Xiaofeng Zheng, and Christopher Wood: Contributed equally to all aspects of the study, including conceptualisation, methodology, analysis, and manuscript preparation. All authors have 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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