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Parametric Performance Analysis of the Cooling Potential of Earth-to-Air Heat Exchangers in Hot and Humid Climates

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Abstract: Earth-to-air heat exchangers (EAHEs) are widely used to reduce the indoor temperature and associated cooling energy demand of buildings. This study investigated the potential reduction in indoor temperatures via energy-efficient ventilation through EAHEs in an existing architectural campus building (ACB) with an energy-efficient renovated building envelope in the hot and humid climate of Karachi, Pakistan. The building information modeling (BIM) program Autodesk Revit was used to develop a virtual ACB BIM model. An EnergyPlus parametric analysis of the ACB BIM model in DesignBuilder facilitated quantification of the influences of operating parameters such as pipe installation depth and pipe diameter for EAHEs with similar total pipe lengths and air-exchange rates on the performance of the EAHEs during the cooling season. A 3 m deep and 0.1 m diameter pipe layout in open space significantly reduces indoor temperature via a specific duct layout in an exemplary ACB. The results show that a pipe diameter above 0.1 m is unsuitable because of the reduction in convective heat transfer due to the increase in the pipe's surface area and the decrease in pressure in the pipe. The findings of this study can be used to improve the indoor thermal comfort of buildings in climates with comparable properties.

Keywords: earth-to-air heat exchanger; educational building; thermal comfort; ducts; hot and humid climate; BIM; EnergyPlus

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1. Introduction

According to the International Energy Agency (IEA), the building sector accounts for over 40% of total energy consumption and contributes to 24% of global CO_2; emissions [1–3]. Buildings are reported to account for one-third of the total global energy consumption, with about half of it being used for heating, ventilation, and air conditioning (HVAC) systems [1,4]. The high energy consumption of buildings is a major contributor to global environmental impacts [5]. Pakistan's building sector, similar to those in other developing countries, consumes more energy than other sectors [6]. Energy-inefficient electric fans and lighting are responsible for increased electric energy consumption in Karachi, Pakistan [7]. A major percentage of the total energy in Pakistan is consumed to provide indoor thermal comfort. The National Energy Conservation Center of Pakistan set a target to reduce energy consumption from 45% to 30% through low-energy solutions [8] to overcome the energy shortage crisis that began in 2006.

New buildings provide an opportunity to restrict the practice of the existing energy-inefficient, conventional systems and implement energy-efficient solutions for thermal comfort [9]. Increasing energy efficiency in existing buildings is a challenge, because most renovations focus primarily on expanding the usable area, and rarely on improving the thermal comfort of the building. Efficient implementation of passive energy efficiency measures in buildings can substantially reduce their heating and cooling demand whilst providing a thermally comfortable indoor environment [10,11]. The energy-efficient renovation and retrofitting of existing building envelopes offers opportunities for transformation into thermally comfortable and energy-efficient buildings [12]. Saleem (2016) retrofitted an existing college building in Mianwali, Pakistan, to reduce indoor temperature and achieved a significant improvement in indoor environmental quality (IEQ) [13]. Mahar et al. (2020) studied the impact of passive design measures for improving thermal comfort in an existing building in Quetta, Pakistan; their study provided evidence-based and informed design recommendations for architects and designers to incorporate passive design measures in building designs [14]. Furthermore, Ahsan et al. (2019) applied passive cooling techniques to reduce energy demand in a case study building in Pakistan; their results indicated that passive cooling techniques were efficient and reduced the building's cooling load by 35% while maintaining a thermally comfortable environment [5].

One of the effective passive measures for cooling and heating buildings is the employment of ground temperatures, which stay nearly constant at a certain depth due to the ground's thermal inertia [15,16]. The ground temperature of a specific location remains constant at a depth of 1.5–4 m throughout the year [17–21]. At a certain depth, this temperature is lower in summers and higher in winters than the ambient temperature. An earth-to-air heat exchanger (EAHE) is a passive air-heating and -cooling tool that uses a network of pipes buried at a certain depth for heat transmission. There are two subgroups of EAHEs based on their configurations: open-loop and closed-loop systems. In closed-loop systems, the same air is circulated multiple times through the same pipes, whereas in open-loop systems fresh air is circulated once through the pipes to meet a building's cooling or heating demand [22]. Open-loop systems directly ventilate fresh air from outdoors to indoors through an EAHE; hence, these are the most preferred systems [12,23]. In an EAHE, the fresh air flows from the inlet through the buried pipes for precooling in summers and preheating in winters. The EAHE uses the thermal capacity of the ground—mainly influenced by mean outside ambient temperatures, solar radiation, and humidity—as a renewable and sustainable energy source for passive cooling and heating through the ventilation of buildings. The working concept of EAHEs is shown in Figure 1, where pipes of specific sizes are buried underground at a certain depth, with one end of the pipe network functioning as fresh air inlet. The fresh air penetrating through the buried pipes exchanges heat with the pipe walls that are in contact with the surrounding ground, transmitting heat via convection and conduction. The other end of the pipe network functions as an air outlet for the distribution of fresh air inside the building. EAHEs' performance is dependent on the climatic conditions, ground properties, heat transmission between the ground and the buried pipes, the size of the pipes, and the installation depth [9]. The main indicators to evaluate the performance of EAHEs are the air temperature differences between the inlet and outlet—also called the temperature drop—and the heat transfer rate.

EAHEs are installed worldwide in different building types and different climates for the provision of thermal comfort and energy efficiency [24,25]. Contemporary research on EAHEs involves the development of mathematical models, dynamic computer simulations, and experimental studies. Dynamic computer simulations facilitate simple, comparable, and time-efficient performance analysis and prediction in the framework of real case scenarios [26]. Various studies have reported that dynamic computer simulations are reliable and consistent with relevant mathematical models and experimental studies; thus, dynamic simulations are important tools for the optimized design and layout of EAHEs for specific applications [23,27].

Previous studies have reported various factors that influence the performance of EAHEs [28]. The pipe layout is crucial, as it impacts the pipes' density along with their thermal interaction with the surrounding ground. The three most common layouts are ring, serpentine, and grid. The ring layout is used for single-family houses, the serpentine layout is used for medium-sized buildings that require longer pipes, and the grid layout (Tichelmann grid) is used in large buildings such as offices and schools [18,22]. Laknizi et al. (2019)

conducted a parametric study for design space exploration to determine the design geometry of EAHEs and found that the Tichelmann layout with a pipe diameter of 100 mm, length of 30 m, and velocity of 2 m/s results in optimal EAHE performance. The system was able to achieve the desired indoor comfort temperature according to the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) guidelines while reducing the heating and cooling loads and decreasing the annual energy demand by 250.675 MWh [29]. Akbarpoor et al. (2021) developed a numerical model to simulate multiple parallel-pipe EAHEs. The authors validated the numerical model with experimental data, and revealed that the investigated EAHE has great potential for providing thermal comfort and, subsequently, reducing the building's energy demand for cooling [30].

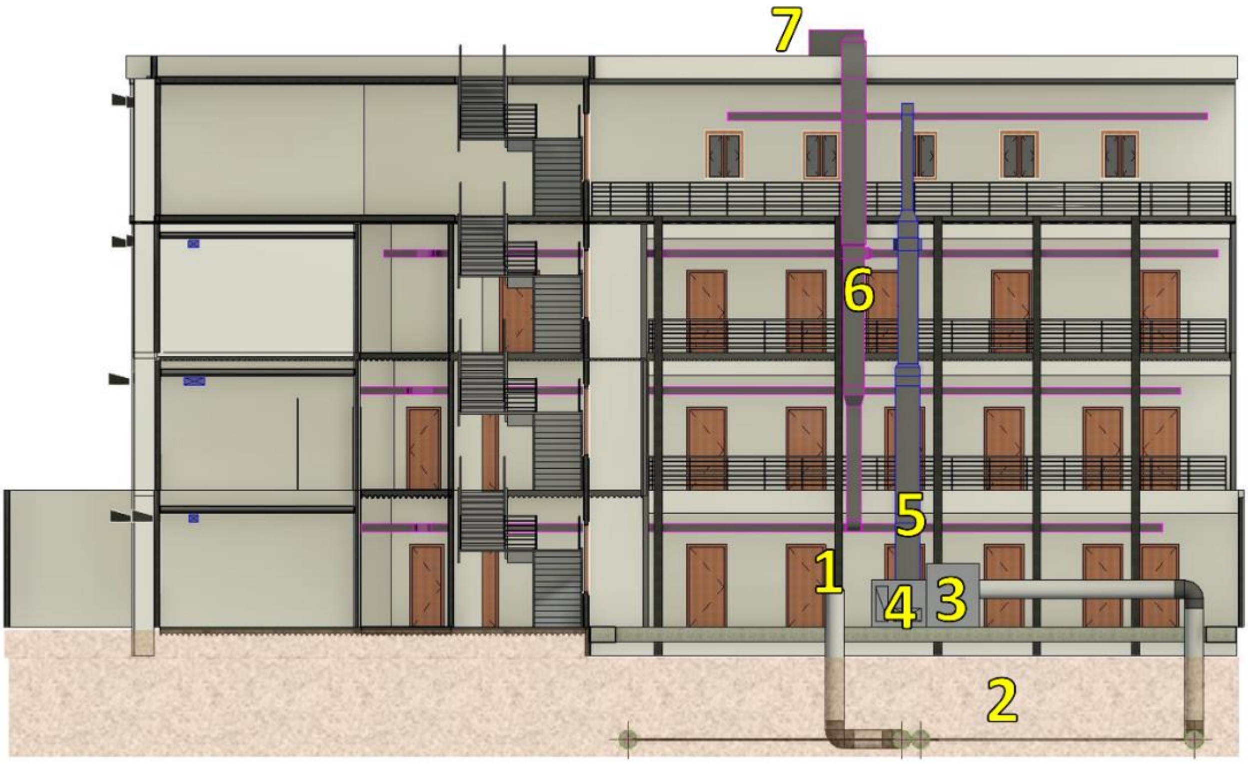


Figure 1. The working concept of the earth-to-air heat exchanger. Legend: 1, fresh air intake; 2, buried pipes (3 m depth); 3, fan; 4, air-handling unit fresh air supply; 5, supply air ducts (blue); 6, exhaust air ducts (pink); and 7, air-handling unit exhaust air extraction.

The ground properties and pipe characteristics significantly affect the performance of an EAHE [31]. The thermal conductivity of the ground influences its thermal interactions with the pipes. The pipe characteristics influence the operation of the EAHE, since the rate of heat transmission is dependent on the contact between the ground and the pipes [31]. Babar et al. (2018) conducted an experimental study in Sahiwal, Pakistan, to evaluate the potential of geothermal space cooling; they concluded that the installed geothermal system with the selected piping material for geothermal air cooling had an average temperature difference of 23 °C between the outlet and the inlet [32]. Furthermore, Khan et al. (2020) installed an EAHE system in a university in Lahore, Pakistan, to investigate the efficiency of an EAHE in a hot, semi-arid climate; their results indicated that the EAHE was able to reduce the temperature from 40 °C to 30 °C and was an efficient passive solution for thermal comfort [33]. Ariffin et al. (2014) performed a study to analyze the influence of pipe materials on an EAHE's performance as a passive cooling system; their study focused on optimal air temperature reduction through dynamic computer simulation studies to achieve thermal comfort., and their results revealed that the simulated system was able to achieve air temperature differences of 6 °C between the inlet and the outlet with specific pipe characteristics [34].

Various studies have been conducted to examine the potential of passive design measures in Pakistan [35,36]. However, the potential of EAHE applications for passive cooling through the ventilation of energy-efficient renovated educational buildings in Karachi, Pakistan, has not yet been investigated. Furthermore, research publications on the integration of energy-efficient building envelope renovation with EAHEs in Karachi, Pakistan, could not be identified. Therefore, for the sake of this knowledge gap, this study investigated the potential application of EAHEs for improving indoor thermal comfort in the context of an educational building in Karachi, using an exemplary architecture campus building (ACB). To illustrate the synergies that can be created by the combination of the EAHE with energy-efficient, passive-design building renovation measures, we investigated the indoor thermal comfort influences of EAHE-based ventilation system for two scenarios: (i) the original building, and (ii) the building after energy-efficient renovation of the building envelope.

The case study's building and its site layout and characteristics determine important system layout parameters—for instance, the available areas for the installation of EAHEs. The main objectives of this study were to use dynamic computer simulations for (a) the determination of the optimal installation depth of the pipes, (b) the determination of the optimal pipe diameter, and (c) the determination of the pipe characteristics providing indoor temperatures and airflows that meet the comfort requirements of building users and facilitate the reduction in the ACB's cooling energy demand.

2. Materials and Methods

This section is divided into three subsections that discuss the climate of Karachi, the modeling and description of the ACB, and the EAHE system. A virtual BIM model of the exemplary ACB was developed and imported into DesignBuilder (DesignBuilder Software Ltd, Stroud, UK) for parametric analysis. The parametric analysis of the performance of the EAHE—specifically, the pipe length, pipe diameter, and installation depth—in reducing the indoor temperature and energy demand of the ACB was evaluated. Available literature on EAHE applications in similar climates [17,23,37–41] was reviewed, and the findings were compared with the results of this research. A detailed discussion of the research results and a comparison with previous research publications are presented in the Results section to demonstrate the importance of this research in the context of Karachi. Figure 2 presents the modeling and analysis framework used in this study, described in the sections that follow.

2.1. Climate of Karachi

Karachi (24.90° N, 67.13° E) is a coastal city located in Sindh, Pakistan, at an elevation of 22 m above sea level [42,43]. Karachi experiences a hot and humid climate throughout the year, comprising hot summers, mild winters, and temperature variations. The city has a hot and humid season from May to August, and a warm and subhumid season from November to February. The remaining months—March, April, September, and October—are hot and subhumid seasons [42]. The maximum daily dry-bulb outside air temperature is 44 °C in May, and the lowest daily dry-bulb temperature is 6.1 °C in January. Figure 3 presents the daily average rainfall in Karachi. Karachi receives a maximum average rainfall of 40 mm during July and August and a minimum average rainfall of 0–1 mm from October to December.

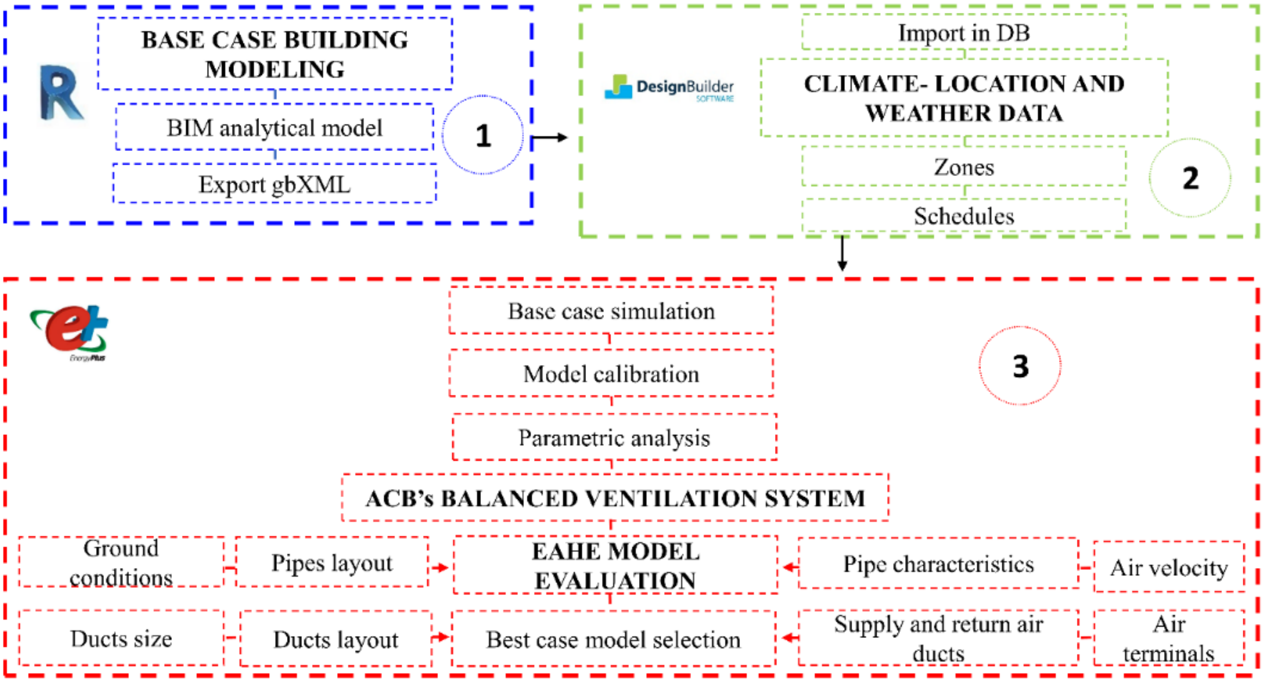


Figure 2. The modeling and analysis framework. Legend: BIM, building information modeling; gbXML, Green Building Extensible Markup Language; DB, DesignBuilder; ACB, architectural campus building; EAHE, earth-to-air heat exchanger.

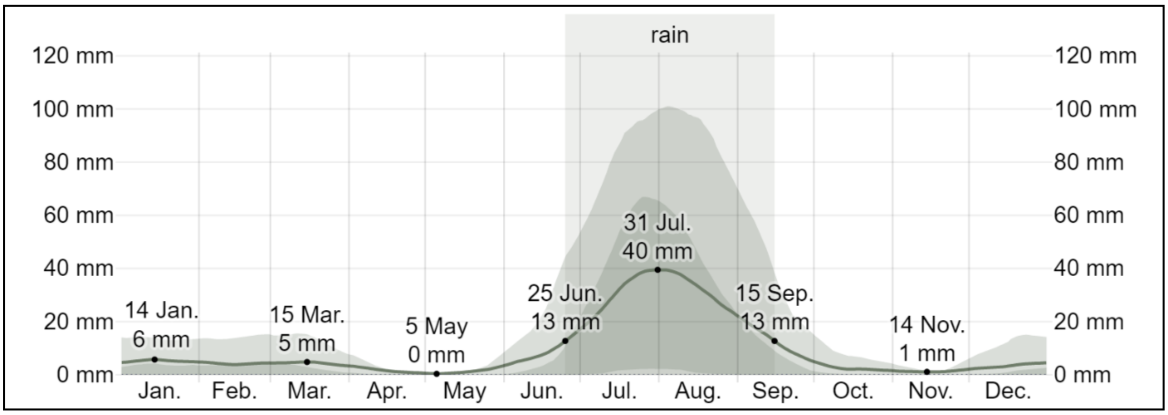
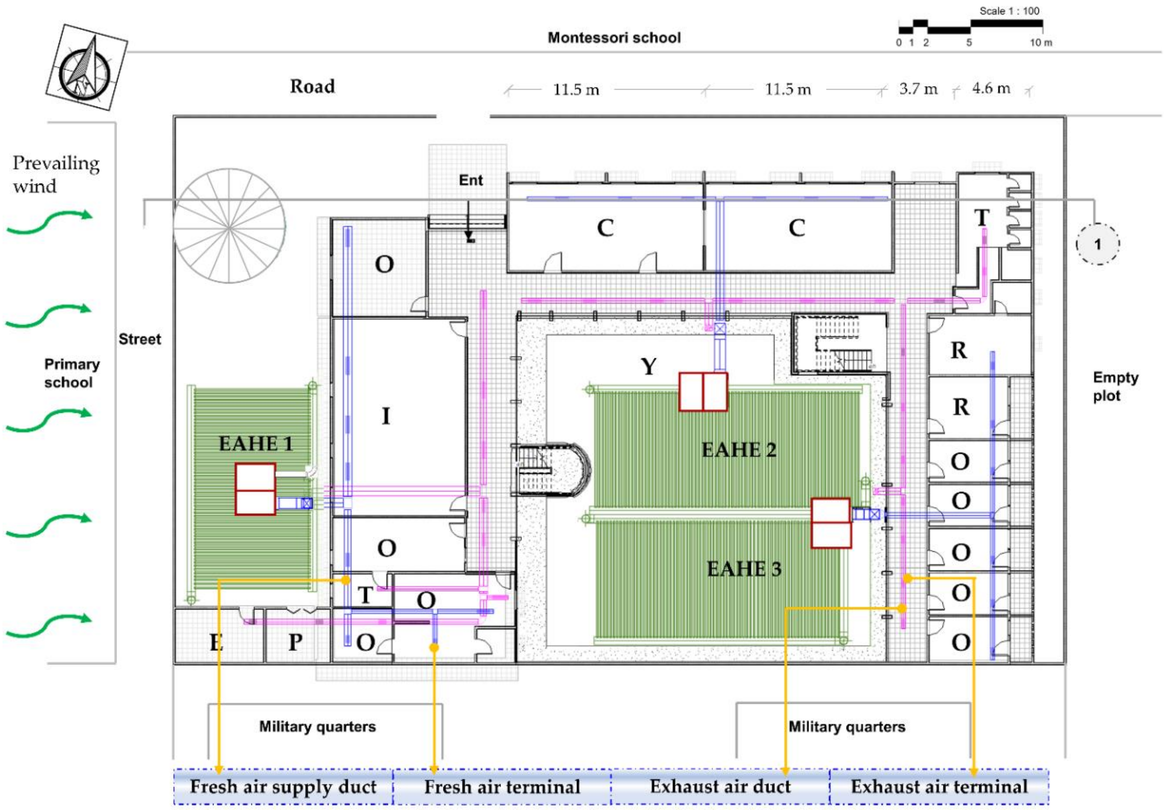


Figure 3. The average monthly mean (dark gray) and maximum (light gray area) and daily maximum (line with dots) rainfall in Karachi, 2014–2022 [44]. The rainy season (rain) from June to September is also indicated.

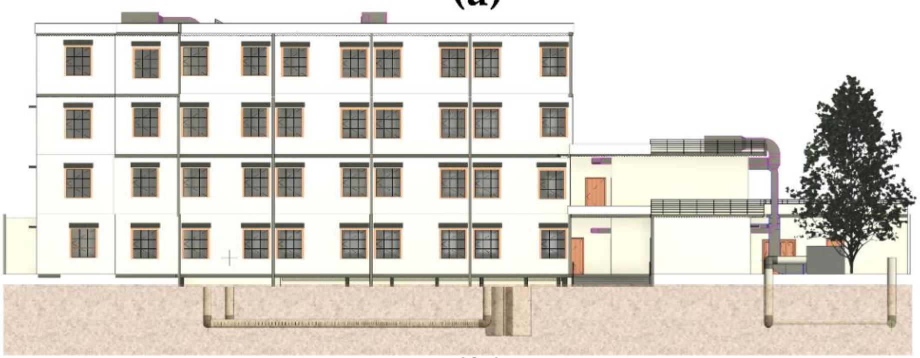
2.2. *Base Case General Building Description and Building Modeling*

An exemplary ACB was selected as a case study building for this research based on the findings published in [42,45]. The exemplary ACB is an adaptive reuse building; therefore, the building faces various challenges in maintaining indoor thermal comfort, good indoor air quality, and sufficient ventilation. The ACB has a U-shaped footprint (land plot area = 1836.9 m^2; gross building area = 1166.88 m^2) with a central courtyard that is open to the south. The property borders are defined by roads in the north and west and neighboring properties in the south and east (Figure 4). The west wing is two stories high, while the north and east wings are four stories tall. Figure 5 illustrates the ground floor plan, north elevation, and section of the exemplary ACB. The available space for the installation of the EAHE is 391 m^2 (23 m $\times$ 17 m) in the courtyard and 281 m^2 (9.5 m $\times$ 29.5 m) beside the west wing. The external ACB walls consist of medium-weight concrete blocks with a U-value of 2.7 W/m^2 K. The roofs are constructed in the form of reinforced cement concrete (RCC) slabs and have a total U-value of 2.58 W/m^2 K. The ACB consists of 50% opening single-glazed sliding windows with a U-value of 5.7 W/m^2 K. Most buildings in Karachi, including the ACB, are hybrid buildings dependent on fans and individual air-to-air heat-pump-based split air conditioners (2.7 EER) for cooling. The fans and air conditioners are responsible for the high electricity consumption in the existing ACB. Natural ventilation in the ACB is facilitated by manually openable windows and doors. Air exchange is created by cross-ventilation and the differences in air pressure between indoors and outdoors. The manual ventilation strategy via building envelope openings (i.e., windows and doors) is based on the traditional habit in the vernacular architecture of Karachi. Natural ventilation is negatively influenced by the adaptive reuse of buildings, which is associated with an increase in building users and higher ventilation demands. The ACB users experience high indoor temperatures and high airflow, even though they desire balanced airflow and air-exchange rates [42,45]. The actual existing thermophysical properties of the ACB in Karachi are presented in Table 1, which also presents the thermal transmittance of the renovated component layers, facilitating a reduction in energy demand and indoor temperature, and improving airtightness and airflow in the renovated ACB. The data and renovated component layers presented in Table 1 are research findings published previously by the authors of this research [45].

Figure 4. Isometric view of the U-shaped case study ACB's 3D model, with surrounding buildings.



(a)



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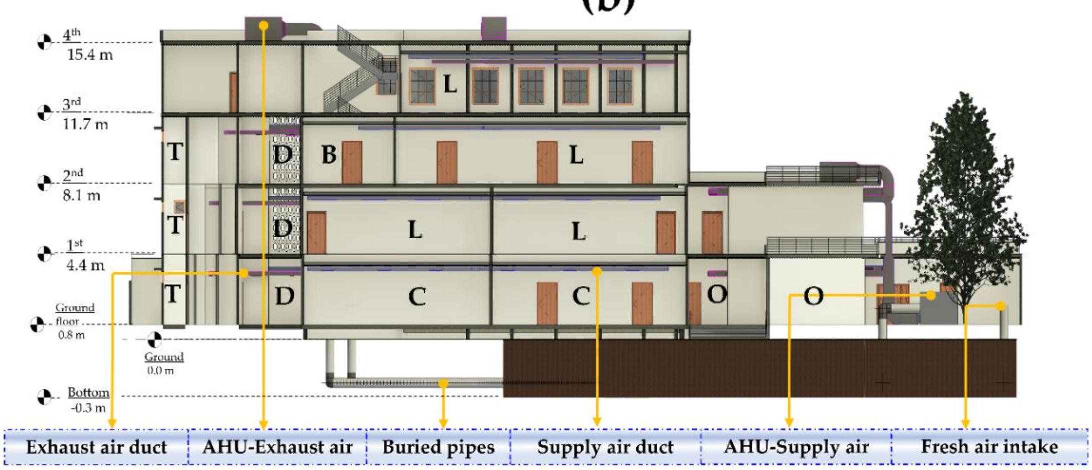
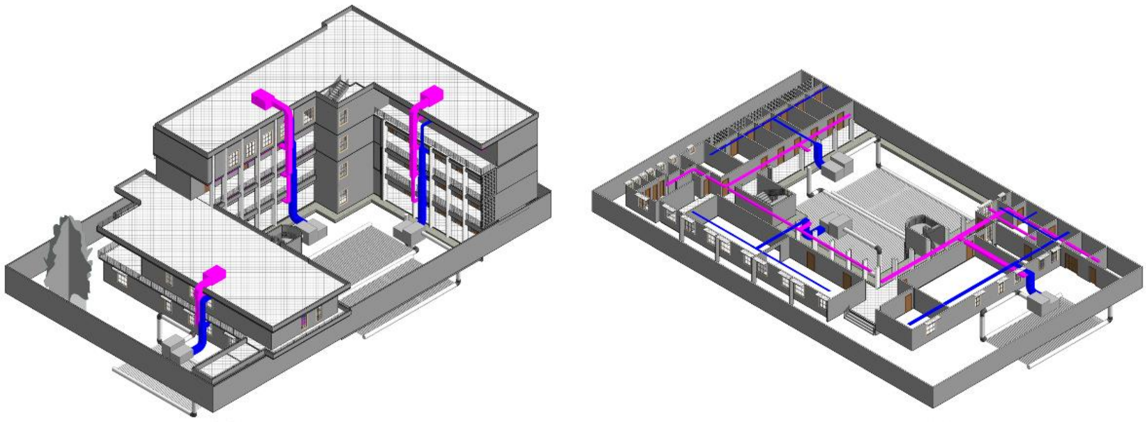


(c)

Figure 5. *Cont.*



(d) (e)

Figure 5. Spatial features of the exemplary case study ACB: (**a**) ground floor plan with the indication of EAHEs and room types, (**b**) north side elevation, (**c**) section, (**d**) view of the ACB in the south direction, and (**e**) sectional view. Legend: EAHE, earth-to-air heat exchanger; AHU, air-handling unit; C, computer lab; O, office; R, common room; I, library; Y, courtyard; T, toilet; E, canteen; P, photocopier; L, lecture hall; B, lab; D, corridor.

Table 1. The thermal transmittance of the building envelope. Legend: EPS, expanded polystyrene; RCC, reinforced cement concrete; LoE, low emissivity.

Description	Existing Component Layers and Thickness from Outside to Inside	Renovated Component Layers and Thickness from Outside to Inside
Wall	Plaster (0.95 cm) Concrete block (20 cm) Plaster (0.95 cm)	Plaster (0.95 cm) EPS (10 cm) Concrete block (20 cm) Plaster (0.95 cm)
U-value (W/m^2 K)	2.7	0.32
Roof	Plaster (0.95 cm) RCC slab (10 cm) Plaster (0.95 cm)	Screed (0.95 cm) Waterproofing layer (0.05 cm) EPS (10 cm) RCC slab (10 cm) Plaster (0.95 cm)
U-value (W/m^2 K)	2.58	0.319
Window	Single clear 6 mm glass window	Double LoE clear 6 mm glass/13 mm argon
U-value (W/m^2 K)	5.8	1.49
Energy demand (kWh)	20,975.48	14,271.72
Energy demand reduction (%)	0	31.96
Indoor temperature (°C)	34.3	29.4
Airtightness	2.5	1.2
Airflow (m^3/s)	North wing = 0.46 East wing = 0.40 West wing = 0.58	North wing = 0.40 East wing = 0.35 West wing = 0.45

2.3. The ACB's Balanced Ventilation System

Figure 1 shows the working principle of the simulated EAHE applied in this research. Multiple pipes were buried at a certain depth in the Tichelmann grid layout, with one end of the pipe network functioning as a fresh air inlet, and then penetrating through the buried pipes and exchanging heat with the pipe walls. A balanced ventilation system incorporates exhaust air extraction and supply of fresh air via separate air ducts. Therefore, this system uses two AHUs: one for fresh air supply, and the other for exhaust air extraction. The fresh air from the EAHE pipe network is supplied through fresh air supply ducts (depicted in blue in Figure 5) to all rooms of the ACB, excluding toilets and printing areas. The exhaust air is extracted from each room of the ACB through exhaust air ducts (depicted in pink in Figure 5). The supply and extract AHUs power is equal to 3 kW.

Considering the available space, the Tichelmann grid layout was applied, ensuring that all supply air would have similar heat-exchange conditions in the EAHEs. According to EN15251, the air change rate for lecture halls should be 25.2 m^3/h per person. Hence, we used 25.2 m^3/h per person to calculate the volumetric flow rate of each lecture hall for an occupancy of 50 people. The total volumetric flow rate required for ACB was calculated to be 16,000 m^3/h. As shown in Figure 5, the ACB contains three EAHEs—two installed in the central courtyard, and one in the open space beside the west wing. EAHE1 serves the west wing, designed for a volumetric flow rate of 4500 m^3/h; EAHE2 serves the north wing, designed for a volumetric flow rate of 6000 m^3/h; and EAHE3 serves the east wing, designed for a volumetric flow rate of 5500 m^3/h. Circular constant velocity ducts were designed to provide equal airflow rates in all rooms of the ACB. In lecture halls, 55 cm ducts were designed for a flow rate of 25.2 m^3/h at 3 m/s, whereas 25 cm ducts for flow rates of 13.6 m^3/h at 3 m/s were designed for the offices. The ductwork was located under the ceiling at a 90 cm distance from the exterior walls of the ACB and exposed to the usable space. The fresh air supply ducts were designed in the rooms, while the exhaust air ducts were located in the corridors (Figure 5).

2.4. Model Description of the ACB's EAHE

The ACB's EAHE is integrated into the building's balanced ventilation systems, which are divided into three subsystems each assigned to one of the three building wings in both the existing and renovated energy-efficient ACB building envelopes. The performance of the EAHE depends on the airflow volume, the properties of the ground, and physical constraints such as ACB size, pipe diameter, length, depth, and the design of boreholes, along with the duct layout. EAHEs can be designed as a whole-building solution or can be zoned to enhance the efficiency of the individual AHUs. In this research, several simulations were performed simultaneously using the advanced simulation tool DesignBuilder (DB) version 6.1.6.008 (DesignBuilder Software Ltd, Stroud, UK). The simulations were executed for the actual geometry of the exemplary ACB. DesignBuilder was developed to run EnergyPlus simulations [46] in buildings, and is a user-friendly and validated simulation tool with specifications for dynamic energy simulations of 3D building models [47]. For this research, virtual BIM reconstruction for the ACB was executed with Autodesk Revit 2020 [48], and was imported thrice to the DB software to run simulations using the gbXML format (1) in actual conditions, (2) after installing the EAHE with the existing building envelope, and (3) after installing the EAHE with the renovated energy-efficient building envelope. After importing the ACB model, the different thermal zones were specified, the construction properties were manually entered, and the occupancy schedules for each zone were defined. Before executing the simulations, the ACB model was validated and then calibrated using ASHRAE Guideline 14-2014 [49]. The NMBE and CV (RMSE) equations, along with linear regression, were applied to calibrate the model by using simulated and measured electricity consumption. The values 2.26%, 13.8%, and 0.9921 of the NMBE, CV (RMSE), and correlation coefficient (R^2), respectively, were found to be suitable to verify the simulation model's calibration. The detailed modeling process and building description are presented in a previous journal article by the authors [45].

2.4.1. Ground Conditions

The ground temperature significantly affects the performance of EAHEs. Therefore, accurate prediction of ground temperatures is required. The ground surface temperature above the EAHE should be estimated prior to the calculation of the ground temperature around the EAHE. CalcSoilSurfTemp (CSST) is an EnergyPlus auxiliary program used to predict the annual average ground temperature, the amplitude of the ground temperature, and the phase constant of the ground surface temperature [50]. CSST predicts these parameters by considering the solar radiation absorption by the ground, convective heat transfer between the ground and the air, latent heat loss due to the evaporation of moisture at the surface of the ground, and longwave radiation emitted from the ground. The weather data file is required to run the CSST program. The ground temperature parameters were calculated by using the Karachi weather data. CSST is a user-friendly program requiring only two input fields: ground surface condition, and ground condition. The ground condition exists in 4 types: (1) heavy and saturated, (2) heavy and damp, (3) heavy and dry, and (4) light and dry. The heavy and damp ground condition was selected for Karachi's ground considering the authors' observations during the field visit and literature studies [33]. Through this, the surrounding ground's thermal conductivity and diffusivity were determined. The ground surface condition exists in 8 types: (1) bare and wet, (2) bare and moist, (3) bare and arid, (4) bare and dry, (5) covered and wet, (6) covered and moist, (7) covered and arid, and (8) covered and dry. The authors chose covered and moist ground surface conditions based on their observations and previous studies [32,33]. The fraction of the evaporation rate at the ground surface and the absorption coefficient were determined through ground surface conditions. The acquired values of annual average ground surface temperature, the amplitude of ground surface temperature, and the phase constant of ground surface temperature are the average values listed in Table 2. After acquiring these parameters, the values were added to the DB EAHE.

Table 2. Ground temperatures in Karachi.

Description	Values
Annual average ground surface temperature	25.47
Amplitude of ground surface temperature	5.5
Phase constant of ground surface temperature	19

2.4.2. EAHE Assumptions and Description

High-density polyethylene (HDPE) is reportedly the most suitable material for EAHEs due to its superior durability, physical properties, cost-effectiveness, and chemical resistance [23,51,52] compared with galvanized iron and copper (Table 3). All three wings were equipped with a 7 m long pipe with a 5 m/s air velocity through the transfer pipes (Table 4). The maximum pipe air velocity was 5 m/s, since higher air velocities negatively affect the thermal performance and heat transfer rate of an EAHE system, i.e., the amount of heat transmission from the air to the ground per time unit increases with an increase in air velocity. Over time, this causes more heat accumulation in the ground and less thermal conductivity interacting with the pipe surface. Therefore, high air velocities in pipes have a detrimental effect on the efficiency of an EAHE [53]. Hence, the pipe inlet boundary conditions were constant air velocity and constant air inlet temperature, which were acquired from the weather data of Karachi. The heat transfer rate per pipe loop was derived from Equation (1) [15,54]:

$$Q = m \cdot c_{\text{pfla}} \left(\frac{T_{\text{in}} - T_{\text{out}}}{1000} \right) \tag{1}$$

where Q is the heat transfer rate per loop (kW), m is the air mass flow rate (kg/s), $c_{\text{p,a}}$ is the specific heat of the air (J/kg·K), T_{in} is the inlet air temperature (°C), and T_{out} is the outlet air temperature (°C). T_{out} is derived from Equation (2):

$$T_{\text{out}} = T_1 + (T_{\text{in}} - T_1)^{\frac{-hA}{m \cdot c_{\text{p}}}} \tag{2}$$

where T_1 is the ground temperature (°C), h is the convection coefficient of the air inside the pipe (W/m^2 K), and A is the heat transfer surface of the pipe (m^2) [15,54].

Table 3. Comparison of available pipe materials in Karachi, Pakistan [33,52].

Materials	Life Span in Years	Thermal Conductivity (W/m K)	Durability	Flexibility
HDPE	70	0.5	Non-corrosive	No
Galvanized iron	70	55	Corrosive	No
Copper	20	401	Highly corrosive	No

Table 4. Specifications and boundary conditions of EAHEs. Legend: HDPE—high-density polyethylene; AHU—air-handling unit.

Description	EAHE 1 (West)	EAHE 2 (North)	EAHE 3 (East)
EAHE configuration	Tichelmann grid	Tichelmann grid	Tichelmann grid
Pipe material	HDPE	HDPE	HDPE
Pipe length	7 m	7 m	7 m
Pipe inner diameter	9.8 cm	9.8 cm	9.8 cm
Pipe outer diameter	10 cm	10 cm	10 cm
Pipe air velocity	5 m/s	5 m/s	5 m/s
Air inlet temperature	34 °C	34 °C	34 °C
Ground temperature	25.47 °C	25.47 °C	25.47 °C
Total volumetric flow rate	4500 m^3/h	6000 m^3/h	5500 m^3/h
Fan	4500 m^3/h@150 Pa	6000 m^3/h@150 Pa	5500 m^3/h@150 Pa
AHU	4500 m^3/h@180 Pa	6000 m^3/h@180 Pa	5500 m^3/h@180 Pa
Thermal conductivity of HDPE	0.510 W/m K	0.510 W/m K	0.510 W/m K
Air outlet temperature	27.3 °C	27.3 °C	27.3 °C
Total heat transfer rate	9.39 kW	12.52 kW	11.47 kW
Total pipe length	1160 m	1547 m	1418 m

The authors made the following assumptions to simplify the mathematical equations:

(1) The temperature of the surrounding ground of the pipe is constant.
(2) The ground surface temperature is the same as the air inlet temperature (i.e., ambient air temperature).
(3) The cross-section of the pipe is uniform, with a smooth inner side.
(4) The thermophysical properties (i.e., viscosity, specific heat capacity, density, etc.) of the ground and air are constant.

The authors tested various EAHE cases based on previous studies in similar climates [34,37,41]. We observed the EAHE specifications in Pakistan and compared them to previous studies in hot and humid climates. Considering the EAHEs in Pakistan, the authors tested different specifications in the following sections based on previous studies in similar climates.

3. Results

3.1. EAHE Measure (EM) 1: Pipe Depths

Compared with outdoor air temperatures, subsurface ground temperatures remain more constant throughout the year. Based on previous studies, the authors analyzed the subsurface ground temperature at four different pipe depths (1 m, 2 m, 3 m, and 4 m) to determine the optimal installation depth (Table 5). Hence, the HDPE pipes were simulated separately, at 1 m, 2 m, 3 m, and 4 m depths. Each pipe had a fan connected to provide an airflow of 5 m/s through the buried pipes.

Table 5. Average monthly outdoor air temperatures and simulated ground temperatures at 1, 2, 3, and 4 m depths.

Months	Temperature (°C)				
	Outdoor Air	**Ground 1 m Depth**	**Ground 2 m Depth**	**Ground 3 m Depth**	**Ground 4 m Depth**
Jan	29.06	28.4	28.1	27.6	27.4
Feb	31.91	28.3	28	27.5	27.3
Mar	35.41	28.5	28.2	27.7	27.5
Apr	36.28	28.4	28.1	27.6	27.4
May	44.11	28.2	27.9	27.4	27.2
Jun	41.75	28.1	27.8	27.3	27.1
Jul	37.33	28.3	28	27.5	27.3
Aug	34.83	28.4	28.1	27.6	27.4
Sep	35.03	28.5	28.2	27.7	27.5
Oct	34.91	28.3	28	27.5	27.3
Nov	34.66	28.2	27.9	27.4	27.2
Dec	29.45	28.1	27.8	27.3	27.1

Table 5 presents the average monthly subsurface ground temperatures at various depths over the period of one year. A subsurface ground temperature of 28.3 °C and 28 °C was simulated at 1 m and 2 m depths, respectively. At 3 m depth, the subsurface ground temperature was 27.3 °C, which is a comfortable temperature in Karachi [55]. At 4 m depth, the subsurface ground temperature was 27.1 °C. Due to the small temperature difference between 3 and 4 m but the increased effort for ground excavations and EAHE installation, a 3 m installation depth was regarded as the optimal installation depth for the exemplary ACB EAHE. In contrast, Sanusi et al. (2013) performed an experimental study to evaluate passive cooling using an EAHE and indicated 1 m below the ground surface as the optimal installation depth in Malaysia. The resulting EAHE ventilation exit air temperatures were 6–9 °C lower than the ambient temperature [38]. Babar et al. (2018) reported an installation depth of 3.96 m to be suitable for Sahiwal, Pakistan [32]. Furthermore, Khan et al. (2020) reported 4.5 m as the optimal EAHE installation depth in Lahore, Pakistan [33]. These differences in optimal installation depths between studies can be attributed to the varying location, the thermal and physical properties of the ground, and the varying climatic conditions.

3.2. EAHE Measure (EM) 2: Pipe Diameter

Three different pipe diameters (0.1 m, 0.15 m, and 0.2 m) were used for the simulation and evaluation of the ACB's EAHE pipe inlet and outlet ventilation air temperatures. Table 6 presents the pipe inlet and outlet temperatures with variations in pipe diameter. Higher outlet temperatures were observed in pipes with larger diameters due to the reduction in convective heat transfer. Peretti et al. (2013) mentioned a minimum pipe diameter of 0.1 m for reduced outlet air temperatures [56]. Ghosal et al. (2005) developed a thermal model to evaluate EAHE potential in Delhi, India. Parametric studies were executed to analyze the effects of pipe diameter, pipe length, and installation depth. They reported higher air temperatures with increasing diameter, which they attributed to the small convective heat transfer coefficient due to the increase in the pipes' surface area [57]. Darius et al. (2017) and Ibrahim et al. (2013) also reported that an increase in diameter resulted in lower thermal performance in EAHE systems [26,41].

Table 6. The EAHE's average monthly pipe inlet and outlet ventilation air temperatures for three different pipe diameters.

Months	Temperature (°C)					
	0.2 m		0.15 m		0.1 m	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Jan	28.06	28.8	28.2	28.5	27.06	27.6
Feb	30.91	28.3	30.21	28	29.91	28
Mar	34.41	29.8	33.81	29.5	33.41	28.4
Apr	35.28	30.3	34.78	30	33.98	28.7
May	42.11	31.8	41.41	31.5	40.61	29.4
Jun	40.75	32.3	40.15	32	39.75	30
Jul	36.33	32.6	35.83	32.3	35.33	29.8
Aug	33.83	30.2	33.43	29.9	32.53	28.9
Sep	34.03	30	33.73	29.7	33.03	28.6
Oct	33.91	29.8	33.51	29.5	32.41	28.3
Nov	33.66	29.9	33.16	29.6	32.66	27.9
Dec	29.83	29.4	29.23	29.1	28.73	27.6

3.3. EAHE Measure (EM) 3: Airflow and Temperature with Existing Building Envelope

As discussed in Section 2.2, the existing building envelope is not airtight (airtightness value = 2.5) and has high airflow in each wing (north = 0.46 m^3/s, east = 0.40 m^3/s, west = 0.58 m^3/s). Figure 6 presents airflow in the ACB under various scenarios, as presented in Table 7. As illustrated in Figure 6, the existing airflow in the ACB is high. The proposed airflow rate is 0.35 m^3/s according to EN 15251 [58]. After installing EAHEs with the existing building envelope, it was expected that a balanced airflow close to the standard airtightness target value of 0.35 m^3/s would be achieved. Case 3 achieved the closest airflow to the desired value of 0.35 m^3/s in each wing. The effect of pipe diameter on airflow shows that with an increase in the pipe diameter up to 0.2 m, the pressure drop between the pipe inlet and outlet decreases. As the air entering the buried pipes is atmospheric, the reduction in the pressure drop in the buried pipes increases the pressure at the outlet of the pipe. Figure 7 represents the temperature in each ACB wing with case 3. Case 3 stands out as the most suitable pipe specification for a good thermal performance of EAHEs in the ACB, since this case provides the most comfortable temperature and airflow in the ACB. The temperature difference between the ground and the ambient air is high at the pipe inlet, but as the ventilation air penetrates through the pipe, the temperature difference decreases, so the heat exchange between the ground and the ventilation air at the pipe outlet is reduced.

Table 7. EAHE specifications of cases 1, 2, and 3 with similar pipe lengths, installation depths, and air velocity but different pipe diameters.

Cases	EAHE	Length (m)	Diameter (m)	Depth (m)	Air Velocity (m/s)
1	1 West 2 North 3 East	1160 1547 1418	0.2	3	5
2	1 West 2 North 3 East	1160 1547 1418	0.15	3	5
3	1 West 2 North 3 East	1160 1547 1418	0.1	3	5

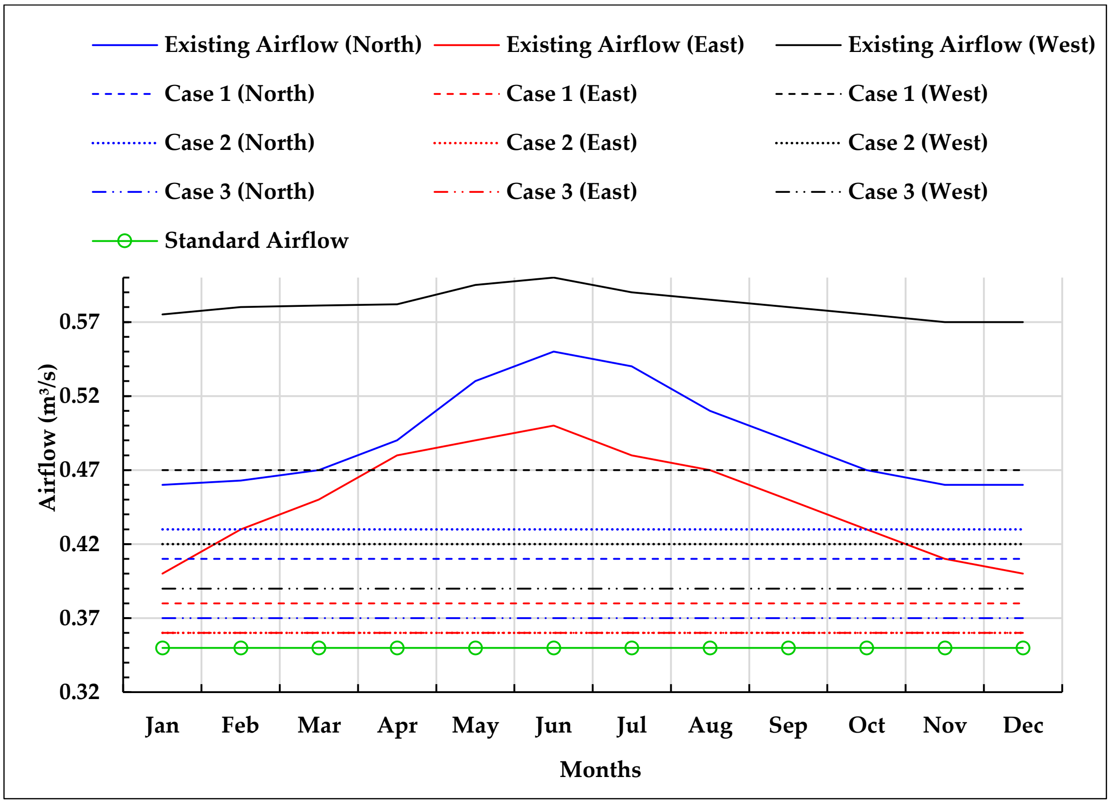


Figure 6. Airflow in the ACB with EAHEs 1 (west), 2 (north), and 3 (east) under cases 1, 2, and 3.

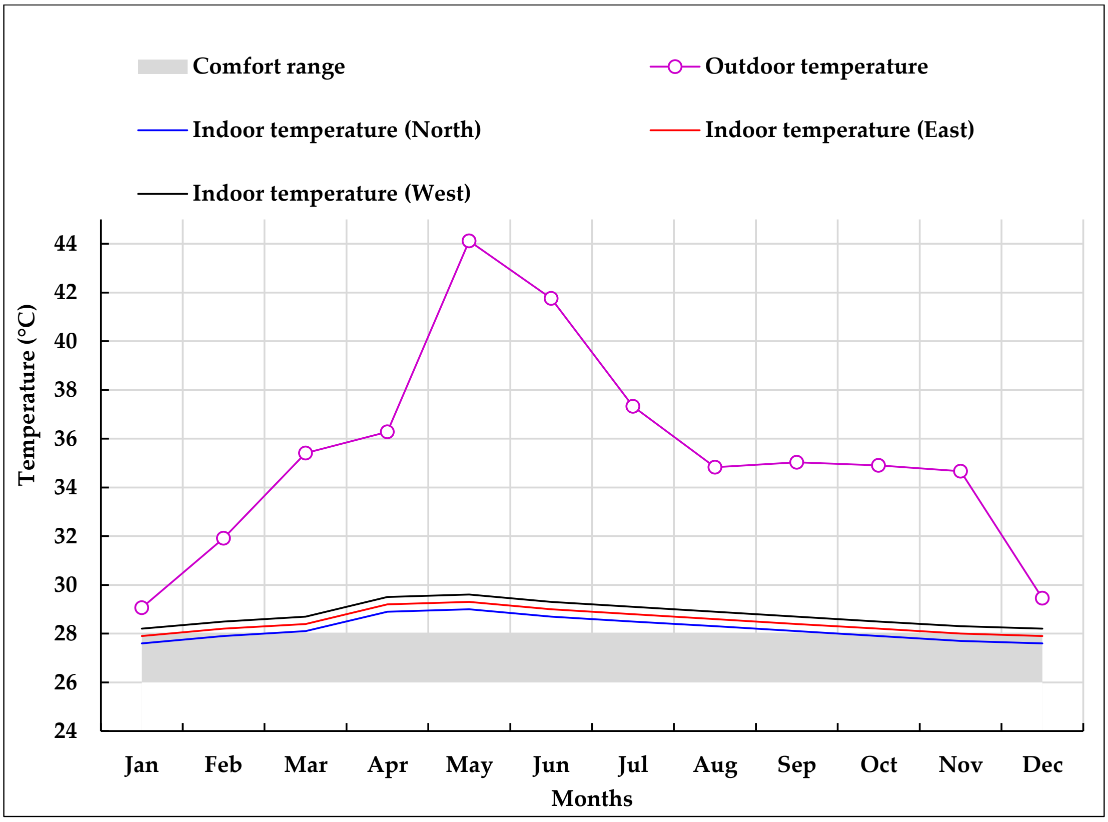


Figure 7. The average monthly indoor temperatures in the ACB in EAHEs 1 (west), 2 (north), and 3 (east) under case 3.

3.4. EAHE Measure (EM) 4: EM (3) with a Renovated Energy-Efficient Building Envelope

Table 1 represents the composition of the existing building envelope and the renovated energy-efficient building envelope of the ACB. The results of research regarding the ACB's energy-efficient building envelope renovation have been published by the authors in a previous journal article [45]. The airflows in the existing ACB before the installation of EAHEs, after the installation of EAHEs, and after full interventions (i.e., energy-efficient building envelope renovation and EAHE installation) are presented in Figure 8. The airflow difference between the existing ACB and the ACB with a renovated energy-efficient building envelope and EAHEs was up to 0.24 m^3/s in the west wing, up to 0.197 m^3/s in the north wing, and up to 0.145 m^3/s in the east wing. The building simulations resulted in a balanced airflow close to the target value of 0.35 m^3/s in the ACB's wings after the installation of EAHEs with the renovated energy-efficient building envelope (Figure 8). Figure 9 illustrates the renovated ACB's indoor temperatures. The temperature difference between outdoors and indoors was up to 15.2 °C (Table 8). The indoor temperatures and airflows were significantly lower after the renovation and EAHE installations, due to the lower airtightness value (1.2) compared to the existing building envelope (2.5) and the lower thermal transmittance of the renovated energy-efficient building envelope compared to the existing building envelope components. Furthermore, the electricity demand for cooling was also reduced from 20,975.48 kWh/a (according to the authors' previous publication [45]) to 10,786.7 kWh/a after the interventions, constituting a 51.4% reduction in electric energy demand (Table 8).

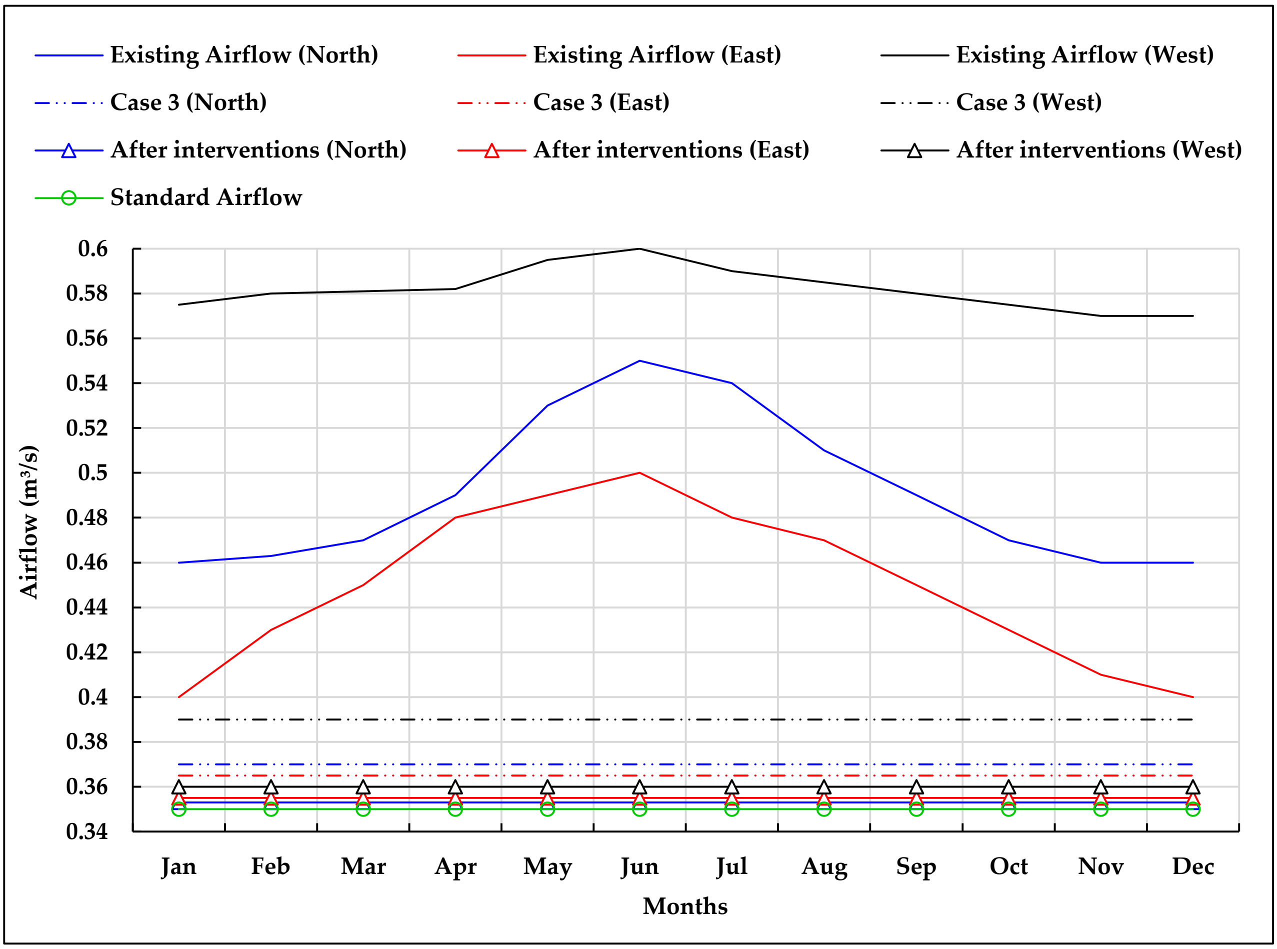


Figure 8. Airflow in the existing ACB; airflow in the existing ACB with EAHEs representing the north, east, and west wings (case 3); and airflow in the renovated building envelope with EAHEs representing the north, east, and west wings.

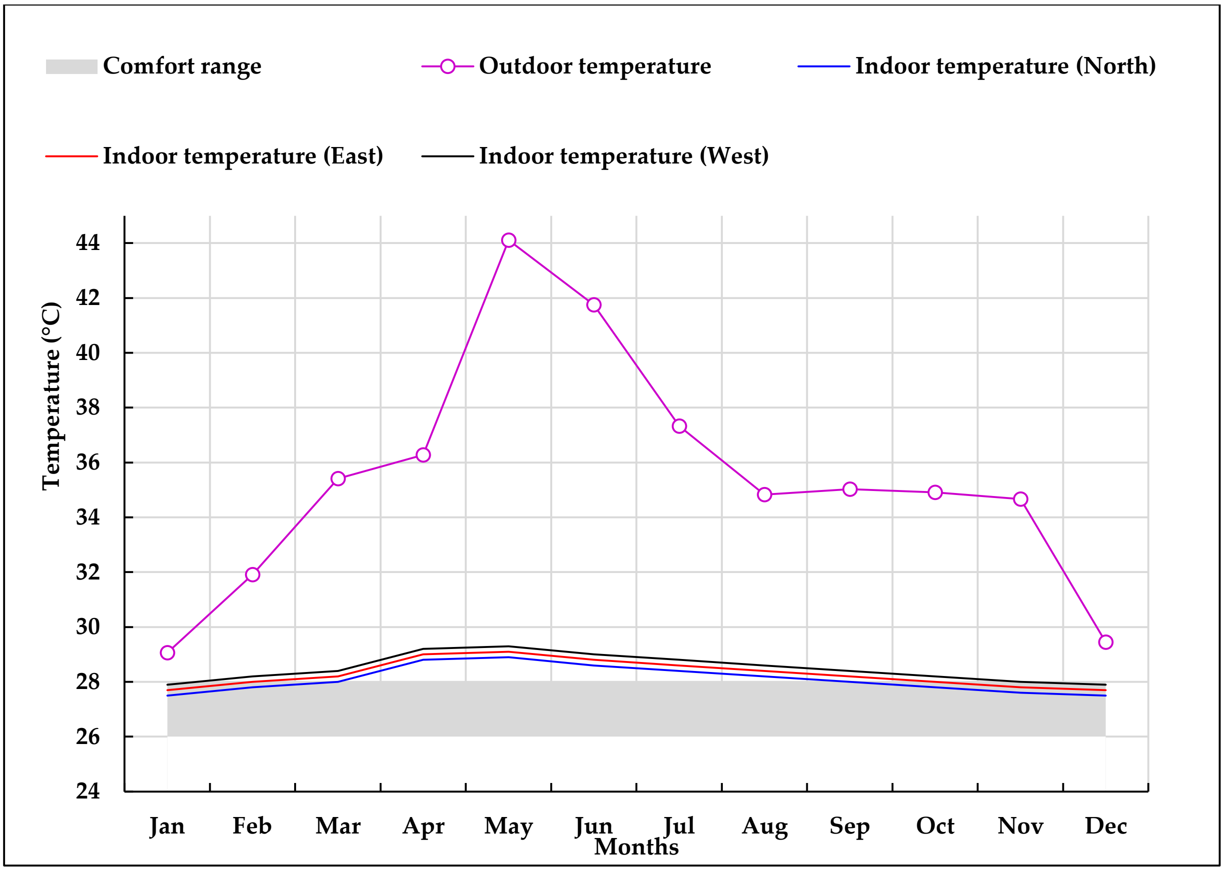


Figure 9. The average monthly indoor temperature in each wing after EAHE installation.

Table 8. The average monthly reduction in energy demand, indoor temperature, and airflow in each wing of the ACB after interventions.

Month	Airflow (m^3/s)			Outdoor Temperature	Temperature (°C)			Base Case ACB Energy Demand (kWh)	Renovated ACB Energy Demand (kWh)	Reduction in Energy Demand (%)
	North Wing	East Wing	West Wing		North Wing	East Wing	West Wing			
Jan	0.35	0.35	0.36	29.06	27.5	27.7	27.9	1331.1	1277.8	4
Feb	0.35	0.35	0.36	31.91	27.8	28	28.2	2073.17	1699.9	18
Mar	0.35	0.35	0.36	35.41	28	28.2	28.4	2176.84	936.04	57
Apr	0.35	0.35	0.36	36.28	28.8	29	29.2	2073.17	663.4	68
May	0.35	0.35	0.36	44.11	28.9	29.1	29.3	2111.01	358.8	83
Jun	0.35	0.35	0.36	41.75	28.6	28.8	29	337.29	64.08	81
Jul	0.35	0.35	0.36	37.33	28.4	28.6	28.8	2384.15	643.7	73
Aug	0.35	0.35	0.36	34.83	28.2	28.4	28.6	2280.49	1277	44
Sep	0.35	0.35	0.36	35.03	28	28.2	28.4	2176.84	1001.3	54
Oct	0.35	0.35	0.36	34.91	27.8	28	28.2	390.54	210.8	46
Nov	0.35	0.35	0.36	34.66	27.6	27.8	28	2176.84	1262.5	42
Dec	0.35	0.35	0.36	29.45	27.5	27.7	27.9	1464.04	1390.8	5

4. Discussion

4.1. Key Findings, Recommendations, and Limitations

The authors selected a calibrated simulation model of an exemplary U-shaped ACB as the case study building. Three open-loop EAHEs were installed to ventilate three building wings located in the north, east, and west. Operating parameters such as installation depth, pipe diameter, and pipe length were investigated to improve the EAHEs' energy efficiency and thermal comfort in an exemplary ACB. The results showed that installation depth and pipe diameter have a significant influence on the performance of EAHEs. Furthermore, an increase in pipe diameter caused a reduction in convective heat transfer. Additionally, the application of EAHEs in the ACB played a vital role in reducing the indoor temperature and facilitating the reduction in energy demand.

The novelty of this research is associated with the building type, climate conditions, and context. The main strength of this study is the selection of an exemplary case study educational building. The authors evaluated the potential of EAHE applications in a hot and humid climate. The research method and results are essential examples and resources for researchers working in the field of passive design measures for enhancing thermal comfort in existing buildings. Furthermore, this research fills a knowledge gap by investigating the combined application and creation of synergies of EAHEs with energy-efficient building envelope renovation measures in Karachi.

The results and recommendations of this research will be beneficial for the design of EAHEs for enhancing thermal comfort in existing educational buildings in similar climates. The limitations of this research are associated with the EAHE operating parameter focus on the installation depth and pipe diameter, due to the limited available property area of the case study building for the installation of EAHEs. It is recommended that future studies with no limitations in EAHE installation area should include the effect of total pipe length on the overall performance of EAHEs. The methodology developed in this research can be transferred to other buildings and applied in the design of EAHEs for mechanical ventilation systems.

The results of this research confirm the assumption that EAHEs are effective in reducing the ventilation air temperature compared with outdoor temperatures, enhancing thermal comfort, and reducing the cooling energy demand in the exemplary ACB with an energy-efficient renovated building envelope. Furthermore, our findings revealed that dynamic simulations are reliable and time-saving methods to investigate the performance of varying operating parameters of EAHEs. Moreover, integration of EAHE ventilation systems in the ACB with an energy-efficient renovated building envelope resulted in lower average monthly indoor air temperatures and positively influenced the overall passive cooling performance of the building envelope and the ventilation systems. The main findings of this research are as follows:

- The optimal EAHE burial depth in Karachi is 3 m, with a subsurface ground temperature of 27.3 °C.
- The increase in an EAHE's pipe diameter from 0.1 m to 0.2 m results in a decreasing airflow pressure drop between the pipe inlet and outlet.
- The energy-efficient renovation of the existing ACB's building envelope and installation of a mechanical ventilation system with EAHEs can reduce the electric energy demand for cooling by 51.4%.

Based on this study's findings, the following recommendations can be made for building designers and researchers working in the field of passive design measures for enhancing thermal comfort in existing educational buildings in hot and humid climates:

- The findings from previous studies cannot be transferred to the context of Karachi, due to the differences in location, thermal and physical properties of the ground, and climatic conditions. Hence, this study plays a significant and novel role in solving the energy crisis in Pakistan, since the implementation of EAHEs in the existing exemplary ACB significantly reduced the building's cooling energy demand.
- The energy-efficient renovation of existing buildings' envelopes and installation of balanced ventilation systems with EAHEs facilitates their transformation into thermally comfortable and energy-efficient buildings.
- The research on EAHEs includes developing numerical models, experimental field analyses, and dynamic computer simulations. The first two of these are time-consuming and complex, whereas dynamic computer simulations combined with numerical analysis are reliable and offer a performance analysis and prediction of real case scenarios in less time and in a simplified manner.
- Most educational buildings in Karachi are naturally ventilated through windows and doors. However, poor indoor thermal comfort occurs in educational buildings

due to inappropriate use of openings. Hence, passive design measures—such as the energy-efficient renovation of building envelopes and installation of mechanical ventilation systems with EAHEs—should be included in buildings to improve indoor thermal comfort.

4.2. Study Implications and Future Research

The adaptive reuse of buildings is widespread in Pakistan, where building users' thermal comfort is neglected. Therefore, the building users depend on active cooling measures associated with high electric energy consumption [35,59,60]. Hence, passive cooling design measures are appropriate solutions to such challenges. Building renovations mainly focus on the extension of the usable area, instead of enhancing the thermal comfort of the building users and the indoor air quality via balanced ventilation and reducing the energy demand. This research will serve as a starting basis for the implementation of EAHEs to reduce the cooling energy demand in the framework of educational building renovations in Karachi while providing a thermally comfortable environment. Future research on ACBs should focus on (i) integration of EAHEs with mechanical ventilation systems and renewable energy production technologies such as building-integrated photovoltaics (BIPV) for covering the buildings' electricity demand, e.g., for ventilation, lighting, and appliances; (ii) sensitivity analysis focusing on the evaluation of the effects of passive design measures on thermal comfort and energy efficiency; and (iii) integration of active and passive measures to acquire optimal thermal comfort and energy efficiency in ACBs.

5. Conclusions

This research focused on the performance analysis of EAHEs in an exemplary ACB in Karachi's hot and humid climate to promote passive design strategies for achieving a high level of indoor thermal comfort. Considering the building size and volumetric flow rate, three individual EAHEs were installed outside of an existing ACB to precool the ventilation air of three individual wings of the building. Different EAHE system layouts with similar pipe lengths but varying installation depths and pipe diameter specifications were investigated to optimize the system performance, reduce the indoor temperature, and minimize the use of air conditioning while optimizing indoor thermal comfort. The exemplary ACB showed significant potential in lowering the indoor temperature and, accordingly, the active cooling energy demand. Based on this research, the following conclusions can be drawn:

1. EAHEs have great potential for reducing indoor temperature and providing balanced ventilation in buildings in a hot and humid climate.
2. The optimal burial depth and diameter for EAHE pipes in Karachi are 3 m and 0.1 m, respectively.
3. The employed interventions in the ACB can reduce the energy demand by up to 51.4%.
4. The applied interventions in the ACB have the potential for a temperature difference of up to 15.2 °C from outdoors to indoors.
5. EAHEs should be integrated with other passive cooling design strategies, such as energy-efficient building envelope renovations, to further improve indoor thermal comfort and reduce electric energy demand for active cooling measures.

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Nomenclature

The following abbreviations are used in this paper:

ACB	Architectural campus building
AHU	Air-handling unit
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
CSST	CalcSoilSurfTemp
CV(RMSE)	Coefficient of variation of root-mean-square error
DB	DesignBuilder
EAHE	Earth-to-air heat exchanger
EPS	Expanded polystyrene
gbXML	Green Building Extensible Markup Language
HDPE	High-density polyethylene
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
IEQ	Indoor environmental quality
LoE	Low emissivity
NMBE	Normalized mean bias error
RCC	Reinforced cement concrete

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