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CFD-Based Thermal Analysis and Experimental Validation of Pipe Materials in Earth Air Heat Exchangers for Energy-Efficient Buildings

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Abstract The Earth Air Heat Exchanger (EAHE) is a passive energy system that utilizes the thermal energy of the ground to reduce cooling and heating loads in buildings. This study investigates the thermal performance of EAHE systems constructed with different pipe materials through both computational and experimental approaches. A CFD analysis using ANSYS Fluent was conducted to simulate airflow and heat transfer within buried pipes under steady-state conditions. The simulation results were validated with experimental data obtained from a test rig installed in Ajmer, India. The thermal efficiency of helical pipe configurations made from various materials was assessed using CFD, focusing on changes in air temperature, the extent of heat exchange between the air and surrounding soil, and the thermal performance at the knee point. During heating mode, a maximum air temperature rise of 13.56°C was observed for air through copper and steel pipes, while a minimum temperature rise of 12.32°C was achieved by air through an asbestos cement pipe. On the other hand, during the cooling of air maximum temperature drop of 19.68°C was observed through the steel pipe, whereas a minimum temperature drop of 17.91°C was observed for air through the asbestos pipe. The study demonstrates that the thermal performance of Earth Air Heat Exchanger (EAHE) systems is significantly influenced by the choice of pipe material. Both CFD simulations and experimental data confirm that metallic pipes, particularly steel and copper, offer superior heat exchange efficiency compared to non-metallic alternatives like asbestos cement.

Keywords: cooling; earth air heat exchanger; heating; helical pipe; pipe material

1. Introduction

As the global population continues to grow and economies expand, the demand for energy is steadily increasing. Buildings alone account for about 30–40% of the world's total energy consumption and contribute roughly 28% of global CO₂ emissions. of the energy used in buildings, a significant portion—around 32–33%—goes toward heating and cooling. Maintaining thermal comfort can be achieved through either active or passive heating and cooling systems, depending on the season. Passive systems use little to no external energy, making them far more energy-efficient than active systems. In contrast, conventional space heating and cooling methods tend to be

energy-intensive and often rely on fossil fuels, which pose serious environmental and health risks¹). Energy consumption by end users significantly influences economic growth by impacting energy production, distribution, and conservation efforts²).

Therefore, it is inexorable to develop systems and technologies that require minimum energy to operate and have minimum impact on the environment while maintaining thermal comfort for the occupants³). The EAHE takes advantage of the fact that, at depths greater than 3 meters under the earth's surface, the temperature remains nearly constant year-round—cooler than the surrounding air during summer and warmer during winter.

Harnessing geothermal energy for electricity generation offers a sustainable and reliable alternative to fossil fuels⁴). Performance of heat EAHE systems depend upon the pipe material, its dimensions, soil properties, air velocity and duration of operation⁵). Low thermal conductivity soils are less effective for extended use of EAHE, as they tend to reach thermal saturation more rapidly than high conductivity soils⁶). EAHE systems are more appropriate to use in dry and hot conditions in comparison to humid conditions due to problem of condensation of water and defile by microorganisms in humid areas⁷). EAHE systems can be installed as standalone or in pair with the traditional HVAC systems, to reduce the energy consumption associated with HVAC system in buildings, however, this technology is suffering higher economic cost due to higher cost of excavation and requirement of large pipes⁸). Several factors influence how well an EAHE system performs, including the type of pipe used, how fast the air moves through it, the length and diameter of the pipe, and the thermal properties of the surrounding soil. Among these, air velocity has the greatest impact, while the choice of pipe material has a comparatively smaller effect. A computational fluid dynamics (CFD) tool was employed to evaluate how soil thermal diffusivity affects EAHE performance by simulating three different soil types at a constant inlet air velocity⁹). After 12 hours of continuous operation, it is experiential that the soil with the lowest thermal diffusivity resulted in the greatest temperature rise (2.56 °C) at a specific location along the pipe, due to greater heat retention. In contrast, the soil with the highest thermal diffusivity showed the smallest temperature increase (2.02 °C), as it allowed less heat to accumulate near the pipe. One experimental study also studied the effect of soil moisture on EAHE performance during winter conditions¹⁰). They reported that COP and heat transfer by wet EAHE (15% soil moisture) increases by approximately 26% and 26.1 %, respectively, compared to dry EAHE¹¹). Moreover, Knee point with wet EAHE was obtained at 26 m length of pipe compared to 40 m length with dry EAHE. One researcher¹²), used numerical methods to determine the result of pipe diameter, spacing between pipe and air velocity on the performance of EAHE in terms of outlet air velocity and soil-air heat transfer in warm- summer climate. The space between the pipes can be reduced from 1 to 0.5 meters without any significant reduction (maximum 6%) in heat transfer. They also found that, for a pipe with a fixed diameter, the average heat transfer rate improves as the air velocity increases. Their study focused on assessing the performance of the EAHE system in warm and humid climates.

On the other hand, the system was working as heater & cooler during day and night operation. In heating mode, during winters, the system heated the air up to 5.8 °C, while in cooling mode the system was able to cool the air up to 4.8 °C during summer operation¹³). Integrating an Earth–

Air Heat Exchanger with a nanofluid-based solar-driven absorption chiller creates a hybrid, low-exergy cooling system¹⁴). A review of existing literature reveals that a wide range of pipe materials—such as PVC, CPVC, galvanized zinc, copper, steel, concrete, asbestos cement, and reinforced cement concrete (RCC)—have been utilized in Earth Air Heat Exchanger (EAHE) systems¹⁵). However, most of these studies have focused on individual materials or specific configurations, and there remains a significant gap in comprehensive, comparative analyses that systematically assess the influence of different pipe materials on the thermal performance of EAHE systems. In this study, a numerical method is used to explore and compare how well the EAHE system performs when built with eight different pipe materials. The analysis focuses on key factors like the temperature of the air at the outlet, the heat exchanged between the air and the soil, and what's called the 'knee point'—the pipe length over which 90% of the total change in air temperature happens, whether it's heating or cooling¹⁶).

A CFD model has been developed to assess the thermal behaviour of an EAHE operating in cooling mode¹⁷). The data, showing a deviation of 6.07% in the outlet air temperature. This discrepancy may be due to assumptions made in the simulation, such as the friction coefficient of the pipe material, as well as practical inconsistencies in the experimental setup, including insulation quality and pipe joint conditions. Various CFD simulations using chlorinated polyvinyl chloride (CPVC) pipes of different diameters revealed that smaller pipe diameters led to a reduced temperature drop, while larger diameters enhanced thermal performance in cooling mode.

In the present study, a CFD model was utilized to evaluate the thermal behavior of an EAHE system for HVAC applications in buildings. A decrease in temperature of 18.59 °C was observed in cooling mode, while heating mode achieved a temperature increase of 12.8 °C. The model's results closely matched the experimental data, with a maximum difference of just 11.4%. It was also noted that higher airflow rates led to smaller changes in air temperature. According to existing research, the type of pipe material used underground has little impact on the system's thermal efficiency, suggesting that more affordable materials can be used without greatly affecting performance. For instance, a temperature increase ranging from 8.0 °C to 12.78 °C was noted for a 23.42 m long pipe with a diameter of 0.15 m, with experimental and simulated results showing a maximum deviation of only 2.07%. Similarly, another setup with the same dimensions achieved a temperature increase between 4.1 °C and 4.88 °C. Based on the available literature, the material of the buried pipe does not significantly impact EAHE system efficiency¹⁸). However, the objective of this paper is to conduct a detailed fluid flow analysis of various pipe materials used in EAHE systems under both cooling and

heating conditions, utilizing CFD simulations in ANSYS Fluent and validating the results with experimental data¹⁹⁻²²).

In various studies²³⁻²⁷, based on EAHE design and performance optimization with modeling and simulation with heat exchanger and obtained the significant temperature difference between under earth and outside air. Energy efficiency plays an important role in EAHE for HVAC system space cooling and heating process²⁸. Utilization of heat pipe in geothermal low temperature utilization²⁹. CFD analysis for psychrometric air loop system is done for space cooling³⁰. Concept of geothermally is widely used EAHE now a days³¹. Performance of EAHE using tunnel heat exchanger also done by CFD analysis and conclude that optimization can achieve with good energy efficiency³²⁻³⁴. So, at last geothermal cooling and heating using EAHE analysis is done in several ways is well explained by certain review³⁵. CFD has emerged as a powerful tool for simulating the thermal behavior of EAHE systems, allowing detailed analysis of airflow, pressure drop, and heat transfer mechanisms. CFD parametric study on EAHE systems, demonstrating that airflow rate, pipe length, and burial depth significantly affect outlet air temperature and thermal efficiency³⁶. Similarly, CFD is used to optimize pipe geometry and arrangement, finding that shallow burial and shorter pipe length reduce pressure drop while maintaining effective cooling. More recently integrated CFD with machine learning techniques to dynamically optimize EAHE operation under variable climatic conditions, enhancing both energy efficiency and control strategies³⁷.

2. Research Objective & methodology

In this study, the heat transfer analysis for different pipe material of EAHE is investigated by using the CFD fluent model for cooling and heating mode for Bikaner region of India. The outside temperature of Bikaner region during summer and winters is considered 47.60 °C and 12.80 °C, respectively, which is corresponding to the inlet temperature of EAHE. The EAHE model was constructed using CATIA, a computer aided designing tool. As shown in Figure 1 the model consists of three parts- inner, central and outer, which are fluid domain, pipe and soil surrounding the pipe. The various geometrical parameters of the helix are- length 20 m, diameter 1m, diameter of pipe is 0.15m and pitch is 0.5m. Thickness of the soil surrounding was considered as 200 mm.

After creating the EAHE model in CATIA, it was imported in ANSYS 14.5, and later ANSYS ICEM was employed for meshing of the model. The tetrahedral meshing is used for meshing the EAHE model which is shown in Figure 3. The meshing close to the pipe wall is kept denser due to honed temperature variation, while sparse meshing was

generated away from the pipe wall due to less variation in temperature. For this purpose, advanced size functions, which are integrated in ANSYS meshing were used. These

Table 1: Properties of pipe material reference

Material	Thermal Conductivity (W m ⁻¹ K ⁻¹)	Density (kg m ⁻³)	Specific heat (J kg ⁻¹ K ⁻¹)
Air	0.0242	1.225	1006
Soil	0.52	2050	1840
PVC	0.16	1380	900
Cement Concrete	1.4	2300	880
Asbestos Cement	0.1163	770	816
Priceline	1.035	2400	1089
HDPE	0.4	630	2250
Copper	387.6	8978	381
CPVC	0.16	1560	900

advanced size functions refine the mesh automatically without need of any user input, by considering the norm which is based on local curvature and local proximity. The element sizes in the mesh ranged from a minimum of 5.34 mm to a maximum of 683.85 mm. In this study, CFD simulations were carried out using an unstructured grid. The thermophysical properties of the materials used in the simulation are listed in Table 1.

To evaluate the quality of the developed CFD model, grid independence test was performed. To get grid independent solution, simulations were run for six different number of elements (element sizes) with same operating parameters, and found that after 94,92,039 number of elements the solution (air temperature) become independent of number of elements Figure 4. The 94,92,039 number of elements were chosen over 1,22,92,650 number of elements due to less computational duration and better accuracy.

A CFD-based model was developed to predict the thermal performance of an EAHE system. This model is validated against data from a previously published study, which involved experimental evaluation of an EAHE in the hot and arid climate of Ajmer, located in western India. The study used pipes made of two different materials—PVC and mild steel—with each pipe having an internal diameter of 0.15 meters, a length of 23.42 meters, and installed horizontally at a depth of 2.7 meters below the ground surface. Figure 5 illustrates the comparison between the experimental and simulated temperature profiles along the PVC pipe at an airflow velocity of 5 m/s. The CFD model consistently predicted lower temperatures along the pipe length compared to experimental values, except at the pipe inlet. The temperature deviation ranged from 0% up to 6.07%, which may be attributed to differences in the friction coefficient used in the simulation versus the actual

pipe surface, as well as structural irregularities like pipe joints in the experimental setup.

The performance of various pipe materials used in EAHE has been analyzed through CFD using ANSYS Fluent,

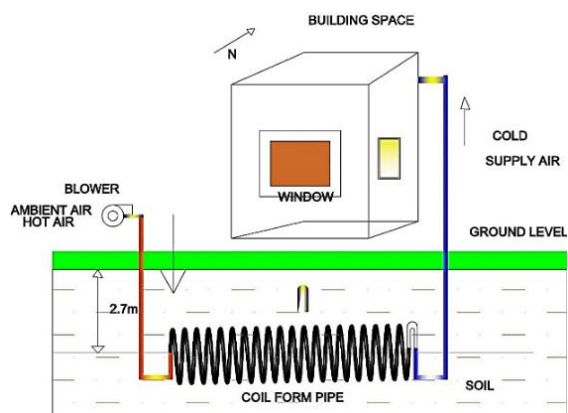


Fig. 1: Experimental Set up of earth air heat exchanger

under both cooling and heating conditions specific to the climatic conditions of Bikaner. For this study, ambient temperatures typical of the region were applied—47.60 °C for summer and 12.80 °C for winter—as inlet air temperatures entering the heat exchanger. The surrounding soil temperature was maintained at a constant 23 °C to simulate steady-state conditions. The simulation focused on evaluating the thermal behavior of air as it flows through pipes made of different materials, embedded in soil with an outer thickness of 200 mm, which corresponds to four times the pipe diameter. The analysis aimed to determine the optimal pipe material by assessing the resulting air temperature profiles under these defined conditions.

3. CFD Model

CFD has long been a reliable method for analyzing heat and mass transfer processes. It employs numerical techniques to solve complex fluid flow problems. By applying discretized forms of partial differential equations (PDEs), CFD provides detailed numerical insights into airflow behavior and heat transfer phenomena. Advanced software tools such as ANSYS FLUENT enable the simulation as shown in Figure 2 indicate the intricate fluid motion and thermal interactions.

The CFD process generally involves three main stages:

(i) Pre-processor:

This stage involves setting up the fluid flow problem within a CFD environment. It includes defining the geometry of the domain under study and generating a computational mesh or grid. The domain is divided into numerous smaller control volumes or elements, allowing the software to trace boundaries and apply governing equations accurately across the entire domain.

(ii) Solver:

At this stage, numerical algorithms are used to solve the

governing equations of heat transfer fluid flow. The solver typically employs methods like the finite volume technique to compute variables such as velocity, pressure, and temperature at each point in the grid.

(iii) Post-processor:

After the simulation is complete, the post-processing phase involves visualizing the results. This can include contour plots, vector plots, graphs, and animations to better understand flow behavior and thermal characteristics within the domain.

3.1. Model Specifications

The Computational Fluid Dynamics (CFD) model of the Earth Air Heat Exchanger (EAHE) was initially designed using CATIA, a high-precision CAD tool, to accurately replicate the physical dimensions and configuration of the system. Owing to the cylindrical structure of the buried pipe, the EAHE geometry was conceptually divided into three concentric zones to facilitate precise thermal analysis:

Outer Domain (Soil Region):

This region represents the surrounding soil which acts as a heat sink or source depending on the season. The extent of this domain is chosen sufficiently large to minimize the influence of boundary conditions on the heat transfer process near the pipe wall.

Middle Domain (Pipe Wall):

This layer corresponds to the pipe material—such as steel, copper, or asbestos cement—and plays a crucial role in heat conduction between the air and the soil. Different material properties were assigned to this region based on the thermal conductivity of the respective pipe materials to study their impact on thermal performance.

Inner Domain (Air Passage):

The innermost cylindrical region carries air as the working fluid, flowing through the pipe. This domain is critical for analyzing convective heat transfer between the air and the pipe wall.

After the CAD model was developed in CATIA, it was imported into ANSYS ICEM CFD for meshing and further pre-processing. Figure 2 illustrates the imported EAHE geometry within the ANSYS environment. Boundary conditions were then defined based on the operational mode (heating or cooling), including:

Inlet: Defined as a velocity inlet or mass flow inlet with a specified temperature depending on the test scenario.

Outlet: Defined as a pressure outlet at atmospheric pressure.

Wall Conditions: Thermal contact and conduction were modeled at the pipe-soil and air-pipe interfaces. No-slip boundary conditions were applied at the pipe walls.

Soil Boundary: Outer soil boundaries were assumed to have either a constant temperature or adiabatic behavior, depending on the simulation scenario.

The mesh quality, refinement at interfaces, and domain

size were optimized to ensure accurate resolution of the thermal gradients while keeping computational costs manageable. A grid independence study was also conducted (to be discussed in the next section) to validate that the results are not sensitive to mesh density.



Fig. 2: Geometry of EAHE model

3.2. Meshing

Mesh generation is a crucial step in the pre-processing phase for ANSYS simulations. In this study, the geometry was meshed using ICEM, applying a tetrahedral mesh to the heat exchanger component of the earth-to-air system, as illustrated in Figure 3. The model includes an 'inlet' where air enters the pipe and an 'outlet' where it exits. An unstructured grid was utilized for the CFD simulations. The mesh quality varies based on curvature and proximity to surfaces. A default meshing algorithm automatically selects an appropriate method based on the geometry. Mesh sizing was determined by the overall dimensions of the model. Parameters such as "relevant center" and "smoothing" were optimized for mesh quality. The smallest and largest element sizes were set at 5.34 mm and 683.85 mm, respectively.

4. Mathematical Modelling²³⁾

Heat gain/ released by air to surroundings calculated by

$$Q = \dot{m} C_p (T_{out} - T_{in}) \quad (1)$$

4.1. Governing equations

As per the continuity equation,

$$\left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right] = 0 \quad (2)$$

As per law of conservation of energy, Mathematically, this principle is expressed as:

$$\left[u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right] = \left[\frac{\partial^2 T}{\partial x^2} + v \frac{\partial^2 T}{\partial y^2} + w \frac{\partial^2 T}{\partial z^2} \right] \quad (3)$$

Where,

α = Thermal diffusivity of the material

4.2. Conservation of Momentum Principle

"The fundamental expression governing momentum conservation is described by the Navier–Stokes equation, which embodies Newton's second law applied to fluid motion. This equation is used to quantify the

changes in momentum within a fluid system."

X-momentum equation:

$$\left[u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right] = - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left[\frac{\partial^2 u}{\partial x^2} + v \frac{\partial^2 u}{\partial y^2} + w \frac{\partial^2 u}{\partial z^2} \right] \quad (4)$$

Y-momentum equation:

$$\left[u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right] = - \frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left[\frac{\partial^2 v}{\partial x^2} + v \frac{\partial^2 v}{\partial y^2} + w \frac{\partial^2 v}{\partial z^2} \right] \quad (5)$$

Z-momentum equation:

$$\left[u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right] = - \frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \left[\frac{\partial^2 w}{\partial x^2} + v \frac{\partial^2 w}{\partial y^2} + w \frac{\partial^2 w}{\partial z^2} \right] \quad (6)$$

In Equations (2–6), u , v , and w represent the velocity components along the x , y , and z axes, respectively. T denotes the temperature, and P refers to the pressure of the air in motion. The symbol " ρ " stands for the air density, while ν indicates the kinematic viscosity.

5. Results and discussion

5.1. Grid Independence Study

To ensure the accuracy and reliability of the CFD model developed for the Earth Air Heat Exchanger (EAHE), a grid independence study was conducted. This involved analyzing the model's sensitivity to varying mesh densities by simulating thermal performance with different numbers of mesh elements.

As illustrated in Figure 4, a graph was plotted between the outlet air temperature and the number of mesh elements. The results indicate that beyond approximately 9,492,039 elements, the outlet temperature stabilizes and remains consistent, even when further refining the mesh up to 12,292,650 elements. This consistency confirms that the solution is independent of the mesh beyond this point. Hence, for subsequent simulations, a mesh size comprising 9,492,039 elements was selected as an optimal balance between computational efficiency and result accuracy. In this mesh configuration, the maximum and minimum element sizes were set to 0.15 mm and 0.011 mm, respectively. These mesh parameters were adopted for all further CFD analyses of the EAHE model to ensure both precision and computational feasibility.

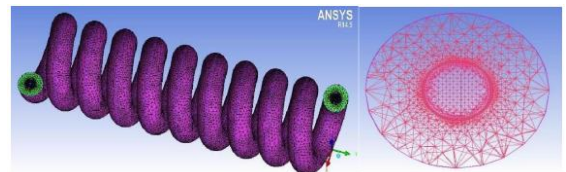


Fig. 3: Meshing geometry of helical coil for EAHE

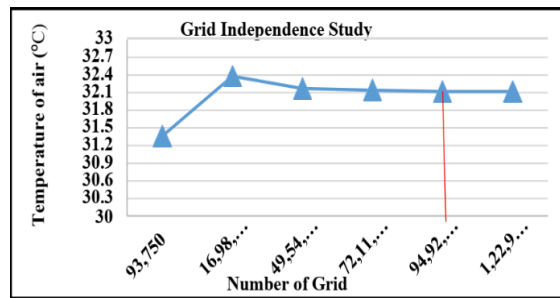


Fig. 4: Graph of grid independency study

5.2. Validation of CFD model to experimental setup

The CFD based EAHE mode is validated with publish research paper which has been done experimental as well as simulation for hot and dry climate of Ajmer (Western India).

In the experimental work two pipe material has been selected for cooling mode which is PVC and steel pipe and flow velocity, diameter and length of pipe is 2m/s 0.15 and 20 m respectively.

The experimental setup has been fabricated at 2.7m depth of earth, at this depth soil temperature is constant throughout the year. In the present study model is validated with experimental setup and variation between experimental and simulation is shown in Figure 5.

5.3. CFD Investigation of Earth-to-Air Heat Exchanger Performance in Summer for Building Cooling

The fluid flow analysis of the EAHE system in cooling mode was carried out using the CFD Fluent software, with a focus on evaluating the performance of different pipe materials used in the heat exchanger., such as PVC, steel, cement concrete, asbestos cement, porcelain, HDPE, copper, and CPVC, were considered. Simulations were carried out for the EPHE to assess its thermal performance.

5.4. CFD Investigation of Earth-to-Air Heat Exchanger Performance in Summer for Building Cooling

The fluid flow analysis of the EAHE system in cooling mode was carried out using the CFD Fluent software, with a focus on evaluating the performance of different pipe materials used in the heat exchanger., such as PVC, steel, cement concrete, asbestos cement, porcelain, HDPE, copper, and CPVC, were considered. Simulations were carried out for the EPHE to assess its thermal performance. Figure 6 shows the graph of EAHE for different pipe material. Horizontal axis represents the length of pipe in meter and vertical axis represent the temperature in degree Celsius. Temperature sensor at equal distance of 3.14m has been inserted in order to find temperature at different sections. Different pipe material of EAHE has been analyzed for cooling mode. Temperature falls in asbestos

cement, CPVC and PVC pipe is in the range of 17.5 °C to 18.5 °C and copper, HDP, porcelain, cement concrete and steel is in the range of 18.5 °C to 19.5 °C. Maximum and minimum temperature fall in steel and asbestos cement pipe is 19.65 °C and 17.89 °C respectively. Figure 7 shows the graph of heat transfer rate verses length of earth pipe heat exchanger where horizontal axis represents the length of pipe in meter and vertical axis represent the temperature in heat transfer rate. Heat transfer rate has been calculated at each 3.14 m length of pipe area. Different pipe material

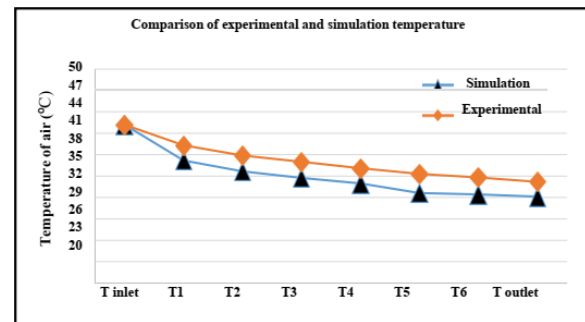


Fig. 5: Graph of validation

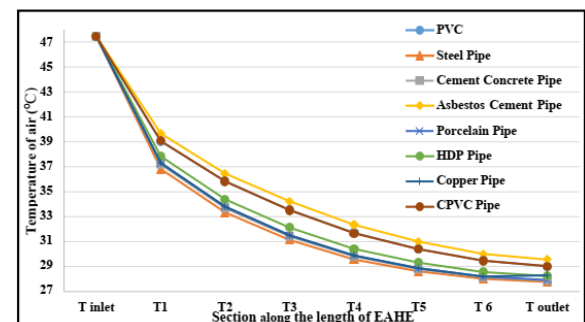


Fig. 6: Graph of temperature v/s length for different material of pipe EAHE for cooling mode

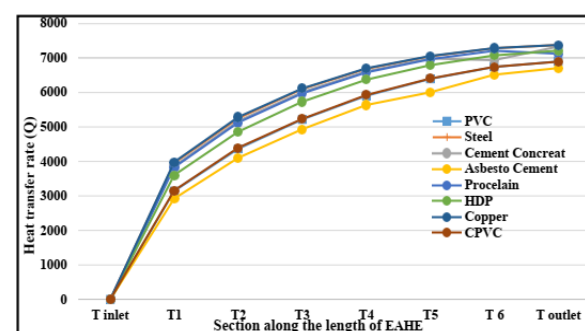


Fig. 7: Graph of heat transfer rate v/s section length

of EAHE have been analyzed for cooling mode and it absorbs that maximum and minimum heat transfer rate in steel and asbestos cement pipe is 10714.18W and 9739.665W respectively.

5.5. CFDs Study of Earth-to-Air Heat Exchanger for Building Heating in Winter

The fluid flow analysis of the EAHE is conducted using

the CFD model in Fluent, focusing on the cooling mode. Various pipe materials are considered for heat exchangers, including PVC, steel, cement concrete, asbestos cement, porcelain, HDPE, copper, and CPVC. The thermal performance of the heat exchanger is evaluated for each of these different pipe types.

Figure 8 shows the graph of EAHE for different pipe material. Horizontal axis represents the length of pipe in meter and vertical axis represent the temperature in degree Celsius. Temperature sensor at equal distance of 3.34 has been inserted in order to evaluate the temperature at

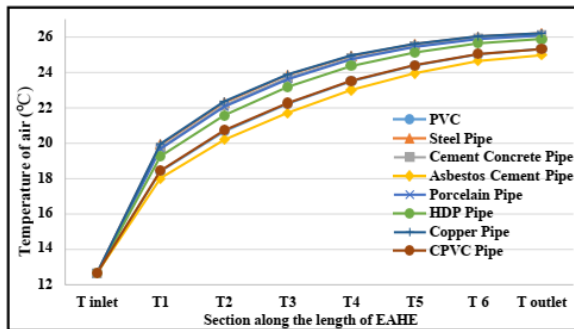


Fig. 8: Graph of temperature v/s length for different material of pipe EAHE for heating mode

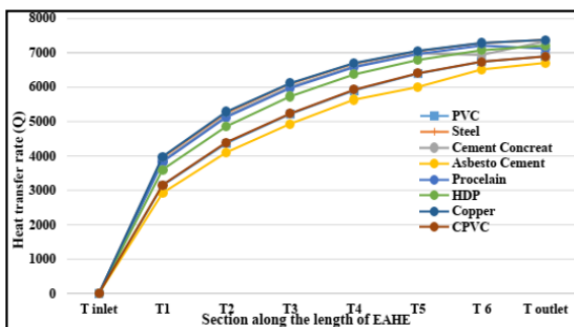


Fig. 9: Graph of heat transfer rate v/s section length

different section. Different pipe material of heat exchangers for earth has been analyzed for heating mode. Temperature rise in asbestos cement, CPVC and PVC pipes are in the range of 12 °C to 13 °C and copper, HDP, porcelain, cement concrete and steel is in the range of 13 °C to 14 °C. Maximum and minimum temperature rise in steel and asbestos cement pipe is 13.56 °C and 12.32 °C respectively.

Figure 9 shows the graph of heat transfer rate verses length of EPHE where horizontal axis represents the length of pipe in meter and vertical axis represents the temperature in heat transfer rate. Heat transfer rate has been calculated at each 3.14 m length. Different pipe material of EAHE has been analyzed for heating mode and it absorbs that maximum and minimum heat transfer rate in steel and copper pipe is 7382.328W and 7382.328W. Minimum heat transfer rate is found in asbestos cement pipe which is 6707.248W.

The results demonstrate that copper and steel materials

exhibit superior thermal performance compared to other materials evaluated in the study. This observation can be attributed primarily to the differences in thermal conductivity and their influence on heat transfer efficiency within the system.

Copper, known for its exceptionally high thermal conductivity ($\sim 385 \text{ W/m}\cdot\text{K}$), facilitates rapid heat transfer from the absorber surface to the working fluid. This enables more efficient collection and transport of thermal energy, resulting in a higher outlet temperature and improved overall system efficiency. The laminar flow typically observed in such systems benefits from the minimal thermal resistance offered by copper, allowing for uniform and consistent heat distribution.

Steel, while possessing a significantly lower thermal conductivity than copper ($\sim 50 \text{ W/m}\cdot\text{K}$), still outperforms materials such as PVC or aluminium in many thermal applications due to its favourable mechanical properties and moderate conductivity. Steel's higher density and heat capacity also contribute to stable heat transfer over time, particularly under conditions where thermal inertia is beneficial. Additionally, the inner surface roughness of steel can induce mild turbulence at higher Reynolds numbers, enhancing convective heat transfer coefficients in the fluid domain.

From a flow dynamics perspective, both copper and steel exhibit compatible surface characteristics that support efficient fluid flow with minimal pressure drop, especially when compared to rougher or less thermally conductive materials. The improved flow stability and enhanced convective heat transfer synergy explain their superior performance.

In conclusion, the thermal performance advantage of copper and steel is rooted in their high thermal conductivity and favourable flow characteristics, making them ideal choices for heat exchanger applications where rapid and efficient heat transfer is essential.

6. Conclusion and Future Work

This research investigates a HPHE for EAHE applications using various pipe materials such as PVC, steel, cement concrete, asbestos cement, porcelain, HDP, copper, and CPVC. A CFD model was created in ANSYS Fluent to evaluate the thermal performance of the heat exchanger intended for building HVAC system.

To ensure consistency, velocity, pipe length, and inlet temperature were kept constant across all pipe materials. The results and discussions have led to the following conclusions:

- Temperature falls in asbestos cement, CPVC and PVC pipe is in the range of 17.5 °C to 18.5 °C and copper, HDP, porcelain, cement concrete and steel is in the range of 18.5 °C to 19.5 °C.
- Maximum and minimum temperature fall in steel

and asbestos cement pipe is 19.65 °C and 17.89 °C respectively.

- Temperature rise in asbestos cement, CPVC and PVC pipes are in the range of 12 °C to 13 °C and copper, HDP, porcelain, cement concrete and steel is in the range of 13 °C to 14 °C.
- Maximum and minimum temperature rise in steel and asbestos cement pipe is 13.56 °C and 12.32 °C respectively.

Building upon the promising results of this study, several avenues for future research are recommended:

- Investigate the impact of surface coatings (e.g., selective or nanostructured coatings) on copper and steel to further enhance absorptivity and reduce emissivity, thereby improving thermal performance without compromising structural integrity.
- Conduct long-term experimental studies to evaluate the corrosion resistance and thermal degradation of copper and steel in varying environmental conditions, especially when exposed to high-temperature fluids or humid air.
- Explore the use of composite or hybrid materials (e.g., copper-aluminum or steel-polymer laminates) that combine the thermal advantages of metals with the lightweight or cost-saving benefits of alternative materials.

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Nomenclature

$\dot{m}$	mass flow rate (kg s ⁻¹)
CFD	Computational fluid dynamics
COP	Coefficient of performance
C _p	specific heat (J kg ⁻¹ K ⁻¹)
CPVC	Chlorinated Polyvinyl Chloride
EAHE	Earth air heat exchanger
EPHE	Earth pipe heat exchanger
HDPE	High-Density Polyethylene
HPHE	Helical pipe heat exchanger
HVAC	Heating ventilation and air conditioning
ICEM	Integrated Computational Materials Engineering
PDEs	Partial differential equation
PVC	Polyvinyl Chloride
Q	heat released by the soil to surrounding soil via pipe material (W)
T	Temperature in °C

Greek symbols

α	Thermal diffusivity of the material
ρ	Air density
ν	Kinematic Viscosity

Subscripts

out	Exit air
In	Supply air

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