Journal of Neonatal Surgery
*ISSN(Online): 2226-0439*
*Vol. 14, Issue 18s (2025)*
https://www.jneonatalsurg.com

# Assessment of the Solar-Coupled Earth Air Heat Exchanger (EAHE) System for Sustainable Residential Cooling

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Cite this paper as: Girish kumar Khare, Dr. Sachin Kumar Nikam*, (2025) Assessment of the Solar-Coupled Earth Air Heat Exchanger (EAHE) System for Sustainable Residential Cooling. *Journal of Neonatal Surgery*, 14 (18s), 989-996.

**ABSTRACT**

As the need for sustainable and energy-efficient cooling solutions in residential buildings increases, Earth Air Heat Exchanger (EAHE) systems have surfaced as a viable alternative to traditional HVAC systems. This research examines the design, modeling, and experimental assessment of three configurations of Earth Air Heat Exchangers (EAHE)—Parallel (Existing), Series, and Modified—for residential cooling applications. The efficacy of each arrangement was evaluated under actual summer circumstances in Gwalior, India. The Modified EAHE system was combined with a Solar Chimney to improve passive airflow and thermal efficiency.
ANSYS FLUENT was used to perform Computational Fluid Dynamics (CFD) simulations for modeling heat transfer and airflow dynamics across various EAHE setups. The simulation results were corroborated by experimental testing, demonstrating a robust link between expected and observed performance. The Modified EAHE system achieved a maximum temperature drop of 14°C, with air changes per hour (ACH) values between 4.19 and 5.56, in accordance with international indoor air quality requirements. The incorporation of the solar chimney enhanced natural ventilation and decreased energy reliance. This study highlights the viability of solar-assisted EAHE systems as economical and environmentally sustainable cooling solutions for structures in arid and high-temperature regions. The results underscore the impact of critical design parameters—such as pipe length, burial depth, airflow velocity, and soil characteristics on the overall efficiency of the system. The verified CFD models provide a dependable foundation for further design optimization and performance prediction. This research advances the focus on passive and renewable energy thermal comfort solutions, facilitating scalable and sustainable implementation in the built environment.

**Keywords:** Earth Air Heat Exchanger (EAHE); Solar Chimney (SC); Computational Fluid Dynamics (CFD); Thermal Comfort; Sustainable Cooling

## 1. INTRODUCTION

The worldwide surge in population, urbanization, and industrialization has exerted considerable strain on current energy infrastructure, especially in emerging countries such as India. The escalating demand for power, projected to exceed 100% in the forthcoming decades if unregulated, presents a twofold threat: the exhaustion of fossil fuel supplies and the exacerbation of environmental deterioration [1, 2]. The burning of fossil fuels for energy generation significantly adds to greenhouse gas emissions, which are primary catalysts of global warming and climate change. Thus, a fundamental transition to sustainable energy solutions is essential for preserving ecological equilibrium and guaranteeing energy security [3].
India is positioned among the top five worldwide energy users, with a consumption rate of roughly 376 million tons of oil equivalent. The Ministry of New and Renewable Energy (MNRE) reports that energy production in the nation mostly relies on coal (56%), followed by liquid fuels (32%) and renewable resources (merely 3%). The constructed environment, especially residential and commercial structures, constitutes about one-third of worldwide energy consumption, with heating, ventilation, and air conditioning (HVAC) systems responsible for around 40% of this total [4]. As buildings significantly contribute to greenhouse gas emissions, the energy efficiency of HVAC systems is under heightened examination.

HVAC systems are crucial for maintaining interior thermal comfort; nonetheless, they rank among the most energy-intensive systems in buildings. Traditional HVAC systems mostly depend on power sourced from fossil fuels, leading to elevated carbon emissions and substantial running expenses. Furthermore, their effectiveness is directly affected by architectural design, insulating materials, occupant conduct, and existing climatic conditions. The pursuit of alternatives that guarantee thermal comfort while minimizing energy consumption has therefore emerged as a pivotal domain of research and innovation.

Solar energy stands out among renewable energy sources owing to its availability, sustainability, and technical adaptability. Solar technologies, including photovoltaic (PV) systems, solar thermal systems, and hybrid photovoltaic-thermal (PVT) systems, have shown their capacity to diminish reliance on non-renewable energy sources. Photovoltaic systems directly transform sunshine into energy, whilst solar thermal systems are used for heating applications. Hybrid systems improve energy efficiency by concurrently generating heat and electricity [5]. The incorporation of solar energy systems with building elements may substantially reduce the energy demands of HVAC operations.

Earth Air Heat Exchanger (EAHE) systems provide a passive and sustainable method for space conditioning by using the relatively stable subsurface earth temperature to pre-heat or pre-cool air prior to its entry into the building [6]. This technology circulates ambient air via pipes buried at a set depth, facilitating heat exchange with the surrounding soil—cooling the air during summer and heating it in winter [7]. The thermal inertia of the Earth enables EAHE systems to efficiently manage interior temperatures with minimum energy consumption, making them appropriate for various climatic situations.

The operation of EAHE is regulated by the temperature difference between the ambient air and the subterranean earth. During summer, the system intake hot ambient air, which dissipates heat to the cooler soil, so producing cooled air for inside circulation. In contrast, during winter, the frigid air absorbs heat from the comparatively warmer earth before to entering the structure. Multiple factors affect the efficacy of an EAHE system, such as the pipe material, diameter, length, burial depth, soil conductivity, and airflow velocity [8]. The choice of these parameters is contingent upon the application - either heating or cooling - and the geographical and climatic circumstances of the installation location.

EAHE systems are categorized as closed-loop, open-loop, and hybrid systems. Closed-loop systems recycle interior air via subterranean pipes, whereas open-loop systems intake fresh external air, providing superior ventilation but necessitating more maintenance. Hybrid or combination systems provide adaptable operational modes based on external air quality and user specifications. Each arrangement has distinct benefits, limits, and design concerns, with their selection being determined by site-specific criteria such as available land area, closeness to water sources, and local climate.

In recent years, novel designs of EAHE for residential use have gained attention. One innovation is integrating EAHE systems with solar chimneys (SC), which use natural convection from sun-heated vertical shafts to improve air circulation. This hybrid EAHE-SC system improves the thermal efficiency of passive cooling by augmenting air extraction rates, hence more effectively lowering interior temperatures in hot and arid conditions [9]. The technology integrates geothermal and solar energy to overcome the constraints of independent systems and enhances thermal comfort without elevating energy consumption.

The soil encasing the EAHE pipes is crucial in influencing system efficiency. Moisture content, thermal conductivity, density, and diffusivity affect the rate of heat transfer between soil and airflow. Moist and dense soils, such as clay, are favored for their superior heat retention capabilities [10]. Researchers have investigated the impact of artificially enhancing soil qualities using minerals such as quartz, bentonite, and treated metal powders to augment system efficiency [11].

Numerous researches conducted in India and elsewhere have shown the efficacy of EAHE systems in lowering indoor temperatures. Experiments in Ajmer shown average summer temperature reductions of up to 10°C when using PVC and mild steel pipes buried at a depth of 2.7 meters. In Bhopal, studies indicated a temperature drop of 12.9°C using PVC pipes of 9.11 meters in length. Performance measurements often include the temperature differential between the intake and output, the coefficient of performance (COP), and energy conservation. The coefficient of performance (COP) values have been shown to vary from 2 to 5, contingent upon the system setup and operational circumstances [12].

Computational Fluid Dynamics (CFD) has become an effective instrument for modeling EAHE systems. Computational Fluid Dynamics (CFD) enables researchers to simulate airflow, heat transfer, and temperature distribution across many operating and climatic scenarios, thereby enhancing design efficiency without the need for lengthy field experiments. Analytical models, although less computationally intensive, can depend on simplifying assumptions and may fail to encapsulate the intricacies of real-world applications [13]. Contemporary CFD technologies such as ANSYS FLUENT have been used to assess diverse EAHE designs, facilitating enhanced performance forecasts.

Global studies, spanning desert places such as Kuwait to humid subtropical areas like Brazil, have shown the effectiveness of EAHE systems across many climates [14]. In Thailand, EAHE systems used in greenhouses shown seasonal performance fluctuation, achieving a COP of 3.56 in summer and 0.77 in winter [15]. The results indicate that while EAHE systems are often beneficial, their effectiveness should be assessed considering local climate, soil conditions, and architectural design. Utilizing adaptive design parameters and hybrid systems may augment their appropriateness across diverse settings.

Notwithstanding significant advancements, several research deficiencies persist. Empirical evidence on the efficacy of EAHE systems combined with solar chimneys in actual home settings is few. The economic feasibility, including installation expenses, operating savings, and payback durations, remains a rather neglected domain. Moreover, the scalability of EAHE systems in urban and high-density environments remains inadequately explored. Advanced research on innovative materials, geometric optimization, and automation for performance regulation may provide significant insights for mainstreaming these systems.

## 2. MATERIALS AND METHODS

### 2.1. System Configuration and Experimental Arrangement

This study examines the efficacy of Earth Air Heat Exchanger (EAHE) systems for residential cooling by analyzing three configurations: Parallel (Existing), Series, and Modified EAHE systems, both with and without solar chimney (SC) integration. All experimental configurations were established and evaluated at Gwalior, India, under standard tropical climatic conditions.

**Fig. 1. Experimental setup**

Each system consisted of subterranean air ducts constructed from PVC pipes, buried at an optimal depth of 2.5 meters, using the practically constant temperature of the subsoil. The pipes varied in length, configuration (parallel or series), and arrangement to evaluate performance variations. The Modified EAHE system was designed to improve thermal performance by optimizing factors like pipe length, air velocity, and burial depth. This architecture was also integrated with a Solar Chimney intended to provide natural circulation via buoyancy-driven ventilation, particularly effective during peak daytime temperatures.

**Table 1. Principal elements of the experimental configuration**

| Components | Specification |
|---|---|
| Pipe material | PVC |
| Pipe diameter | 0.15 m |
| Burial depth | 4 m |
| Air velocity | Up to 2.5 m/s |
| Solar chimney integration | Yes |

Measurement tools used included K-type thermocouples, anemometers, data recorders, and digital flow meters to assess intake and output temperatures, airflow velocity, and ambient conditions.

### 2.2. Computational Fluid Dynamics Simulation Methodology

The thermal performance of all EAHE variants was simulated using ANSYS FLUENT.

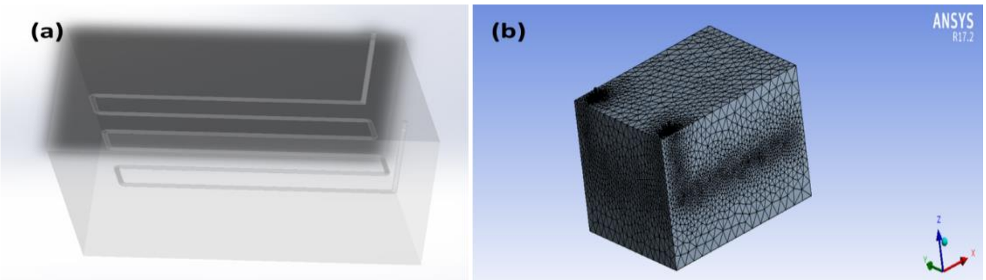


**Fig. 2. (a) CAD model (b) Meshing**

**Table 2. Boundary conditions during test**

| | |
|---|---|
| Inlet air temperature | 36 to 42$^0$C |
| Soil temperature | Presumed constant at 28°C at a depth of 2.5 meters |
| No-slip condition | Implemented at the walls |
| Initial velocity | 2 m/s at the pipe entrance |

CAD models for each configuration were developed using ANSYS DesignModeler, and refined meshes were produced with inflation layers next to the pipe-soil contact to precisely represent temperature variations. Mesh independence analyses were performed to guarantee precision.

### 2.3. Experimentation of EAHE-SC system

This system consists of three parts namely EAHE, Room under thermal investigation and SC. The EAHE comprises of elongated aluminium pipes that are concealed under the dry soil at a penetration of 4.0 m. The SC consists of a glass surface oriented to the south and an absorber wall that works as a capturing surface. EAHE is connected at the lower part of the wall and SC is connected at the opposite side wall in the higher part. Fig. 3 showed the schematic of a solar coupled EAHE system.

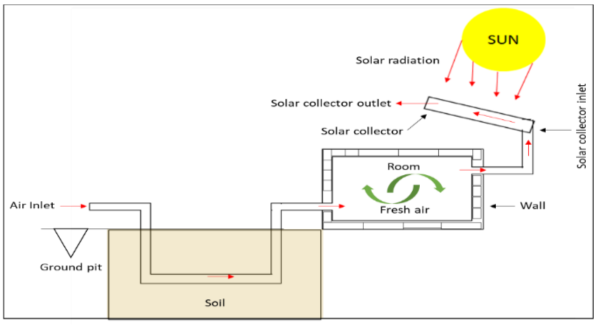


**Fig. 3 Schematic Presentation of EAHE-SC setup**

In the roof portion of the room, the SC inclined at an angle of 38$^0$. In the study location, hot summer begins in April, with the annual higher temperature recorded during May. In this aspect, this current research work is done in May 2024. Figure 3 showed the ambient air temperature and solar intensity recorded from 8 am to 5 pm in the installed location on 25 May 2024.

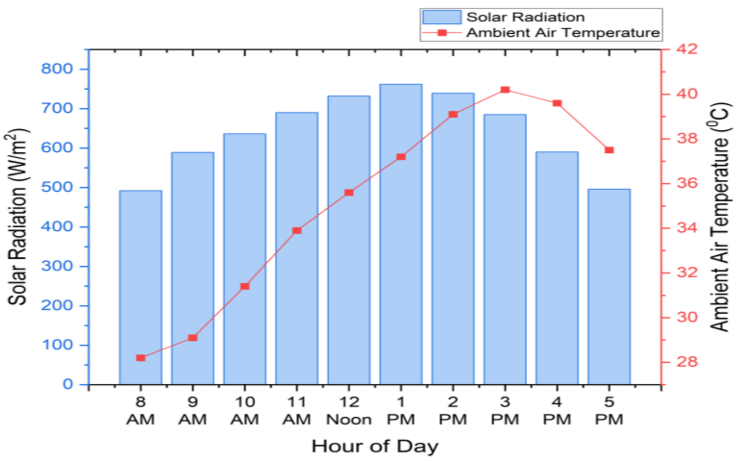


**Fig. 4. Solar Radiation Intensity and Ambient air Temperature vs Time**

### 2.4. Analytical modelling of EAHE-SC for room ventilation

An analytical model includes models of EAHE and SC. Finding the maximum allowable air flow rate for a given design and set of operational parameters is crucial for making ventilation estimates for the planned room. Predicting the performance of a connected system so requires taking the whole energy balance into account. An analytical model is one of the best ways of representing the model structure. Nevertheless, the process of modelling and developing the structure enable us to understand the functions of an integrated system.

#### 2.4.1. Modelling of SC

The energy conservation principle is adopted to find the energy balance equation for SC by solving various differential equations (Maerefat & Haghighi 2010). Figures 5(a) and 5(b) showed the schematic of air flow and heat transfer path respectively.

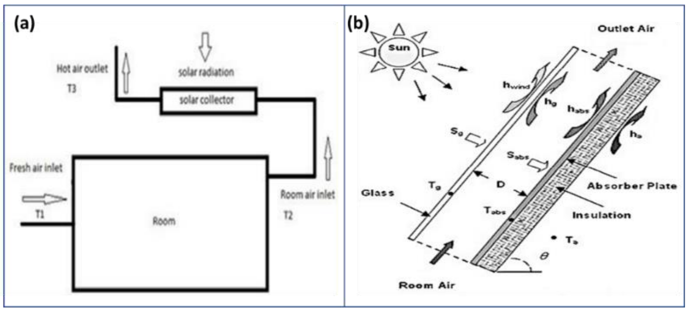


**Fig. 5. (a) Schematic Representation (b) Heat transfer of the air flow path process in SC system**

**Table 3 Thermal-Physical Properties of Solar Chimney**

| Parameters | Values |
|---|---|
| Glass transmissivity | 0.79 |
| Glass absorptivity | 0.05 |
| Glass emissivity | 0.88 |
| Absorber thickness | 0.023 m |
| Absorber emissivity | 0.92 |
| Absorber absorptivity | 0.92 |
| Insulation thickness | 0.02 m |
| Insulation's thermal conductivity | 110 W/m$^0$C |
| Operating Range (Maximum) | 90$^0$C |
| Material of Pipe | Aluminum |

### 2.5. Modelling of Room Ventilation

The modelling of area under investigation was prepared usinf computer aided design software. The place of investigation was in Gwalior District of Madhya Pradesh. The effect of solar energy absorption induced ventilation during daylight hours, whereas electrical energy is not needed to facilitate exhaust ventilation. Because of the temperature difference between the inside and outside of a building, a phenomenon known as the chimney effect occurs, which propels buoyant air into and out of the structure. The pressure differential between the EAHE input and the SC exit determined the driving potential for the room's air flow. The rising buoyant pressure in SC pulls in both hot and cold air via the EAHE.

Length of the room = 3.69 m
Width of the room = 3.69 m
Height of the room = 3.38 m
Area of glass = 1.3 x 1.6 = 2.08 m$^2$
Area of the door = 1.0 x 2.15 = 2.15 m$^2$
Outside wall area = (3.69 x 3.38) -2.08 = 10.39 m$^2$
Partition wall areas = (3.69 x 3.38) + (3.69 x 3.38) + (3.69 x 3.38 -2.08) = 35.34 m$^2$
Now the amount of infiltrated air through windows and walls is
= (3.69 x 3.69 x 3.38 x 1)/60 = 0.77 m$^3$/min
Ventilation requirement/m$^2$ = 0.02 m$^3$/min
Total ventilation required = 0.02 x 20.4 = 0.41 m$^3$/min
Occupant heat gain for room = Sensible heat gain = 70W/person and Latent heat gain = 45W/person
Lighting heat gain for room = 15W/ m$^2$ Room total heat gain = 4.9 kW

The total heat gain of the study room is approximated as 4.9 kW, in order to design a device to provide cooling at a minimum of 1 ton of refrigeration. Total room heat gain is varied based on no of persons, solar radiation and ambient conditions. This study aims to reduce the cooling demand through improving the ventilation and reduction of indoor temperature.

## 3. EXPERIMENTAL RESULT AND DISCUSSION

### 3.1. Evaluation of EAHE-SC Model

**Table 4 Result of observed values from SC on May 2024**

| Time of day | Average air temperature | Room temperature | SC pipe inlet temperature ($^0$C) | SC pipe outlet temperature ($^0$C) | Solar Radiation (W/m$^2$) | Density of Air (kg/m$^3$) |
|---|---|---|---|---|---|---|
| 08:00 | 32.1 | 29.5 | 30.9 | 61 | 492 | 1.1102 |
| 09:00 | 34 | 32.2 | 33.4 | 60 | 589 | 1.1167 |
| 10:00 | 35.9 | 33.1 | 34.2 | 59.7 | 636 | 1.0998 |
| 11:00 | 37.4 | 35.0 | 35.9 | 71 | 690 | 1.0925 |
| 12:00 | 41.9 | 39.1 | 40.1 | 78.4 | 732 | 1.0858 |
| 13:00 | 43.1 | 41.2 | 42.3 | 71 | 762 | 1.0891 |
| 14:00 | 45.2 | 41.5 | 42.9 | 62 | 739 | 1.1027 |
| 15:00 | 47 | 43.6 | 44.8 | 52 | 685 | 1.1310 |
| 16:00 | 43 | 40.5 | 45.3 | 45 | 590 | 1.1569 |
| 17:00 | 41.9 | 40.9 | 45.7 | 43 | 496 | 1.1592 |

The system's ability to deliver the anticipated indoor thermal comfort under various input condition. The results of geometrical specifications of both the systems from the parametric study and conditions of the outdoor environment have to be analyzed. The combined system function was intended to control the indoor temperature irrespective of environmental conditions. A room has a size of 3.69 m × width 3.69 m × 3.38 m height was considered for the modelling, without any infiltration the minimum cooling demand is calculated based on heat gain (ambient conditions), Here the effect of SC is investigated in terms of various cooling demands.

Experimental observations in the designed system at various solar radiations and its efficiency measures are summarized in Table 4. The room was completely sealed before studying the experiment to avoid exhaust or entry of air from the room. From beginning the air temperature and air velocity at inside the room were checked, thus the same as monitored at the outlet. Table 4 depicts the realized values of output parameters taken on 25 May 2024 from 8 AM to 5 PM.

### 3.2. Evaluation of Thermal Comfort

**Table 5 ACH combined with modified EAHE system**

| Time of Day | Ambient Air Temperature ($^0$C) | Absorber Area (m$^2$) | Solar Radiation $I_t$ (W.m$^{-2}$) | ACH Result |
|---|---|---|---|---|
| 8 AM | 28.2 | 2.0 | 492 | 4.19 |
| 10 AM | 31.4 | 2.0 | 636 | 4.96 |
| 12 Noon | 35.6 | 2.0 | 732 | 5.56 |
| 2 PM | 39.1 | 2.0 | 739 | 5.48 |
| 5 PM | 37.5 | 2.0 | 496 | 5.24 |

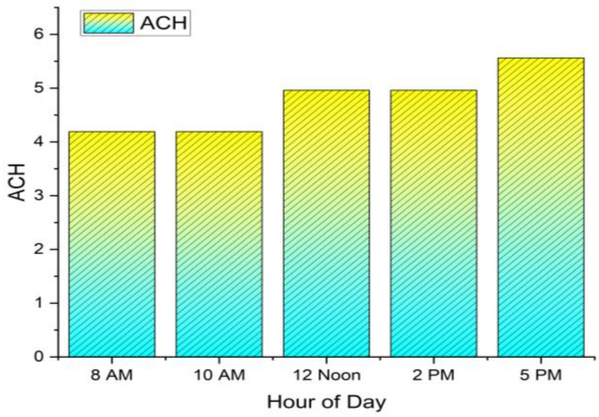


**Fig. 6. ACH of the present study**

From the table observed that the designed system is capable to attain the required 3-5 ACH (minimum of 4.19, maximum of 5.56) for living room comfort (Lal *et al*. 2013). The major effects of the study are highlighted in the Table 5. The achieved ACH results on the test day is graphically shown in Fig. 6.

## 4. CONCLUSION

This research provided a thorough performance assessment of several Earth Air Heat Exchanger (EAHE) designs for residential use, emphasizing the incorporation of solar energy via a solar chimney. The study included three configurations—Parallel (Existing), Series, and Modified EAHE systems—evaluated under both solo and solar-coupled settings. Experimental studies carried out in the arid and hot environment of Gwalior, India, revealed that the Modified EAHE system, particularly when combined with a Solar Chimney, achieved the most substantial temperature drop of up to 14°C. This is very efficient for preserving interior thermal comfort throughout the hot months. The use of CFD-based simulation using ANSYS FLUENT confirmed the experimental results, demonstrating substantial concordance and so bolstering trust in predictive modeling for system design and optimization. The system attained air changes per hour (ACH) between 4.19 and 5.56, fulfilling ventilation standards while minimizing energy use.

The study emphasizes the significance of critical design elements, including pipe length, diameter, burial depth, airflow velocity, and soil thermal characteristics, which directly influence heat exchange efficiency. The integration of renewable energy via solar chimney optimization and passive geothermal exchange creates a hybrid system that is both sustainable and economically feasible for residential applications.

Future research may investigate adaptive control systems, integration with intelligent energy grids, alternate pipe materials, and the use of sophisticated computational fluid dynamics methods for enhanced environmental flexibility. This research enhances the existing information on hybrid passive cooling systems and advocates for their use in energy-efficient architectural design in tropical and subtropical areas.

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