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Evaluating the energy-saving potential of earth-air heat exchanger (EAHX) for Passivhaus standard buildings in different climates in China

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ABSTRACT

The significance of constructing low-carbon buildings has been on the rise because of the growing public concern about global warming and energy prices. The Passive House (or Passivhaus) standard is widely applied throughout Europe to reduce building energy consumption. However, a large percentage of the world's population lives in regions with not only heating demand in winter but also high cooling and dehumidification energy consumption in the hot and humid summer, such as in several regions in China. The energy consumption of buildings in these regions could not be reduced by designing or retrofitting the buildings to Passivhaus standard only, but applying appropriate low energy cooling and dehumidification technologies are also necessary. The earth-air heat exchanger (EAHX) system is a suitable solution for utilizing low-temperature soil in summer, but the performance of the EAHX system in different climates was not previously evaluated. Thus, this research aims to evaluate the energy-saving potential of the EAHX system in a multi-storey Passivhaus standard building in different cities in China with different climatic conditions. A model of the Passivhaus building with the EAHX system was developed and verified using the Passive House Institute (PHI) prediction tool, PHPP and the commercial building energy simulation tool, IES Virtual Environment (VE). The results have shown that the EAHX system achieved an annual building energy load saving of up to 12.8 kWh/m^2 in regions with hot and humid summers and cold winters, such as Beijing and Shanghai. The present study shows the potential of the addition of the EAHX in enhancing the building performance to satisfy the Passivhaus standard in hot and humid climates.

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1. Introduction

The construction sector contributes up to 40% of the direct and indirect global carbon emissions [1]. The global carbon emissions are projected to increase by 50% by 2050 [2]. These problems are much more severe in developing countries, especially in China. The increasing urban population resulted in the massive growth of the construction industry [3]. This significantly increased the building sector's energy consumption, which accounts for up to 44.7% of the total energy consumption and over 33% of carbon emissions in China [4]. While over 50% of the energy consumption of buildings is spent on the use of heating, ventilation and air-conditioning (HVAC) systems [5]. Moreover, China is striving to reach peak carbon emissions by 2030 and carbon neutrality by 2060. Hence, reducing the building energy consumption is a vital part of the low-carbon development in China [6].

In cold climates, space heating is responsible for a significant part of the residential energy consumption, while over 80% of the space heating load could be reduced by retrofitting the existing building to Passivhaus standard. In the study of [7], 96% of the initial heating load was reduced by retrofitting a 10-storey residential building to the Passivhaus standard. However, achieving the Passivhaus standard in hot and humid climates is a considerable task because of the challenge of meeting the performance target for cooling [8]. In addition, the dehumidification load increase in summer, particularly in southern China, leading to condensation issues and high energy demand [9]. A significant part of global electricity is used for cooling and dehumidification, putting enormous strain on electricity systems and driving up emissions [10]. With the increasing demand for healthy and comfortable indoor environments, the energy consumption for cooling and dehumidification has also been increasing [11]. Thus, reducing the cooling and dehu-

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Nomenclature

Symbol	Physical meaning
v	Velocity (m/s)
ΔP	Pressure difference between inlet and outlet (Pa)
$\dot{q}_{tube}$	Airflow rate in each tube (m^3/s)
$\dot{q}_{total}$	Total airflow rate (m^3/s)
D	Tube width (m)
Re	Reynolds' number
h	Convective heat transfer coefficient ($W/m^2/K$)
C_p	Specific heat capacity (J/kg°C)
Pr	Prandtl number
f	Friction factor
A	Tube section area (m^2)
ΔT	Log-mean temperature difference between soil and air (°C)
T_{in}	Air temperature at inlet (°C)
ΔT_{in}	Temperature difference at inlet (°C)
ΔT_{out}	Temperature difference at outlet (°C)
T_{out}	Air temperature at outlet (°C)
T_{soil}	Soil temperature (°C)
T_{air}	Air temperature (°C)
T_{amp}	Maximum amplitude of the temperature wave (°C)
T_m	Annual average temperature (°C)
z	Depth under the ground (m)
Greek lettersρ	
	Density (kg/m^3)
μ	Viscosity (Pa·s)
ω	Angular velocity of the temperature wave (rad/s)
φ	Constant phase shift
AbbreviationsCFD	
	Computational Fluid Dynamics
COP	Coefficient of performance
EAHX	Earth-air heat exchanger
HVAC	Heating, ventilation and air conditioning
PER	Primary Energy Renewable
PHPP	Passive House Planning Package

midification energy consumption is vital for carbon emission reduction, and effective solutions must be investigated for buildings in China.

The earth-air heat exchanger (EAHX), also known as the subsoil heat exchanger or earth tube, is a possible solution to reduce building energy consumption and help satisfy the Passivhaus standard in these climates. This can be installed with the building ventilation system to provide pre-heating to the supply of air in winter and pre-cooling in summer [12]. Because the soil temperature is stable for the whole year compared with the air temperature, which fluctuates every day and the whole year. In most climates, the soil temperature is higher than the air temperature in winter and lower than the air temperature in summer, creating a temperature difference for heat exchange between the soil and the supply air [13]. The EAHX system could also provide pre-dehumidification to the supply air if the soil temperature is lower than the dew point temperature of the outdoor air. EAHX systems have already been widely applied in residential and commercial buildings, schools, libraries, farmhouses and even industrial applications, and the number of EAHX applications has been increasing in recent years [14].

Applying the EAHX system in a Passivhaus building was more effective than a non-Passivhaus building for providing thermal comfort in summer, based on the findings of [17]. The summer cooling load in a non-passive building is typically caused by the fabric, solar, internal heat and ventilation gains. The high-quality building envelope minimizes the fabric and solar gains in a Passivhaus with appropriate shading, but the ventilation and internal gains in summer could not be avoided. A larger percentage of the overall cooling energy consumption can be reduced in a Passivhaus with a lower total cooling load than in a non-Passivhaus building. Hence, the EAHX system is an effective passive cooling technology suitable for Passivhaus buildings [17]. With the same EAHX system, the indoor air temperature can be decreased to or even lower than the cooling requirement in a Passivhaus building, while additional cooling is still necessary for a non-Passivhaus building. In other words, the cost of the EAHX system can be reduced by applying a smaller EAHX system in buildings with lower cooling loads [18].

1.1. Novelty and contribution to knowledge

Because the EAHX system is not suitable for all climate conditions because of the requirement for appropriate soil temperature, investigating the regions with good potential for applying the EAHX system is necessary [12]. Previous research works have investigated the EAHX system performance in different case studies [15], but comparing the results can be challenging because of the building function and quality differences. In addition, none of the research investigated and compared the performance of the EAHX system in regions such as China, which has the most diverse climate conditions in the world [16], to provide guidelines and recommendations for implementation [14]. Moreover, the implemented strategies could also be applied in other regions or countries with similar climatic conditions. Limited research also focuses on EAHX systems in Passivhaus buildings to reduce the cooling and dehumidification demand in hot and humid regions. The present work will address these research gaps by developing a simplified method, based on a simulation approach using the Passive House Institute (PHI) prediction tool, PHPP to evaluate the performance of the EAHX system integrated into a Passivhaus multi-storey building in diverse climatic conditions and provide design recommendations for regions or countries with similar climates. Furthermore, this work will provide a detailed comparison of the EAHX system's energy-saving performances in a Passivhaus building in different climatic conditions. The proposed method can simplify the evaluation process of the EAHX system's energy-saving potential for the Passivhaus building at the early design stages and for practical planning purposes.

1.2. Aim and objectives

This research aims to investigate the energy-saving potential of the earth-air heat exchanger system integrated with a Passivhaus building in different climates in China to achieve low heating, cooling and dehumidification demand. In this research, we will develop a verified multi-storey Passivhaus building model and evaluate the energy performance in twelve major cities in China with eight different climatic conditions. A mathematical model will be developed and validated to evaluate the effectiveness of the EAHX system. The energy performance of a building with and without the EAHX system will be predicted using the Passive House Institute (PHI) prediction tool Passive House Planning Package (PHPP), and the energy-saving potential of the EAHX system in different climates will be assessed to provide design recommendations. The study will assess the suitability of buildings in different Chinese cities and climates for adapting to Passivhaus standards and the EAHX application. Finally, the work will conclude if the addition of the EAHX can help satisfy the Passivhaus standard in these regions.

2. Literature review

A literature review on the Passivhaus standard and earth-air heat exchanger (EAHX) systems is presented in this section to analyse the relevant research works on Passivhaus buildings, EAHX and the application of EAHX in Passivhaus buildings.

2.1. Passivhaus standard and design

The Passivhaus standard is a German standard with strict design and operation requirements to minimize building energy consumption. The Passivhaus standard design and operation requirements are shown in Table 1 [19], which mainly focus on minimizing the heating energy demand. Until 2016, over 60,000 Passivhaus were built and most of the projects were located in European countries with cold winters [20]. However, for a vast country like China with diverse climates and indoor comfort demands, additional criteria must be added according to the local conditions, such as appropriate cooling and dehumidification load limitations [9].

To compare the building performance in different regions, a fixed building standard has to be applied. However, different cities have different building quality standards because of the diverse climates in China, but most of the standards and building qualities are far away from Passivhaus standards. For example, the U-value limit is 1.0 W/m^2K in Shanghai [21], and there is no limit to the building's airtightness. An n50 test was conducted for buildings in Dalian, Liaoning, and the average airtightness of the tested buildings was 1.42 h^{-1}, which was also far away from the Passivhaus standards of 0.6 h^{-1} [22]. The poor building insulation and airtightness of an air-conditioned building would result in high energy consumption in winter heating and summer cooling, and a case study showed that retrofitting the current building in China to Passivhaus standard could reduce 90% of the initial heating loads and 70% of the cooling loads [8].

In most of the research and case studies, reducing the building heating load by designing or retrofitting a building to Passivhaus standards was practical, while reducing the cooling loads can be challenging, especially in hot and humid climates [7,23]. Hence, by designing or retrofiting a building to Passivhaus standard and applying appropriate passive and low-energy cooling and dehumidification technologies, the heating, cooling and dehumidification load can be decreased all together.

2.2. Earth-air heat exchanger and applications (Subsoil heat exchanger)

The earth-air heat exchanger is a widely used low-energy cooling technology that utilizes the thermal mass of soil [24]. The soil temperature at the level of a few meters below the ground is almost constant over the whole year, while the ambient air temperature fluctuates throughout the year and a day [25]. There arethree general types of ground heat exchanger, including the open system and the closed system [26] and the tube can be placed horizontally or vertically [14]. An EAHX system could provide preheating or pre-cooling to the supply air to reduce energy consumption. A 30 m long EAHX system could provide a 75%–80% of temperature change [27], and a 70-meter-long tube was suggested to provide sufficient air pre-cooling for the open system [28,29].

Table 1
Passivhaus standard design and operation requirements [19].

Performance targets	Limiting values
Space heating	Maximum heating demand 15 $kWh/m^2/year$ or heating load lower than 10 W/m^2
Airtightness	Maximum 0.6 air changes/hr under 50 Pa
Primary energy consumption	Maximum 120 $kWh/m^2/year$
U-value for exterior shell components	Lower than 0.15 W/m^2K
Ventilation heat recovery	Efficiency over 75%
Overheating frequency	$\leq$ 10%(>25 °C)

The performance of the EAHX system in different climates was already evaluated in many research. In Delhi with its humid subtropical climate, an EAHX system in the building could provide 4158 kWh/year of free heating in winter and 3958 kWh/year of free cooling in summer [30]. In Chongqing, China with a humid subtropical climate, a building with the EAHX system had 5.9 °C lower indoor air temperature in summer and 4.29 °C higher indoor air temperature in winter, than a building without the EAHX system [31]. An experimental test and CFD simulations were conducted to evaluate the performance of the EAHX system in a Passivhaus building in southern Poland with a temperate humid climate and 15% of the ventilation heating demand was covered by the heat exchanger [32]. In Bechar, south of Algeria, with a subtropical desert climate, an EAHX system could reduce the indoor air temperature by 10 °C to 14 °C in the cooling season [33]. In Baghdad and Tehran with hot and moderate climate, an EAHX system with a pipe length of 25 m could decrease the room air temperature to lower than the cooling setpoint but the number of systems needs to be increased when the cooling demand exceeds 1000 W [18]. In New Delhi, an EAHX system could increase the air temperature in winter and decrease the air temperature in summer by up to 15 °C with a payback of fewer than two years [34].

2.3. Passive/low-energy cooling and dehumidification technologies

Although the heating load can be minimized by applying the Passivhaus standards, the cooling and dehumidification load should also be addressed in order to prevent discomfort and high energy consumption. Several passive and low-energy cooling methods are compared in Table 2, including solar shading, natural ventilation, evaporative cooling and earth-air heat exchanger. Building solar shading is an effective method to reduce the building solar gains, examples of this are traditional overhang window shading above the window, external Venetian blind shading [35] and vertical greenery systems [36]. More advanced shading systems could also be incorporated with solar technologies [37–39]. However, the window shading could only control the building's solar gains, and the high cooling & dehumidification load in the HVAC system remained. Natural ventilation with appropriate thermal mass for nighttime ventilation could save energy, but it's not suitable for some regions in China with nighttime air temperatures higher than indoor cooling setpoints, such as Shanghai [40]. Evaporative cooling could reduce the air temperature with high COP through the direct or indirect system [41]. However, in the hot and humid summer in China, the evaporative cooling system performance is affected by the high humidity levels. The earth-air heat exchanger is selected as a suitable technology for integration due to its passive/low-energy cooling and dehumidification abilities which could provide a comfortable supply of air temperature and moisture content in both daytime and nighttime [42,43]. However, the other passive cooling technologies such as solar shading and natural ventilation can also be applied in combination with the EAHX system to further reduce the energy consumption in a Passivhaus building.

Table 2
Comparison of different passive or low-energy cooling technologies.

Passive/low-energy cooling technologies	Cooling load-saving strategies	Examples	Advantages	Limitations
Solar shading	Reducing summer solar gains	Overhang external Venetian blind shading [35]	Low initial and operational cost Reducing solar gains effectively	Reduces natural daylight Can impact occupancy views
Natural ventilation (with night-time ventilation)	Removing the heat gains from indoor space	Nighttime ventilation with high thermal mass [44]	Low initial and operational cost Low maintenance	Need appropriate outdoor air conditions
Evaporative cooling	Evaporation of water would absorb the heat	Evaporative cooling system [41]	Low operational cost High energy efficiency	Need low air humidity Water usage Maintenance
Earth-air heat exchanger	Precooling the supply air by soil	Earth-air heat exchanger system [14]	Low air temperature supply	Large capital cost Fans energy consumptions Maintenance

2.4. Literature gap

Most of the research about passive and low-energy cooling technologies in buildings in China were location specfic case studies, and only a few studies evaluated the passive cooling technologies under different sub-climates in China, such as the shading effect of rooftop photovoltaic for different regions in China [45]. Thus, evaluating energy-saving strategies and technologies in different climate zones in China is necessary before applying them in a country with multiple sub-climates [12]. Previous research about the EAHX system in different regions was carried out in Italy [46] and North Africa [47] with a limited number of subclimates. Investigating the EAHX system performance in China with various subclimates could provide design recommendations for more climate regions around the world.

As the Passivhaus standard was developed in the region with mainly heating demand, appropriate passive cooling and dehumidification technologies were not fully considered when the Passivhaus standard was applied in regions with both heating and cooling demand, such as China. Most of the research about Passivhaus did not give the same importance to cooling as to heating, while the overheating issue in summer is getting more serious.

Although a large proportion of the regions in China has a hot and humid summer, appropriate building dehumidification is not fully investigated, and natural ventilation is still a widely used practical method to remove moisture from indoors to outdoors, which could avoid mildew but could not provide indoor thermal comfort in the hot and humid summer. Investigating energy-saving technologies with both passive/low-energy cooling and dehumidification ability is necessary for low-carbon building development in China. Most of the research only focused on the heating, and cooling effect of the EAHX system [14,48] and only a few research considered the impact of the EAHX system on the moisture content. The specific climate conditions for condensation in the EAHX system was strict that the soil temperature needs to be lower than the dew point temperature of air [49].

Overall, a comparison of the EAHX performance in different sub-climates is important to find out the suitable regions and climate conditions to apply the technologies in Passivhaus buildings and improve the cost-effectiveness of its application.

3. Methodology

The research flow diagram is shown in Fig. 1. The energy performance of the benchmark building was evaluated and verified by hourly and monthly methods and the overall energy-saving of the EAHX system was evaluated by the Passive House Planning Package (PHPP) tool. The accuracy of PHPP for Passivhaus energy evaluation was already proven by comparing the existing monitored projects in the Passivhaus database to the dynamic simulation results [50].

The variables were fixed to compare the EAHX performance in different climates, including the identical building model and 100% mechanical ventilation with a controlled ventilation rate. This research will carry out validation of the Passivhaus building and EAHX models, comparison of the EAHX effectiveness with different lengths using the developed mathematical model, evaluation of the building heating, cooling and dehumidification loads following the integration of the EAHX and comparison of the EAHX performance in different regions.

3.1. Passivhaus building energy model

The benchmark simulation model was developed and verified using the building energy simulation software, IES-VE, and the verification result are detailed in Section 4. Several modifications were made to the benchmark model, including increasing the floor number to represent a building in a high desnity city [51], changing the glazing ratio, changing building U-values and setting the internal heat gains according to the data in the Passivhaus database. The maximum ventilation rate for the EAHX system capacity was determined by the design occupants number times the ventilation demand for each person. The space in the unheated area was used for stairs, elevators and ductwork. The 3D model for the building energy simulation and dimensions are shown in Fig. 2. The modified building energy simulation model will be further evaluated in IES-VE and PHPP to verify the results.

The design parameters and operational conditions are shown in Table 3, including the basic building geometry, the set values for the simulation , and the corresponding design principles.

3.2. EAHX system evaluation

The PHPP tool includes the subsoil heat exchanger with a bypass for heating, cooling and dehumidification load calculation which is controlled by the temperature. After the air passes through the tube, the air enters the building and supplied to every room by the mechanical ventilation system. A bypass in the EAHX system needs to be added to control the fresh air entering the building through the heat recovery unit or the EAHX tubes in summer or transitional seasons [55]. As this research is focused on the overall energy performance, a simple one-dimensional calculation method was used for the design recommendations [56].

The supply duct was divided into several small rectangular ducts, as suggested by previous research [57–59], to increase the

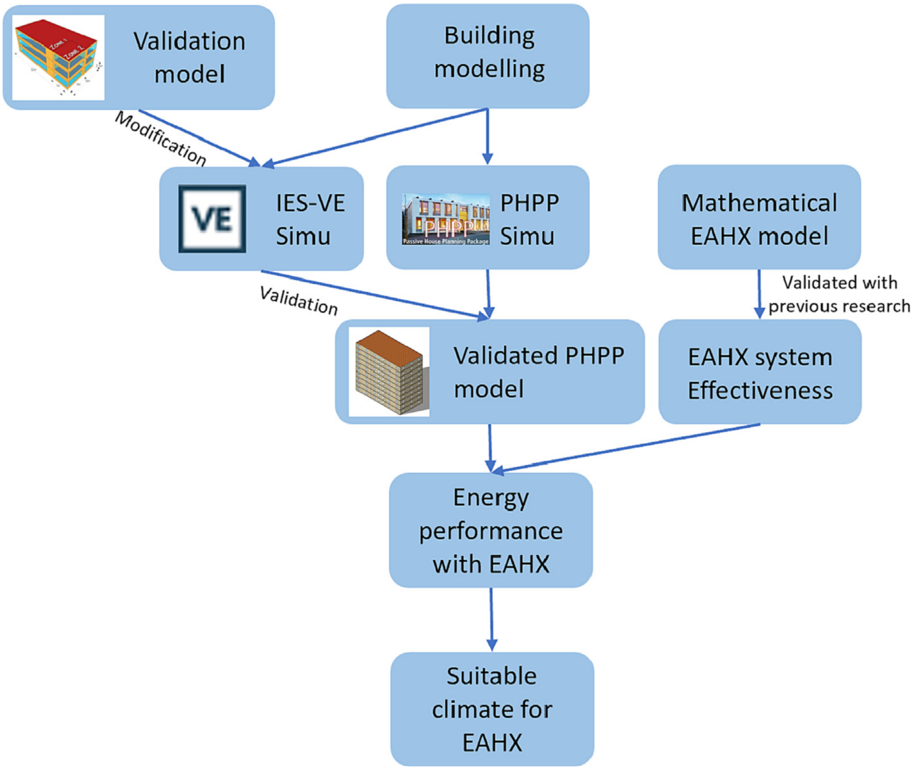

Fig. 1. Research flow diagram for the validation, co-simulation and evaluation of the Passivhaus building model integrated with the EAHX system.

contact area between air and soil. In this building, the design size of each tube was set to be 0.2 m × 0.2 m, and the air temperature leaving the EAHX system with 10, 25, and 50 tubes and air velocities 1 m/s, 2 m/s, 5 m/s, respectively, were calculated using the following equations. To simplify , the calculation was made to estimate the temperature change and pressure loss in a single straight branch pipe. The temperature change was used to calculate the effectiveness, and the monthly heating, cooling and dehumidification load saving was calculated by PHPP.

The monthly calculation method was used to calculate the energy saving in the cooling and dehumidification load and pressure drop in the EAHX system.

The airflow rate in each tube $\dot{q}_{tube}$ was calculated by Eq. (1).

$$\dot{q}_{tube} = \frac{\dot{q}_{total}}{n} \tag{1}$$

The airflow velocity v was calculated by Eq. (2).

$$v = \frac{\dot{q}_{tube}}{D^2} \tag{2}$$

The Reynolds' number Re was calculated by Eq. (3).

$$Re = \frac{\rho u D}{\mu} \tag{3}$$

The Fanning friction factor f was calculated by the Eqs. (4) & (5) for turbulent flow [60,61].

$$f = 0.079Re^{-1/4}\, 2 \times 10^3 < Re < 2 \times 10^4 \tag{4}$$

$$f = 0.046Re^{-1/5}\; 2 \times 10^4 < Re < 2 \times 10^6 \tag{5}$$

By using the Chilton – Colburn analogy [62], Eq. (6), the convection heat transfer coefficient was calculated using Eq. (7).

$$\frac{f}{2} = \frac{h}{\rho u C_p} Pr^{\frac{2}{3}} \tag{6}$$

$$h = \frac{\rho u C_p f}{2Pr^{\frac{2}{3}}} \tag{7}$$

The specific heat capacity C_p was determined by the specific enthalpy difference between the two states divided by the temperature. The specific enthalpy was determined using the psychrometric chart so the latent heat of the air was contained in the calculation.

$$C_p = \frac{h_1 - h_2}{T_1 - T_2}$$

The amount of conventional heat transfer was equal to the internal energy change of air, and Eq. (8) was applied.

$$\Delta Q = h \times A \times \Delta T = (T_{out} - T_{in}) \times C_p \times \dot{q}_{tube} \times \rho \tag{8}$$

Assuming the soil temperature was constant, the log-mean temperature difference was simplified by Eq. (9).

$$\Delta T = \frac{\Delta T_{in} - \Delta T_{out}}{\ln^{\Delta T_{in}/\Delta T_{out}}} = \frac{(T_{in} - T_{soil}) - (T_{out} - T_{soil})}{\ln^{\Delta T_{in}/\Delta T_{out}}} = \frac{T_{in} - T_{out}}{\ln^{\Delta T_{in}/\Delta T_{out}}} \tag{9}$$

Thus, Eq. (9) was simplified and the T_{out} was calculated by Eq. (10).

$$T_{out} = \Delta T_{in} \times e^{\frac{D \times Pr^{2/3}}{2 \times f \times L}} + T_{soil} \tag{10}$$

The pressure drop was calculated by Eq. (11).

$$\Delta P = \frac{4fL\rho u^2}{2D} \tag{11}$$

The effectiveness of the EAHX system was calculated by Eq. (12).

$$\text{Effectiveness} = \frac{T_{in} - T_{out}}{T_{air} - T_{soil}} \times 100\% \tag{12}$$

The temperature of the soil was calculated by Eq. (13) [63].

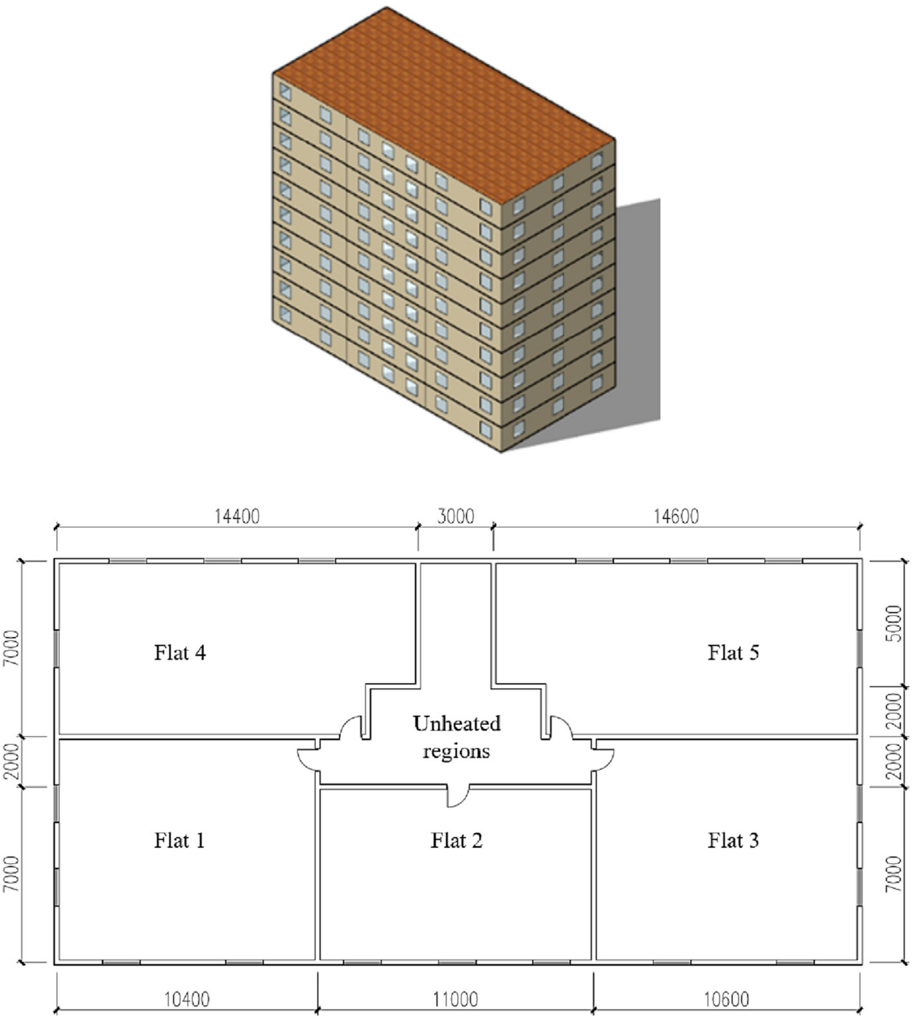

Fig. 2. Building energy simulation model in IES-VE and floor plan with dimensions in mm and locations of windows.

$$T_{soil} = T_m - T_{amp} \times e^{\left(-z\times\sqrt{\frac{\omega}{2\alpha}}\right)\times\cos\left(\omega t-\varphi-z\times\sqrt{\frac{\omega}{2\alpha}}\right)} \tag{13}$$

A 70-meter-long tube was sufficient to pre-cool the supply air [28]. Thus, the initial EAHX system tube length was 70 m in the mathematical model. Identical weather conditions were used to simulate the verification model. The outlet temperature and the effectiveness of this EAHX system in Fig. 3 matched the results of [28]. The mathematical calculation model was validated using the previous research data on the EAHX system's effectiveness, and the validation result is shown in Section 4.

The system effectiveness based on the three airflow velocities is shown in Fig. 4. The effectiveness is approaching 1 with the increase in tube length and the effectiveness increased exponentially in the first 30 m while the pressure drop in the tube was linear to the tube length. A smaller design velocity could have the same effectiveness with a shorter pipe length, and the pressure drop in the tube was decreased dramatically when a shorter tube and lower airflow velocity were applied. As a system with high ventilation rate demand, a high-pressure drop would result in high energy consumption from the fans. Thus, a 30 m tube with 1 m/s designed maximum velocity was sufficient to pre-cool the supply air and the effectiveness was 99% for PHPP simulation with a pressure loss lower than 3 Pa in the branch tube. The effectiveness achieved in the mathematical model was applied in PHPP to calculate the overall EAHX system effectiveness in the long-term operations, as the system effectiveness was not identical to the tube effectiveness in the operation. The longer operation period and heat exchange would result in a lower overall effectiveness. The energy performance of the EAHX system was calculated based on the overall EAHX system effectiveness, as shown in Fig. 8. The EAHX system effectiveness was 100% in some cities that seldomly used the EAHX system and the longer operation time resulted in lower effectiveness. However, a short tube might result in a decrease in system effectiveness because of the lower thermal mass [64,65]. The local soil conditions vary in different regions and the performance of the EAHX system depend on the soil conditions. However, for comparing the EAHX system potential in different climate conditions in this research, the variables were fixed to allow direct comparison between the similated cases. Thus, to to simplify assumptions were made that the design of the EAHX system is adjusted according to the local soil conditions to achieve maximum effectiveness in different cities. As a high-efficiency heat recovery had to be applied in the Passivhaus building, a bypass across the heat recovery unit was necessary for the EAHX system.

3.3. Cities selections for the evaluation of the Passivhaus building with the EAHX system

This research will evaluate how the different local climates could impact the performance of the EAHX system [46]. Several representative cities with large populations, high urbanization levels and different climate conditions were selected in China.

Table 3
Design parameters and operational conditions in the simulation.

Design conditions	Design parameters	References and justification
Building length	32 *m*	Based on benchmark building geometry [52]
Building width	16 *m*	
Floor number	10	
Window-to-Wall (WWR) ratio	South&North: 17% East&West: 15%	
Occupancy density	36.6 $m^2/person$ (Constant)	Average occupancy density [53]
Occupants number	140	
Heating setpoint	20 °C	PHPP certification requirement or CIBSE Guide A recommendation [54]. The constant value is applied.
Cooling setpoint	25 °C	
Humidity setpoint	60%	
Ventilation demand	10 $L/s/person$	
Total internal heat gains 2.6 W/m^2	PHPP database	(Occupants + equipment)
Ventilation strategy	100% mechanical ventilation	Natural ventilation cannot provide thermal comfort in case study areas
Airtightness	0.6 h^{-1}	Passivhaus n50 test limitation
Wall and roof U-value	0.135 W/m^2K	Passivhaus standard for external insulation.
Average window U-value	0.78 W/m^2K	Passivhaus standard
Ground floor U-value	0.143 W/m^2K	Passivhaus standard
Door U-value	0.8 W/m^2K	Passivhaus standard
Ventilation heat recovery	85% Efficiency	Passivhaus standard

The location and information of the selected cities covering eight different sub-climates are shown in Fig. 5 and Table 4.

4. Results

4.1. Model validation results

A building model in London with a form factor of 0.28 was selected for the verification [52]. A hourly simulation model using the weather data file of London in IES-VE and the data provided by the reference model was created for the model verification. The verified hourly simulation model (IES-VE) was then used for validating the co-simulation based on the monthly method (PHPP). The annual heating, cooling, lighting and equipment energy consumption results in the verification model had an average error within 0.1% of the reference model [52], as shown in Fig. 6(a). And the mathematical model of the EAHX effectiveness was validated with previous research [67]. The validation result of the EAHX model is shown in Fig. 6(b), with a Roof Mean Squared Error of about 2.26%. Hence, the models in this research are sufficiently accurate for the simulation required to evaluate the performance of the EAHX system. The comparison of the IES-VE simulation and PHPP calculation results is shown in Fig. 6(c) and good agreement was observed. Hence, the PHPP building model can be used for further evaluation in this study.

4.2. Weather conditions of the case study cities and EAHX potential

The weather conditions in the same climate region were similar but not identical, as shown in Fig. 7, because of the city's latitude and altitude. The locations of cities in the region map are shown in Fig. 8. In Region, I, most of the areas was Tundra (ET) climate, but Lhasa was a subarctic, Dwc, climate [66]. The temperature difference between soil and air in Lhasa (Dwc) was not large enough but cooling in summer and heating in winter was still possible.

In Region II, in the cities with low latitudes, including Guangzhou, Qionghai (Am), and Kunming (Cwb), the soil temperature was almost identical in summer. In Shanghai (Cfa) and Chengdu (Cwa), the temperature difference is high enough for the EAHX system to provide summer cooling. In Region III, in Urumqi (Bsk), the temperature difference between soil and air was large enough in summer to provide a considerable cooling. In all the cities in Region IV, a large temperature fluctuation during the whole year resulted in a huge temperature difference between soil and air in both winter and summer. The soil temperature in summer was also much lower than the cooling setpoints, and the potential of passive cooling was considerable.

The average moisture content in the supply air during the summer cooling period is shown in Fig. 9. In cities from Lhasa (Dwc) to Harbin (Dwb), the moisture content of supply air was decreased by the condensation that occurred in the EAHX system as the soil tem-

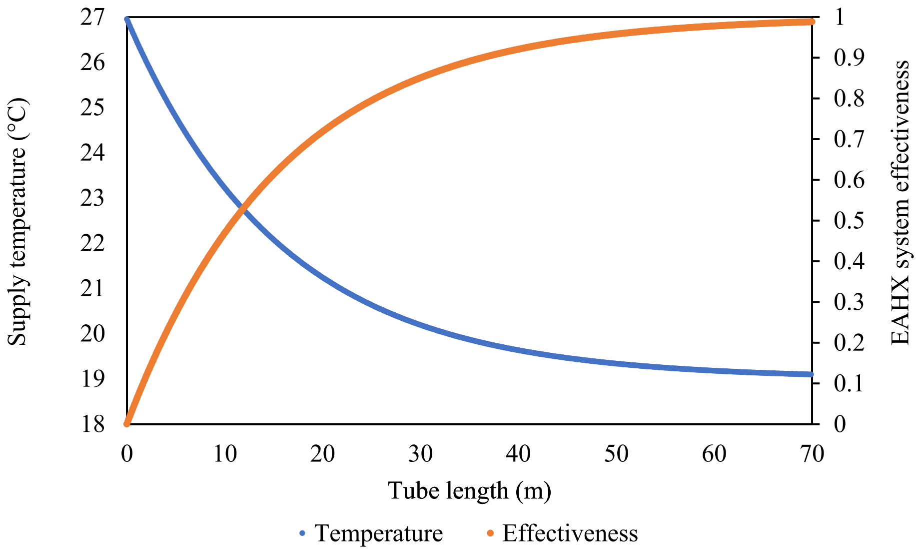

Fig. 3. Outlet temperature and system effectiveness according to the tube length from 0 to 70 m under 19 °C soil temperature and 27 °C environment temperature.

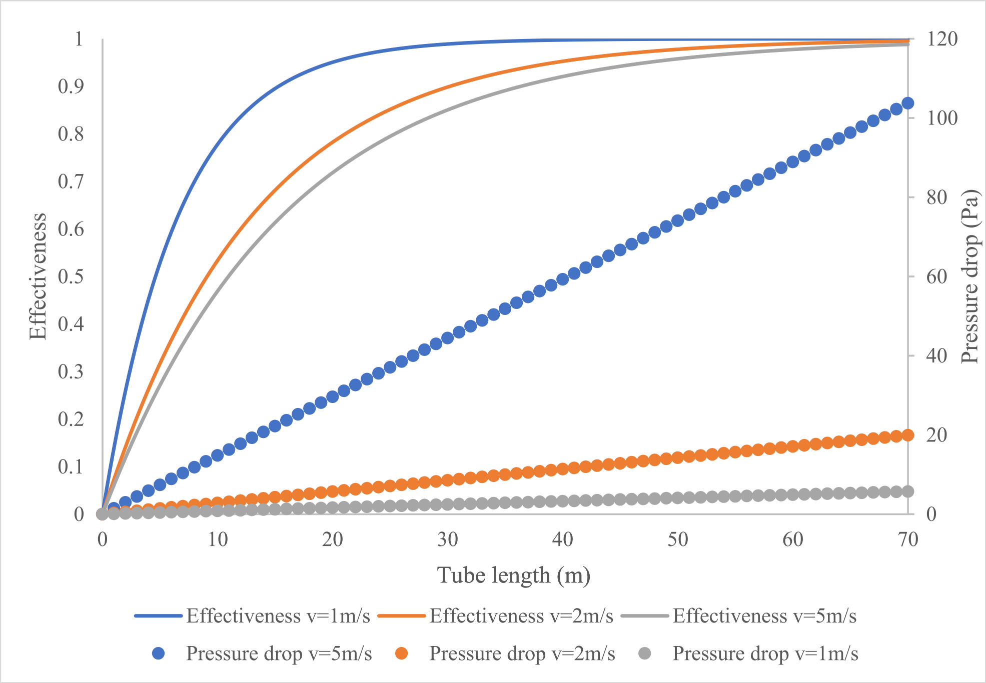

Fig. 4. System effectiveness and system pressure drop according to the tube length and designed airflow velocity.

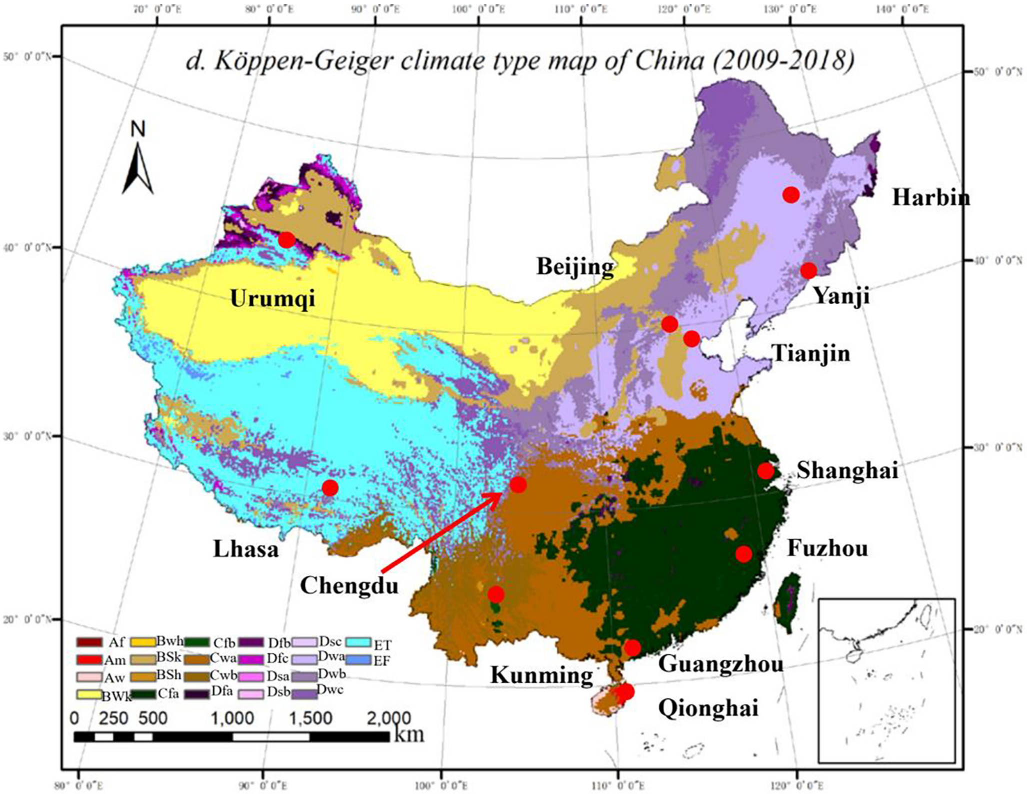

Fig. 5. Selected cities (red dots) in the Köppen-Geiger climate type map of China [66]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

perature was lower than the dew point temperature of supply air. In cities from Tianjin (Dwa) to Harbin (Dwb) and Lhasa (Dwc), the moisture content of supply air was lower than the dehumidification setpoint of 12 g/kg at 25 °C, which means the EAHX system provided dehumidification.

4.3. Building load with and without EAHX system

The average cooling load during the summer is shown in Fig. 10. Excluding Qionghai (Am), the ventilation cooling load was decreased in all the cities, which showed that the EAHX system

Table 4
Sub climates and essential information of the selected cities.

Cities	Sub climates	Symbol	Latitude	Average air temperature (°C)	Population (Million)
Qionghai	Tropical monsoon	Am	19.2	25.5	0.5
Guangzhou	Humid subtropical	Cfa	23.0	22.4	18.8
Kunming	Dry-winter subtropical highland	Cwb	25.0	15.8	8.5
Fuzhou	Humid subtropical	Cfa	26.1	21.0	8.4
Lhasa	Subarctic	Dwc	29.7	9.3	0.9
Chengdu	Dry-winter humid subtropical	Cwa	30.7	17.4	21.2
Shanghai	Humid subtropical	Cfa	31.4	17.2	24.9
Tianjin	Hot summer continental	Dwa	39.1	13.2	13.7
Beijing	Hot summer continental	Dwa	39.7	12.6	21.9
Yanji	Warm summer continental	Dwb	42.9	6.2	0.7
Urumqi	Cold semi-arid	Bsk	43.8	7.7	4.1
Harbin	Hot summer continental	Dwb	45.8	5.0	9.9

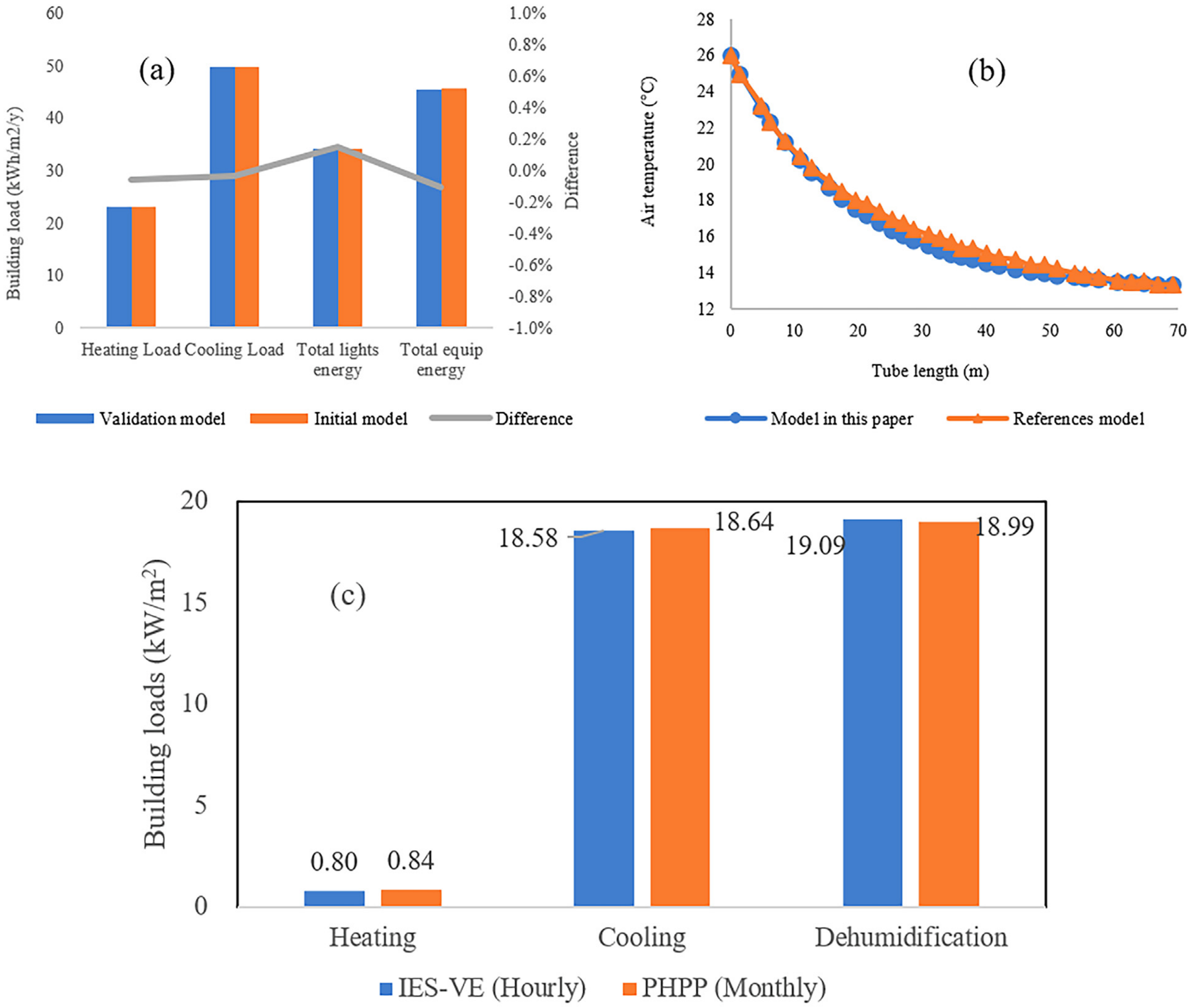

Fig. 6. The results of the (a) building energy simulation model verification [52] (b) EAHX system effectiveness validation (c) Comparison of PHPP (Monthly) and IES-VE (Hourly) results.

was effective in reducing the building ventilation load in summer. In the cities with high latitudes, from Chengdu (Cwa) and Shanghai (Cfa) to Harbin (Dwb), and high altitudes, including Kunming (Cwb) and Lhasa (Dwc), the ventilation cooling load was negative and free cooling was provided from the EAHX system.

The total heating, cooling and dehumidification load of the Passivhaus building and the loads after applying the EAHX system are shown in Fig. 11. The order of cities was from low latitude to high latitude. In the cities with low latitudes, the heating loads in the benchmark Passivhaus building were zero because of the high-quality construction and higher winter environment temperature. All the initial building heating load was limited to under 12 kWh/m^2 because of the high-quality building envelope of Passivhaus building. The heating load increased when the latitude

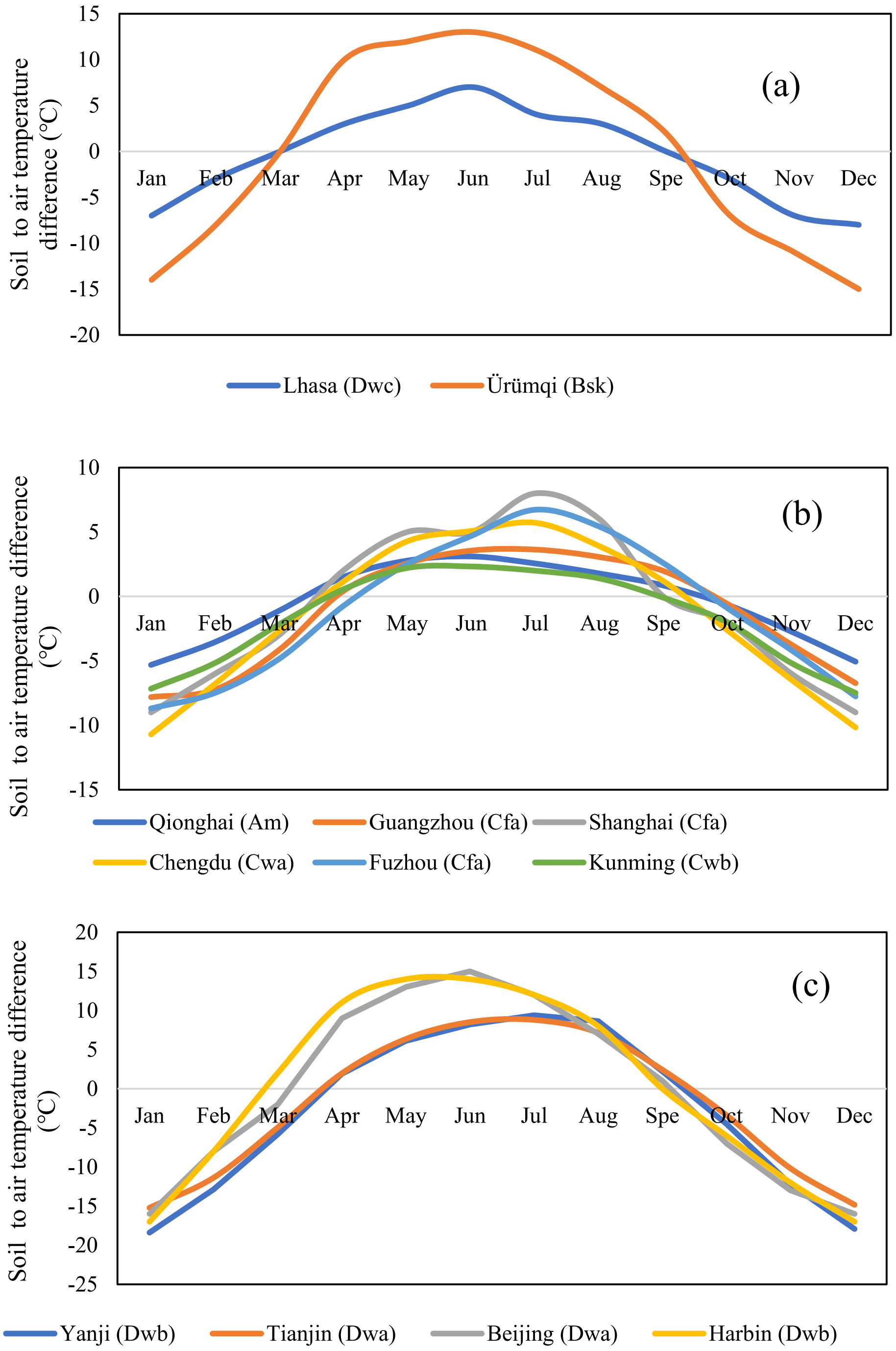

Fig. 7. Monthly average soil to air temperature difference and region classification map (a) Region I & IV (b) Region II (c) Region III (d) Regional classification map [66].

increased because of the cold winter and the EAHX system heating load saving also increased with the higher soil-to-air temperature differences in winter. The initial cooling and dehumidification load were much higher than the heating load as the building envelope of Passivhaus was not designed for reducing cooling demand. With the increase of the latitude, the cooling and dehumidification load reduction increased from Chengdu (Cwa) and Shanghai (Cfa) and the building load reduction by the EAHX system reached the maximum performance at Beijing (Dwa) and Tianjin (Dwa), which had both a very cold winter and a hot summer. Although the winter was cold enough in Yanji (Dwb) and Harbin (Dwb) with a low soil temperature in summer, the building load reduction by the EAHX system started to decrease in those cities without a hot and humid summer like Beijing (Dwa) and Shanghai (Cfa). Most of the cooling load was reduced by the EAHX system in Urumqi (Bsk) because of the high annual temperature difference and the initial dehumidification load was zero because of the local dry climate.

4.4. Building loads and EAHX system energy savings

The EAHX system heating, cooling and dehumidification load savings in different cities are shown in Fig. 12. With the increase in the city's latitude, the heating load increased steadily, but the maximum saving was only 2.3 kWh/m^2. As the weather was not cold enough in the cities with low latitudes and all the heating

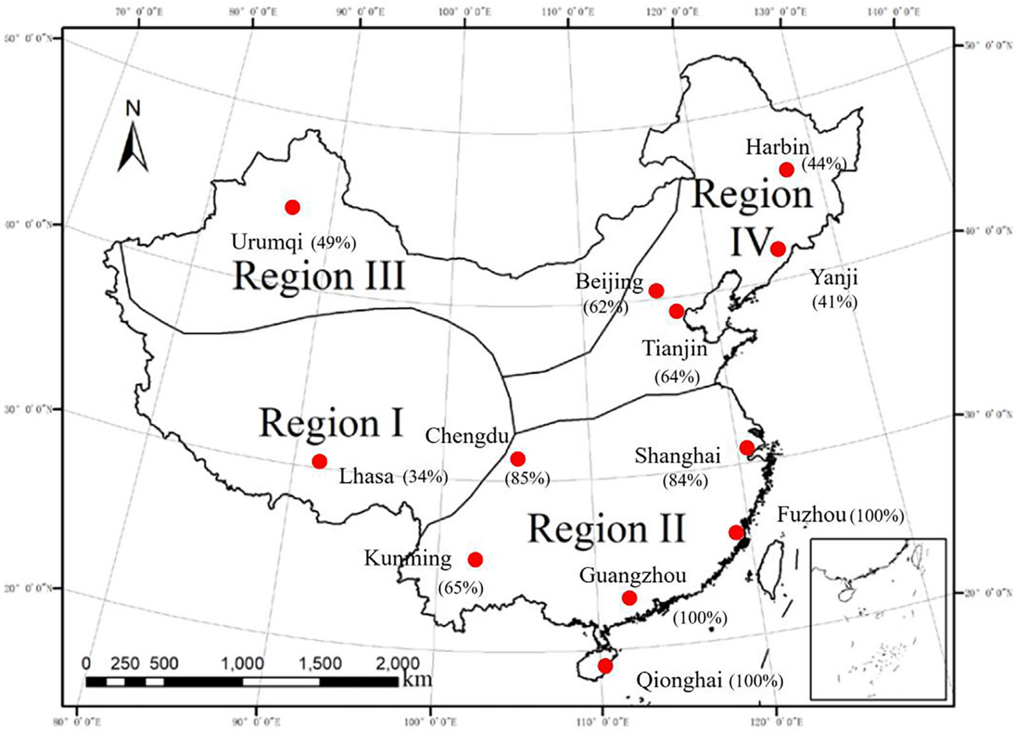

Fig. 8. City locations in region classifications and the overall EAHX system effectiveness in the long-term operations.

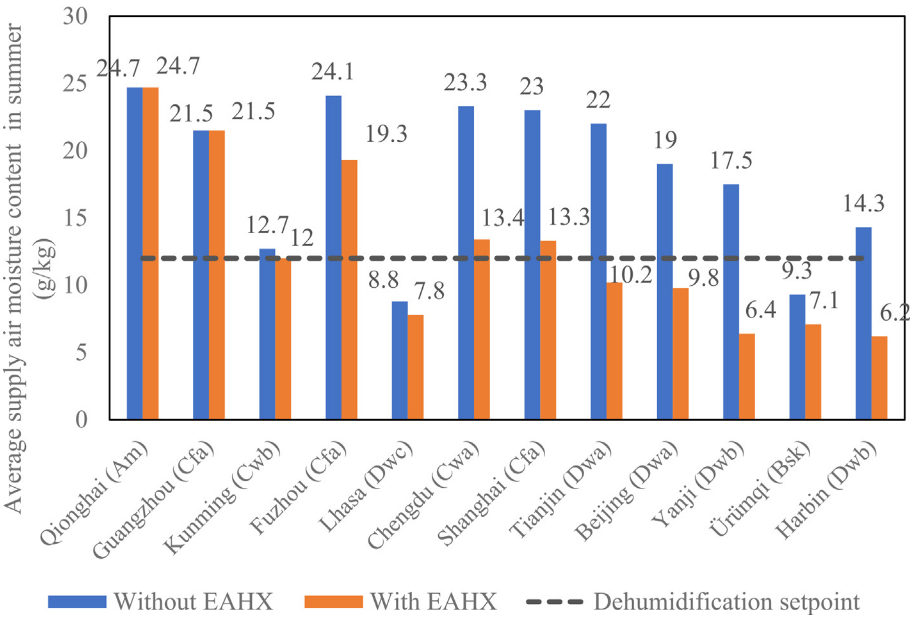

Fig. 9. Average moisture content in supply air in the summer operation period.

loads could be covered by the high-quality Passivhaus building envelope, the energy-saving of the EAHX system was zero.

Excluding Qionghai (Am) and Guangzhou (Cfa) located in the south of Region II, all the other cities had cooling load savings compared with the benchmark Passivhaus building. In Kunming (Cwb) and Lhasa (Dwc), with a higher soil-to-air temperature caused by the high altitude, the cooling load-saving percentage was higher than in other cities with similar latitudes. In Lhasa (Dwc), the cooling load saving by the EAHX system reached 90.1%. However, the situation was different in Fuzhou (Cfa), with the EAHX system only saving 6.7% of the annual cooling load. From the cities in the north of Region II, Chengdu (Cwa) and Shanghai (Cfa), both the cooling load and saving percentage increased. The cooling load saving was higher than 5.8 $kWh/m^{2,}$ and the saving percentage was higher than 36.9%. In Region IV, Tianjin (Dwa) and Beijing (Dwa) had similar latitudes with a cooling load saving of around 10 kWh/m^2. For

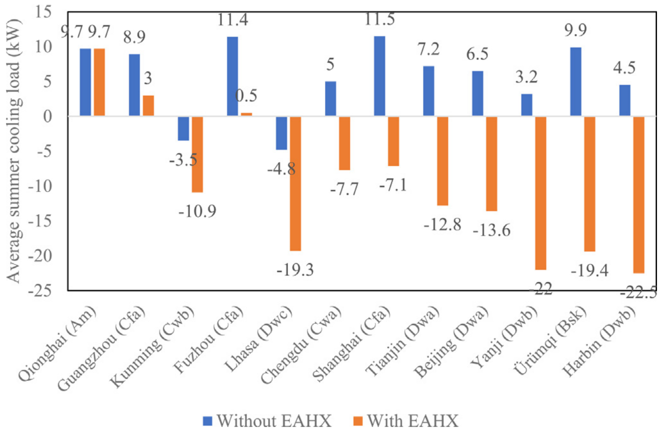

Fig. 10. Average ventilation cooling load in the summer operation period.

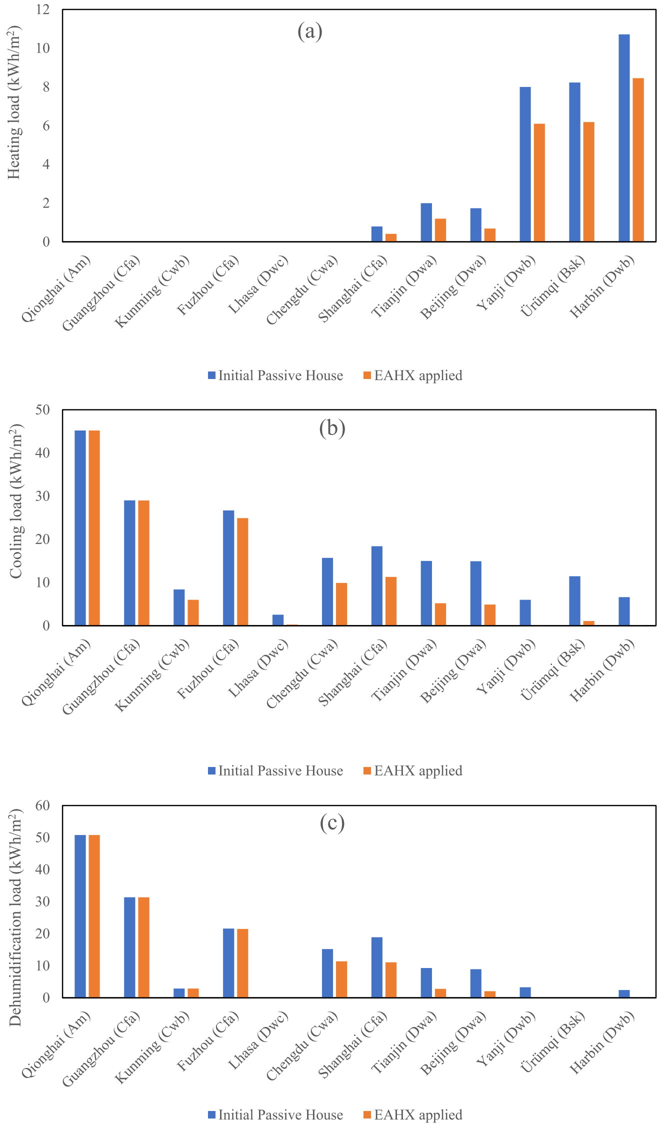

Fig. 11. Building (a) heating (b) cooling (c) dehumidification loads with and without the EAHX system.

Urumqi (Bsk) in Region III, with low annual average temperature and hot summer, the highest cooling load saving, 10.4 kWh/m^2, was achieved and a saving of 90.4%.

A good dehumidification load reduction was observed in cities with higher latitudes than Chengdu (Cwa), excluding Urumqi (Bsk) which has a dry summer. Huge energy-saving potential in not only summer cooling but also dehumidification was proven in cities like Beijing (Dwa) and Tianjin (Dwa). This shows that the EAHX system is suitable for Passivhaus dehumidification in China or other regions in the world with similar climates.

The overall Primary Energy Renewable (PER) reduction is shown in Fig. 13. The EAHX system could save more energy in the northern cities, and the amount of saving was considerable, while the benefits of installing the EAHX system into the building ventilation system were ignorable in the southern cities. In the northern part of the Cfa climate region in China like Shanghai, and all the cities with continental and dry winter climates including Dwa, Dwb and Dwc, a good PER reduction of around 10 kWh/m^2 was achieved which was much higher than that in regions with Cfa and Cwb climates. Overall, the EAHX system was more suitable to be installed in an area with hot and humid summers and cold winters with low soil temperatures, including the whole of Region III & IV (Bsk and Dwa/Dwb/Dwc) and the northern part of Region II (Cfa/Cwb with cold winter).

4.5. Building load savings vs the air temperature difference

The monthly average temperature is an important factor in the building design stage. The temperature difference between the lowest monthly average temperature in the coldest month in winter and the highest monthly average temperature in the hottest month in summer was used. For example, the monthly average temperature in January and July in Shanghai were used to calculate the maximum monthly average temperature gap. The plot of heating, cooling, and dehumidification load saving and savin percentage are shown in Fig. 14. The heating load saving amount was almost linear to the temperature difference after 20 °C. The zero heating load reduction occured for the Passivhaus building in the warm climate with no heating demand. However, most of the heating load in the ventilation system was reduced by the high-efficiency heat recovery units. The increase in heating load saving was very small compared to the cooling and dehumidification load savings. The cooling load reduction started after the temperature difference reached 10 °C and the cooling load saving was higher than 6 kWh/m^2 after the temperature difference reached 20 °C. The dehumidification load saving achieved a similar trend to the cooling load, which increased after 20 °C and decreased at higher temperature differences because the soil temperature was not low enough to make the supply air condense in the low latitude regions and the dehumidification load in the high latitude regions was very small.

The heating load saving percentage did not achieve a linear relationship with the temperature difference. But a linear relationship was achieved in cooling and dehumidification load, excluding the cities with high latitude, which meant that the cooling and dehumidification load saving percentage was mostly linear to the environment air temperature difference in the whole year as the soil temperature in summer was much lower than both the building summer cooling set point and environment air temperature. The result of this research matched the case study which showed that the EAHX system could achieve a good performance in the region with mild winter and hot and humid summer [68]. Overall, the EAHX system has higher cooling and dehumidification effectiveness in the region with high air temperature difference, but the total energy saving depends on the local cooling and dehumidification demand. In the region with a temperature difference between 20 °C and 30 °C, the PER, total energy consumption, saving amount and percentage reached the peak value which was suitable for the EAHX system application.

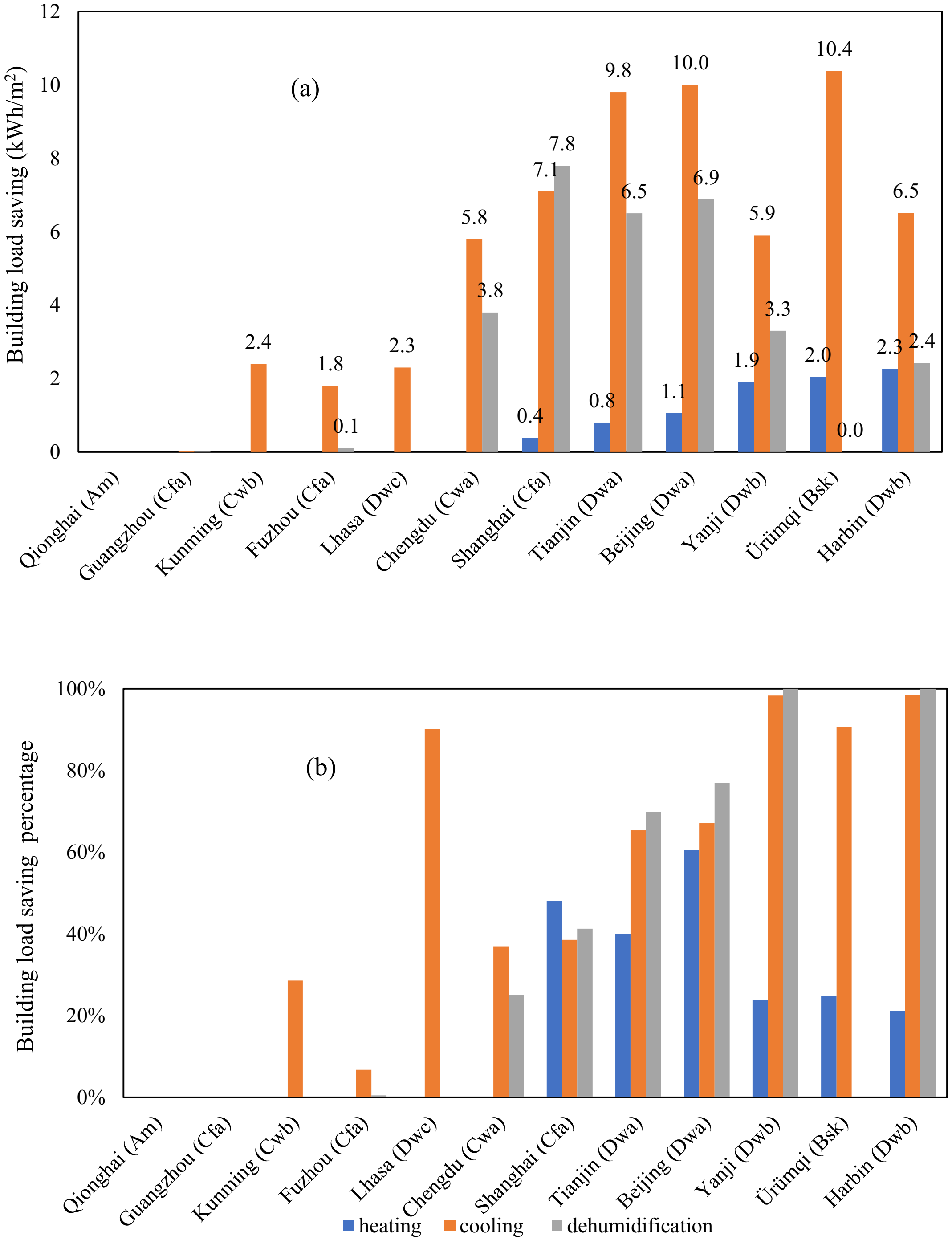

Fig. 12. EAHX system heating, cooling and dehumidification load (a) savings (b) saving percentage.

5. Discussion and research limitations

In the building model verification, the hourly simulation model results were compared against the results of previous works and a good agreement was observed. However, following the modifications of the building fabric, ventilation rate, glazing, building size and the internal heat gains according to the Passivhaus building model, the difference between the initial model and the final model might have an impact on the accuracy. Thus, this should be taken into account when evaluating the simulation data presented in this study. It should be noted that the primary aim of this research is to provide a comparison of the application of the EAHX system in different climates rather than providing an accurate prediction of the EAHX system . Thus, future research could focus on developing a more advanced model to provide higher accuracy for modelling the EAHX.

The PHPP (monthly method) was used in the EAHX energy-saving performance evaluation, using a verified building model with EAHX mathematical model for validation. This provides an evaluation method with sufficient accuracy for comparing the

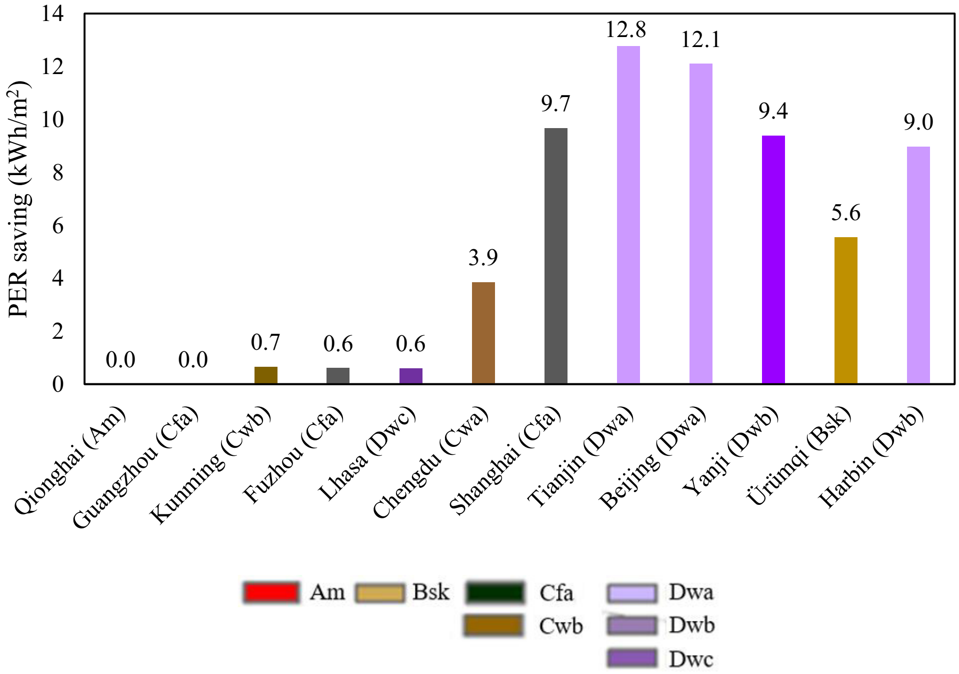

Fig. 13. PER saving by the EAHX system with colour in Köppen-Geiger climate classification.

impact of different climates and providing design recommendations, but an hourly and dynamic simulation method is recommended to be developed in the future to increase the energy prediction accuracy. Occupants' behaviours, thermal comfort requirement, energy usage and soil conditions might vary in different regions of the country. However, to simplify and fixed the variables in this research, those differences were not considered which might result in the gap between actual energy consumption and predictions. A further detailed evaluation using EnergyPlus or other dynamic simulation tools and real-time simulation inputs needs to be applied for the system design and energy performance prediction.

In this research, a mathematical model was developed to evaluate the EAHX system performance. The temperature conditions at the specific distance represented the average air conditions of that section perpendicular to the airflow direction as the air inside the tube was not uniform, and the air temperature closer to the surface was lower than in the middle of the cooling process, especially at the beginning part. Thus, the average conditions in the same section were used in the calculation, and the impact of nonuniform air conditions in the same section was ignored in the tube with enough length.

In the mathematical model of the EAHX system effectiveness, the heat capacity of air was affected by the moisture content, but the heat capacity of air had no impact on the temperature change in the EAHX system. In some of the mathematical models, the supply air was cooled to the dew point temperature without condensation, and the temperature would further reduce with both cooling and condensation occurring in this period [67]. In our research, we assumed that both cooling and condensation occurred at the beginning stage. For a large tube with non-negligible volume, this model might be impractical as the air close to the tube surface might condense at the very beginning stage while the air temperature in the middle was still higher than the dew point temperature. However, with a system with sufficient tube length, the outlet temperature would approach the soil temperature no matter which model was applied. Moreover, the condensation water inside the tube needs to be removed in the operation stage, which has to be considered in the design stage or the system's effectiveness will be affected because of the water on the tube surface**.** The moulds and bacteria are a common problem of the EAHX system because of the humid surface of the inner tube so appropriate tube materials with smooth surfaces and appropriate slope of the system has to be applied to reduce the biological pollutant and condensation issue [69].

The long-term EAHX system operation would have an impact on the tube surface and soil temperature, which decreases the system's effectiveness, especially for a city like Shanghai (Cfa) with a long and hot summer. The overall system effectiveness and the decrease in the long-term operation were evaluated by the PHPP default calculation which depends on the cooling amount provided by the system and the cooling period of the system. Further validation considering the soil components and the tube depth might improve the accuracy of effectiveness evaluation. Increasing the EAHX system tube number and operating it alternately is a possible solution to provide time for soil temperature regulation but a larger space was necessary which would also increase the capital cost.

Because of the solar angle difference in different regions, the monthly temperature fluctuation in the whole year in the northern regions with Dwa, Dwb and Dwc climates was much higher than in regions with Cfa and Cfb climates which provide a higher energy-saving potential by the EAHX system. And the climate data in the same subclimate is not identical such as in Guangzhou (Cfa) and Shanghai (Cfa). Shanghai (Cfa) has a colder winter than Guangzhou (Cfa), which cooled the soil in Shanghai (Cfa) to a much lower temperature than that in Guangzhou (Cfa) and the summer cooling was provided in Shanghai by the soil with lower temperature. Thus, the EAHX system performance is poor in Guangzhou (Cfa) but considerable in Shanghai (Cfa).

As a vast country with multiple subclimates, China does not have a uniform building standard in different regions and using different building qualities would not allow for the direct EAHX system performance comparison. Passivhaus provides a standardized building quality for comparison, so the impact of the EAHX system could be compared without other influencing factors. Thus,

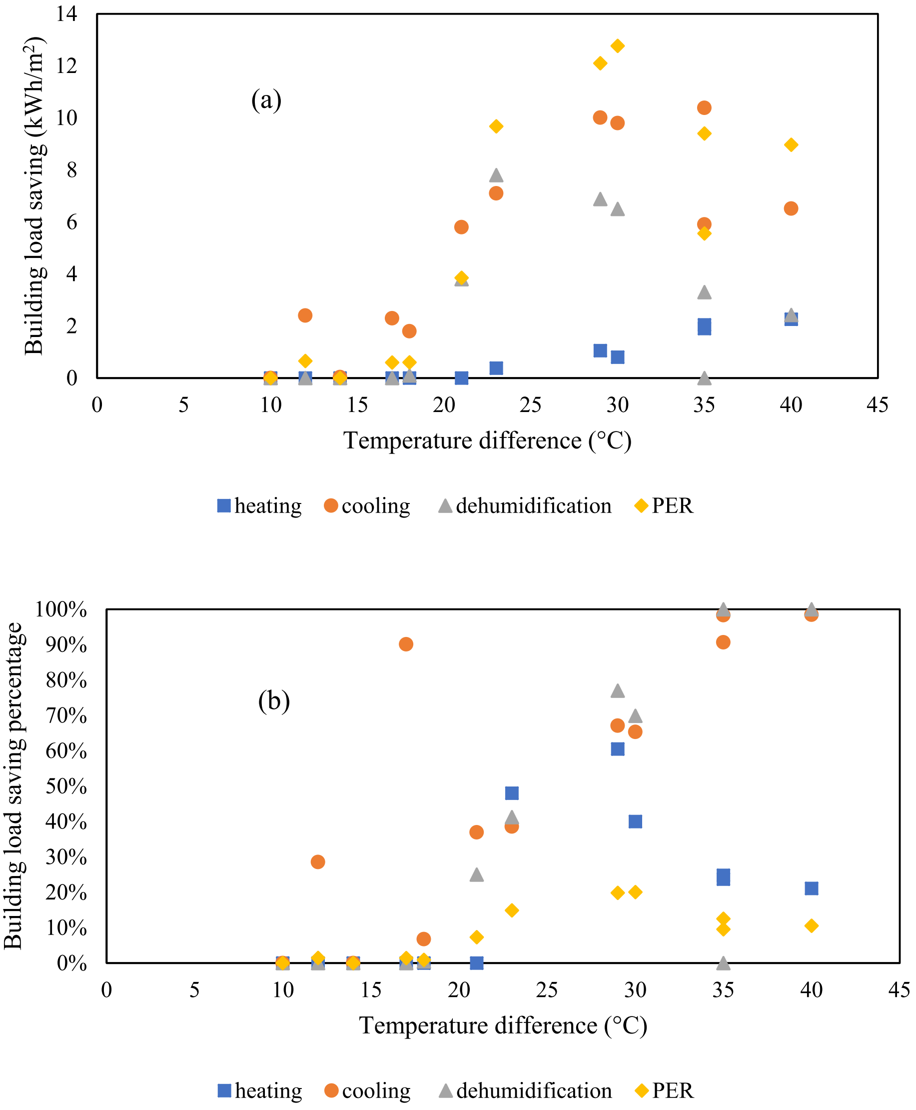

Fig. 14. Overall EAHX system energy consumption (a) saving (b) savin percentage for the benchmark building against the temperature difference between the highest and lowest monthly average temperature.

evaluating the EAHX system in building with Passivhaus standards could reflect the impact of the climate conditions conspicuously.

In this research, the EAHX system was applied in a mechanically ventilated Passivhaus. The calculated pressure loss in the earth tube was ignorable compared to the pressure loss caused by the high-efficiency heat recovery. Thus, the energy consumption of the fan system for the earth tube was not considered in the final energy evaluation.

As the Passivhaus standard was originally developed for cold climates, the Passivhaus certification criteria for cooling and dehumidification performance were not as fixed as the heating because of the diverse climates with different cooling periods and summer temperatures. A clearer standard related to the different climate conditions or classification for the cooling and dehumidification performance of Passivhaus could contribute to the promotion of Passivhaus in hot and humid regions.

6. Conclusion and future works

A Passivhaus building model was developed, and simulated in this research to evaluate the energy-saving performance of the EAHX system. The energy performance of the Passivhaus was verified with the previous research model and the effectiveness of the EAHX system was also validated.

An EAHX system with a temperature recovery efficiency of up to 99% and an overall effectiveness between 34% and 84% in long-term operation was applied in this research. The performance of the EAHX system was evaluated by PHPP, and the monthly predictions in PHPP was verified with simulations in IES-VE. A good agreeement was achieved between the two methods, which was sufficient for evaluating the Passivhaus building energy consumption in different climates. Twelve cities with large populations and various climate conditions were selected for evaluation and comparison. The gap in the research regarding Passivhaus implementation in the southern part of China and the evaluation of appropriate passive cooling and dehumidification technology was addressed. The performance of the Passivhaus building and the impact of the EAHX system was tested in different regions in China. The EAHX system in the Passivhaus building was determined to be an effective passive cooling and dehumidification technology for regions with hot summers and cold winters, such as Shanghai (Cfa) and Beijing (Dwa). The EAHX system heating load maximum saving was 2.3 kWh/m^2, with most of the ventilation load saved by the high-efficiency heat recovery ventilation system while the total building heating loads were very small in the Passivhaus building. The maximum cooling and dehumidification load saving was 10.4 kWh/m^2 and 7.8 kWh/m^2, respectively, and the maximum cooling and dehumidification load saving percentage reached 98.4% and 100%, respectively with an average saving percentage of 51.7% and 34.5% respectively.

A simplified method was introduced in this research using the temperature difference between the coldest month and the hottest month to evaluate the EAHX system's energy-saving potential for a Passivhaus building in the early design stages and for practical planning purposes. A considerable energy-saving performance was achieved by applying the EAHX system in areas with Bsk, Cfa/Cwb with cold winter and Dwa/Dwb/Dwc climates which have high-temperature differences for the whole year, especially in the region with a temperature difference between 20 °C and 30 °C, which has both cooling demands in summer and heating demands in winter. Cities with latitudes over 30° in China have a very good energy-saving potential for the EAHX system such as Shanghai (Cfa) and Beijing (Dwa). The EAHX system also had a good performance in Urumqi (Bsk) with high heating and cooling load saving but the dehumidification load was zero because of the dry climate. The EAHX system has a maximum PER saving amount of about 12.8 kWh/m^2, and a maximum percentage of 20%, but the EAHX system is not effective in the cities in the south of China with low latitudes, such as Guangzhou (Cfa) and Qionghai (Am). The cities with the highest cooling and dehumidification load would still need other passive/low-energy cooling and dehumidification technologies. Even in the cities with good EAHX performance, the cooling and dehumidification loads were not eliminated and additional passive/low-energy cooling and dehumidification technologies were necessary to further decrease the building loads such as solar shading.

The regions beyond China with Bsk, Cfa/Cwb with cold winter and Dwa/Dwb/Dwc climate conditions could also apply the EAHX system particularly if there is a high-temperature difference between winter and summer.

In future research, improving the EAHX system effectiveness in terms of long-term operations should be investigated. The removal and collection of condensation water in the EAHX system should also be investigated. The lifecycle cost and carbon emissions should be investigated in future research. The potential combination of the EAHX system and a windcatcher system should also be investigated.

Data availability

The data that has been used is confidential.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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