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Mathematical Evaluation and Performance Analysis of Renewable Cooling System by using Earth Heat Exchanger

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Abstract:

The need for sustainable and energy-efficient cooling solutions grows as the globe struggles with the effects of climate change and the rising need for cooling in a variety of industries. However, sustaining a comfortable temperature in our buildings requires a lot of energy use, nearly 25% of global energy production is needed for the purpose of heating and cooling homes and commercial buildings. Therefore, utilization of earth's underground unchanged temperature using Earth Heat Exchanger (EHE) system is a better option to eliminate the wastage of energy and emission of greenhouse gases. By experimenting on an actual demonstration small scale model, we can get the performance of the actual EHE system by taking some assumptions and calculations. This paper investigates two performances of the EHE system, the first one by the keeping the constant velocity of the inlet air throughout the day and next one is by varying the velocity to analyse the system performance.

Keywords: Earth Heat Exchanger (EHE), Geothermal Principal, Renewable Cooling System, Heat Transfer, HVAC System.

1. INTRODUCTION

With the growing concerns over climate change and the increasing demand for sustainable energy solutions, the need for efficient and eco-friendly cooling systems has never been more pressing. Traditional air conditioning systems, while effective, often rely heavily on electricity, contributing significantly to greenhouse gas emissions and escalating energy costs. In response to these challenges, the development of renewable cooling systems offers a promising alternative, harnessing natural resources to achieve thermal comfort with minimal environmental impact.

This study focuses on the "Performance Investigation of Renewable Cooling System by Using Earth Heat Exchanger," an innovative approach that leverages the stable thermal properties of the earth to provide efficient cooling. An earth heat exchanger (EHE) utilizes the relatively constant temperatures found a few meters below the ground surface, offering a sustainable solution that reduces reliance on conventional energy sources. The need to provide sustainable and energy-efficient cooling techniques is greater than ever in a time when climate change poses urgent issues and the market for cooling solutions is booming. In order to offer a novel solution to this problem, the goal of this project is to develop a renewable cooling system using Earth Heat Exchanger (EHE) technology.

Using an ancient cooling technology of renewable cooling is similar as EHE system [1], increasing demand for buildings to use less energy has increased interest in natural ventilation and passive geothermal cooling as ways to enhance indoor comfort. Earth air heat exchangers (EAHEs) warm the air in the winter and cool it in the summer by absorbing and/or dispersing heat to the ground. The analytical method varies according to the scale and design of the experiment [2], and soil moisture content greatly affects soil thermal conductivity. It has been noted that the soil property that has the biggest impact on the outcomes is thermal conductivity., high storing water content in soil or holding the moisture content for longer period can significantly affects the soil thermal properties hence we decided the black soil for the experiment[3][4]. The paper explores the utilization of a renewable cooling system through an EHE system which works on geothermal principle. The suggested system makes use of the steady subsurface temperatures of the ground to deliver effective and environmentally acceptable cooling for commercial, industrial, and residential uses [5] [6].

Bansal et al. [2009] According to the "Performance analysis of earth-pipe-air heat exchanger for summer cooling," air temperature decreases with increased flow velocity. This investigation shows that the material of the buried pipe has no effect on the performance of the EPAHE system; as a result, the pipe for the EHE system can be built using a less expensive material [7]. The results of the simulation and experiment for the EPAHE system model accord fairly, with a maximum variance of 2.07%. It is discovered that when flow velocity increases, air temperature rises decreases. [8]. According to a review by Bisoniya et al. (2013), "Experimental and analytical studies of earth–air heat exchanger (EAHE) systems in India: A review," the earth's temperature remains rather constant at a depth of 1.5 to 2 meters. The earth's undisturbed temperature is always higher in the winter than it is in the surrounding air; in the summer, this is not the case. In order to effectively exploit the earth's heat capacity, an EAHE system must be constructed [9]. Darkwa et al. [2011] in this experiment theoretical and practical evaluation of earth heat pipe ventilation comparison is done in this system use diameter of tube is about 400 mm, depth of the tube from the ground is around 1.5m to 3 m and Pipe length is about 50m. In spite of sporadic heat losses to the surrounding soil, the earth-tube system managed to achieve a COP of 3.2 and supply 62% of the heating load. During the heating phase, there was an average 10% decrease in relative humidity levels. The Mathur group [2015] Using the commercial CFD program FLUENT, the thermal performance of EATHE systems was examined with respect to temperature drop, heat exchange rates, and coefficient of performance while taking into account three distinct soil thermal diffusivities. There was a fair amount of agreement between the experimental and numerical results. Greater thermal diffusivity in the soil results in a faster rate of heat transmission from the surrounding soil to the outer subsoil. As a result, a greater temperature was seen in the subsurface layer 0.25 meters from the EATHE pipe. The earth-to-air heat exchanger (EAHE) system, as a clean and effective shallow geothermal energy application technology, has evident impacts on lowering the energy consumption of passive low-energy buildings, according to Zhang et al. [2021]. A novel kind of vertical earth-to-air heat exchanger (VEAHE) system is suggested in this research. The VEAHE system offers a number of benefits, including centralized condensed water discharge, reduced occupation, and effective geothermal energy consumption. A mathematical model of the VEAHE system was created in order to assess the impact of various parameters on the system's thermal performance. Furthermore, the model's estimated data and the experimental data agreed quite well. The findings demonstrated that downcomers' interference with risers can be effectively limited by installing thermal insulation layers at the risers' outlet. Setting the insulation layer's thickness and length at 30 mm and 3 m is advised. Given the trade-off between VEAHE system construction costs and thermal efficiency, duct lengths of 30 to 50 meters and diameters of 150 to 250 millimeters are advised. When the air velocity reaches 3–7 m/s, the air supply volume of a single shaft can reach 500–1200 m3/h. Anshu et al.'s study from 2023 looks at the integration of ground-to-air heat exchangers with Delhi's standalone solar energy systems, with a focus on response surface technique. The system generated an annual energy gain of 8116.7 kWh after being adjusted for pipe diameter, length, and air velocity. This resulted in a 16.18 ton decrease in CO2 emissions and $336.86 worth of carbon credits. The technology offers a sustainable and environmentally beneficial energy solution to both rural and urban locations.

The concept has the potential to replace convectional HVAC systems, reducing energy usage and carbon emissions and promoting energy independence and resilience [10] [11]. They can help mitigate climate change and create a sustainable energy future for buildings and communities worldwide [12][13][29], In order to confirm the thermal and financial viability of the proposed arrangement, an experimental setup was created to investigate the change in outlet air temperature. The system had summer temperatures between 22.4 and 24.4 °C and winter temperatures between 16.0 and 18.0 °C, with a variation of roughly 7 to 3 °C [14] [15] [16]. The use of Earth Heat Exchanger (EHE) systems, which leverage the stable subterranean temperatures to provide heating and cooling solutions, represents a promising avenue for sustainable building technologies. However, several research gaps remain that need to be addressed to optimize their performance, cost-effectiveness, and broader implementation. There are some areas where researchers need to look up: Thermal Performance in Different Geologies, Optimization of System Design, and Integration with Other Renewable Technologies. Based on these gaps this research deals with analyze the performance of system without fines, parametric analysis of the system for better performance, and analyze the performance of the system with constant and varying velocity.

2. METHODOLOGY

Figure.1 Flow chart of overall Methodology

The concept to investigate sustainable heating and cooling solutions gave rise to the Earth Air Heat

Exchanger (EAHE) [17]. This first idea was expanded into a thorough project proposal that described the goals, parameters, and approach of the EAHE system deployment. The proposal was subjected to review and approval processes to determine the feasibility and relevance of the project to the field of sustainable building practices. Based on the decision, the project either proceeded to the next phase or underwent revisions to align with the goals. Data collection was a crucial aspect of this investigation, involving gathering information from various sources such as literature reviews, simulations, and case studies [18] [19] [20].

This data included environmental conditions, building requirements, and relevant information on EAHE systems. The components required for the EAHE system were identified and evaluated for their suitability and compatibility with the project specifications. From the data we found out the research gaps. Once the amount of material and components needed for the EAHE has been estimated, use CATIA V5 to build the model appropriately. We gather the materials and components needed for the model in accordance with the design. For example, we bring a 15m long copper pipe, black soil, a 500W air blower, and a tank of $1.2 \times 0.6 \times 0.4$ m [21]. After gathering all necessary parts and materials, we first shaped the pipe according to the design and then the pipe was buried in the ground. A 10mm sieve is used to refine the soil according to the given specifications; a prototype EAHE system was designed and built as part of the experimental setup. Heat exchange is facilitated by blowing air or a heat-transfer fluid through the underground pipes. To determine the temperature of the pipe's entrance and output, temperature sensors are positioned strategically.

Heat is exchanged with the surrounding soil in the experiment by directing air from the blower through pipes buried in the earth heat exchanger [22][27][30]. By achieving a maximum cooling impact of up to 10 °C, this process demonstrates how well the earth heat exchanger system controls air temperature. The investigation began while taking the readings of constant velocity of air throughout the day for calculations and analysis and taking the reading by varying the velocity noticing the difference of the outlet air temperature. The next step is to calculate after completing the required reading. Heat transfer between air and pipe is calculated [23][28]. During the calculation step, the Reynolds number is used to determine whether the air flow is turbulent or laminar. We concluded from that calculation that the airflow is turbulent. We compute the heat transfer of the air at both constant and variable velocities. That calculation led us to the conclusion that heat transfer increases in tandem with air velocity. To assess the system's effectiveness and compare it to industry norms and theoretical assumptions, data analysis was done.

- **EXPERIMENTAL SETUP**

The schematic experimental model of the Earth heat exchanger system is depicted in Figure 1. All of the components, including the blower, tank, copper pipe, and soil, are arranged in their proper locations. Because soil moisture content has a significant impact on soil thermal conductivity, we selected black soil due to its inherent ability to retain moisture. The blower has fitted the inlet of the suction pipe where the variable velocity of air ranges from15m/s to 60m/s going through inside of the pipe, the copper pipe has the horizontal design making the more surface contact to the soil and the thermometer is used to measure inlet and outlet temperature. Copper pipe has been used because copper has high thermal conductivity it is 398w/mk while the PVC pipes can be used which have low cost if we have large scale of the experiment. The figure 2 shown below has earth (Tank) specification of 1.2×0.6×0.4m has filled of black soil which initially holds the moisture content and has buried the copper pipe inside the soil. The conventional AC system emits harmful gases; the EAHE system produces zero emission.

Figure.2 Actual working EHE system with buried pipe in the soil

Process 1-2 (Adiabatic Compression) indicates the air is coming from the atmosphere by the help of blower and with the appropriate velocity the air is passing throughout the pipe, by means of geothermal principle thepipe get cooled by exchanging the heat of air in earth (tank) shows the process 2-3 (Isobaric Heat Transfer) the air which is flowing inside the pipe will be passes to next process of 3-4 for the filtration of air avoiding the dirt and foreign particles passing clean air to the indoor room or cabin whenever needed for getting cooling effect shows process 4-5(Utilization), for constant circulation of clean and cool air the utilized air needs to be exhausted into the atmosphere by the help of exhaust (outlet of air) i.e. process 5-6 (Isobaric Expansion passing air to the atmosphere) the system is considered as the open loop EHE system.

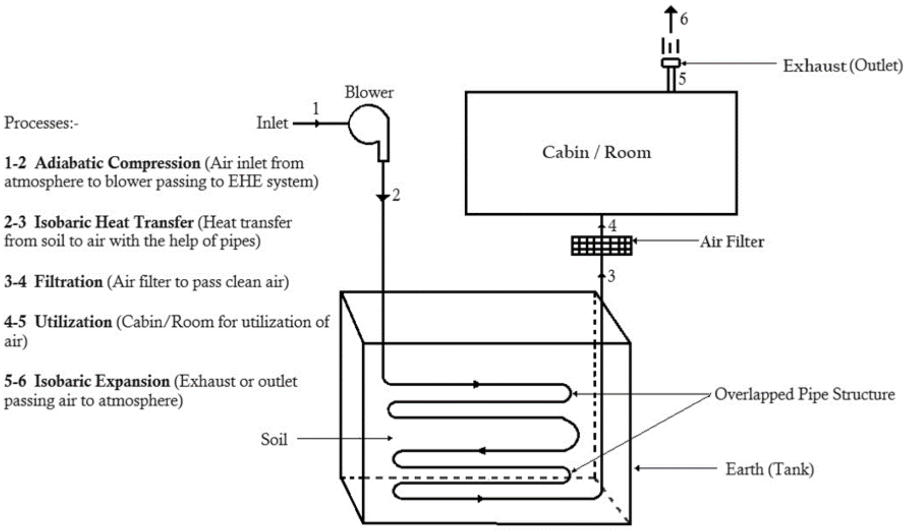

Figure.3 Open loop EHE system.

- **SPECIFICATION TABLE**

Table 1. Specifications

Parameters	Specifications
Diameter of Copper Pipe	0.0127 m
Length of Copper Pipe	8 m
Tank as Earth	1.2 X 0.6 X 0.4 m
Blower	500 W
Velocity of Air	15 m/s
Soil	Black Soil

The above schematic diagram of EHE system shows the components like air blower, overlapping pipe structure which is buried into the earth (Tank) and air filter. The tank dimensions for design are $1.2 \times 0.6 \times 0.4$m, and the pipe's depth is 0.3m. The entire length of the pipe taken into consideration is 8m which is best fit for the complete utilization of the tank.

The schematic structure of the hidden pipe in the tank is shown in the above figure. Eight pipes measuring 0.8 meters in length are straight, while six curved pipes with a radius of 0.05 meters are spaced parallel between two pipes. The parallel distance between two pipes is 0.1 meter.

3. RESULTS AND DISCUSSION

First, we have to calculate the Reynolds Number forget to know the flow of the air inside the pipe by using equation (1)

$$\mathbf{Re}=\frac{\rho\, v\, D}{\mu} \qquad \ldots (1)$$

After that we have to find out Prandtl Number by using equation (2)

$$\mathbf{Pr}= \frac{\mu\ Cp}{k} \qquad \ldots (2)$$

By putting the values of equation (1) and (2) in equation (3) and calculate Nusselt Number

$$\mathbf{Nu}= 0.023\ Re^{0.8} * \ Pr^{0.3} \qquad \ldots (3)$$

Find out Heat Transfer Coefficient by putting the Value of Nusselt Number equation (3) to equation (4)

$$\mathbf{Nu} = \frac{h\ D}{k} \qquad \ldots (4)$$

After calculating Heat transfer coefficient, then we must calculate heat transfer rate by using the equation (5)

$$\mathbf{Q} = \mathbf{h\ A\ (T_{int} - T_{out})} \qquad \ldots (5)$$

Table 2. Calculations with Varying Velocities

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Velocity (m/s)	Inlet Temperature (℃)	Outlet Temperature (℃)	Re	pr	Nu	h (W/m2 K)	Q (W)
15	32	24	11855.368	0.00062	4.571	10.798	27.575
20	32	24	15807.158	0.00062	5.754	13.593	34.711
25	33	25	19758.947	0.00062	6.879	16.250	41.494
30	33.8	26	23710.737	0.00062	7.959	18.802	46.810
35	34	27	27662.526	0.00062	9.004	21.269	47.523
40	34.4	28	31614.316	0.00062	10.019	23.667	48.348
45	35	30	35566.105	0.00062	11.009	26.006	41.504
50	35.4	30.8	39517.895	0.00062	11.977	28.293	41.541
55	36	32	43469.684	0.00062	12.926	30.535	38.985
60	37	33	47421.474	0.00062	13.858	32.736	41.795

The readings and calculations are displayed in the above table at different speeds. When air velocity increases, so does the air's inlet temperature. The heat transfer rate is computed using the Reynolds number, Prandtl number, Nusselt number, and heat transfer coefficient.

Table 3. Calculations with Constant Velocity

Sr. No	Time (Hour)	Inlet Temperature (℃)	Outlet Temperature(℃)	Temperature difference
1	8:00 AM	27	18	9
2	9:00 AM	27	18	9
3	10:00 AM	28	20	8
4	11:00 AM	28	20	8
5	12:00 PM	29	21	8
6	1:00 PM	30	23	7
7	2:00 PM	30	23	7
8	3:00 PM	30	23	7
9	4:00 PM	29	22	7
10	5:00 PM	29	22	7

The computations and readings made with constant velocity in mind are displayed in the above table. The above table displays the temperature differential between the air entering and leaving the system at various times of the day.

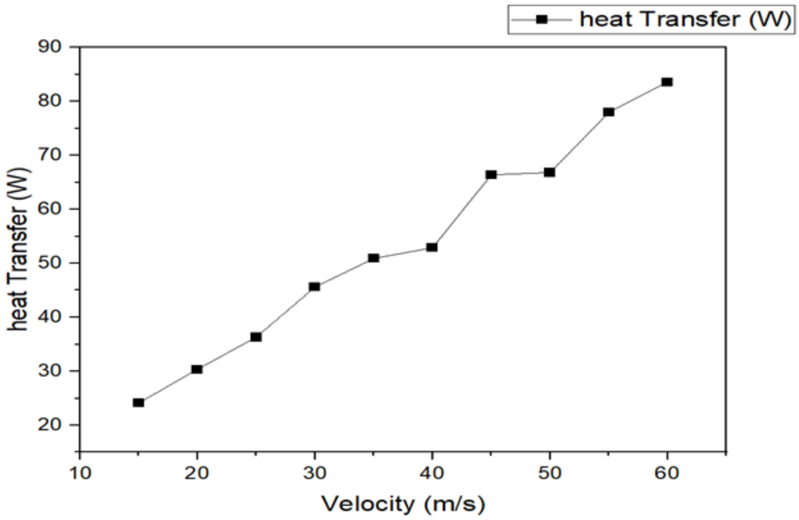

Figure.4 Change of rate of heat transfer with respect to varying velocity.

The above figure illustrates how the inlet air velocity changes in relation to the heat transfer rate. The heat transfer rate is maximum when the velocity of the air is between 30m/s to 40m/s, because when the air velocity is less than 30m/s then air do not come in contact of pipe surface in proper way and when air velocity is more than the 40m/s it goes directly outside without meeting pipe surface. So, when the air velocity is between 30m/s to 40m/s it comes in contact with pipe surface in proper way therefore the heat transfer rate is maximum at this velocity of air.

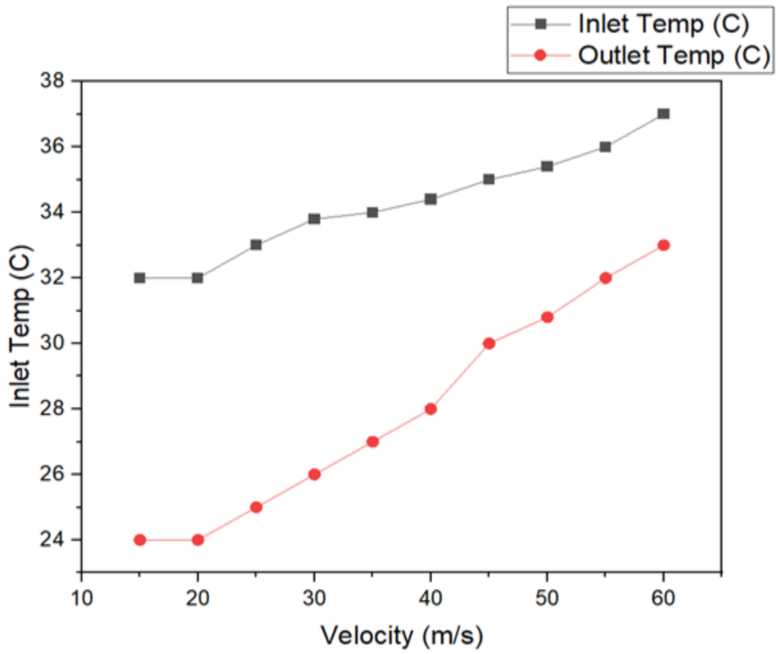

Figure.5 Temperature difference of inlet and outlet with varying velocity

The graph above shows the relationship between air velocity and the associated entrance and exit temperatures in an earth air heat exchanger (EAHE) system. As air velocity increases, there is a noticeable shift in the temperature at the intake and outflow. The relatively modest temperature differential between the input and output at lower velocities indicates reduced heat transfer efficiency. However, the temperature difference increases as air velocity increases, suggesting more heat transfer from the air to the environment. This pattern emphasizes how important airflow velocity is to optimize the effectiveness of the EAHE system for heat exchange.

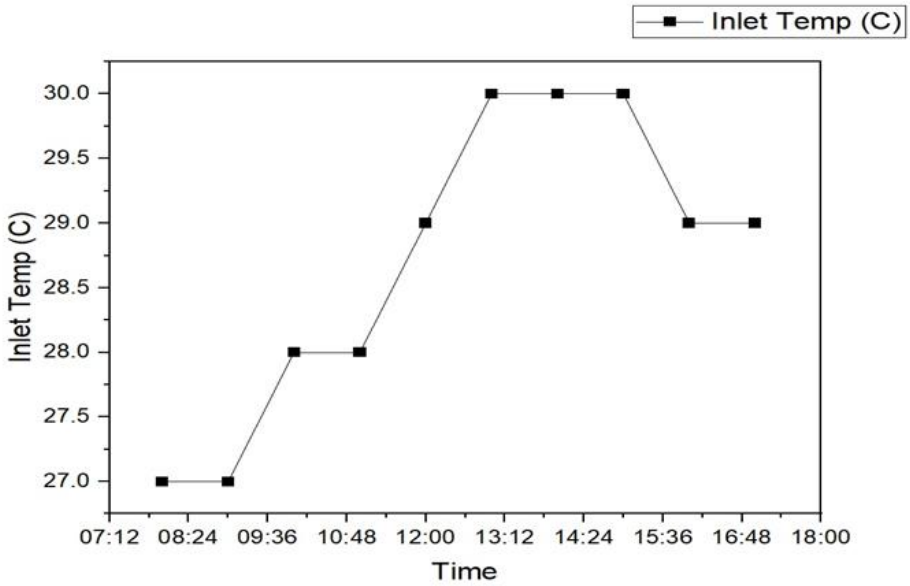

Figure.6 Inlet Temperature of Entire day

An Earth Air Heat Exchanger (EHE)'s (above) input temperature graph over the course of a day usually exhibits a pattern driven by outside variables such variations in the surrounding temperature and solar radiation. The inlet temperature typically rises steadily during the day, reaching its peak in the afternoon after beginning the day low. The warming of the surrounding air as the day goes on and the impact of solar radiation are the causes of this trend, which can have a big impact on the temperature of the air entering the EHE. The ambient temperature declines in the evening, which causes the inlet temperature to drop as well. Comprehending these everyday fluctuations is essential for enhancing the efficiency of EHE systems and creating efficient control plans.

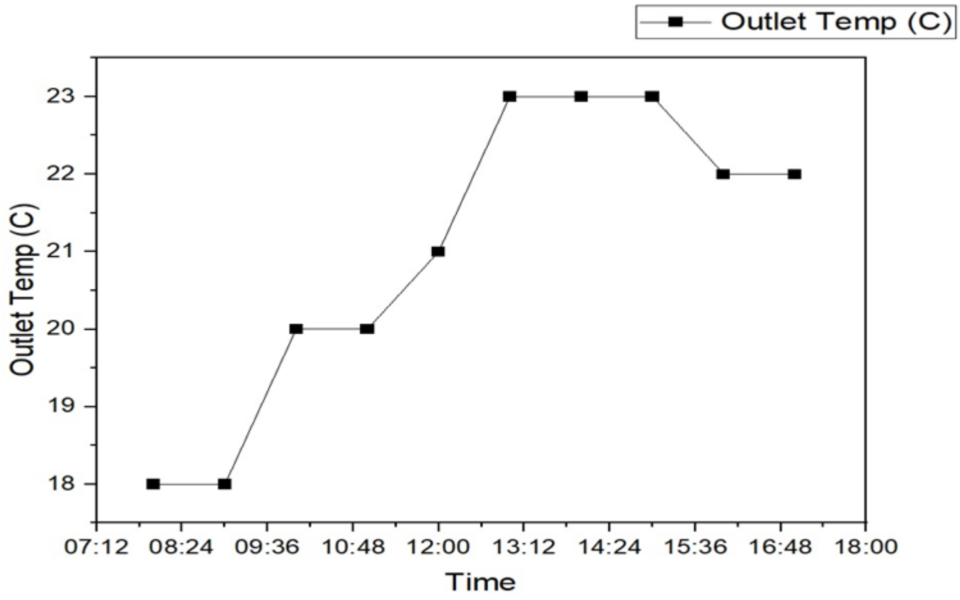

Figure.7 Outlet Temperature of Entire day

The Earth Air Heat Exchanger (EHE) outlet temperature graph shown above shows the temperature changes from dawn to night. In the morning, the outlet temperature starts at a lower value as the ground temperature is cooler, and as the day progresses, it rises steadily, reaching a peak in the afternoon when the ground has absorbed a significant amount of heat from the sun. In the evening, the outlet temperature gradually decreases as the ground begins to lose heat. The EHE's heat transfer properties, air and ground temperatures, and solar radiation all have an impact on this variance. The EHE's design and the surrounding environment can have an impact on the curve's amplitude and shape.

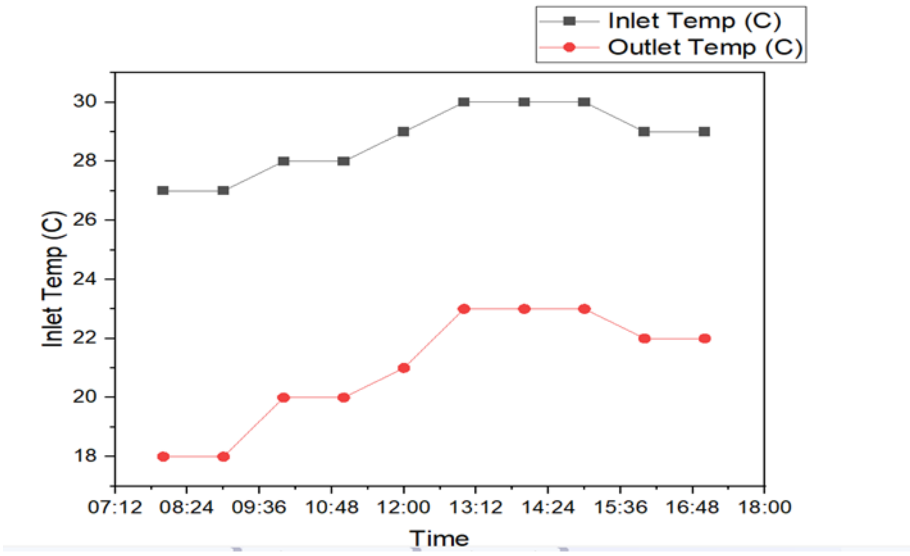

Figure.8 Temperature Difference between Inlet Air and
Outlet Air of an entire day

The graph above illustrates how the temperature difference between the input and output air of an Earth Air Heat Exchanger (EHE) changes over the course of a day at constant air velocity. The earth heating element (EHE) draws more heat from the soil, increasing the temperature of the output air, therefore in the morning when the ground is warmer than the input air, the temperature differential is typically larger. As the day goes on and the ambient air temperature rises, the ground temperature gets closer to or higher than the inlet air temperature, which lowers the temperature differential. It may be a sign that the EHE is releasing more heat into the atmosphere if the afternoon ground temperature is greater than the inlet air temperature.

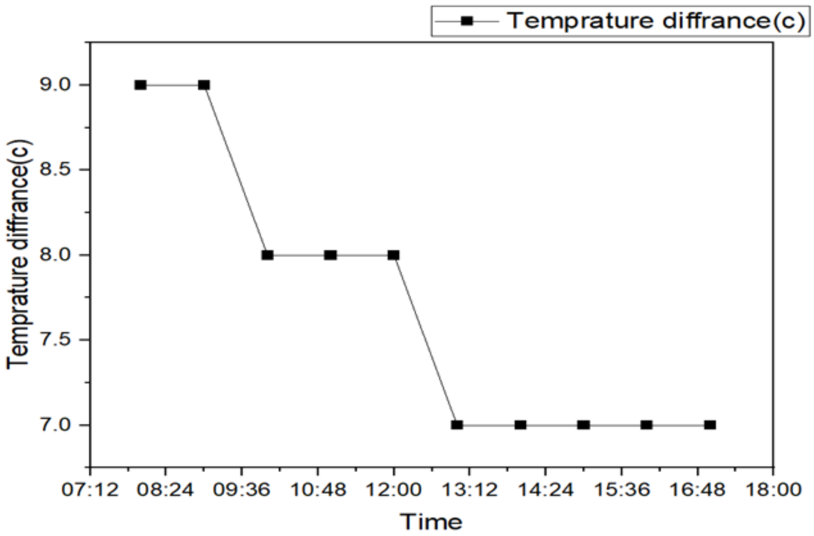

Figure.9Temperature difference with constant velocity

The temperature differential between the input and outlet air of an Earth Air Heat Exchanger (EHE) with constant air velocity is plotted above. This graph usually displays a pattern that represents the system's heat transfer. Since the ground is colder than the incoming air when the EHE first starts up, there is a large temperature differential that permits substantial heat exchange. The ground temperature changes and gets closer to the inlet air temperature as the EHE keeps running, resulting in a reduction in the temperature differential. The underground pipe's thermal conductivity, the air flow velocity, and the EHE's design are some of the variables that affect how quickly the temperature differential decreases.

4. CONCLUSION

An insightful look into eco-friendly heating and cooling solutions has been provided by the Earth Air Heat Exchanger (EAHE) project. Several important insights have been discovered through the examination of design parameters, performance reviews, and cost-effectiveness analyses. The EAHE system has the ability to significantly reduce building energy use by preheating incoming air using the earth's constant temperature. The purpose of this experiment is to determine the relationship between air velocity and air heat transfer rate, and to record temperature variations on summer days while accounting for both constant and changing air velocity.

1 Two tests have been conducted using an earth air heat exchanger to find the heat transfer rate. In the first experiment, the heat transfer rate is moderate in the afternoon and evening and reaches its top performance in the morning of a summer day. The experiment was conducted with a constant air velocity. When the air velocity is constant at 15 m/s, peak performance happens in the morning at 27°C for the air intake and 18°C for the air outflow. With an air temperature of 23°C at the outflow and 30°C at the inlet, the system runs in a moderate manner after breakfast.

2 The system's fluctuating performance is partly caused by an increase in the heat transfer rate as air velocity rises. The air enters at 32°C and leaves at 24°C at a speed of 15 m/s. The air temperature at the entrance is 34°C, and the air temperature at the outflow is 28°C when the air velocity is 35 m/s.

Air velocity is the primary determinant of the cooling effect. A temperature differential of approximately 10°C offers the best cooling power during the day. As we can see, the rate of heat transfer increases with velocity, but the incoming air also heats up, which ultimately results in an increase in the output temperature due to a drop in efficiency.

To maintain optimal performance, the experimental investigation has also brought attention to the significance of appropriate design, installation, and maintenance. It is suggested that additional research and development be conducted in the future to improve the effectiveness and suitability of EAHE systems in different contexts. All things considered, this research has given rise to a strong basis for comprehending and applying earth air heat exchangers as a workable option for sustainable building practices.

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