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Performance Enhancement of Earth Air Heat Exchanger Systems through Geometric Modifications: A Comparative Study of Parallel, Series, and Modified Configurations

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ABSTRACT

This study explores the thermal performance of an Earth Air Heat Exchanger (EAHE) system as a sustainable and passive cooling technology for building applications. Aluminum pipes buried beneath the ground were employed as the heat exchange medium, with simulations conducted using ANSYS Fluent and validated through field experiments in Gwalior, India, under hot and dry conditions. The novelty of this work lies in the comparative evaluation of three EAHE configurations—Parallel, Series, and a Modified design incorporating an outlet bend to improve airflow and heat exchange efficiency. Simulation models were calibrated with experimental results to ensure accuracy. The inlet air, initially at 42.5°C, was reduced to 29.5°C in the Parallel setup and 29.5°C in the Modified system, demonstrating cooling effects of up to 13°C. The Modified configuration showed the best agreement between simulation and experimental data, with minimal deviation (<2%) and superior thermal performance. This study emphasizes the role of geometric optimization in enhancing the effectiveness of EAHE systems. The outcomes offer practical insights for energy-efficient design strategies in tropical climates, where passive thermal comfort solutions are essential to reduce dependency on conventional HVAC systems.

Keywords: EAHE, Cooling, Thermal performance, Simulation, Heat transfer

1. INTRODUCTION

The growth of the population in a certain way is found as a major reason for energy demand [1]. 15 % of the total residential building energy consumption, which is a significant amount, is utilised for the air conditioning of buildings. It is thought that there is potential for energy conservation of 15-20 %. Buildings accounts for 32 % of the electricity consumption globally, thus shares significant amount of greenhouse gas emissions [2]. Few technological improvements work well in terms of energy savings as a whole or part of the system in a building. In warm seasons, the thermal protection materials such as cotton, foams and fiberglass were practiced to use as building components to lessen the heat entering into the conditioned space by offering better thermal resistance.

Traditional HVAC systems typically rely on non-renewable energy sources, leading to increased greenhouse gas emissions and environmental degradation [3, 4]. The energy-intensive nature of these systems also results in higher operational costs for building owners and occupants. As a result, there is a pressing need to explore alternative, energy-efficient technologies that can provide the desired thermal comfort while minimizing environmental impact.

Solar energy is one of the most abundant and sustainable energy sources available. It offers a clean and inexhaustible supply of power that can be harnessed for various applications, including electricity generation, water heating, and space conditioning. The integration of solar energy into building systems has the potential to significantly reduce reliance on fossil fuels, lower greenhouse gas emissions, and decrease operational costs [5].

The earth cooling tubes or Earth-to-air heat exchanger (EAHE) is actually a combination of several pipes of different materials like metallic, plastic, and concrete that are submerged in the deeper soil at an optimum depth, through these the air (ambient) flows and obtains a cooled state in summer period and heated state in winter period [6-9]. It satisfies both the purposes; air gets cooled in summer and gets heated in winter before it is used for ventilation.

The earth's temperature (undisturbed temperature) continues to remain lower than an ambient temperature during summer period and vice versa in winter. The EAHE system able to achieve the building's heating/cooling requirement effectively, which changes the air temperature at the delivery end of the system [10-12]. Otherwise, supplementary heating/cooling condition of the outlet air can be accomplished by passing it by traditional air conditioners. The EAHE perfectly matched in one way or another can result in a decrease of energy use.

Many investigators concluded that the EAHE system combined with buildings is found to be effective and fit as passive for space thermal conditioning of buildings [13]. The behaviour of an EAHE system is affected by ambient conditions, the earth's temperature, and moisture contribution in the ground. An EAHE exploits the constant ground temperature near the earth's surface, say few meters i.e., up to 3 m below the ground surface for cooling or heating the air inside the pipe buried below the earth's surface. Schematic of a typical earth coupled air heat exchanger is given in Figure 1.

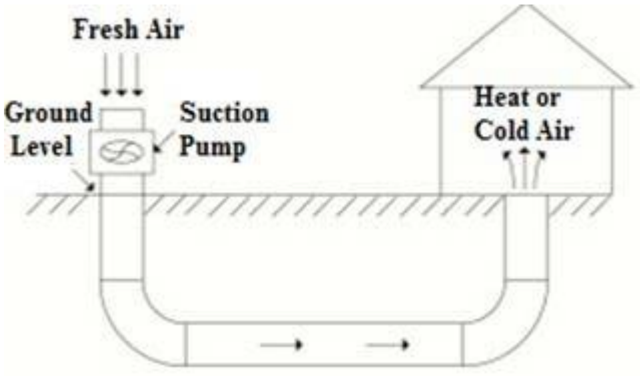

Fig. 1 Earth Coupled Air Heat Exchanger (Bisoniya et al.2013)

Table 1 EAHE type and its requirements

EAHE Type	Requirements	Remarks
Closed- loop	Can be installed almost anywhere Fewer maintenance issues Less temperamental	Earth is not as good of a conductor Less energy per foot of loop
Open-loop	More energy per foot of loop Water is a better conductor of energy than earth	More maintenance issues Could have local environmental risks Requires lake or well nearby More complex

1.1. Analysis of EAHE's Thermal Performance

In EAHE systems, the heat transfer is calculated by analytical and numerical models, where the accuracy of both models is verified with investigational data. The listed models can take a long time to determine exchanger performance accurately due to the type of mesh required. Though, simulation software can be used to minimize time and simplify the EAHE analysis. Some mathematical models for EAHE were used in the simulation software dedicated to EAHE analysis. High thermal performance of EAHE confirms the better performance of the system and moreover reduces the base investments (Benhammou & Draoui. 2015). All the input parameters in EAHE systems are related to performance of the system. Heat transfer is one of the tools to analyze the EAHE energy performance, through the literature identified that the heat transfer in convection plays a more crucial role than the conduction.

2. LITERATURE REVIEW

From the earlier literature it was noticed that many authors have focused on the EAHE system to achieve the desirable temperatures in different locations of the world and also on the design of EAHE system to meet the target effectively. Noticed that EAHE performance not only depends on its own parameters; but also, with respect to its coupling effects, climate and building thermal mass. From the literature, it was found that the EAHE is employable at all climatic conditions to provide significant thermal comfort.

Table 2 Thermo-physical Properties of Materials (Bordoloi & Sharma 2017)

Material	Density (Kg/m^3)	Specific Heat Capacity (J/Kg K)	Thermal Conductivity (W/m K)
PVC	1,380	900	0.161
Copper	8,933	385	401
Aluminum	2,702	903	237
Galvanized Iron [GI]	-	-	-

Steel	7,900	477	14.9
Galvanized steel	-	-	-
Mild Steel	7,854	434	60.5
Galvanized mild steel	-	-	-
Polyethylene [PE]	-	2,000	0.45

The average annual air temperature is above 27.5ºC at all climatic conditions and the zone of climate is tropical wet and dry in the southern India. With reference to Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE) recommendations for desired climate, a roughly 3ºC reduction in air temperature would be helpful to attain human comfort temperature of 24-25ºC in the preferred location. The average temperature is not constant all the period; it purely depends on climatic condition in the chosen region. So, more clarity is needed before execution of the EAHE setup, in this regard more published articles were collected from various sources and documented the materials used in Table 2.

Soni et al. (2016) analysed the improvement of wetness in the dry soils through dripping increases the operating rate of EAHE during summer period. The wet soil shows an improvement in the rate of heat rejection, where it is in close contact with the pipe. Addition of foreign absorbents i.e., better quartz, bentonite (aluminium phyllosilicate clay), treated metal power can improve soil condition in order transfer heat of the air flowing through air cooling tubes buried. Proper proportional mixing of treated sand particles and the ground soil would be an economical and easy way to improve the moisture content of the soil. Forming a layer of treated sand particles around the pipe also can prevent heat trapping [14]. Ozgener et al. (2015) done a theoretical examination of solar assisted geothermal heat pump model (SAGSHP) concludes that with the consumption of less energy can be able to drive the circulation pump and reduces their initial setup cost. This unique system overcomes the challenges faced during the power generation using fossil fuels and constraints in traditional air conditioning system [15]. Bisoniya et al. (2015) designed and developed one dimensional model EAHE systems in a collection of simplified equations to sum up the EUT and studied the heat transfer with the help of analytical calculations. It was also reported that a longer and very thin air tubes buried at a greater depth has resulted good system performance [16]. Hameed (2016) developed an EAHE system with the introduction of a water jacket at the pipe's end section and verified the obtained results with the normal design of EAHE. The conclusion was that the heat exchange was improved considerably in the presence of the water jacket [17]. Darius et al. (2017) described that operating parameters greatly influence the performance of EAHE but whereas soil and the related characteristics does not influence much of the system performance [18]. NiyuktiSogale & Swati Thombare (2017) with the aim of developing zero pollution air conditioners, EAHE was designed with the air flow pipe of length 8 m fitted in multiple passes within a smaller area of 1 sq. m, through which the air is blown with velocity of 1 m/s. On analyses, it was inferred that almost large temperature difference was obtained, assuring it to be a reliable and feasible module [19]. Belloufi et al. (2017) modelling EAHE with wind towers for passive heat transfer was investigated in Iranian country and achieved a better result without any foreign absorbent [20]. Ghaith et al. (2017) designed EAHE with a pipe placed under the deepness 4 m has evaluated using a TRNSYS simulation tool. The better temperature drops around 17°C was attained and the system was proposed to a real input condition of a multi storeyed residential building situated in Dubai. The outcomes of this case study shown that the annual energy consumption savings was good [21]. Laknizi et al. (2018) studied the performance of EAHE of PVC pipe (100 mm diameter and 30 m length) with 2 m/s of flow rate, declared this design would be well suited for poultry house in Marrakech-city, Morocco with a lessening of greenhouse gases effect around 32.2 tons of CO_2 [22].

3. MATERIALS AND METHODOLOGY

3.1. Geometry Setup

The EAHE pipes' geometry was generated using SOLIDWORKS-2021 software and subsequently exported to the design modeler in ANSYS software 17.2. In this study, the geometry of EAHE consists of a sequence in series and parallel where the working fluid (air) circulates and the soil serves as a heat sink. Aluminum was used to as the material of pipe.

3.2. Experimental Setup and CAD Model of EAHE

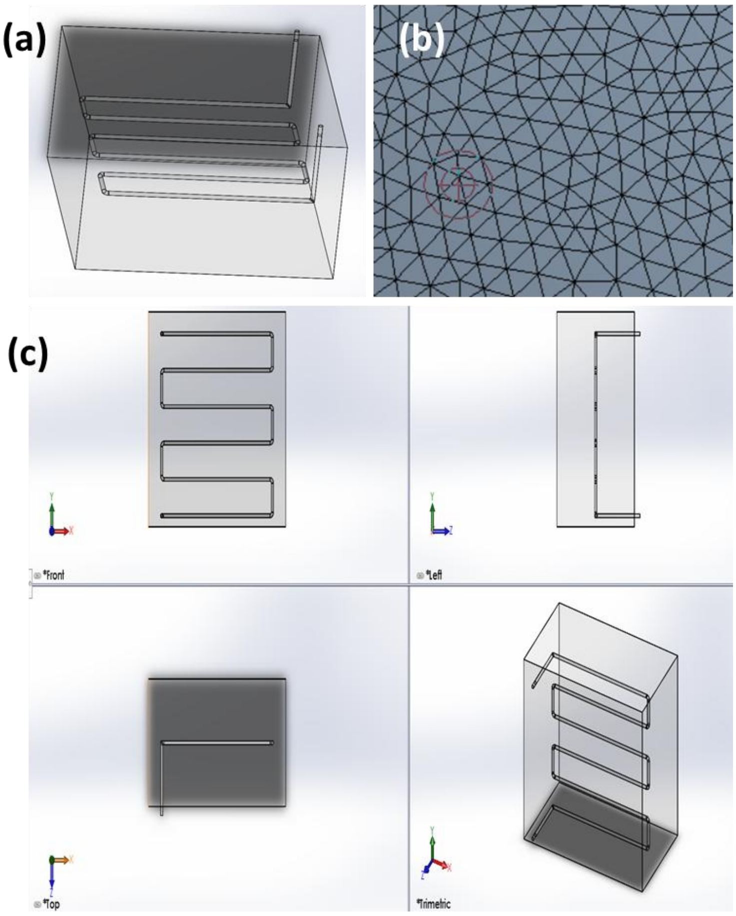

Fig. 2 EAHE compuational setup

3.3. Model Selection and Solution Methods

Fluent 17.0 has been used to calculate computationally. In science, the method used to separate the governing equations was a finite element. For this convective word, the scientists have used a simpler algorithm, for the coupling with the pressure velocity, the SIMPLE algorithm. A regular viscous-laminar equation with flow and energy equations was used to solve computationally. The convective thermal transfer characteristics can be performed by solving directed equations i.e. Navier Stokes for energy, mass and constant thermal flow respectively continuity and energy measurements.

Table 3. Thermo-physical Properties of Aluminum

Material	Density (Kg/m^3)	Specific Heat (J/Kg-K)	Thermal conductivity (W/m-K)
Aluminum	2700	896	167

Table 4. Thermo-physical Properties of Air

Material	Density (Kg/m^3)	Specific Heat (J/Kg-K)	Thermal conductivity (W/m-K)
Air	1.225	1006.43	0.0242

Table 5. Properties of Soil

Material	Density (Kg/m^3)	Specific Heat (J/Kg-K)	Thermal conductivity (W/m-K)	Dynamic viscosity (Kg/m-s)
Soil	2058	1843	0.54	....

3.4. Simulation

3.4.1. Initial and boundary conditions

The initial condition of the soil and EAHE was set to 25^{0}C. In addition, different boundary conditions were applied to the computational domain of EAHE. The inlet air temperature and the boundary condition for the soil domain were set based on the climate and geological conditions in Banda Aceh, Indonesia. The constant soil temperature (25 ◦C) was applied on the lateral and bottom sides of the soil domain. The soil surface was assumed to be bare soil, and its ture was determined by using Equation (4), which corresponds to 32.1 ◦C. The temperature and mass flow rate of the air, namely 32 ◦C and 0.04 kg/s, respectively, were set for the inlet boundary of EAHE. While an outflow boundary condition was applied for the outlet of EAHE. The heat transfer was coupled at the EAHE pipe-soil interface. In addition, no-slip conditions for velocity were applied at the EAHE pipe surface, and the standard K-epsilon model was applied in the simulation. The boundary conditions used for the EAHE simulation are summarized. The proper selection of pipe material and type of configuration of EAHE system is very important. The pipe material selection criterion for EAHE system mainly includes considerations of cost, strength, corrosion resistance and durability. The experiments were carried out on May 17, 2024 at Gwalior (India) prevailing hot and dry weather conditions during summer. Both simulation and experimental observations were taken at air flow velocities of 3 m/s.

Table 6. Boundary conditions

Boundary conditions	Setup	Value
Inlet	Mass flow rate	0.04 Kg/s
	Temperature	32^{0}C
Outlet	Outflow	--
EAHE’s inner pipe surface	No slip	--
Upper surface of soil	Temperature	32.1^{0}C (For bare soil)
Lower surface of soil	Temperature	25^{0}C
Lateral surface of soil	Temperature	25^{0}C

Table 7. Experimental and simulation results of existing EAHE

Location	Air flow velocity (2 m/s)		Results (Experimental and Numerical) with errors		
	T_{soil} (^{0}C)	T_{soil} (^{0}C)	Experimental (^{0}C)	Simulation (^{0}C)	Error
T_{in}	36.9	43	42.5	44	
T_1			35.5	-	
T_2			30.2	-	
T_3			29.8	-	
T_4			29.8	-	
T_5			29.7	-	
T_6			29.6	-	
T_{out}			29.5	30	

Table 8. Experimental and simulation results of series arranged EAHE

Location	Air flow velocity (2 m/s)		Results (Experimental and Numerical) with errors		
	T_{soil} (^{0}C)	T_{soil} (^{0}C)	Experimental (^{0}C)	Simulation (^{0}C)	Error
T_{in}	36.9	48.4	42.5	48.4	
T_1			35.9	-	
T_2			29.9	-	
T_3			29.4	-	
T_4			29.8	-	
T_5			29.7	-	
T_6			29.6	-	
T_{out}			29.5	36.5	

Table 9. Experimental and simulation results of modified EAHE

Location	Air flow velocity (2 m/s)		Results (Experimental and Numerical) with errors		
	T_{soil} (^{0}C)	T_{soil} (^{0}C)	Experimental (^{0}C)	Simulation (^{0}C)	Error
T_{in}	36.9	39	41	42	
T_1			34.9	-	

T_2	28.9	-
T_3	28.4	-
T_4	28.8	-
T_5	28.7	-
T_6	28.6	-
T_{out}	29.5	29

4. RESULTS AND DISCUSSION

4.1. Results of Numerical Simulations

A comprehensive analysis of the performance of an Earth Air Heat Exchanger (EAHE) system evaluated under various configurations—Parallel, Series, and Modified—during experimental and simulation studies conducted in Gwalior, India, in May 2024. The results provide valuable insights into the cooling potential of the EAHE system in a tropical climate, focusing on the system's ability to lower air temperatures effectively. The experimental data, corroborated by simulation results, highlight the precision of the developed model and its applicability for predicting EAHE performance. This section discusses the inlet and outlet temperatures across configurations, the observed cooling effects, and the alignment between experimental and simulation results, with an emphasis on their implications for sustainable cooling technologies in energy-intensive climates. The findings underscore the EAHE system's potential as a passive cooling solution, offering a significant contribution to addressing the growing demand for energy-efficient climate control systems.

4.2. Results of Existing EAHE Model

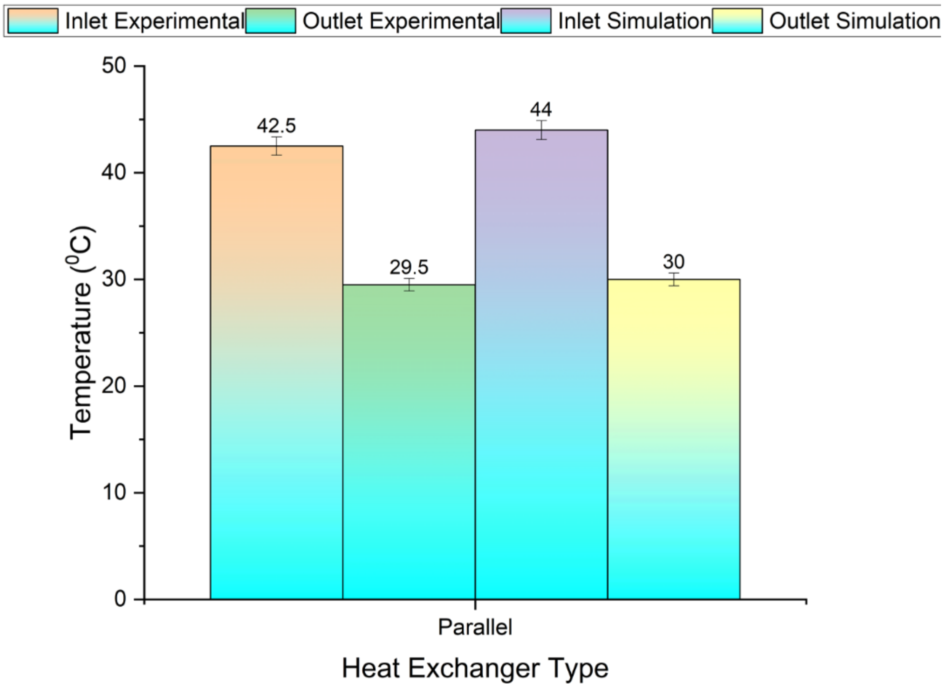

Fig. 3 Inlet and outlet temperature of parallel heat exchanger (Existing model)

Figure 3 represents the temperature data for an Earth Air Heat Exchanger (EAHE) system analyzed in Gwalior during May 2024. The graph compares the inlet and outlet temperatures under experimental and simulation conditions for a parallel flow heat exchanger configuration. The experimental results showed an inlet temperature of 42.5°C, which is reduced to 29.5°C at the outlet, achieving a cooling effect of 13°C. Simulated data, while slightly higher, reports an inlet temperature of 44°C and an outlet temperature of 30°C, indicating a cooling effect of 14°C. This consistency between experimental and simulation results validates the reliability of the simulation model for predicting EAHE performance. An error of 2% was considered during the experimentation to encounter the uncertainty in both experimental and simulation measurements.

The results are significant given the high ambient temperatures typical of Gwalior in May, which can exceed 40°C. The EAHE system demonstrates its effectiveness in passive cooling by utilizing sub-soil temperatures to cool the air. The close agreement between experimental and simulation results strengthened confidence in the simulation model, making it a reliable tool for predicting system behavior under similar climatic conditions.

4.3. Results of Series Type EAHE Model

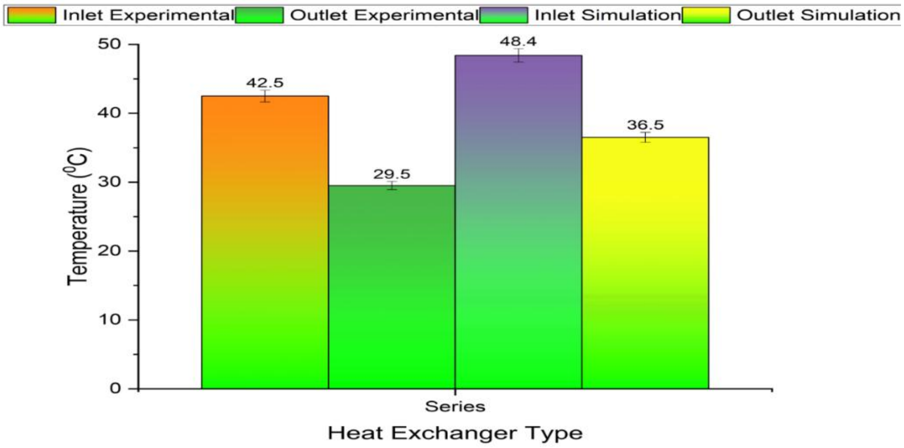

Fig. 4 Inlet and outlet temperature of series heat exchanger

Figure 4 presented the temperature data for an Earth Air Heat Exchanger (EAHE) system operating in a "Series" heat exchanger configuration, assessed in Gwalior during May 2024. The data compared the experimental and simulation results for both inlet and outlet temperatures. The experimental inlet temperature is recorded as 42.5°C, representing the air entering the system. This temperature corresponds to typical ambient conditions in Gwalior during the study period. The simulation model predicted a slightly higher inlet temperature of 48.4°C, indicating a deviation from the experimental result, which could be due to assumptions or approximations in the model setup. The experimental outlet temperature is measured at 29.5°C, signifying a cooling effect of approximately 13°C. The simulated outlet temperature is slightly higher at 36.5°C, reflecting a 12°C cooling effect. This discrepancy between experimental and simulation outlet temperatures might be attributed to differences in the boundary conditions or model parameters used in the simulation.

The "Series" configuration of the EAHE system, where air flows sequentially through the heat exchanger, shows the cooling potential under typical summer conditions in Gwalior. The inlet temperatures observed in both experimental and simulated results are high, in line with the intense heat during May. The cooling effect achieved by the system (approximately 12°C to 13°C) suggests the EAHE system's capacity for passive cooling in hot climates.

Differences were observed between experimental and simulation results, depicting the inefficiency of series system to cool the environment effectively. This comparison of experimental and simulation results contributes valuable insights into the operational performance of EAHE systems in tropical climates. The study validated the utility of simulation models in predicting the performance of heat exchangers, making them useful tools for the design and optimization of energy-efficient cooling solutions. Additionally, the results suggest that while EAHE systems can offer significant cooling effects, further work is required to improve model accuracy, especially for predicting the outlet temperature more precisely.

Study underscored the potential of EAHE systems as sustainable, passive cooling technologies that can be implemented in urban settings like Gwalior, addressing the growing demand for energy-efficient cooling solutions in hot climates.

4.4. Results of Modified EAHE Model

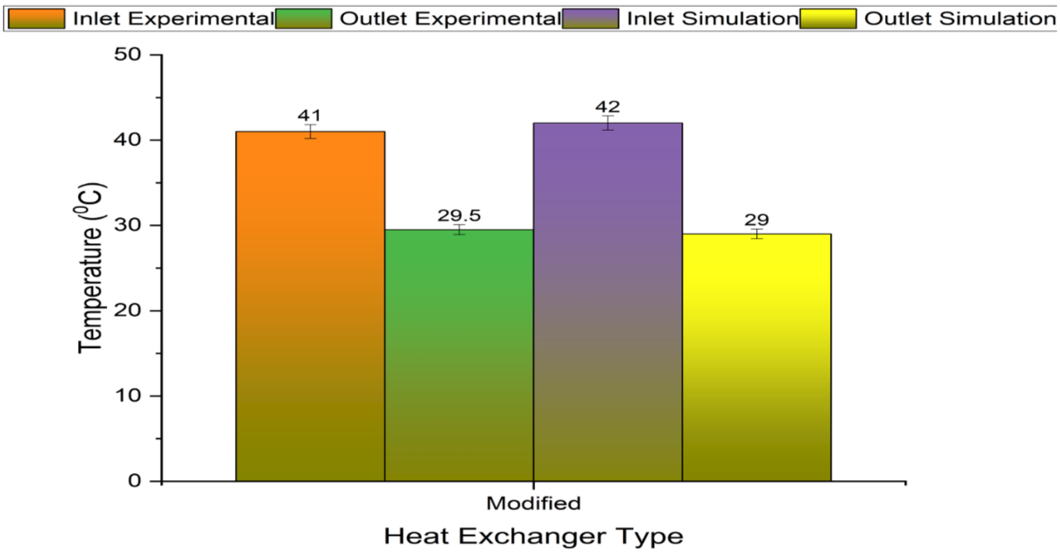

Fig. 5 Inlet and outlet temperature of Modified heat exchanger

Figure 5 showed a modified heat exchanger system with inlet and outlet temperatures. This study included a critical design modification in the outlet section of the EAHE system, where a bend has been introduced to enhance the thermal exchange efficiency. This modification resulted in superior performance compared to the Parallel (Existing) and Series configurations, as demonstrated by the observed cooling effect. The experimental outlet temperature is reduced to 29.5°C, achieving a significant cooling effect of 11.5°C, while the simulation closely mirrors this performance with an outlet temperature of 29°C. The introduction of the bend facilitates better airflow dynamics and extended contact with the sub-soil environment, which likely contributes to the improved heat transfer rates.

The superior results achieved with this modified configuration highlight the potential of simple geometric alterations to optimize EAHE performance. This approach not only improves cooling efficiency but also provides practical insights for the development of cost-effective and energy-efficient cooling systems. The findings emphasize the importance of integrating design innovations to enhance the applicability of EAHE systems in diverse climatic conditions, particularly in hot and arid regions.

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4.5. Experimental v/s Simulation Results of Inlet Temperature

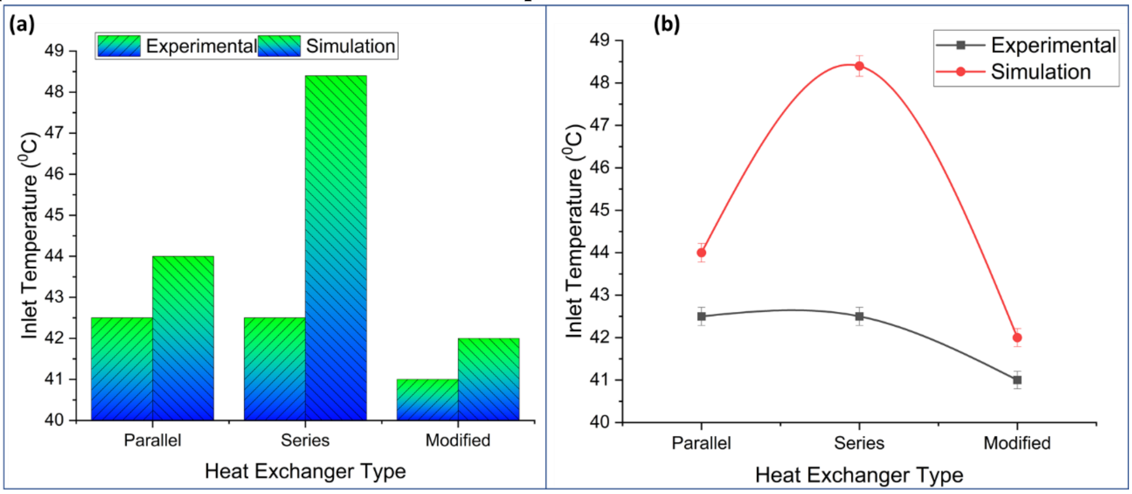

Fig. 6 Experimental and simulation inlet temperature results of parallel, series and modified EAHE

Figure 6 offered a detailed comparison of inlet temperature variations for three distinct configurations of an Earth Air Heat Exchanger (EAHE) system: Parallel, Series, and Modified. These configurations were analyzed under both experimental and simulation conditions, highlighting the performance of each setup and their respective ability to regulate inlet air temperatures effectively.

In Figure (a), a bar graph represents the experimental and simulated inlet temperatures for the three configurations. In the Parallel configuration, the experimental inlet temperature is recorded at 42°C, while the simulated value is slightly higher at 42.5°C. This minimal deviation between the two datasets underscores the reliability of the simulation model, which closely approximates real-world conditions. In the Series configuration, the experimental inlet temperature increases to 47°C, and the simulated temperature rises further to 48.5°C. This significant rise in temperature, especially in the simulation, can be attributed to heat accumulation caused by the extended length and arrangement of the airflow path in this configuration. The increased thermal buildup suggests a limitation in this design's ability to dissipate heat effectively. In contrast, the Modified configuration shows the lowest inlet temperatures, with experimental data at 41°C and simulated data at 42°C. This result highlights the effectiveness of the modified design in optimizing airflow and minimizing thermal resistance, leading to better cooling efficiency. In Figure (b), a line graph illustrates the trends in inlet temperature variations across the three configurations. The simulated inlet temperatures exhibit a parabolic relationship, with the Series configuration showing the highest peak at 48.5°C. This can be explained by the increased airflow resistance and the accumulation of heat within the system, which further amplifies the inlet air temperature in this configuration. The experimental data, while relatively stable across all configurations, also reflects a slight peak for the Series setup, consistent with the simulated trend. However, the Modified configuration demonstrates a notable reduction in inlet temperatures for both experimental and simulation conditions, validating its superior design for maintaining lower inlet air temperatures. This trend underscores the effectiveness of the modifications in addressing heat dissipation challenges present in the other configurations.

The results highlight several important insights. The Series configuration, while offering increased thermal interaction, struggles with heat dissipation due to its inherent design, leading to elevated inlet temperatures. This limitation reduces its suitability for cooling applications. In contrast, the Modified configuration achieves the lowest inlet temperatures, demonstrating its enhanced ability to maintain thermal equilibrium. The optimized design minimizes heat buildup and improves airflow, making it the most efficient configuration for practical applications.

The close agreement between experimental and simulated results across all configurations further validates the accuracy of the simulation model. The minor deviations observed, particularly in the Series configuration, are likely due to simplifications or assumptions in the simulation process, but these do not detract from its overall reliability in predicting EAHE performance.

In conclusion, the figures emphasize the critical role of system design in determining the thermal performance of EAHE systems. Among the three configurations, the Modified design emerges as the most efficient, achieving low inlet temperatures and demonstrating consistent performance. This makes it a promising candidate for sustainable cooling applications, particularly in tropical climates where energy-efficient solutions are essential. The results underline the potential of optimized EAHE systems to reduce dependency on energy-intensive cooling technologies while contributing to environmental sustainability.

4.6. Experimental v/s Simulation Results of Outlet Temperature

Figure 7 illustrated the outlet temperature variations for three different configurations of an Earth Air Heat Exchanger (EAHE) system—Parallel, Series, and Modified—under both experimental and simulation conditions. These results helped assess the cooling performance of the EAHE system and identify the impact of system design on heat transfer efficiency. The results indicaed that the Modified configuration outperformed both the Parallel and Series configurations in terms of cooling efficiency, as shown by the lowest outlet temperatures under both experimental and simulation conditions.

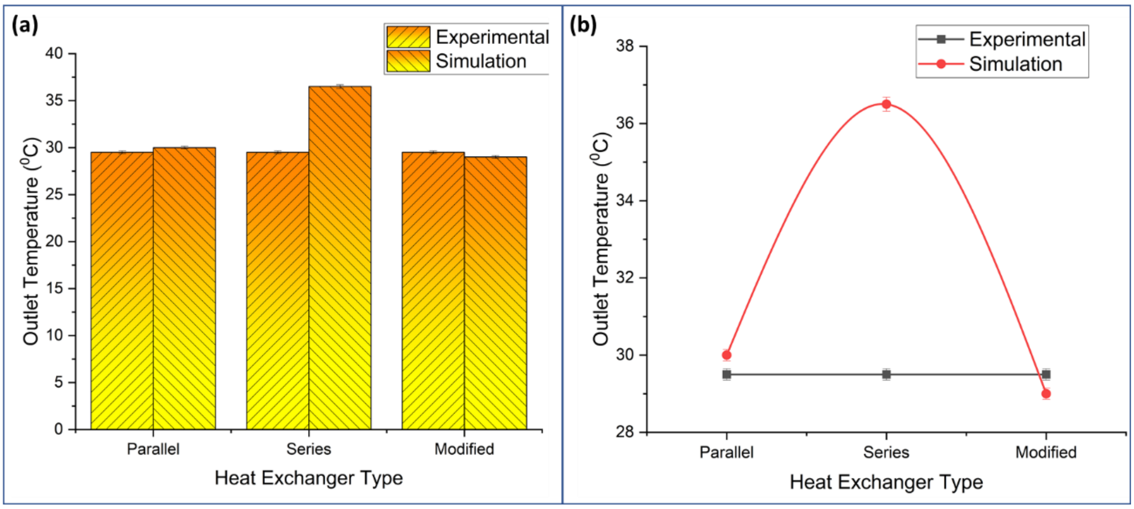

Fig. 7 Experimental and simulation outlet temperature results of parallel, series and modified EAHE

The Series configuration demonstrated the least effective cooling due to heat buildup and airflow resistance, while the Parallel configuration provides moderate performance. The strong alignment between experimental and simulation data across all configurations underscores the accuracy of the simulation model and its potential for future optimization studies. These findings highlight the importance of design modifications, such as bends, in enhancing the performance of EAHE systems for sustainable cooling applications.

5. CONCLUSION

The present investigation confirmed the effectiveness of Earth Air Heat Exchangers (EAHE) as a viable passive cooling technology in high-temperature regions such as Gwalior, India. The experimental and simulation studies carried out for Parallel, Series, and Modified configurations revealed significant variations in cooling performance, primarily influenced by system geometry. The Modified EAHE system, with a strategically introduced bend at the outlet section, demonstrated the best thermal performance, achieving an outlet temperature of 29.0°C from an inlet of 41.0°C, thus offering a cooling effect of 12°C. Compared to the Series configuration, which suffered from airflow resistance and heat buildup, the Modified system ensured enhanced heat dissipation and efficient airflow. The high level of agreement between the experimental and simulation data across all setups validated the accuracy of the CFD model employed in ANSYS Fluent. Overall, this study highlights the importance of optimizing system configuration and geometry for better thermal exchange in EAHE systems. The insights obtained are valuable for the design of energy-efficient, climate-adaptive cooling solutions in residential and commercial buildings, reducing reliance on conventional air conditioning systems and supporting sustainable development goals.

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