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Thermal performance evaluation of an earth-to-air heat exchanger for the heating mode applications using an experimental test rig

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Abstract This paper presents the experimental investigation of an earth-to-air heat exchanger for heating purposes in the Patna region of India, using an experimental test rig. In the view of the author, real field experiments have several limitations such as lack of repeatability and uncontrolled conditions. It also takes more time for the response of parameters that depends on nature and climate. Moreover, earth-to-air heat exchangers may be expensive to fabricate and require more land area. Thus, in this work authors executed their experimental work in indoor controllable environments to investigate the thermal performance of an earth-to-air heat exchanger. The actual soil conditions were created and maintained the temperature at 26°C throughout the soil in the vicinity of pipes. Three horizontal PVC pipes of equal lengths and diameters of 0.0285 m, 0.038 m and 0.0485 m were installed in the test rig. The experiments were performed for different inlet air velocities at ambient air temperature. This study acknowledges that the maximum rise in outlet temperature occurs at a lower speed for smaller pipes. Also, the maximum effectiveness of 0.83 was observed at 2 m/s for the smallest diameter pipe.

Keywords: Heat transfer; Earth-to-air heat exchanger; Ground heat exchanger; Geothermal energy; Renewable energy; Passive heating/cooling; Effectiveness

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Nomenclature

η	–	Einstein coefficient
R	–	calculated result
W	–	uncertainty
X	–	independent variable
ΔT	–	temperature difference, °C
T	–	temperature, °C
L	–	length, m
D	–	diameter, m
n	–	number of measurements
Δx_j	–	accuracy of the measuring instruments
$\Delta x_{s,j}$	–	absolute systematic uncertainty
$\Delta x_{R,j}$	–	absolute random uncertainty
$\Delta x_{G,j}$	–	absolute general uncertainty
$\delta x_{G,j}$	–	relative general uncertainty

Greek symbols

ε	–	effectiveness

Subscripts and superscripts

e	–	entrance
i	–	inlet
o	–	outlet
g	–	ground
R	–	result

Abbreviations

CFD	–	computational fluid dynamics
EAHE	–	earth-to-air heat exchanger
GHE	–	ground heat exchanger
EATHE	–	earth-to-air tube heat exchanger

1 Introduction

Energy provides an essential ingredient for all human activities and is also necessary for all living organisms. It is the foundation stone for the economic growth of any country. One thing we do know at this time is that the world requires energy in growing quantities to aid economic and social development and to build a better lifestyle, especially in developing countries. The majority of this growth comes from countries that are not members of the Organization for International Cooperation and Development (OECD), and it is concentrated in regions where strong economic growth is stimulating demand, especially in Asia. These increased energy consumptions add CO_2 and other greenhouse gases to the air and affect the global climate. Hence, the diversification of energy sources and the energy-saving potentials might be used to meet the energy requirements and reduce harmful emissions. The challenges for the present researchers are the increased demand for energy along with severe environmental issues, which may be covered by renewable stored energy. Amongst all renewable energy, one significant energy source is earth subsurface stored energy that comes from solar radiation. The building sector consumes the highest energy, more than 40% of the overall world's energy consumption with an annual growth rate of 8%, of which 51% is used for getting indoor thermal comfort [1]. This indoor thermal comfort is generally obtained by a conventional heating, ventilation, and air conditioning (HVAC) system, which is one of the largest drivers of global energy demand and is also unfriendly to the climate. As a result of these limitations, the researchers set out to find a renewable-energy-based solution for heating and cooling. Numerous passive systems are being developed and implemented these days to meet the cooling and heating necessities just as diminishing the reliance on primary resources. The most well-known passive system amongst them is the earth-to-air heat exchanger (EAHE) system. There is also another method for cooling/heating that works on earth's energy named active system, in which the building is directly, partly or wholly, in contact with the underground [2]. The earth has a great affinity to absorb approximately 46% of the total sun's energy, due to which the fluctuation of temperature arises at the earth's surface and shallow depth. The temperature fluctuation is observed up to the shallow depth of the soil by the sinusoidal wave. The influence of fluctuation of temperature reduces gradually and becomes stable up to a certain depth due to the high thermal inertia of underground soil. The temperature gradient between the earth's surface and underground soil is an important parameter for heating/cooling purposes. Hence this temperature gradient can be utilized by EAHE for space heating in winter and space cooling in summer. The soil temperature at a depth of 1.5–2 m at a given location remains constant throughout the year due to earth subsurface properties. This underground constant temperature remains higher in the winter season than the surrounding temperature and vice-versa in the summer season [3]. The EAHE comprises a pipe of any affordable material buried in the earth at a given depth. In the summer, the air flowing through the pipe with the help of a fan/blower releases heat to the soil, while in the winter; it absorbs heat from the earth. In this way, the air that comes out from the pipe may be utilized for thermal comfort purposes. Therefore, convection is used to transfer heat between moving air and pipe's inner surfaces, while conduction is used to transfer heat between pipe material and bounded soil [4]. D'Agostino *et al.* [5] conducted numerical analysis and compared EAHE with air-to-air heat exchangers in terms of energetic, economic, and environmental aspects for office buildings of two places located in Italy. Their results show that the energy performances of the air-to-air heat exchanger are better in winter while EAHE is more suitable in summer. So, they coupled both types of heat exchangers to buildings and used air to the air heat exchanger in winter while others in summer. Benrachi *et al.* [6] performed a numerical parametric study of EAHE and found that the outlet air temperature decreases with increasing the length of pipe. Abbaspour-Fard *et al.* [7] concluded in their study that each of the parameters had some impact on EAHE performance aside from pipe material. Lin *et al.* [8] used the proposed analytical approach of soil thermal characteristics to investigate the impact of soil moisture on the long-term energy performance of the EAHE system at dry, partly, and fully saturated circumstances. When air velocity is greater than the threshold value for reaching the fully developed turbulent flow, soil moisture content has a very small impact on low air circulation velocity, but it has a significant impact when air velocity is greater than the threshold value for reaching the fully developed turbulent flow. For the maximum recommended air velocity of 4 m/s, the difference is more than 40%. Agrawal *et al.* [9] investigated the effect of soil moisture content on the thermal performance of an EAHE heating system. Their findings show that the average heat transfer rate in the wet EAHE system is higher than in the dry EAHE system, with the greatest heat transfer rate occurring at 15% moisture content. As a result, for the same pipe length, the wet system produced a higher temperature rise than the dry system.

At a bulk density of 1300 kg/m^3, Abu-Hamdeh investigated the impact of density and moisture content on the thermal characteristics of soil and discovered that increasing moisture content from 0 to 25% (by mass) increased the specific heat of sandy soil from 0.83 to 1.67 kJ/kgK [10]. Balghouthi *et al.* [11] conducted an experimental investigation to compare the thermal and moisture behaviour of wet and dry soils heated by subsurface capillary plaits and discovered that wet soil had a higher thermal diffusivity than dry soil.

Mihalakakou *et al.* [12] created a model of EAHE system and determined that both moisture and temperature gradients along axial and radial directions drive the energy transfer inside the soil. To estimate the dynamic thermal and moisture interactions between the EAHE, atmosphere, and soil, Gan *et al.* [13] used a thermal model. The findings demonstrate that the interactions between the atmosphere and the soil cannot be overlooked. According to Abu-Hamdeh and Reederb, soils with high organic content have low thermal conductivity [14]. Due to the linked heat and moisture flow phenomenon in the soil, the soil close to the ground heat exchanger (GHE) pipe dries out throughout the cooling process [15]. The drying out of the soil around GHE pipe causes an increase in thermal resistivity and, as a result, a decrease in the ground's thermal capacitance. Shojaee and Malek [16] examined three distinct types of soils (silt, loam, and clay) and found that silt soil saved more energy than loam and clay due to its higher thermal conductivity. In Gambit geometry and mesh generation software, Mathur *et al.* [17] created a three-dimensional transient numerical CFD (computational fluid dynamics) model, which he subsequently simulated in Fluent solver and validated with experimental data. This research also found that EAHE system with a greater thermal conductivity soil can run constantly, whereas EAHE system with a lower thermal conductivity soil must run intermittently. To anticipate air and soil temperature, Serageldin *et al.* [18] also developed a three-dimensional stable and double precision CFD Ansys Fluent simulation model. The results of the CFD simulation were compared to those derived from experiments. A good agreement was found with an average error and correlation coefficient of 2.09, 97%, respectively. The CFD model was also employed in a parametric study, which looked into the effects of pipe diameter, pipe length, pipe space, pipe material, and flowing fluid velocity. Using Taguchi research, Ahmad and Prakash optimised various parameters of EAHE for cooling applications [19]. Vargas *et al.* [20] performed the computational, theoretical, and experimental study for optimizing the geometry of GHE for transferring the maximum heat. Ahmad and Prakash optimized the GHE based on exergetic analysis [21]. Using Taguchi technique, they found that the most influencing parameter which affect the output results was inlet fluid temperature with a contribution factor of 56.03%. Gao *et al.* [22] reviewed the latest research of the GHE and demonstrated their potential in achieving zero energy buildings. They also reviewed the integration of various heating or cooling system with GHEs aimed at improving energy efficiency. Ahmad and Prakash reviewed the various criteria that must be kept in mind before installing the EAHE system [23]. Yassine *et al.* [24] analysed the design aspects of EAHE for minimising energy consumption while achieving thermal comfort. The structure of a multi-pipe EAHE for a greenhouse is optimized by Qi *et* *al.* [25]. They compared the impact of various structural characteristics on the EAHE system's performance. The heat exchange rate was highest and the air distribution was most uniform when the spacing between pipes, and the depth of pipes were 1.2 m and 3 m, respectively. The optimal integrated performance appeared when the branch pipe entered the airflow at a 75° angle.

Amanowicz studied the flow characteristics of a multi-pipe (U-type and Z-type) EAHE system to see how geometrical parameters affected pressure losses and airflow division uniformity [26]. He concludes that using a U-type structure to reduce overall pressure losses and increase airflow equality in parallel branch pipes is a costless solution. Total pressure losses for U-type structures are 6–36% lower than for Z-type structures in a multi-pipe EAHE system, and the coefficient of airflow division infirmity is 11-80% higher in U-type structures than in Z-type structures. Amanowicz and Wojtkowiak evaluated the energy gains and electricity consumption of single and multi-pipe EAHEs in the Central European climate [27]. Their findings show that multi-pipe EAHEs can be substituted with single-pipe constructions of greater diameter that have equivalent energy performance and electricity usage over the year. For a 600 m^3/h airflow, a seven-pipe EAHE of $L = 14$ m and diameters ("diametre nominel") DN200 might be substituted with a single-pipe of length 35.5 m and DN250, resulting in a 35% reduction in annual electricity use. A seven-pipe EAHE of $L = 54.4$ m DN200 might also be substituted with a single-pipe DN315 of $L = 139$ m with virtually the same annual electricity usage for airflow of 1500m^3/h. Hasan *et al.* [28] used numerical simulation to investigate the impact of design parameters on the overall performance of the EAHE system. Their findings suggest that a pipe diameter of 0.1524 m is ideal for overall system performance, but a 0.0508 m pipe diameter is better for thermal performance. Wu *et al.* [29] calculated the temperature of the outlet air for three different pipe sizes. They discovered that for diameters of 0.1, 0.2, and 0.3 m, the outlet temperature ranged from 22.3°C to 25.6°C, from 22.6°C to 28.6°C, and from 25.4°C to 32.4°C, respectively. In a later investigation, Serageldin *et al.* [18], it was discovered that increasing the tube widths from 0.0508 m to 0.0762 m increased the exit temperature from 0.4°C to 18.7°C. By increasing the pipe diameter, the temperature difference between the inlet and output air is reduced [30–32]. Liu *et al.* [33] created a numerical model of a vertical earth-to-air tube heat exchanger (EATHE) and conducted a parametric analysis on it. According to their parametric analysis, the tube with a smaller diameter has a higher thermal capacity at constant airflow. Hasan and Noori investigated the reduction in energy consumption for heating and cooling loads of a residence that is coupled with EAHE system [34]. Their findings revealed that the largest reduction in cooling load in August was 10.34%, while the maximum reduction in heating load was 19.69% in February. In addition, the cost saving in energy consumption for both seasons was 398 USD and the payback period was 2 years. Ahmad and Prakash performed a parametric study on EATHE to examine the variation of length with inlet and outlet temperature for the cooling mode [35]. Their results reveal that for a comfortable condition of 26°C the length of tube was 8.42 m with an inner diameter of 0.05 m for an inlet temperature of 36°C. The impact of airflow distribution patterns on the thermal performance of a multi-pipe EAHE system was investigated by Amanowicz and Wojtkowiak [36]. They discovered that seasonal heat gains computed for real airflow distribution conditions are up to 28% lower than those calculated assuming ideal airflow distribution for exchangers with short branch pipes of identical diameter as the main pipes. The influence of non-uniform airflow distribution between parallel branch pipes on the heat exchanger's thermal performance is demonstrated by Amanowicz and Wojtkowiak [37]. The findings reveal that heat and cool gains predicted over a year for real airflows can be up to 20% lower than maximum gains calculated assuming ideally uniform airflow distribution between parallel branch pipes.

Sakhri *et al.* [38] performed the experimental analysis of the EAHE system combined with a solar chimney for heating and cooling mode. The system is completely based on passive technology with zero energy consumption. The airflow takes place by buoyancy effect through the solar chimney. The authors' results showed that this system is capable to increase outlet temperature of 14°C for heating purposes, while for cooling this system is able to decrease temperature up to 11.6°C. Chel and Tiwari conducted an experimental study on the performance of a solar photovoltaic (PV) powered EAHE system that was employed to provide indoor thermal comfort in an adobe house [39]. The blower that blew the air in the system was powered by a solar PV panel. Uddin *et al.* [1] investigated a PV-powered EAHE system that was constructed and deployed to provide thermal comfort in a ground-floor office. To operate the system in a natural passive mode, Li *et al.* [40] used a solar collector in addition to the solar chimney (SC)-EAHE coupled system. This hybrid system was able to maintain a temperature and humidity ratio of 21.3–25.1°C and 50–78%, respectively, in the indoor air. A solar chimney integrated EATHE system was presented by Maerefat and Haghighi [41]. The sun energy warmed the air in the solar chimney, which sucked outside air via the EAHE and flowed higher due to the stack effect. It was proved that the solar chimney can be utilized to power the EAHE without using any electricity during the day. They also calculated the number of SCs and EAHE systems required based on the intended indoor thermal comfort conditions. It was determined that a pipe with a length of more than 20 m should be constructed in order to achieve indoor thermal comfort. Singh *et al.* [42] evaluated the cooling potential of the EAHE system using concrete pipes. They simply compared the cooling potential of EAHE and its parametric effect between hot-dry climate and hot-humid climate. At four separate sites, Lee and Strand investigated the effect of air velocity inside the pipe on the earth tube heat exchanger [43]. Serageldin *et al.* [18] discovered that increasing air velocity reduces mean efficiency, coefficient of performance (COP), and the change in air temperature. Zhao *et al.* [44] found that as air velocity increases, the effectiveness of temperature extraction decreases. Air velocity and pipe diameter are essential parameters that affect the thermal performance of the EAHE system, according to Rosa *et al.* [45].

Nowadays, several pieces of research are being performed to examine the thermal performance of EAHE using analytical and simulation studies, in which various studies being validated with real field experimental approach having lacked sufficient data. In the view of several authors, the real field experimental approach is the usual practice to analyse the performance of EAHE. Besides that, real field experimental setups have several limitations such as, it takes more time for the response of parameters that depend on nature and climate. The EAHE are expensive to fabricate and require more land area. In addition, experiments should not be carried out in controlled conditions for performing comparative studies. These are the strong reasons for researchers to shift their attention from a real field experimental approach to a laboratory-scale experimental setup that has sufficient data, more controllable and robust conditions along with high experiment repetition chances. Mishra *et al.* [46] performed an experimental test on a prototype model of EAHE appropriate for small homes made utilizing reasonably-priced material like PVC (polyvinyl chloride). After conducting the experiment for three weeks their results revealed that outlet temperature of air ranges between 20°C and 22°C, regardless of inlet air temperature ranging from 34°C to 44°C. Also, the minimum energy efficiency ratio became observed as 3.34 which is equivalent to a 5-star rating as per the Bureau of Energy Efficiency (BEE). They also investigated the influencing parameters of its performance and found that it is not affected by pipe materials. Hence, it is better to use cheaper materials rather than costly materials for the pipe. Yoon *et al.* [47] estimated the heat exchange rate of three types of horizontal GHE, slinky, spiral-coil, and U-type, all of which were mounted in a steel box of dimension (5 m×1 m×1 m). They performed a thermal response test for 30 h by filling the steel box with commercial dry sand and observed that the U-type GHE exhibits the highest heat exchange rates amongst the other two, approximately 2 and 2.5 times higher than slinky and spiral coil type heat exchanger, respectively. The result of cost efficiency analysis reveals that U-type is also the most economical. Molcrette and Autier [48] present a simple analytical method to predict the recoverable energy by a ground-air heat exchanger for the heating season for three types of soil in France, as well as the influence of various parameters on the heat exchanger size. Yang *et al.* [49] conducted a laboratory test for investigating the thermal performance of energy pile using spiral coil type GHE. They examined the impact of different factors on its thermal efficiency, including intermittent operation mode, pile material, spiral pitch, inlet temperature, as well as soil temperature distribution. Elminshawy *et al.* [50] designed and fabricated an experimental test rig to test the thermal performance of an earth-to-air pipe heat exchanger (EAPHE) under various working conditions and soil compaction levels. According to their findings, the inlet temperature of air diminished somewhere in the range of 8°C to 24°C across the system, and the system's effectiveness ranged between 0.3 and 0.7 relying upon working conditions and soil compaction. Kim *et al.* [51] performed a laboratory thermal response test of horizontal spiral coil type GHE installed on a steel box of dimension 5m × 5m × 1 m in order to verify the designed finite element model by modifying the boundary conditions. Yusof *et al.* [52] conducted an experimental study of EAHE and investigated the performance of the system. They examined the performance of the system by varying the input parameters such as inlet temperature of air from 31°C to 35°C, air mass flow rates from 0.03 kg/s to 0.07 kg/s, and ground temperature from 23°C to 25°C. Their experimental findings reveal that the ground temperature of 23°C and the air mass flow rate of 0.03 kg/s give maximum temperature reduction, the maximum heat transfer rate was also achieved at the same ground temperature of 23° but at 0.07 kg/s air flow rate. Zhao *et al.* [44] investigated the performance of the EAHE system and different affecting boundaries by considering different variants of its model and checking its attainability. Their outcomes demonstrate that the cooling and heating limits are 21.17 kW and 21.72 kW, respectively, likewise the temperature extraction efficiencies increase with pipe length increment and decrease for increased diameter. Agrawal *et al.* [53] performed the experimental investigation of a ground-air heat exchanger by making a laboratory simulator using sand bentonite mixture and compared its performance with a ground-air heat exchanger having native soil. Thus, the thermal performance of the EAHE system is influenced by various geometric and flow parameters. Therefore, for investigating the performance of the system for any climatic region a laboratory test setup should be made. In the knowledge of authors, no one has developed a laboratory setup using a variable diameter set. Clearly, it is an urgent need to establish an experimental test rig that exhibits all the parametric effects i.e., variation of temperature along the length of pipes with different diameters at various airflow. The objective of the present study is to use a laboratory-scale experimental setup to investigate the thermal performance of the EAHE using Gangetic (river) soil from the Patna area at a given depth under controlled conditions.

2 Description of experimental setup

There is a lot of limitations and uncontrollable parameters in the real field experimental approach, so the laboratory scale simulator is a common concept that is used by researchers for investigating the performance of a system. Therefore, to investigate the thermal performance and parametric effects of EAHE for climatic and soil conditions of Patna, an experimental test rig has been designed and fabricated at the National Institute of Technology (NIT) Patna, India. This test rig is able to provide the actual ground conditions to the pipe of the EAHE system throughout the experiment. The ground usually has the potential to have an infinite thermal capability [54]. The soil temperature at a depth of 3–4 m below the surface of the ground is not affected by solar radiation and other climatic conditions [55–58]. Also, the huge thermal inertia of the earth plays a key role in maintaining the constant temperature at this depth. Hence, for providing these conditions the experimental test rig was fabricated in the shaded room, and it acts as a real ground approach, that is the experimental setup has infinite thermal inertia. Here, the infinity thermal inertia means constant temperature everywhere in the vicinity of the pipe. In order to maintain the constant temperature in the soil that is kept in the container, two U-type heating cables are arranged in the soil at appropriate places. Further, four K-type thermocouples are plunged in the soil at an equal distance above and below the pipes. The bulk temperature of the entire soil in a container was controlled by using a temperature controller. In this experiment, the ground temperature was considered to maintain at 26°C. The different components and measuring equipment with their accuracy have been compiled in Table 1.

Table 1: Components and instruments used in experiment.

Components and Instruments	Peoperty/Dimensions/Accuracy
Soil container (GI Sheet)	1.5 m × 0.6 m × 0.6 m
Inside diameter of PVC pipes	0.0285 m, 0.038 m, 0.0485 m
Pipe thickness	0.003 m
Pipe length	1.67 m
Heating coil	Copper (1500 W)
Vane probe anemometer	Mextech (MEX104), 0.8−30, ±0.1 m/s
Thermocouple	K type (±0.4 K)
Temperature indicator	230VAC, ±10%, 50−60 Hz
Air blower	Bosch (620 W)
Flow rate adjustment valve	PVC
Temperature controller	Aptech, control range: −50−110°C Control accuracy = 0.1°C

Figure 1 shows the complete schematic diagram of the EAHE experimental test rig. This experimental rig consists of: (1) a container of dimension 1.5 m × 0.6 m × 0.6 m made of galvanized iron (GI) sheet filled with Ganga soil, (2) three PVC pipes of internal diameters 0.0285 m, 0.038 m, and 0.0485 m (based on availability in the market), each of the same length of 1.67 m and thickness of 0.003 m, (3) two U-type heating coils, (4) measuring devices, including vane probe anemometer for measuring the airflow velocity, thermocouple for temperature measurement and a temperature indicator, (5) blower for air circulation, (6) other auxiliary components such as pipes, fittings, flow rate adjustment valves, and temperature controller. All the three pipes have been arranged horizontally in the central plane of a container at an equal distance of 0.2 m between them, while the side pipes were positioned at a distance of 0.1 m from the container sidewalls. The purpose of multiple pipes of different diameters was to investigate the parametric effects of the system that is analysing the system with different diameters. The vane-type rotational anemometer was connected at a common inlet point. The velocity of air was measured at a single point. The cross section of the vane probe was the same as the inner diameter of the common inflow pipe. The instrument was fitted after the development length i.e., it is used at a fully developed section at a distance of 0.95 m from the air blower. The dimensionless form of length is $L/D = 25$ (entrance length/inner diameter). For measuring the temperature of the air flowing inside these pipes four K type thermocouples were installed in each pipe at 0.42, 0.84, 1.25, and 1.67 m from the inlet. A common inlet air temperature measuring point was located just after the flow meter section for measuring the inlet temperature of air for all three pipes. In this way, a total of 13 thermocouples were mounted on these three pipes and fittings. For measuring the soil temperature four thermocouples were plunged in it. Two thermocouples were plunged at 0.55 m and 1.1 m from the inlet side below the pipes, and two more were plunged in the soil at the same distances from the inlet side above the pipes. For measuring the ambient temperature one thermocouple was kept free in the air. Therefore, a total of 18 thermocouples were arranged for temperature measurement.

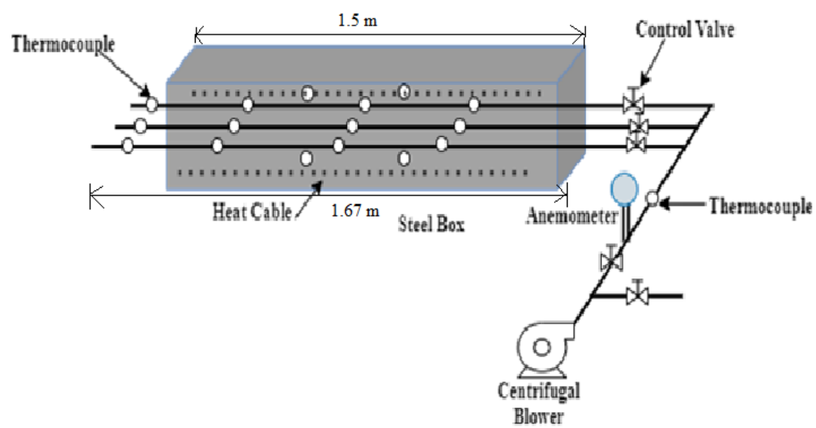

Figure 1: Schematic diagram of the EAHE test rig.

The experimental EAHE rig has been established in a shaded corridor of the Mechanical Engineering Department of the National Institute of Technology Patna in India as shown in Fig. 2. The experiments were carried out in February for heating purposes. The corridor air temperature was at ambient temperature and it was sucked directly into the pipe inlet using an air blower. In the experiment, two main parameters such as temperature and airflow velocity were measured for analysing the system. The variation in outlet air temperature for each pipe was determined by altering the length, diameter and airflow rate.

Figure 2: Photograph of the EAHE test rig.

3 Uncertainty analysis

In order to perform good quality and accurate experiment, an uncertainty analysis was carried out. Uncertainty is a quantification of doubt about measurement and calculated results. The selection of measuring instrument, its condition and calibration, environment conditions, data analysis, and test planning may all contribute to experimental uncertainty.

The error estimates for both measured and calculated parameters are used in the uncertainty analysis of this experiment. In the current study, the measured parameters (independent variables) include length, diameter temperature, and air velocity while the calculated parameter (dependent variable) is the effectiveness of the system. The appropriate instruments were used for measuring parameters and the correct method was used in the calculation to ensure the accuracy of the results.

Amanowicz and Wojtkowiak assumed that the systematic uncertainty of independent variables has a uniform distribution, and their random uncertainty follows a Gaussian distribution [37]. The calculated result R is the given function of independent variables $X_1, X_2, \ldots, X_n$, thus $R = \{X_1, X_2, \ldots, X_n\}$. With a 95% confidence interval, the independent variable's absolute systematic uncertainty is [37]

$$\Delta x_{s,j} = \frac{\Delta x_j}{\sqrt{3}}\,, \tag{1}$$

where Δx_j is the accuracy of measuring instruments. The independent variable's absolute random uncertainty with a 95% confidence interval, is

$$\Delta x_{R,j} = \frac{1.96}{\sqrt{n}} \times \text{standard deviation.} \tag{2}$$

With a 95% confidence interval the general, absolute, and relative, uncertainties of the independent variable are, respectively

$$\Delta x_{G,j} = \sqrt{(\Delta x_{S,j})^2 + (\Delta x_{R,j})^2}\,, \tag{3}$$

$$\delta x_{G,j} = \frac{\Delta x_{G,j}}{\text{average value}}\,. \tag{4}$$

The calculation results of uncertainty for measuring parameters are shown in Table 2.

Table 2: Results of the uncertainty analysis (percentage uncertainties with 95% confidence).

Measured parameters (independent variable)	Value	Accuracy	Uncertainty [%] (with a 95% confidence interval)		
			Systematic	Random	General
Length, mm	1670	±1	0.03	0.16	0.16
Diameter, mm	48.5	±0.1	0.12	1.4	1.4
Temperature, °C	290–299	±0.4	0.08	0.1	0.12
Air velocity, m/s	2	0.05	1.44	5	5.2

The uncertainties in the desired result of the experiment may be estimated based on the uncertainties in a primary measurement using the following equation [59]:

$$W_R = \left[\left(\frac{\delta R}{\delta X_1} w_1\right)^2 + \left(\frac{\delta R}{\delta X_2} w_2\right)^2 + \ldots + \left(\frac{\delta R}{\delta X_n} w_n\right)^2\right]^{0.5}. \tag{5}$$

Here, W_R is the uncertainty in calculated result, $w_1 w_2, \ldots w_n$ are the uncertainties of the respective independent variables X_1, $X_2, \ldots X_n$.

The uncertainty in effectiveness can be estimated as

$$\frac{W_\varepsilon}{\varepsilon} = \left[\left(\frac{w_{\Delta T}}{\Delta T}\right)^2 + \left(\frac{w_{\Delta T}}{\Delta T}\right)^2\right]^{0.5}. \tag{6}$$

The maximum value of uncertainty in effectiveness was calculated as 6.29%.

4 Results and discussions

Using the test rig, the thermal performance of an earth-to-air heat exchanger was evaluated in terms of temperature rise, heating capacity, and system effectiveness. The different parameters and setting conditions of these experimental works are tabulated in Table 3. The readings were noted after every 30 min of continuous operation when the data becomes steady.

Table 3: Parameters and setting conditions.

Parameter	Value
Soil container made by GI sheet, m	1.5 × 0.6 × 0.6
Inside diameters of EAHE pipes (made of PVC), m	0.0285, 0.038, 0.0485
Pipe thickness, m	0.003
Pipe length, m	1.67
Soil temperature, °C	26
Velocity of flowing air, m/s	2, 3.5, 5, 6.5
Inlet air temperature, °C	17 (ambient temperature)

The important parameter obtained from the experimental work is the temperature variation of air flowing inside the pipe. The tests were carried out for four separate induced airflow velocities: 2, 3.5, 5, and 6.5 m/s. Meanwhile, the corresponding soil temperature was fixed at 26°C. The ambient air was directly sucked by the air blower and it remained unchanged at the exit of the blower due to the lower air velocity range. The induced airflow was directed to one pipe at a time by closing valves of the other two pipes. The temperature variation along the length of the three types of pipes for various velocity rates and at fixed soil temperature is depicted in Fig. 3. The graphs (Figs. 3a–d) show the same pattern of temperature variation for all three diameters (0.0285 m, 0.038 m, and 0.0485 m) i.e., the air temperature increases along the pipe length. The reason for this can be traced to the fact that the holding time of air molecules inside the pipe and the surface area for heat transfer increase with length. The rise in temperature in the larger diameter pipe is less as compared to the lower diameter pipe for all the sets of velocity rates of air. This may be related to the fact that as the diameter of the pipe increase the airflow rate decrease which in turn reduces the convective heat transfer coefficient.

The rise in temperature for all sets of pipes decreases with increasing the airflow velocity. It has also been indicated in Table 4. This may be explained by the fact that when the velocity of air increases the convective heat transfer coefficient increases, while the duration of flowing air inside the pipe gets reduced. Since the latter effect is dominant, this causes a lesser gain in temperature by increasing the velocity.

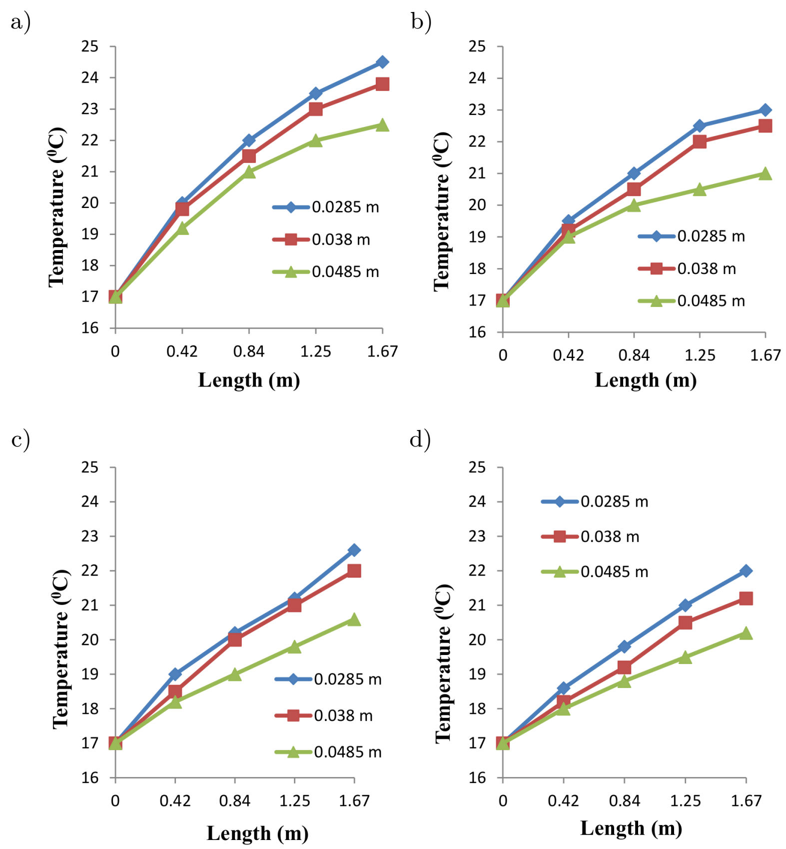

Figure 3: Air temperature variations along the pipes of different diameters at a velocity of (a) 2 m/s, (b) 3.5 m/s, (c) 5 m/s, (d) 6.5 m/s.

Table 4: Rise in air temperature along pipes (°C) for various flow velocities.

Air velocity, m/s	Pipe diameter		
	0.0285 m	0.038 m	0.0485 m
2.0	7.5	6.8	5.5
3.5	6.0	5.5	4.0
5.0	5.6	5.0	3.6
6.5	5.0	4.2	3.2

The effectiveness measures the performance of the heat exchanger in terms of temperature. Here, the effectiveness of EAHE may be defined as the ratio of actual temperature gain by pipe to maximum possible temperature gain by a pipe. Hence, the effectiveness of this system may be calculated using the following equation:

$$\varepsilon = \frac{T_o - T_i}{T_g - T_i}, \tag{7}$$

where T_o is the air temperature at the outlet from pipe, T_i is the inlet temperature of air and T_g represents the ground temperature at a given depth. Therefore, using the above equation, the effectiveness of EAHE was calculated for all the pipes at different air velocities. Figure 4 shows the variation of effectiveness with air velocity for examined pipes at a constant ground temperature of 26°C. From this figure, it is clear that the effectiveness of EAHE decreases with increasing the velocity of air. The explanation for this is that, as the velocity of airflow increases the volumetric flow rate inside the pipe increases which in turn reduces the time of flow of air molecules inside the pipe. In consequence, the total rise in temperature inside the pipe reduces, thus in this way the effectiveness of the EAHE system decreases. From Fig. 4, it is also clear that the effectiveness of a larger diameter pipe is lower than a smaller diameter pipe, because when the pipe diameter increases the area between tube and unit volume of air shrinks.

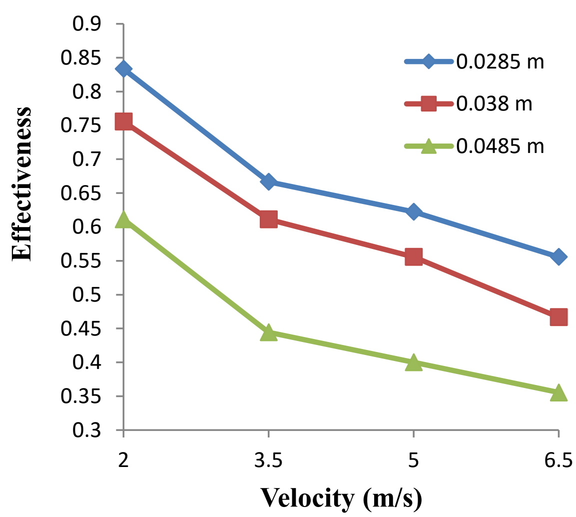

Figure 4: Effectiveness of the EAHE for all the sets of induced air velocities.

This experimental research work was validated with the experimental results of other researchers' studies. Bansal *et al.* [60] performed their study to investigate the thermal performance of EAHE using experimental and simulation studies. They observed that as the length of pipe increases the temperature also increases and when the velocity increases the gain in temperature decreases. Hence, in our investigations temperature also raised with the length of pipe, and gain in temperature reduced with velocity. In the other study of Zhao *et al.* [44], the temperature extraction efficiency or effectiveness decreased with the increased velocity of airflow, which is also in good agreement with our effectiveness results. Thus, by installing this type of experimental test rig, i.e. for variable pipe diameter, one can easily investigate the performance of the EAHE system for any climate and season for its applicability. This test rig is a portable type, so it can be easily transported to any place. Also, by changing the type of soil or backfilling materials its performance can be easily investigated. For future work, the effectiveness of the system can be enhanced by using phase change materials in the annulus of a pipe. Also, for cooling purposes, a solid desiccant system can be integrated for increasing the cooling effect. The effect of grass and vegetation on the surface of the soil where the pipe is buried may also be examined in future work.

5 Conclusion

In this research, the thermal performance of the earth-to-air heat exchanger was investigated for heating mode applications using an experimental test rig. The test rig of the earth-to-air heat exchanger was developed with a combination of three pipes of diameters 0.0285, 0.038, and 0.0485 m, and a length of 1.67 m each. The following conclusions may be taken from the study of experimental results:

- The temperature of the air inside the pipe at an air velocity of 2 m/s is increased from 17°C to 24.5°C for 0.0285 m diameter pipe, from 17°C to 23.8°C for 0.038 m diameter pipe and from 17°C to 22.5°C for 0.0485 m diameter pipe. Thus, the temperature of flowing air increases gradually with the length of a pipe, but at the pipe exit the rise in temperature declines due to the heat losses. But these rises in temperature are greater in a smaller diameter pipe than the larger ones.

- For the air velocity of 2, 3.5, 5, and 6.5 m/s the rise in temperature for 0.0285 m diameter pipe is 7.5, 6, 5.6, and 5°C, respectively. Hence, it may be concluded that with an increase in airflow velocity the rise in temperature decreases slightly. Also, for the same velocity, the temperature rise in a larger diameter pipe is lesser than in a smaller one.

- The heat exchange effect of an EAHE decreases as the velocity of the flowing air increases.
- The effectiveness of an EAHE decreases as the velocity of the airflow increases. The drop of effectiveness for a given set of velocity in smaller diameter pipe is 34%, in medium diameter pipe is 38.2% and in larger diameter pipe it is 42%. Thus, the larger diameter pipe has lesser effectiveness than a smaller pipe.

Therefore, the concept of developing the experimental test rig for different diameters is feasible for investigating the thermal performance of earth-to-air heat exchangers.

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