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Review

Physical and hybrid modelling techniques for earth-air heat exchangers in reducing building energy consumption: Performance, applications, progress, and challenges

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ABSTRACT

Noteworthy advancements are seen in developing the earth-air heat exchanger (EAHE) models in the past several decades to reduce building energy consumption. However, it is still an ongoing challenge in selecting and implementing the most suitable and appropriate EAHE modelling technique in buildings based on the climates, performance, and limitations of the techniques. Therefore, this paper aims to review the published research related to the physical, and hybrid EAHE modelling techniques used in buildings, and highlight the prospects, benefits, progress, and challenges of these techniques. This is the first study that comprehensively evidences the prospects and technical challenges caused by unmeasured disturbances, assumptions, or the uncertainties generated in experimental and numerical works of all EAHE modelling techniques. Nevertheless, this study found that hybrid modelling is more effective than physical models for accurate prediction. On the contrary, the hybrid models suffer from high complexity if EAHE operating conditions and all key parameters are considered during the model development. Regarding the generalization capability, the physical models offer improved performance followed by the hybrid models. A minimum number of training data is needed for developing physical models, whereas medium training data is required for the hybrid models. The outcome of this study also provides valuable information regarding the physical and hybrid EAHE modelling techniques to the scientists, researchers, and so on in adopting the most appropriate EAHE modelling technique for their climates.

1. Introduction

The energy crisis has become the main obstacle in the progress of human development. The rate of energy consumption is gradually increasing throughout the world (Ong et al., 2020). The global energy demand is predicted to increase from 630 to 910 quadrillion Btu between the periods 2020 and 2050 (IEO, 2019). Most of this growth is seen among the developing countries. The noticeable growth rate in population and income are the primary reasons behind such a substantial energy demand (Mahlia et al., 2020; Mofijur et al., 2013). The population is projected to rise 9.7 billion globally by 2050, which means that additional energy will be needed for 1.9 billion people over the next 30 years compared to the current population of 7.8 billion. About one-third of global energy is used by buildings (Ahasan et al., 2014; Azad et al., 2014; Wang et al., 2020), transportation and industrial are the other dominating sectors. The amount of whole energy consumed in buildings varies among the countries. Most of these are consumed in the developing countries ranges from 35 to 40%, of which 50 to 65% is used in the form of electricity (Mardiana and Riffat, 2015). Building energy consumption relies on several factors, namely geography and climate, construction design, operation, size and age, consumption patterns,

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Nomenclature

u_i,u_j	Velocity components of the fluid (m s^{-1})
x_i	Length components (m)
υ	Kinetic viscosity (molecular) of the fluid (m^2 s^{-1})
P	Pressure (Pa)
ρ	Density of the fluid (kg m^3)
μ	Viscosity of the fluid (kg m^{-1} s^{-1})
t	Time (s)
ε	Dissipation rate (m^2 s^{-3})
k	Kinetic energy (m^2 s^{-2})
G_b	Kinetic energy generation for turbulence due to buoyancy (kg m^{-1} s^{-2})
G_k	Kinetic energy generation for turbulence due to the mean velocity gradients (kg m^{-1} s^{-2})
Y_M	Fluctuating dilatation contribution in turbulence to the overall dissipation rate (kg m^{-1} s^{-2})
$C_{1\varepsilon},C_{2\varepsilon},C_{3\varepsilon}$	Constants
σ_ε	Prandtl numbers for the turbulent dissipation rate
σ_k	Prandtl numbers for turbulent kinetic energy
S_K,S_ε	User-defined source terms
i,j,k	Direction vector indices
k_{eff}	Effective thermal conductivity (W m^{-1} K^{-1})
k_t	Turbulent thermal conductivity
J_j	Diffusion flux components (m^{-2} s^{-1})
T	Temperature (K)
h	Enthalpy (J kg^{-1})
S_h	Total entropy (JK^{-1})
λ_{eff}	Effective thermal conductivity (W m^{-1} K^{-1})
Q	Heat extraction/injection (J)
H	Borehole heat exchanger length (m)
$x,$	Axes of symmetry
kW	Kilowatt
kWh	Kilowatt-hour
m	Meter
mm	Millimeter

community wealth, required service levels, and cost and availability of several energy forms (Mardiana and Riffat, 2015).

Significant energy usage in the building sector is mostly because of space heating and cooling. Therefore, it is necessary to employ energy-efficient methods in buildings utilizing novel and new technologies with innovative building designs. The innovative designs may be built by adopting different active or passive cooling and heating strategies. Sources of renewable energy, for example, geothermal energy, solar energy, ocean energy, and wind energy are desirable alternatives to the sources of non-renewable energy as it has numerous potentials to save noticeable energy in buildings. EAHE is viable in reducing both the cooling and heating loads of buildings. The EAHE takes advantage of the Earth's constant temperature to cool or heat the spaces in industrial, agricultural, and residential buildings (Ahmed et al., 2014b). The underground temperature at a particular depth gets almost constant all over the year (You et al., 2020). It diminishes with growing the depth in summer, which allows the usage of the soil as a heat sink, whereas it increases with increasing the depth during winter, which uses the soil as a heat source (Soni et al., 2015). During summer, a 20%-50% reduction in energy consumption can be attained using the EAHE system than other air-source heat pumps (Ommen et al., 2014). The soil's high thermal inertia is the main fact behind this. Since the EAHE can assist in reducing the air-conditioning load, there is a substantial potential to save building energy using the EAHE system. As the EAHE uses underground spaces, it offers various additional benefits such as safeguarding from radiation, noise, storms, dust, and air infiltration. It occurs in different forms that utilize the ground, surface water, or groundwater as a heat sink and heat source. EAHE technology is capable of saving more energy compared to any other traditional air conditioning system. It can also reduce greenhouse gas (GHG) emissions effectively, and thus assists to develop the environment.

The assessment of the thermal efficiency of the EAHE system is critical to calculating its heating and cooling capacity. The system cooling capacity was found noticeably in several studies (Agrawal et al., 2018; Ahmed et al., 2013; Dores and Lautze, 2020; Elghamry and Hassan, 2020; Li, H. et al., 2019; Shojaee and Malek, 2017; Wengang et al., 2019; Zhou et al., 2018) conducted in different places throughout the globe. For example, a maximum cooling capacity of 1.755 kWh per day, and 246.815 kWh per annum was achieved using a simple EAHE in an arid climate of Algeria (Belatrache et al., 2017). A room temperature reduction of about 2.8 °C and 2.0 °C was obtained during summer in a Kuwaiti and an Australian climate, respectively (Al-Ajmi et al., 2006). Mongkon et al. (2014) also reported a substantial cooling potential of the EAHE system during the daytime while studied the cooling efficacy of an agriculture greenhouse in Thailand (Mongkon et al., 2014). In winter, the EAHE is used to heat the interior spaces of a building. A good number of research outcomes were published on the interior heating performance (Bansal et al., 2009; Jakhar et al., 2016; Mathur et al., 2015; Ozgener and Ozgener, 2010; Ozgener and Hepbasli, 2005b; Yang et al., 2016) of the EAHE system. According to Bansal et al. (2009), the EAHE system provided a noticeable performance in heating ranges from 4.1 °C to 4.8 °C for a 23.42 m long pipe and 2 to 5 m/s airflow rates. In addition, the airflow rate significantly influenced EAHE heating performance, whereas the pipe materials had minimal effect. Another experimental investigation was made in a Turkish climate having an ambient air temperate of 18.67 °C and relative humidity of 48.16% (Ozgener and Hepbasli, 2005b). The EAHE heating capacity of 7.67 kW was found for a greenhouse with a relative humidity of 40% and an average air temperature of 21.5 °C.

In some cases, the EAHE is also supported by a heat pump positioned within the buried pipes (Ahmed et al., 2016; Ozgener and Hepbasli, 2005a). The idea of utilizing the ground for a heat pump is first introduced in 1912 in a Swiss patent (Yang et al., 2010). Although this concept associated with the EAHE has been commenced for more than a century, there are many ongoing researches (Blázquez et al., 2020; Ishaque et al., 2020; Kemmler and Thomas, 2020; Li et al., 2020; Mirl et al., 2020; Wang et al., 2020; Yu et al., 2020) on this because of its necessity in improving the modelling technique and system design. Several uncertain factors mainly affect the sizing of an EAHE such as the allowed maximum and minimum temperature of fluid moves to the heat pump, employed methodology, GHE layout, ground properties, annual net energy transfer into the ground, and the borehole configuration. Inefficient operation and poor design of the EAHE can result in more energy consumption. The EAHE can contribute to reducing energy consumption in a more significant amount by improving system efficiency. Based on the building type and climate, the proper operation, and selection of the EAHE technique can provide more energy savings within the building. Using the EAHE, the ratio of the building energy savings to the investment are varied in different climates. For example, this ratio was calculated as 1:2 in New Delhi, India (Chel and Tiwari, 2009) whereas it was measured as 8.2:17.5 in China (Liu et al., 2019). The effectual operation of this system depends on its optimization parameters. Emphasizing enhancing the building energy efficiency, several types of research (dos Santos Coelho and Askarzadeh, 2016; Hu et al., 2012; Kusiak et al., 2011; Oldewurtel et al., 2012; Wei et al., 2015; Zeng et al., 2015) have been conducted using different innovative control algorithms. By improving the algorithms, an accurate and appropriate modelling strategy can be chosen and implemented for the best optimization techniques.

A suitable and appropriate EAHE system does not deal with only the heat loss or gain through the system, but also with the temperature and humidity control, soil moisture, soil thermal resistivity, air quality, airflow rate, thickness, depth, diameter, and materials of the pipes buried under the ground. Taking all of this non-linearity, discrete, boundary conditions, and constrained parameters of the EAHE systems into account, it is very challenging to develop the most appropriate model for the EAHE systems that can represent reality. A proper guideline regarding the weakness and strengths of different modelling techniques, role, operation, and the application of the system in real-world conditions should be provided to the building occupants, management community, and engineers to develop modelling research. A comprehensive and critical review addressing these key issues can furnish a deep understanding of the current modelling approaches used in the EAHE systems. Several studies (Ahmed et al., 2014a; Ahmed et al., 2014; Bortoloni et al., 2017; Chiesa, 2018; Cui et al., 2018; Diaz et al., 2013; Niu et al., 2015; Noorollahi et al., 2017; Serageldin et al., 2016; Wang et al., 2018; Zhang and Haghighat, 2010) were carried out on EAHE modelling using only one or two basic modelling techniques either from physical, or hybrid models due to their some limitations. A physical model for vertical EAHE ground loop was constructed to measure its thermal performance in an Australian subtropical climate using a computer simulation program, ANSYS Fluent (Ahmed et al., 2014a). The model performance was compared with another physical model of the horizontal EAHE ground loop in the same climate (Ahmed et al., 2014), where the vertical EAHE showed better performance due to its piping arrangements buried underground. Bansal et al. (Bansal and Mathur, 2009) built a hybrid thermal model in evaluating the EAHE performance incorporated with an evaporative cooler. The hybrid approach contributed to reducing 93.5% of the total buried pipes used in the EAHE to obtain the desired air temperature at the pipe outlet.

A literature search was conducted to find the available review studies on the modelling techniques for the EAHE used in buildings. The search involved some related keywords such as modelling techniques, EAHE system, EAHE modelling, applications of EAHE modelling techniques, and a combination of those. Through the extensive literature search, it is identified that there have been minimal review works (Aresti et al., 2018; Cui et al., 2018; Florides and Kalogirou, 2007; Singh et al., 2018; Soni et al., 2016; Yang et al., 2010) published by reporting only one of the basic modelling techniques for the EAHE as shown in Table 1. However, no review has been found covering all of the basic two modelling techniques (physical, and hybrid models) used in measuring the EAHE performance. It is therefore essential to comprehend the shortcomings and strengths of these modelling techniques utilized in the EAHE system to advance in modelling research. This study comprehensively reviews the physical and hybrid modelling techniques of the EAHE system to identify the shortcomings and strengths based on their performance, progress, application, and challenges. Physical and hybrid modelling techniques were considered in this review as these models are commonly used in measuring EAHE performance, and thus sufficient scientific literature is available. The review will provide a proper guideline to the policymakers, building energy researchers, and energy management communities to choose the best suitable and appropriate modelling technique to enhance EAHE efficiency.

2. EAHE and its types

EAHE is one of the passive technologies which is viable to save a substantial amount of energy in heating and cooling a space with minimal or no negative environmental impacts. It works with the pipes buried underground where intake ambient air comes from the inlet and moves through the underground pipes, and consequently, the intake air exchanges heat under the ground (Peretti et al., 2013). Then the cooled/warmed air comes into space through the pipe outlet. An exhaust fan or a heat pump is installed within the pipe to suck the intake air through the inlet. As stated earlier, it utilizes the earth's constant temperature achieved at a certain depth to transfer heat from or to the tunnel air passes through the pipes buried underground. The heat is then transferred from or to the neighboring soil by convection with the air moves through the underground pipes and by conduction through the wall of the pipes.

Table 1
Comparison of the current review article and review articles published over the last 13 years on physical and hybrid modelling techniques used in the EAHE system.

Review study	Physical model (No. of the model)	Hybrid model (No. of the model)	Total no. of the models	Remarks
This study	√ (5)	√ (8)	13	All the basic models have been reviewed
Cui et al. (Cui et al., 2018)	√ (1)	×	1	Most of the physical and the other models were not reviewed. The study emphasized only one physical model.
Yang and Cui (Yang et al., 2010)	√ (1)	×	1	
Florides and Kalogirou (Florides and Kalogirou, 2007)	√ (1)	×	1	
Singh et al. (Singh et al., 2018)	×	√ (6)	6	Although most of the available hybrid systems were discussed, none of the physical models was considered in the review.
Soni et al. (Soni et al., 2016)	×	√ (6)	6	
Aresti et al. (Aresti et al., 2018)	√ (2)	×	2	Two of the physical models were reviewed. Hybrid models were not included.

√ Available; × Not available.

Two different types of EAHEs are used to reduce building energy consumption; they are open and closed loop. In an open-loop, intake air comes through the inlet continuously and passes through the pipes buried underground into the room to cool or heat a space and moves out through ventilation (Fazlikhani et al., 2017) as seen in Fig. 1(a). Although the materials used for the loops are extraordinarily durable, it allows heat to transfer to the surroundings efficiently.

Fig. 1(b) shows a closed-loop approach, where the air is distributed frequently into the room through the underground pipes (Sivasakthivel et al., 2014). No air is exchanged with the outdoor air in this system. It is considered more viable than the open-loop since the cooled/warm air is redistributed inside the pipes covered underground. As a result, the closed-loop can reduce the pipe length used in the EAHE. The loop/pipe length depends on some crucial factors, namely loop configuration type, cooling and heating loads, soil conditions, and local climate. The underground pipes can be set up in slinky, spiral, vertical, horizontal, or even in a water body surface.

Two main techniques are applied in constructing the EAHE: indirect and direct earth contact (Jacovides et al., 1996). The direct earth contact comprises a partial or full building envelope (Fig. 1) which is positioned in connection with the earth directly, whereas the indirect one does not place a full or partial building envelope directly into the earth. Low maintenance is required for maintaining direct earth contact with minimum solar exposure and heat gains. Utilizing these benefits, underground buildings were constructed in eastern Spain and southern Tunisia, and the buildings large in size were excavated to cope up with

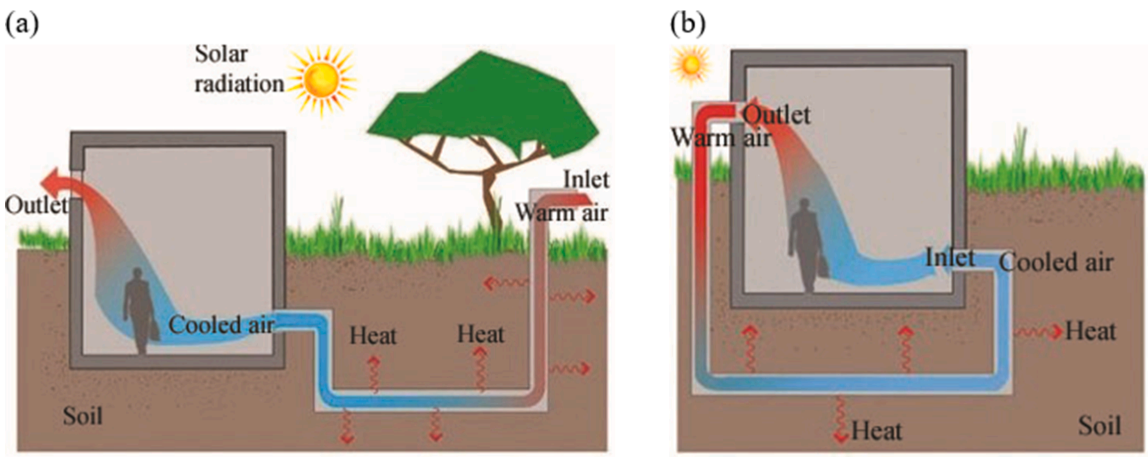

Fig. 1. Earth-air heat exchanger types during summer (a) Open-loop system (b) Closed-loop system reprinted with permission of Elsevier copyright from (Ahmed et al., 2015b).

the extreme winter climate in China (Krarti and Kreider, 1996). On the contrary, it also generates ecological problems like poor indoor air quality, the longevity of the building, and indoor condensation (Jacovides et al., 1996). Also, large excavations are not suitable in some climates such as semi-desert and desert countries due to their geographical conditions. The main important merits and demerits of these two systems are summarized in Table 2.

3. Physical and hybrid modelling techniques for measuring EAHE performance

Physical (physics-based), and hybrid modelling are commonly used for predicting EAHE thermal performance. A physical model provides a physical concept of the modeled system whereas a hybrid model involves two or more physical systems to enhance the efficiency of the integrated system, which is the fundamental difference between these two models. Both the models can be dynamic (Rodriguez and Rasmussen, 2016) or static (Keniar et al., 2015), non-linear (Rodriguez and Rasmussen, 2016) or linear (Mustafaraj et al., 2010), implicit (Bansal et al., 2009), or explicit, continuous or discrete, probabilistic or deterministic, transient (Ahmed et al., 2015; Dubey et al., 2013; Su et al., 2012), inductive, or deductive. Parameters used in the unsteady state/transient/dynamic models are changeable with time while the parameters are considered as constant in the steady-state/static models. Therefore, the problems that occur in transient processes can be dealt with by the dynamic models. Most of these physical modelling techniques go under the deductive models, whereas the hybrid models are categorized into inductive or deductive models. The physical modelling techniques can occur in static or dynamic, implicit or explicit, and linear or non-linear. Both models have been discussed below:

Table 2
A comparison between open and closed-loop systems.

System	Merits	Demerits
Open-loop	▪ Simple and stable due to its simplicity in layout, and so easier to construct ▪ As conductor water is better than the earth	▪ Need more maintenance ▪ Might have local environmental risks ▪ Requires a well or lake nearby ▪ Less accurate and reliable in outcomes
Closed-loop	▪ More accurate and reliable ▪ Can be fitted almost anywhere ▪ Less maintenance is needed ▪ Noise reduction in the system ▪ Less unpredictable	▪ Costly because of its complexity in construction ▪ Earth would not be as good of a conductor ▪ Less stable

3.1. Physical (physics-based) modelling

Physical models represent a physical concept whose characteristics bear a resemblance to the physical attributes of the modeled system. It is an effective approach to investigate fluid flows through a system with different dimensions. Physical models are formed based on the basic laws of heat transfer, energy and mass balance, flow balance, continuity, and momentum in which a system of mathematical equations are solved. Several assumptions or hypotheses are the basis of these models. The models are initially used to design several components of the EAHE system for predicting and assessing their performance. The simplest EAHE can involve a single pipe with a proper dimension buried below the ground at a specific depth in which air moves.

One of the main benefits of a physical modelling approach is to model a large system on a small scale. The purpose of using a small scale is to provide a better overview of the individual components involved in the system. As a result, a physical model can show the invisible inner parts of the particular system. All the components/parts modeled on a smaller scale can be then integrated to model the whole system. On the contrary, physical models suffer from low prediction accuracy as these involve a good number of assumptions while developing the model. In addition to this, these models require fewer data compared to other models and thus lose accurate prediction. However, this model can be used when sufficient data are not available. The EAHE physical models can include horizontal (Ahmed et al., 2014; Congedo et al., 2020; Congedo et al., 2016; Gan, 2017; Habibi et al., 2020; Larwa and Kupiec, 2020), vertical (Ahmed et al., 2014a, 2015a; Choi et al., 2011; Gao et al., 2008; Li et al., 2006; Liu et al., 2019b; Shonder et al., 1999; Yu et al., 2020), slinky (Fujii et al., 2012; Wu et al., 2010), spiral (Bezyan et al., 2015; Cui et al., 2011; Man et al., 2011; Mathur et al., 2017), and helical (Park et al., 2012; Zarrella et al., 2013a; Zarrella and De Carli, 2013; Zarrella et al., 2013b) ground loop model, heat pump model (Bi et al., 2004), wind tower (Benhammou et al., 2015; Sadeghi and Kalantar, 2018), and solar chimney (Li et al., 2014; Serageldin et al., 2020; Settou and Benmhidi, 2010; Yu et al., 2014). Effective modelling of a physical system can be accomplished through the following steps:

- Physical mechanisms need to be identified first by direct investigations or observations.
- The model should be constructed using available modelling tools.
- The Model must be tested by comparing it with other data, and rectify the model if needed.

3.2. Hybrid modelling

The basic configuration of a hybrid model is mainly structured by physics-based techniques. However, a hybrid model can be formed in combination with any two or more of the physical models. As a result, the hybrid modelling approach is reflected as the best effective way to improve system efficiency. The EAHE hybrid modelling may include the EAHE system coupled with solar chimney (AboulNaga and Abdrabboh, 2000; Haghighi and Maerefat, 2015; Li et al., 2014; Maerefat and Haghighi, 2010; Naraghi and Blanchard, 2015; Poshtiri et al., 2011; Yu et al., 2014), evaporative system (Bansal and Mathur, 2009; Bansal et al., 2012a; Bansal et al., 2012b; Khalajzadeh et al., 2012), wind tower (Benhammou et al., 2015; Sadeghi and Kalantar, 2018), solar photovoltaic (Chel and Tiwari, 2010; Elminshawy et al., 2019; Hepbasli, 2013; Jakhar et al., 2018; Nayak and Tiwari, 2009; Uddin et al., 2016), phase change material (Liu et al., 2019a; Rodrigues and Gillott, 2015; Zhou et al., 2020), ventilated roof (Serres et al., 1997), solar air heater (Jakhar et al., 2015), air conditioner (Misra et al., 2012), and heat pump based on the artificial neural network (Gang et al., 2014).

4. Recent advances in physical and hybrid of EAHE modelling techniques

The EAHE modelling has been using for the last several decades in order to analyze, improve, and optimize its performance, and make the design more effective and efficient. Most of the modelling techniques commonly used for EAHE have been comprehensively reviewed in this section in order to identify their weaknesses and strengths. Modelling approaches, along with their applications, applied methodologies, shortcomings, and outcomes of some developed models are also pointed out in this review.

4.1. Physical (physics-based) models

Physical modelling technique is based on the design of different components and subsystems used in the EAHE system, which are deliberated in the followings:

4.1.1. Horizontal ground heat exchanger (HGHE) loop model

HGHE loop model involves several connecting pipes/tubes aligned straight and horizontally under the ground either in parallel (Fig. 2) or series. Parallel tubes are frequently used in this loop as it helps to increase the EAHE performance by reducing pressure drop. In addition, the pipes having smaller diameters are chosen for constructing parallel loops which allows fluid to transfer more heat to its surroundings. The horizontal pipes are typically buried 1 to 2 m below underground and are 35 to 60 m long per kW of cooling or heating capacity (Florides and Kalogirou, 2007). In the case of heating-only mode, it is essential to uncover the ground surface to allow solar radiation. The HGHE system is cost-effective while the pipes are easy to excavate, and sufficient land space is available. It is comparatively easy to install during the construction of a building. However, it can also be installed after construction, for example, in the yard or the driveway.

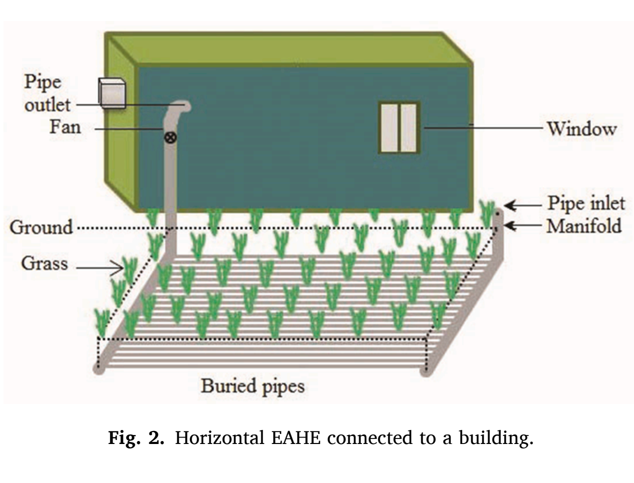

Fig. 2. Horizontal EAHE connected to a building.

The transient behavior of the HGHE system can be represented well by dynamic models. A dynamic model was developed for the HGHE in ANSYS Fluent to analyze the EAHE performance (Congedo et al., 2014). The analysis was conducted in a three-dimensional domain of 5.0 m × 2.0 m × 4.0 m (length × width × depth) with a 200 mm pipe diameter, 20 mm pipe thickness, and 2.5 m pipe depth. The Realizable k-ε turbulence model was chosen to illustrate the dynamic characteristics of the fluid (air). The HGHE model was simulated in various operating conditions. Although the study showed a temperature reduction of 2 to 4 °C at the pipe outlet during summer, it was not capable of providing maximum efficiency as the HGHE system involved only a single pipe of 5 m long. A single pipe system cannot meet air conditioning requirements in a building. Parallel piping systems are appropriate in achieving better thermal performance for the HGHE system.

The realizable k-ε turbulence model was also used in another study to model the HGHE (Ahmed et al., 2015b). The turbulence model was considered for modelling the HGHE as the airflow moving through the pipes buried underground was found turbulent (for turbulent flow, the Reynolds number must be more than 4000). The Reynolds number calculated inside the pipes was between 8,220 and 31,700. The HGHE model comprised twenty Polyvinyl Chloride (PVC) corrugated pipes of 20 mm each that were fitted horizontally at 0.6 m depth under the ground. Each pipe of length 7.5 m with a thickness of 2 mm was separated by 20 mm in a row. Some other features of the system were overlooked while evolving the model. Consequently, this model is not feasible to foresee the nature of the HGHE.

The $k-\varepsilon$ turbulence model used in the studies discussed above is mainly derived from the Navier-Stokes (N-S) equations. The N-S equation and transport equations of motion for the turbulence model are represented by (Fluent, 2017):

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\upsilon\frac{\partial^2 u_i}{\partial x_j\partial x_j} \tag{1}$$

and

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_j)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_K \tag{2}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_j)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\rho C_1 S\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\upsilon\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon \tag{3}$$

The energy equation for the heat transfer problems is solved over the whole domain and is expressed as:

$$\frac{\partial(\rho E)}{\partial t}+\nabla.(\vec{v}(\rho E+P))=\nabla.\left(k_{eff}\nabla T-\sum_j h_j\vec{J}_j+\left(\bar{\bar{\tau}}_{eff}.\vec{v}\right)\right)+S_h \tag{4}$$

To achieve the optimum thermal performance for a heat transfer problem, optimization techniques need to be applied to the system. The optimization techniques were used in the HGHE system by developing a three-dimensional (3D) model (Selamat et al., 2016). The study involved different piping layouts and pipe materials in the optimization. In the parametric study of pipe materials, copper showed 16% more efficiency in comparison to other conventional pipe materials. Horizontal straight piping layouts was found worthy in terms of overhead costs. However, the effectiveness of the layouts may be varied in different periods throughout the year. During the model development, some assumptions were made, which eventually affected the accuracy of the system.

The HGHE was also optimized by developing a two-dimensional (2D) thermal model in ANSYS Fluent (Ahmed et al., 2016). Modelling equations were solved numerically using a finite volume approach for the computational domain discretization. The main parameters that affect HGHE performance were taken into account to assess their influence. A noticeable impact of air velocity and diameter and length of the pipe was seen on the HGHE performance while the other parameters were dominated by the pipe length. The developed 2D model was not capable of calculating absolute values of the modeled parameters as geometrical attenuation is not properly captured in a 2D model. Rosa et al. (2020) also developed an HGHE model by considering three effective parameters of the EAHE, namely pipe diameter, airflow rate, and space between two pipes. A higher airflow rate at the pipe inlet of the EAHE showed lower thermal performance while the other two parameters were kept constant. However, the authors did not consider some important parameters that would not reflect the heat exchanger performance accurately.

4.1.2. Vertical ground heat exchanger (VGHE) loop model

A VGHE loop model consists of a single tube/pipe or several connecting pipes aligned straight and vertically buried underground. This system normally contains high-density polypropylene or polyethylene plastic pipe(s) installed below the ground, backfill material with grout which assists in reducing thermal resistance as well as to confirm a good contact between the underground pipes and ground. Vertical or borehole EAHE as shown in Fig. 3 can be fitted within a limited land space. A borehole EAHE is usually 20 to 300 mm deep with a diameter of 100–150 mm based on the ground conditions and energy demand of space. It is broadly used to utilize the maximum heat exchange capacity of EAHE when a minimum disturbance is desired for the landscape and/or the earth's surface is rocky. The VGHE requires fewer pipes to achieve the same efficiency as other EAHEs because of the earth's constant temperature found at a specific depth under the ground. However, the installation cost is quite expensive as higher excavation is required to install the pipes.

A thermal response test (TRT) on the boreholes is essential to understand the thermal properties. A quantified heat load is usually applied into the holes for the thermal response test in which the changes in resulting temperatures are evaluated for the circulating fluid. This is the process to calculate the borehole thermal conductivity allowing different sizes of the boreholes based on the underground data. The line source theory can be utilized to measure the test data that is considered the easiest approach (Li et al., 2019). A TRT also enables to calculate of the borehole's thermal resistance(R_b). The temperature drop between the inner fluid of the pipes and ground is obtained from this thermal resistance value. The value of R_b can also be determined using the materials and dimensions used in the boreholes. The following formula was used to determine thermal conductivity:

$$\lambda_{eff} = \frac{Q}{4\pi Hk} \tag{5}$$

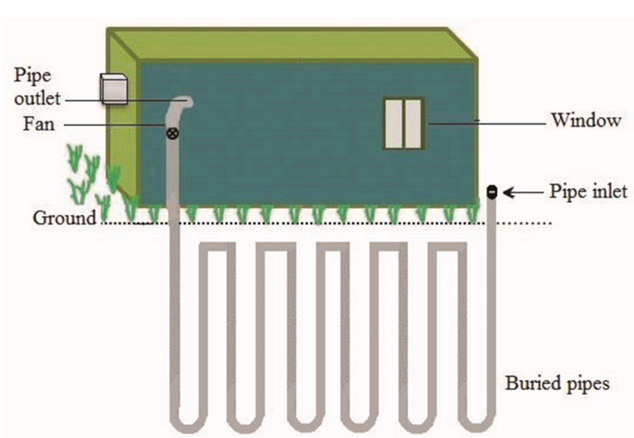

Fig. 3. Vertical earth-air heat exchanger.

An understanding of thermal properties is a key part of assessing the thermal performance of a VGHE. Borehole or vertical EAHE were modeled by several researchers where some models were developed to assess their thermal properties. Based on Fourier's heat conduction law, these models include cylindrical (Bernier, 2001; Hellstrom, 1992; Kavanaugh, 1985) and line source models (Hart and Couvillion, 1986; Li et al., 2020), and various numerical models. The most broadly used modelling technique is the line source model which may be of finite or infinite length. However, the infinite line source modelling technique is recommended to use for applications (Ingersoll, 1948).

The heat transfer problem for the EAHE is quite complicated, which needs to be simplified. Because of the complicacy in constructing the EAHE models, the heat transfer method can be partitioned into two different regions: outside and inside the borehole. Most of the heat transfer models outside the borehole were developed based on either numerical and/or analytical methods. Solid rock/soil heat conduction is investigated outside the borehole. These models may include Kelvin's line source (Hart and Couvillion, 1986; Ingersoll, 1950), finite line-source solution (Diao et al., 2004; Yu et al., 2002), Eskilson's model, cylindrical source model (Bernier, 2001; Carslaw and Jaeger, 2001; Kavanaugh, 1985), short (Yavuzturk and Spitler, 2001; Yavuzturk et al., 1999), or long-time step model, and other classic numerical models.

On the other hand, the VGHE models inside the borehole comprise the vertical underground pipes, and the fluid moves within the buried pipes. Sometimes it is analyzed using a quasi-steady-state or steady-state model, and sometimes using a transient model. The incoming and outgoing fluid temperatures circulate in the borehole, its thermal resistance, and the heat flow is measured in this investigation. The models inside the borehole are widely used for evaluating VGHE performance. These models may be generated in any of the three different dimensions: one, two, or three.

A basic one-dimensional (1D) model was suggested for designing the ground heat exchanger (Gu and O'Neal, 1998). The model consists of a U-tube which was considered equivalent to a single pipe. The borehole thermal capacitance and the heat flow inside the pipe walls were neglected in this model as the dimensional scale of the borehole is too small in comparison to the outer ground of the borehole. Although the simplified model was found convenient and appropriate for most of the engineering practices, it is not suitable to analyze dynamic behavior within a short period. Also, the model appears insufficient because of its incompetence in assessing the influence of thermal short-circuiting between the borehole pipes on the VGHE performance.

A two-dimensional thermal model was constructed for the VGHE in a subtropical climate of Australia (Ahmed et al., 2015b). The simulation program, ANSYS Fluent, uses the finite volume technique was utilized to simulate the VGHE physical model. A realizable k–ε turbulence model was employed to analyze the heat transfer approach of the system. The pressure-based-coupled solver was utilized to solve the modelling Eqs. (1)–(3) numerically. The pressure was discretized with the PRESTO scheme considering its strong converge capacity. Since the second-order discretization is accurate for the viscous terms, the spatial discretization with a second-order scheme was utilized to calculate the dissipation rate and kinetic energy for the turbulent flow. The model contributed to saving maximum energy of 866.54 kW for a space of volume 27.23 m^3. However, the model did not consider all the components used in the VGHE system.

Al-Khoury et al. (Al-Khoury and Bonnier, 2006; Al-Khoury et al., 2005) presented two three-dimensional models for the VGHE with a single U-shaped tube using the finite element approach. These models were addressed the transient and steady flows for a geothermal system. Thermal contact between the two legs of a single U-shaped tube was considered in a one-dimensional model to characterize the borehole heat transfer. The model was extended to a three-dimensional heat flow model for the VGHE with a double U-shaped tube. The focus was given on the double and single U-shaped tubes associated with their thermal interactions. Another 3D model was developed by Al-Khoury et al.

(2010) for multiple borehole heat exchangers which are applied to analyze the thermal interactions among the borehole heat exchanger components. Some features of the system were disregarded while building up the model. Thus the model is not completely equipped for anticipating the modulating concept of the VGHE.

The borehole or vertical heat exchanger pipes are usually designed in two different arrangements: coaxial pipes and U-shaped pipes. One or more pipes with a smaller diameter are injected into the main larger pipe in the design of coaxial pipes. This design can perform in two different flow directions: upward flow through the inside tube, and downward through the outside. The U-pipe designs contain one or more U-shaped pipes, as shown in Fig. 4. The configuration of single and double U-pipes is frequently used in this design. The performance of these tubes was measured by Desmedt et al. (2012) in Belgium. The double U-shaped tube showed better performance followed by the single U-shaped and the complex coaxial tube. A very similar performance was obtained between the single U-shaped tube and the complex coaxial tube of a larger diameter. The effect of the pipe diameters was not considered in this model to measure heat exchanger performance.

The impact of the coaxial pipe diameter on the heat exchanger performance was investigated computationally using a computer simulation program, COMSOL (Zanchini et al., 2010). The inner-tube diameter and the fluid flow rate showed a noticeable impact on the long-coaxial vertical heat exchanger. To improve the thermal efficiency of the system, it was suggested to increase the diameter of the inner-circular-tube while the diameter of the outer-annular-tube remains unchanged. The suggested design contributed to increasing a 5% efficiency during winter, whereas the efficiency is decreased in summer. Reducing the average pipe diameter results in a lower Reynolds number.

The double U-shaped tubes showed in Fig. 4 can be positioned in a borehole in two different alignments: series or parallel connection. These configurations were analyzed using the finite element model builder software, FlexPDE (Florides et al., 2013). A similar result to Desmedt et al. (2012) was found in this study where both the double U-shaped tubes with the series and parallel connection performed better than the single U-shaped tube. In comparison to the single U-shaped tube, the parallel-connected tubes absorbed 26% more heat, whereas the series connection absorbed 59% more heat. However, not all the key factors that affect system performance was considered in the ground heat exchanger model.

The thermal performance of both the single and double U-shaped tubes was also compared by Sivasakthivel et al. (2017). More efficient outcomes were found for the double U-shaped tube in comparison to the single U-shaped tube, which is similar to the results obtained in the studies of Desmedt et al. (2012), Florides et al. (2013), and Wood et al. (2012). The double U-shaped tube provided an average performance of 30% and 26% higher than that of the single U-shaped tube in cooling and heating mode respectively. In the case of short-term operations of the heat exchanger system, it was found that the heat transfer performance of the double U-shaped tube is comparatively higher. The double U-shaped tube has more heat transfer capacity as it gets more time to exchange heat due to its larger surface area.

4.1.3. Slinky ground heat exchanger (SLGHE) loop model

The slinky ground heat exchanger loop model comprises several circular tubes/pipes designed as slinky which are installed horizontally or vertically underground. The SLGHE performs well if the underground pipes are orientated vertically. The buried pipes can be overlapped or separated one to each other, as shown in Fig. 5. In the case of the overlapping piping arrangement, attention should be given to filling the gap between any two overlapping pipes. Since this configuration requires longer pipes, a sufficient flow rate needs to be ensured throughout the pipes. It can be a good choice for those people who have limited land space to install it as the SLGHE needs less space compared to other conventional heat exchanger systems. The studies on the SLGHE modelling techniques are not sufficient due to the complexity in its geometry and the lack of its proper design method, although there are significant advantages of using the SLGHE. Most of the available studies were conducted on a small scale that considered a representative geometry of either a 2D or the cross-sections of one or maximum two circular pipes. This is because the model formation is time-consuming and quite complicated. The computational requirements for constructing the model is also expensive.

The SLGHE thermal performance was evaluated in several studies by applying different modelling techniques. In one of these studies, a 3D model was developed for the SLGHE orientated horizontally (Wu et al., 2010). No noticeable difference was found in the extraction of the specific heat for different diameters of the coils. However, the coil with a larger diameter gives a higher heat extraction rate per meter of soil. The extraction rate for the specific heat was increased, but the heat extraction rate was decreased per meter soil with the growth of the interval distance of the coil. The impact of heat extraction was also measured

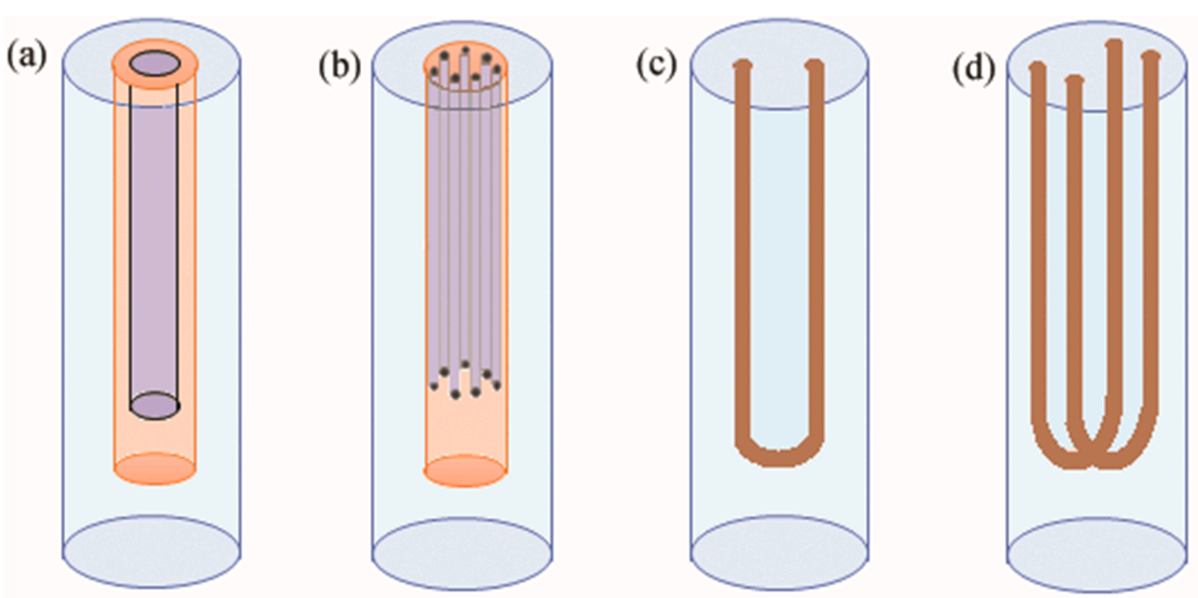

Fig. 4. Vertical ground heat exchanger designs. (a) simple coaxial, (b) complex coaxial, (c) single U-shaped tube, and (d) double U-shaped tubes.

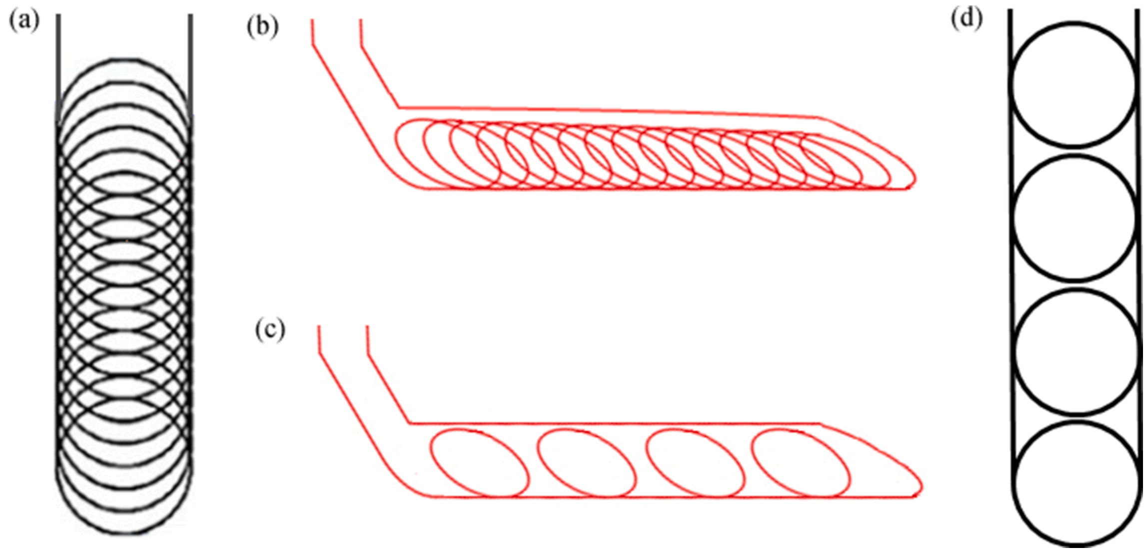

Fig. 5. Slinky ground heat exchanger designs. (a) overlapped vertically, (b) overlapped horizontally, (c) non-overlapped (separated) horizontally, (d) non-overlapped (separated) vertically.

using the SLGHE (Gonzalez et al., 2012). The slinky configuration influenced the neighboring soil by diminishing soil temperatures significantly.

The SLGHE model was simulated using ANSYS Fluent in evaluating its performance (Congedo et al., 2012; Wu et al., 2011). Since the SLGHE model geometry is complex, a smaller computational domain compared to the size-independent domain needed for an accurate simulation was considered to simulate the SLGHE models. A larger computational domain must be required to be size-independent for which the transient fluid flow will not be affected by the size of the domain during operation. Therefore, the models did not meet the requirements to provide the exact performance of the system. To achieve the optimum performance of the SLGHE model, its design was optimized using FEFLOW. In the simulation, energy balance was considered at the ground surface. The model accuracy was validated through history-matching computations based on the thermal response and air-conditioning tests under different conditions. The model was validated by making a comparison between numerical results with the measured data, which was found reliable to exchange heat under the ground. To calculate the SLGHE heat exchanging capacity, a parameter $\Delta T/\dot{q}$was introduced by Fujii et al. (Fujii et al., 2010):

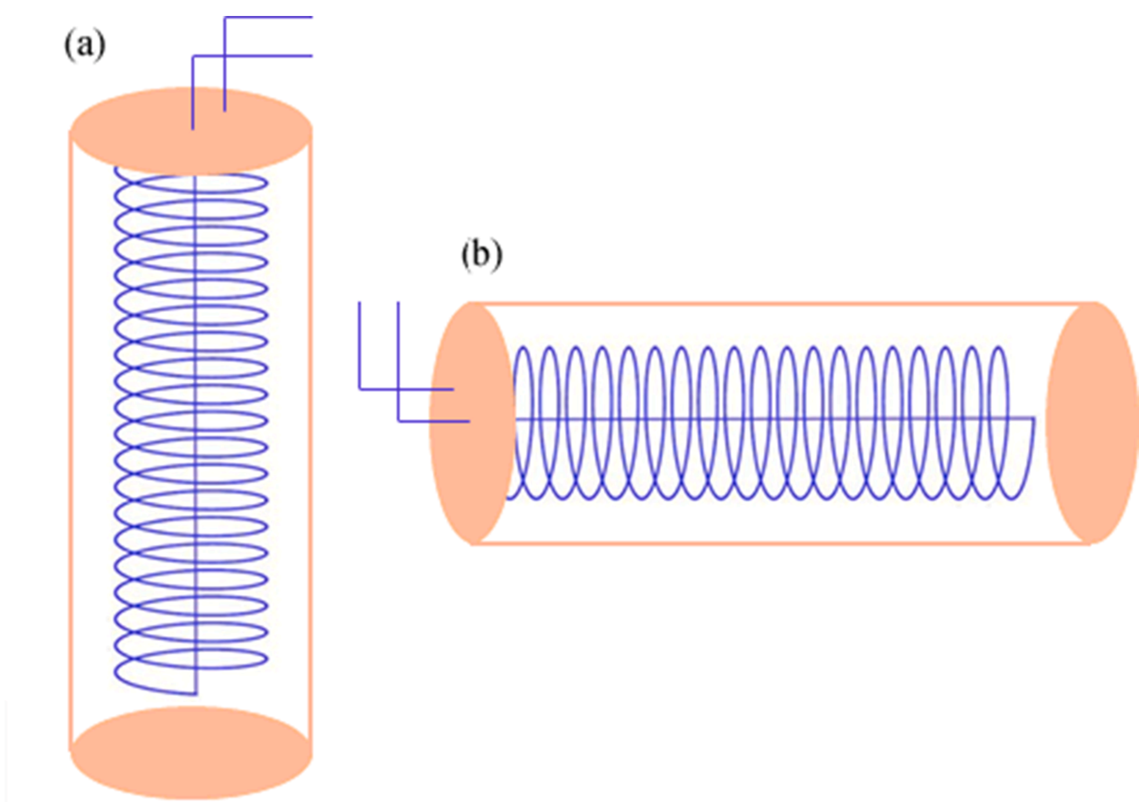

Fig. 6. Spiral ground heat exchanger designs. (a) installed vertically, (b) installed horizontally.

$$\frac{\Delta T}{\dot{q}} = \frac{|T_{avg} - T_{ff}|}{q/L_{tr}} \quad (6)$$

whereT_{avg}, the heat medium mean temperature is determined by taking the average of inlet and outlet temperatures of the heat medium; T_{ff}, the far-field temperature is determined at a certain point which is at the equivalent depth to the coils and over 5 m far away as of the loops. The impact of the difference between the ground temperatures and heat exchange rates is eliminated by using the term, $\Delta T/\dot{q}$. The higher $\Delta T/\dot{q}$ represents a quicker change in the temperate of the heat medium. A lower $\Delta T/\dot{q}$ is preferred as regards the heat exchange capacity of the heat exchanger.

4.1.4. Spiral ground heat exchanger (SPGHE) loop model

The spiral ground heat exchanger loop model contains longer tubes in spiral designs placed under the ground vertically or horizontally, as shown in Fig. 6. The main benefit of using the SPGHE is its effective usage of space. Another advantage is that it has a more heat exchange area and provides a better flow than parallel or serial U-shaped tubes in the borehole/pile without air blocking inside the pipes. A compact SPGHE may be utilized for smaller footmarks and hence lower the capital costs while an oversized SPGHE may be utilized to have a smaller amount of pumping energy and pressure drop, fewer energy costs, and more thermal efficiency.

More attention is given to the SPGHE in the last few decades because of its numerous advantages. However, its installation cost is comparatively higher than the overlapping slinky pipe configurations, although the thermal interference is significant in the spiral pipe configurations. The SPGHE utilizes its self-cleaning strategy by which the fouled surface causes a limited growth in fluid flow and hence increasing the drag on the fouled surface. The spiral piping would be more appropriate to use in the method of energy pile as a wider diameter is needed to install the SPGHE. Zhao et al. (2016) built a 3D SPGHE model to measure its thermal performance. The SPGHE model performance was compared with U and W-shaped ground heat exchanger models. The SPGHE has been predicted to have the best thermal performance due to its geometrical construction and the longer pipe used in the SPGHE. The model failed to provide the exact performance due to the several assumptions made in the study. A similar result to Zhao et al. was demonstrated in another study (Kim et al., 2016). The SPGHE and SLGHE were compared in terms of the thermal response test (TRT), where the SPGHE performed better.

A 3D SPGHE model was validated with the measured outlet temperature data (Bezyan et al., 2015). Three models with different configurations were also compared to investigate the temperature reduction at the pipe outlet. The model of spiral configuration showed maximum efficiency in terms of energy output and heat transfer compared to the other models. Park et al. (2015) also evaluated the performance of the SPGHE model using different spiral pitches along with their lengths. Spiral coil pitches of 500 m with pipe length 12.5 m, and 200 m with pipe length 14 m were considered to compare and measure their performance. A terminology for the heat exchange efficacy of the pipe and pile was presented in this comparison. The results demonstrated that by increasing the spiral pitch the pipe efficiency gets higher, whereas the pile efficiency becomes lower. This indicates that the efficiency of the pile is not directly proportionate to the pipe length.

Bi et al. (2002) built a 2D SPGHE model using the cylindrical coordinate system. The temperature distribution inside the spiral coil laid underground was numerically solved and compared with the experimental measurements. The temperature distribution was found as a key to enhance the ground heat exchanger performance. Mathur et al. (2017) also built an SPGHE model to investigate its heating and cooling capacity. A dimension of 60 m long pipe with 0.1 m diameter and a pipe depth of 3 m was considered for constructing the model. This comparative study followed the previous researches carried out on the SPGHE; the spiral configuration functioned more efficiently than the straight pipe configuration. However, the numerical studies were grounded on a good number of assumptions which eventually affected the accuracy of the system capacity.

4.1.5. Helical ground heat exchanger (HLGHE) loop model

HLGHE loop model consists of helical-shaped pipes (Fig. 7) which are typically installed at 10 to 20 m depth below the ground. Since the diameter of the helical-shaped pipe is thicker than other conventional heat exchangers, it is quite difficult to place the pipes in profound depth. Therefore, the HLGHE is generally mounted in climates with undulated soil temperature due to the solar radiation and surrounding air temperature (Bennet et al., 1987). The HLGHE would be a better choice for a limited space like the SPGHE. It is broadly used because of its capability in increasing heat transfer (Yoon et al., 2015).

A model was presented by Zarrella et al. (2013a) to evaluate HLGHE performance. The interactivity between the environment and the ground was considered in this model. Two different heat exchangers, namely helical-shaped and double U-shaped, were investigated in the same working conditions. The main focus was given on the comparison of a shorter helical-shaped tube configuration with a long and widespread double U-shaped configuration. The HLGHE model contributed to reducing the depth of the borehole by approximately 50%, and thus diminished the installation expenses. However, the numerical simulation results indicated that the axial effects play a vital role in the performance of the heat exchanger. Therefore, the axial effects should not be neglected in installing a short HLGHE.

The heat transfer behavior of the HLGHE was studied experimentally and numerically (Park et al., 2012). Indoor TRTs were reported in arid

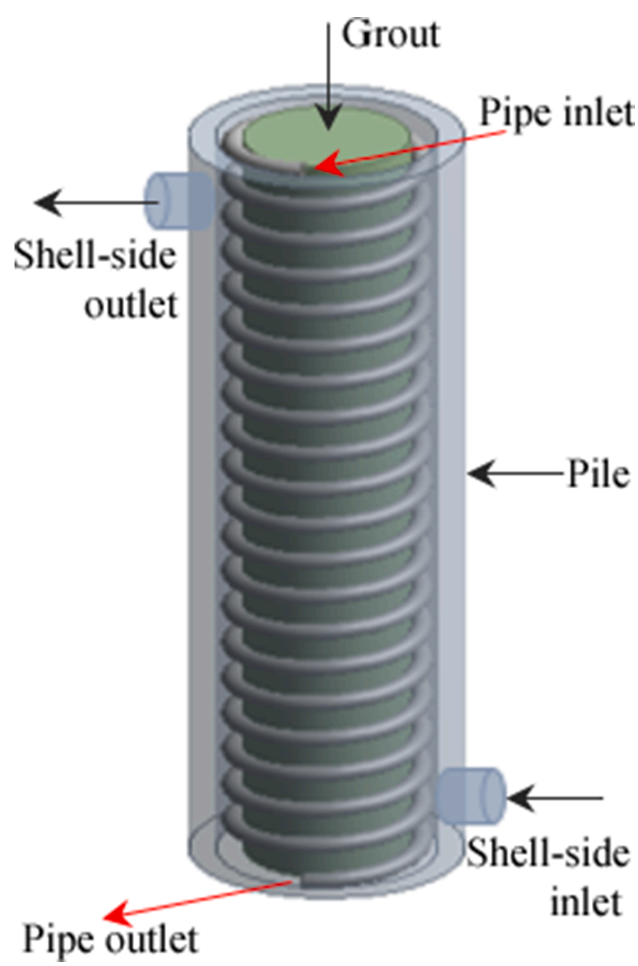

Fig. 7. Helical GHE design.

sand with different helical pitches. These tests were investigated based on the finite element methods and the heat source model published on the spiral GHE. The analytical and numerical models were utilized in the field of TRTs, where the analytical solutions noticeably overestimated the rise in temperature at the plie exterior compared to the numerical estimations. It was concluded that rational deliberations might be required in estimating the effectual thermal properties while employing the heat source models for the energy pile. A similar contribution was made by Rabin and Korin (1996). The HLGHE was modeled and solved numerically using the finite difference approaches.

Congedo et al. (2012) built a CFD model in measuring the thermal performance of HLGHE. To measure the performance, the HLGHE was compared with a single tube and SLGHE in both the summer and winter. The HLGHE was found more effective than the other GHEs considered in this study, although its installation cost was high. Another comparative study was conducted by Zarrella et al. (2011) through a numerical and experimental investigation. A triple U-tube configuration was considered to compare and measure HLGHE thermal performance. The helical GHE showed better performance compared to the triple U-tube arrangement. Some assumptions were made in constructing the models. Therefore, the assumptions need to be reduced to improve HLGHE performance.

Table 3 summarizes the main studies surveyed on the physical model emphasizing their method, primary objective, outcome, and application field along with relevant comments/remarks based on their strengths and shortcomings.

4.2. Hybrid models

The concept of developing hybrid models is to overcome the weakness of physical models. The hybrid model structure is mainly formed from the physics-based modelling approaches where the model parameters are directed by utilizing the parameter assessment algorithms on the recorded data. These models are especially beneficial to enhance system performance. Based on the available literature, different hybrid EAHE modelling approaches used in the buildings are discussed in this section.

4.2.1. EAHE coupled with a solar chimney

A solar chimney (SC), often called a thermal chimney, assists to improve buildings' natural ventilation by utilizing air convection. The air within the chimney is heated by passive solar energy during day time to create air updraft in the chimney (Khanal and Lei, 2011). The suction made at the base of the chimney can be utilized to ventilate and cool the building. The basic structure of a solar chimney generally includes a solar collector, ventilation shaft, and an outlet and inlet air aperture, as shown in Fig. 8. The solar collector assists the solar chimney to connect to the building that can incorporate the whole ventilation shaft or is

Table 3
Overview of the major physical model studies.

Type of model	Method	Main Task(s)	Outcome(s)	Application	Remarks	Ref.
Horizontal GHE	Finite volume approach	- Optimize the horizontal GHE model.	GHE performance was improved by about 16% when copper was used as a pipe material.	Building cooling and heating	The number of assumptions needs to be reduced to improve model performance.	Selamat et al. (Selamat et al., 2016)
	Finite volume approach	- Assess the influence of three key parameters, namely pipe diameter, space between pipes, and airflow rate on the EAHE performance in a warm-summer climate.	Keeping pipe diameter and distance between two pipes as constant, the higher airflow rate at the inlet provided the lower thermal performance for the EAHE system.	Building heating and cooling	All the key factors that influence EAHE performance can be considered to get optimum performance.	Rosa et al. (Rosa et al., 2020)
Vertical GHE	Finite element method	- Develop a model for double U-tube borehole heat exchangers (BHE). - Analyze a parametric investigation.	The parametric analysis recommended the model to utilize for future researches and design optimization.	Building cooling and heating	The focus should not be given only on the numerical analysis to describe the heat exchanging capacity of a borehole.	Al-Khoury et al. (Al-Khoury et al., 2010)
	Finite volume approach	- Thermal performance measurement by developing a vertical GHE model. - Calculate energy savings.	A room temperature reduction of 2 °C was achieved in summer which contributed to saving 866.54 kWh energy per annum.	Building cooling	A model of single-input–single-output type cannot characterize the interactive phenomena of multivariable.	Ahmed et al. (Ahmed, Shams Forruque et al., 2015b)
	Field experiment	- Performance assessment of single and double U-shaped vertical GHE.	Vertical GHE with a double U-shaped tube performed better than the single U-shaped tube in both cooling and heating mode.	Building cooling and heating	The model should be validated to make it reliable.	Sivasakthivel et al. (Sivasakthivel et al., 2017)
Slinky GHE	Finite volume approach	- Evaluate the thermal performance of slinky GHE.	Heat extraction for the slinky GHE was substantially higher than the straight one.	Building heating	The model performance can further be enhanced by using minimum assumptions.	Wu et al. (Wu et al., 2010)
Spiral GHE	Analytical method	- Heat conduction investigation surrounding the spiral coils buried underground.	Spiral GHE is capable of transfer heat with a noticeable amount.	Building cooling and heating	The spiral coil cannot be assumed as a ring coil that may cause a deviation from the real system.	Cui et al. (Cui et al., 2011)
	Finite element method	- Measure the thermal performance of spiral GHE.	Spiral GHE showed better performance compared to U and W-shaped piping systems.	Building cooling and heating	The payback period can be calculated to identify model feasibility.	Zhao et al. (Zhao et al., 2016)
Helical GHE	Finite element method	- Assess the heat transfer characteristics of helical GHE.	Reasonable deliberation in estimating the effective thermal characteristics might be required while the heat source models are applied to the helical energy pile.	Building cooling and heating	Attention should be given to designing the helical GHE to achieve better performance.	Park et al. (Park et al., 2012)
	Finite element method	- Predict the thermal performance of helical GHE.	A shorter borehole depth was required for helical-shaped tubes as helical GHE performed better than triple U-tube configuration.	Building heating	Some of the assumptions could be minimized to improve model performance.	Zarrella et al. (Zarrella et al., 2013a)

positioned at a point of the chimney. It is crucial to select the proper structure of the ventilation shaft emphasizing its thermal properties, cross-section, height, and location in order to achieve optimum performance (Shi et al., 2018).

Maerefat and Haghighi (Maerefat and Haghighi, 2010) proposed a hybrid EAHE model by coupling EAHE with a solar chimney to measure its performance. The study revealed that SC could effectively be used to supply power during the day in operating the EAHE with no electrical input. Also, the EAHE and SC configuration, outdoor air temperature, and solar radiation noticeably affected the hybrid EAHE performance. The number of CSs and buried pipes required for the EAHE were also calculated to reduce room temperature in achieving thermal comfort level. The results demonstrated that the amount of SC reduces with the taller SC usage. The taller SCs usage may cause thermal discomfort, and therefore, the number of pipes buried underground should be increased to get cooler air and keep the indoor environment comfortable. A pipe diameter of 0.5 m was found as optimum that requires a minimum amount of SCs and buried pipes used in the EAHE. But, the other parameters that affect the indoor comfort level were not addressed in this study.

Design parameters for the system of EAHE and SC were reported by Haghighi and Maerefat (Haghighi and Maerefat, 2015) to maintain the thermal requirements for flat buildings. The authors showed that the SC design having an air gap with 0.2 m outlet sizes and the EAHE design with a 25 m pipe length and a 0.5 pipe diameter provides better performance which was also found in Poshtiri et al. (Poshtiri et al., 2011). The thermal comfort investigation indicated that the SC could supply power to operate the EAHE heating system during a sunny day even at a very low temperature such as 0 °C without any habitual mechanical units. The amount of SC and the air channels needed for operating the hybrid EAHE are strongly affected by the building's heating demand and outdoor conditions.

The EAHE performance coupled with a solar chimney was also investigated by Yu et al. (2014). Three different experiments were made sequentially from passive to active cooling, and then active cooling to passive mode. The outcome of this study shows that the hybrid EAHE is feasible to cool space in natural operational mode at free of cost, that means, without any use of electricity. This is because the solar collector used in the SC can supply more airflow into the system with strong solar intensity. The system cooling capacity dropped rapidly after a week of forced airflow experiment because of the increasing soil temperature under the ground, and thus the indoor environment was found more stable under the passive modes compared to active cooling modes. Therefore, minimum controlling techniques should be applied to the EAHE system for improving its performance.

Li et al. (2014) investigated an EAHE system integrated with an SC to assess its thermal performance. It was observed that the SC could drive up to 1000 m^3/h (0.28 m^3/s) ambient air into space during the experimental measurements, and the EAHE provides a cooling capacity of a maximum 3308 W during daytime while the intensity of solar radiation was vigorous. The study concluded that the hybrid EAHE system could keep up the indoor comfort level at a reasonable range that agrees with the ASHRAE standard of thermal comfort. The EAHE-SC performance can further be enhanced by integrating a wind-catcher. Tavakolinia (2011) investigated the wind-catcher by incorporating with a solar chimney to allow natural ventilation and the EAHE system to supply cool air into single-story spaces. It was recommended to use this system as an effective alternative to any other conventional cooling and heating system.

4.2.2. *EAHE coupled with an evaporative cooling system*

In a system of evaporative cooling, the air gets cooler through water evaporation as illustrated in Fig. 9. It utilizes the way that water retains a good amount of heat to evaporate; that means, the evaporative cooling system has larger enthalpy in vaporization (Wang et al., 2014). In extremely arid climates, evaporative cooling offers benefits for air conditioning with additional moisture to achieve indoor thermal comfort for building residences. It is mainly implemented and used in climates of hot air and low humidity. This is because the evaporative cooling technique can substantially reduce internal air temperature and increase the humidity level (lal Basediya et al., 2013). Evaporative cooling is a viable option in energy savings and maintains indoor thermal comfort that has already been established in several studies (Al Horr et al., 2020; Narayanan, 2020; Sellami et al., 2019; Zhang et al., 2017).

The performance of the evaporative system is further improved when it is integrated with other systems like EAHE. Such a coupled system was modeled by Bansal et al. (2009) to measure its thermal performance. This study involved parametric studies in assessing the impact of some

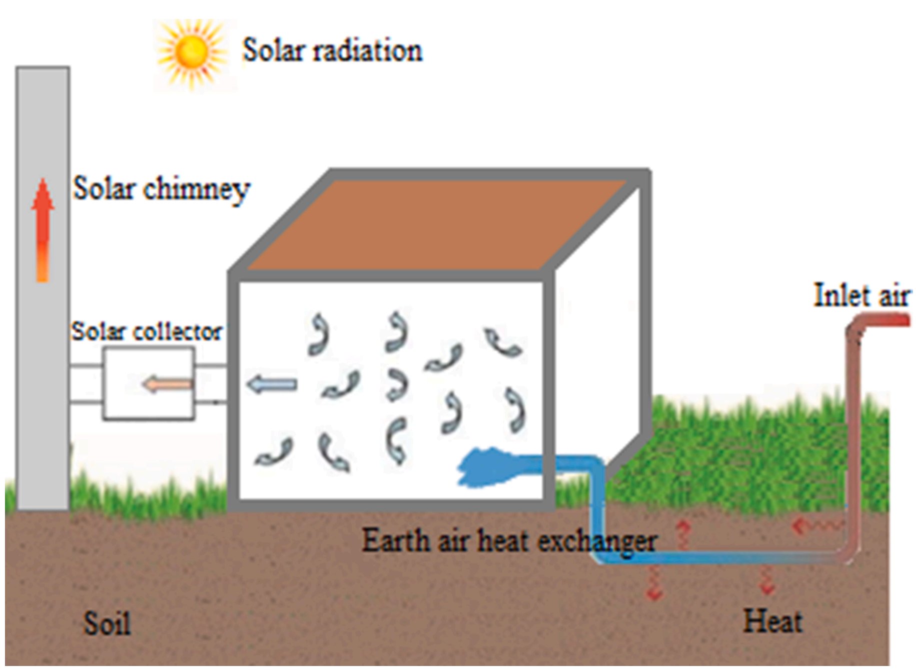

Fig. 8. EAHE design coupled with solar chimney.

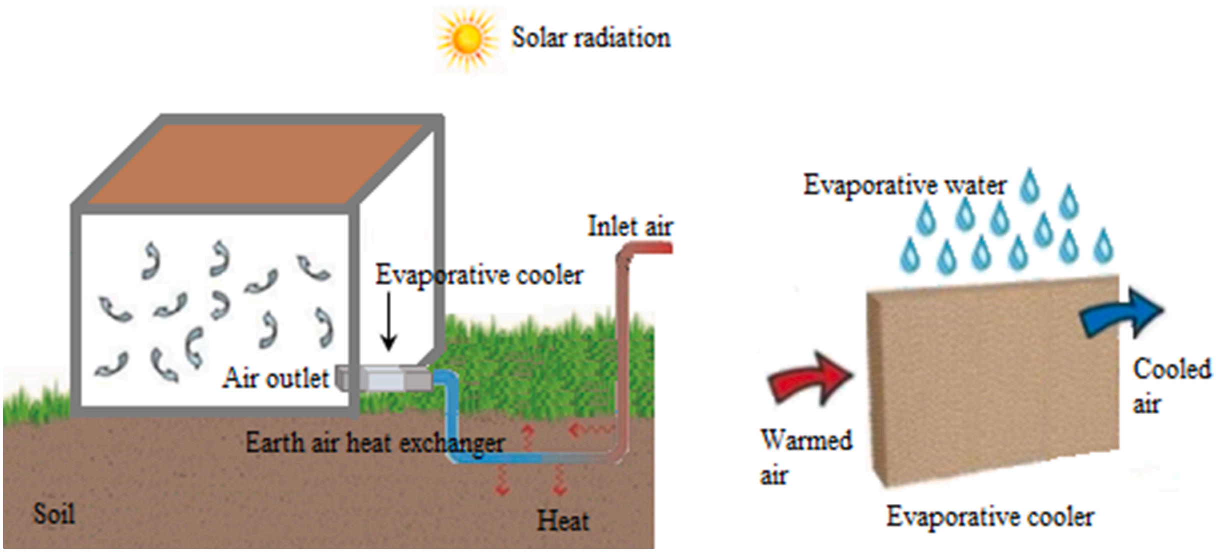

Fig. 9. Schematic diagram of EAHE - Evaporative cooling process.

influential parameters, namely, airflow rate, surface-to-volume ratio, pipe diameter, and pipe length on the hybrid EAHE performance. The results obtained from the hybrid EAHE were compared with the EAHE system, which does not involve the evaporative cooling system. It was demonstrated that the hybrid EAHE could significantly reduce (93.5%) the pipe length to obtain the desired outlet temperature. However, the other vital parameters such as pipe material, pipe depth, and pipe thickness were not included in the parameter study.

The EAHE performance was also evaluated by Bansal et al. (2012a, 2012b) integrating with the evaporative cooling system. Both heating and cooling capacities of the hybrid EAHE were calculated and compared with a simple EAHE (Bansal et al., 2012a). During the summer, the hybrid EAHE contributed to an additional 3109 MJ cooling effect compared to the simple EAHE system. From the economic point of view, the hybrid EAHE was analyzed to find its payback period (Bansal et al., 2012b). The economic analysis showed that the payback period for the hybrid EAHE is around 2 years with the use of an energy-efficient blower whereas the system is not viable with an inefficient blower because of the higher payback period. Consequently, the EAHE coupled with an evaporative cooling system improves the financial and technical performance of a simple EAHE system. These studies emphasized only the building's energy savings, no thermal comfort level of building occupants were discussed or investigated.

4.2.3. *EAHE coupled with wind tower*

A wind tower, also known as windcatcher is a customary architectural component used to generate natural ventilation to cool a building in a passive process. The wind towers can be designed in various arrangements such as bidirectional, multidirectional, and unidirectional. Its construction relies upon the prevailing direction of the wind at that particular place; for example, it might have one opening only if the wind blows from one side only (Saadatian et al., 2012). An optimized wind tower may have a bigger base diameter, require less material, and thinner walls (Barutha et al., 2019) is as shown in Fig. 10. The wind towers have been used for the last three thousand years and are broadly used in Western Asia and North Africa.

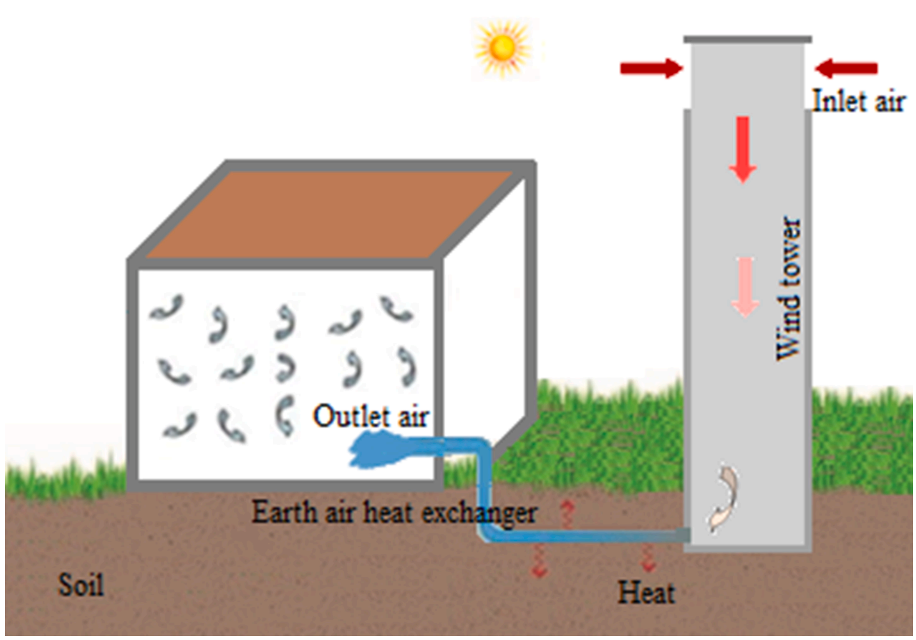

Fig. 10. EAHE design integrated with wind tower.

The thermal performance of the wind tower has been addressed in some researches (Khani et al., 2017; Mohamadabadi et al., 2018; Sadeghi et al., 2017; Soltani et al., 2018). In these studies, a noticeable performance was observed in terms of energy savings, temperature reduction, and or indoor thermal comfort. The wind tower was coupled with an EAHE system by Benhammou et al. (2015) to find the thermal performance of the coupled system. A transient model was constructed in this study to measure the effect of influential parameters, namely air velocity and pipe depth on the EAHE performance. Also, a sensitivity analysis was conducted to assess the impact of pipe and tower dimensions on the airflow rate and the EAHE performance. The dimensions (cross-section, height) of the wind tower showed less influence than the EAHE pipe dimensions (diameter, length). The results of the coupled system demonstrated that a tower of 5.1 m height and a 0.57 m^2 cross-section area could create a 592.61 m^3/h air flow rate. In addition, a maximum cooling potential of 30.7 kW h was achieved on a daily basis for a 70 m pipe length. These results were compared with other studies carried out using EAHE only, and it was found that the hybrid EAHE provides more efficiency than the simple EAHE system.

The performance of the EAHE-wind tower coupled system was also investigated by Sadeghi and Kalantar (2018). A numerical model was built to measure its performance and validated with the experimental measurements. Two different types of underground channels, dry and wet were taken into account in comparing the hybrid EAHE performance. The dry and wet channels contributed to the hybrid system to reduce the room air temperatures of 15.4 °C and 7.6 °C, respectively. A significant amount of relative humidity (52%) was increased by utilizing the wet channel system. Therefore, the wet channel was found more effective compared to the dry channel in cooling a space. However, the EAHE-wind tower coupled studies did not consider all of the essential parameters, and some assumptions were made in their investigations that may affect the actual performance of the coupled system.

4.2.4. EAHE coupled with a photovoltaic system

A photovoltaic system often called a PV system, or sometimes solar power system involves several components such as solar panel(s) to absorb sunlight and convert it into electricity, an inverter to transform current from direct to alternating, and other mechanical and electrical hardware accessories to make the system functional (Al-Waeli et al., 2017). A schematic of the PV assisted EAHE has been shown in Fig. 11. The PV cells are broadly adopted as an important and significant renewable energy source (Ma et al., 2019). Although a solar panel generates energy on a small scale, the PV system can produce a high volume of energy by connecting more panels. Due to the advancement in this technology and the increasing scale in manufacturing and modernity, the photovoltaics cost is gradually decreasing (Bazilian et al., 2013).

The photovoltaic system was coupled with EAHE in many kinds of research (Chel and Tiwari, 2010; Elminshawy et al., 2019; Hepbasli, 2013; Jakhar et al., 2018; Li, Z. et al., 2019; Mahdavi et al., 2019; Nayak and Tiwari, 2009; Uddin et al., 2016) for the performance improvement of the simple EAHE system. Nayak and Tiwari (Nayak and Tiwari, 2009) constructed a thermal model to measure EAHE-PV thermal performance installed with a greenhouse. This hybrid approach contributed to increasing indoor greenhouse temperature by 7–8 °C during the winter. The hourly thermal energy of 33 MJ was produced during the daytime, whereas 24.5 MJ was generated during the night using the system. The annual thermal energy produced by the coupled hybrid system was calculated as 24,728 kWh while the annual net energy savings was 805.9 kWh.

PV operated an EAHE performance was also investigated experimentally by Chel and Tiwari (2010) in an adobe house. The simple EAHE used the blower to such the intake air from the pipe inlet that was powered by the PV panel. An air filter was fitted with the suction pipe to keep the blower safe from the dust particles. The insulation was made properly for the air suction and transport into the pipes to avoid extra heat gain during summer or heat loss during winter from the ambient air. The cooling and heating potentials of the coupled system for energy savings were calculated around 889 kWh/year and 1109 kWh/year respectively for a single room while the simple EAHE consumed 5994 kWh/year in three (3) rooms.

Uddin et al. (2016) designed and built a PV-assisted EAHE system in achieving thermal comfort for a 20 m^3 office room in Bangladesh. The EAHE was configured with a PVC pipe of length 14.33 m, diameter 0.0381 m, and depth 2.44 m. The coupled system demonstrated its ability to make the office comfortable achieved from two extreme conditions, 34 °C air temperature with 77% relative humidity and 11 °C air temperature with 91% relative humidity in summer and winter respectively. Elminshawy et al. (2019) measured the performance of the PV module in terms of its electrical and output power efficiency with the

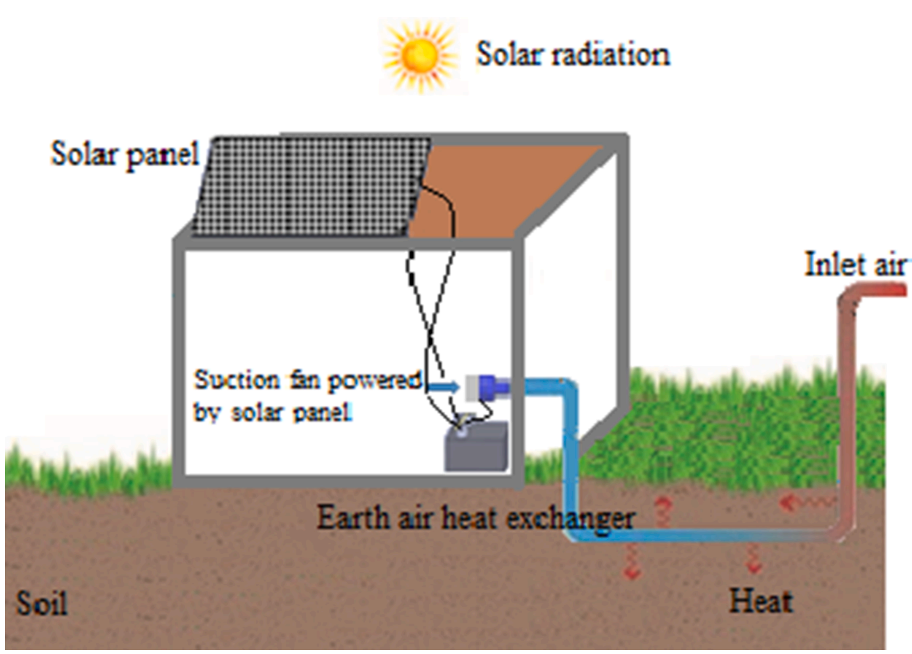

Fig. 11. EAHE-PV coupled design.

EAHE optimum flow rate of 0.0288 m^3/s. An improvement of 22.98% and 18.90% was achieved on average in electrical, and output power efficiency for the EAHE-PV coupled system. The energy cost was also improved by 12% using the coupled cooling system that contributed to reducing CO_2 emissions of around 13896 g in the summer.

Jakhar et al. (2018) conducted a numerical study to calculate the thermal efficiency of the EAHE-PV coupled device for three different climates: Ajmer, India, Pilani, India, and Las Vegas, USA. Parametric analysis was performed to examine the effect of different operating parameters on device performance. The authors recommended a pipe depth of 10 m in the EAHE, which provides better performance for the coupled system. The EAHE heating capacity was found between 324.49 Wh and 435.99 Wh, 331.77 Wh and 571.73 Wh, and 314.74 and 530.71 Wh for Ajmer, Pilani, and Las Vegas respectively. It was noticeably increased when the EAHE integrated with the PV system, for example, the heating capacity was observed between 408.37 Wh and 709.18 Wh, 367.76 Wh and 735.29 Wh, and 356.17 Wh and 711.35 Wh for the corresponding climates. However, none of the EAHE-PV coupled studies considered the heat transfer between the zones, surface phenomena, and occupancy level variations.

4.2.5. EAHE coupled with phase change materials (PCM)

The mechanism of energy storage integrated with the EAHE system can enhance the cooling efficiency. This hybrid system uses wall surfaces as cooling and heating sources to enhance the thermal comfort level and to provide healthier temperature distribution with lower energy. Rodrigues and Gillott (Rodrigues and Gillott, 2015) inspected the EAHE-PCM coupled system as an alternative to traditional air-conditioning systems. The concept of using EAHE to supply cool air in discharging the PCM was utilized to overcome the more significant part of the constraints of both the technologies. By comparing with a room of reference, the results indicate that this hybrid technique can reduce about 47% of temperature swings.

In view of steady output temperature and high level of energy density in the heat storage process of phase change, a cylindrical PCM was integrated with EAHE (Fig. 12) to enhance the thermal performance of the hybrid system (Zhou et al., 2020). A 3D numerical model was constructed in ANSYS Fluent to measure its performance. The hybrid EAHE performance was compared with the simple EAHE system to measure its improvement. It was observed that the PCM could increase the EAHE heat exchange rate in both cooling and heating mode. The maximum capacity was found in cooling mode enhanced by 28.55% to 39.74% when the hybrid technique was compared with the simple EAHE system (Zhou et al., 2020). However, both the studies discussed above did not calculate the cost-efficiency of the hybrid system. The feasibility of the hybrid system needs to be investigated for commercial usage.

Liu et al. (Liu et al., 2019a) used a numerical modelling approach for a hybrid system in combination with vertical EAHE and tabular PCM systems to enhance EAHE performance. Impacts of PCM component, PCM conductivity, container length, and tube depth on the hybrid EAHE were also assessed. The tabular PCM efficiently assisted the vertical EAHE to reduce air temperature from 25.74 °C to 21.01 °C, outlet temperature fluctuation from 3.59 °C to 0.62 °C, and improve the EAHE cooling potential. Results illustrated that the fluctuation in the outlet temperature decreases when the length of the container increases. For a container diameter of 50 mm, the air outlet temperature was not much influenced by different PCM thermal conductivity. However, the authors recommended a 150 mm diameter for the container to achieve better performance. The payback period of the hybrid system was found longer (18.03 years), and therefore this system may not be considered as viable.

A hybrid modelling approach can also integrate the EAHE system with a ventilated roof, a solar air heater, and an air conditioner, which are discussed in the following miscellaneous section.

4.2.6. Miscellaneous systems assisted EAHE

EAHE was integrated with a ventilated roof (Fig. 13) and installed in a gymnasium building located in France (Serres et al., 1997). The ventilated roof was composed of iron metal covering, an air gap of 0.08 m with forced ventilation, and an insulation material of thickness 0.08 m. A pipe depth of 1.7 m and plastic pipe materials with different diameters were chosen for the EAHE system. Air comes through the ventilated roof was driven to the EAHE by a non-insulated air-pipe network before being moved into the building during winter while the air was extracted directly either from the underground buried pipes or the ventilated roof to be ousted outside during summer. Results indicated that air optimization has no impact on building energy consumption in a cold climate, whereas substantial energy savings can be attained in a warmer environment.

A solar air heater was coupled with an EAHE to experimentally investigate the heating performance of the coupled system during winter (Jakhar et al., 2015). The experiments involved a 60 m long PVC pipe with a diameter of 0.10 m that was installed horizontally buried

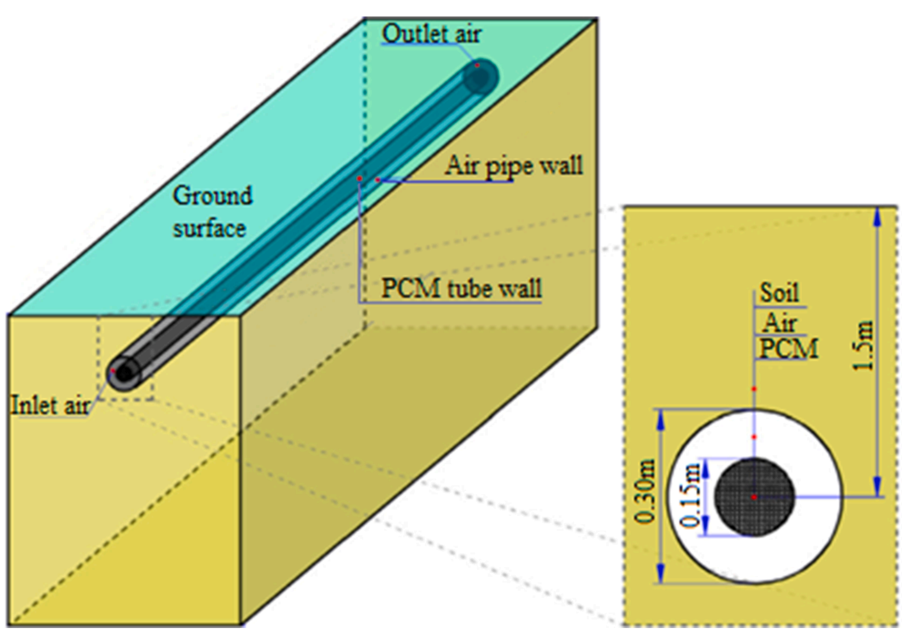

Fig. 12. Schematic diagram of EAHE-PCM reprinted with permission of Elsevier copyright from (Zhou et al., 2020).

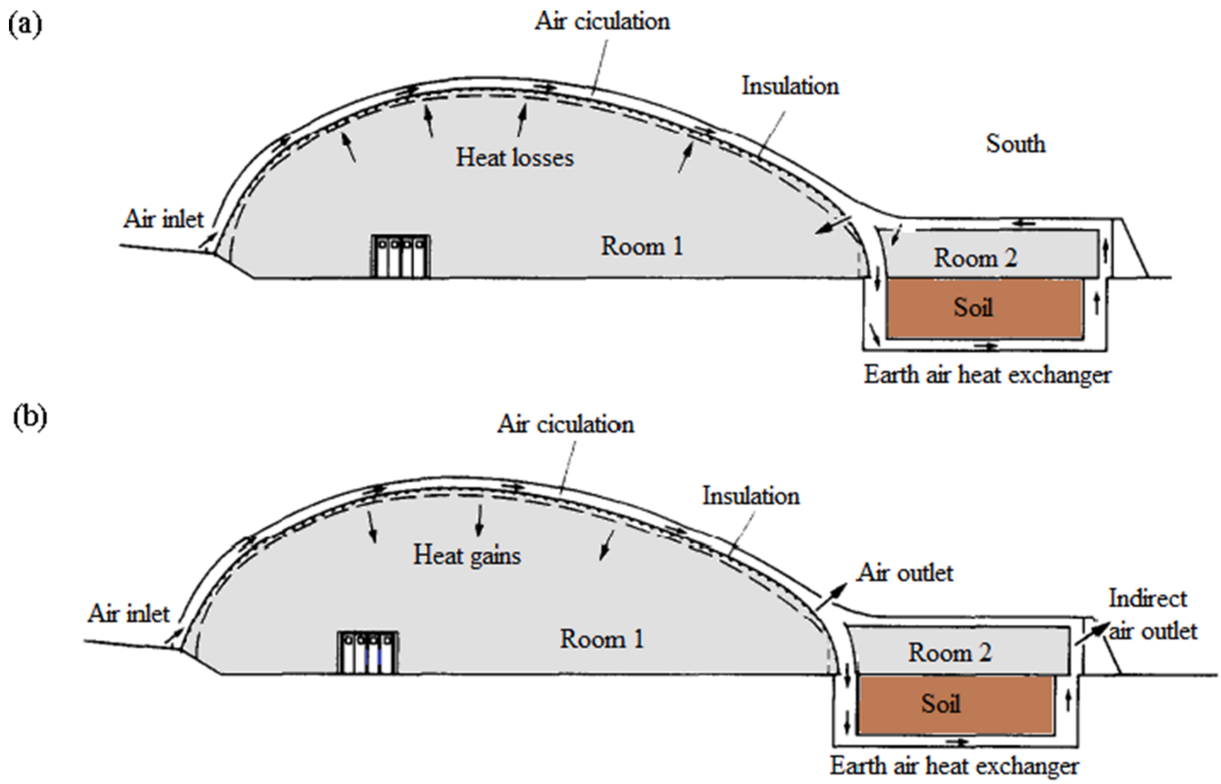

Fig. 13. Ventilated roof design assisted EAHE. (a) during winter (b) during summer (reprinted with permission of Elsevier copyright from (Serres et al., 1997)).

underground at 3.7 m depth. A 0.75 kW blower with a maximum of 0.0945 m^3/s flow rate was connected to the pipe inlet of the EAHE system. A galvanized solar air heater with a solar assemblage area of 3 m^2 placed in a U-shaped duct was fitted with the EAHE pipe outlet by a T-socket. The solar heater assisted the EAHE to provide a heating capacity of an additional 1217.63–1280.75 kWh which contributed to increase the room temperature by 1.1–3.5 °C. This hybrid system was also studied by Kaushal et al. (Kaushal et al., 2015) to evaluate its heating performance. To evaluate the performance, a CFD model was developed in ANSYS Fluent. Maximum temperature variations between the pipe inlet and outlet were calculated as 14.4 K and 49.83 K for the simple and hybrid EAHE respectively, which means, significant heating performance can be achieved by using such a hybrid system. However, this hybrid model cannot assess the cooling performance.

Misra et al. (Misra et al., 2012) have carried out a study to boost the cooling performance of an active system by integrating it with the passive EAHE system. Energy consumed by a window type conventional air conditioner (AC) of capacity 1.5 TR was calculated and compared it with the integrated hybrid system. The experimental test involved four different modes where the AC delivered conditioned air to the experimental room in all the modes. Mode-I was considered as a base mode in which the EAHE was not operated. The EAHE provided 100% cooled air to the room in Mode-II whereas the EAHE supplied 100% cooled air to the condenser coils of the AC in Mode-III. In Mode-IV, the EAHE supplied 50% cooled air directly to the room, and the other 50% was used for cooling the AC's condenser. The maximum performance was observed in mode-III where the EAHE assisted the AC to reduce energy consumption by 18.1%. This is because the EAHE supplied 100% air to the AC's condenser coils in mode-III only. But, there is a chance to consume more energy by combining a passive strategy with an active strategy.

Table 4 summarizes the key studies investigated on the hybrid models highlighting their method, main objectives, outcome, and application field along with relevant comments/remarks based on their weaknesses and strengths.

5. Benefits and challenges

EAHE thermal performance depends on the length, diameter, thickness, pattern, and depth of the pipes buried underground, materials thermal conductivity, ambient air temperature, climatic and geographical conditions, season, soil characteristics, moisture content, and its configuration. The EAHE system dynamics generate a noticeable amount of disturbances, uncertainties, and constraints due to the complexity in the EAHE design. To overcome these issues, the selection of an appropriate modelling technique is much needed for a particular climate. The basic two modelling techniques: physical and hybrid, have been compared based on their performances that is very important in selecting an appropriate modelling technique. Based on the performances/outcomes, the benefits and challenges of the developed EAHE models utilized in buildings were investigated and identified. This section briefly describes the benefits and challenges of these EAHE modelling techniques through comparative studies.

5.1. Benefits of different modelling techniques

The performance of a model mainly depends on its capacity in generalization, level of complexity, prediction accuracy, and data requirement. To select an appropriate model, it is expected to have a strong generalization capacity, good prediction accuracy, less data requirement, and model simplicity. Any of these four measures can be negotiated based on the available research facility and research aims. Suppose a physical model can be a better option in the case of insufficient training data of the EAHE system. The physics-based modelling has few useful features, for example, simplicity in analysis, strong generalization competency, and functioning ability with a small set of training data. In terms of strong generalization capability, the physical models perform better, which is followed by hybrid models. Minimum training data is needed for developing physical models, whereas the hybrid model structures are quite complicated in constructing the model compared to physical models. On the contrary, physical models have

Table 4
Summary of the studies surveyed on the hybrid EAHE model.

Coupling system	Main Task(s)	Outcome(s)	Application	Remarks	Ref.
EAHE + Solar chimney	- Predict the cooling capacity of the EAHE-solar chimney integrated system.	EAHE provided the cooling capacity of a maximum of 3308 W during daytime while the intensity of solar radiation was strong.	Building cooling	Some unnecessary assumptions should be avoided in the model development for getting better performance.	Li et al. (Li et al., 2014)
	- Thermal performance investigation of the EAHE-Solar chimney system.	The hybrid system was found feasible to cool a space without the use of electricity.	Building cooling	Minimum controlling techniques need to be applied to the system for improving system performance.	Yu et al. (Yu et al., 2014)
	- Cooling performance measurement of the EAHE system coupled with solar chimney.	During the day, a solar chimney can efficiently be utilized to generate and supply power in operating the EAHE.	Building cooling and heating	All influencing parameters that affect indoor comfort must be considered.	Maerefat and Haghighi (Maerefat and Haghighi, 2010)
EAHE + Evaporative cooling	- Parametric investigation to measure the effect of some influential parameters on the hybrid EAHE performance.	EAHE integrated with evaporative cooling significantly reduced (93.5%) the pipe length to achieve the desired outlet temperature.	Building cooling	Important parameters such as pipe material with thickness and pipe depth should not be neglected.	Bansal et al. (Bansal and Mathur, 2009)
	- Calculate the payback period of the evaporative cooler assisted EAHE system.	The payback period for the hybrid EAHE was calculated as two years using an energy-efficient blower.	Building cooling	The hybrid system is not feasible with an inefficient blower that may cause a higher payback period.	Bansal et al. (Bansal et al., 2012b)
EAHE + Wind tower	- Performance assessment of the EAHE-Wind tower hybrid system.	The dimensions (cross-section, height) of the wind tower showed less influence than the EAHE pipe dimensions (diameter, length) on the performance of the hybrid system.	Building cooling	Making several assumptions during the model development cannot be reachable in a real system.	Benhammou et al. (Benhammou et al., 2015)
	- Thermal performance prediction of the coupled system using wet and dry underground channels.	The dry and wet channels contributed to the hybrid system to reduce the room air temperatures of 15.4 °C and 7.6 °C respectively.	Building cooling	The actual performance of the coupled system is affected by excessive assumptions and not considering all the important parameters.	Sadeghi and Kalantar (Sadeghi and Kalantar, 2018)
EAHE + Photovoltaic	- Evaluate the thermal performance of the coupled EAHE-PV system installed with a greenhouse.	EAHE-Photovoltaic system contributed to increasing indoor greenhouse temperature by 7–8 °C during the winter.	Building heating and cooling	The payback period of the system needs to be calculated to make the model reliable.	Nayak and Tiwari (Nayak and Tiwari, 2009)
	- Photovoltaic operated EAHE performance through experimental investigation.	Annual energy savings were calculated about 889 kWh and 1109 kWh for cooling and heating a single room respectively.	Building cooling and heating	The results must be validated for the feasibility of the model.	Chel and Tiwari (Chel and Tiwari, 2010)
	- Conduct a parametric analysis to obtain the optimum performance of the hybrid system.	The results recommended a pipe depth of 10 m for installing the EAHE to achieve better performance for the coupled system.	Building heating	Soil temperature gets uniform at a specific depth (2–4 m) under the ground based on the particular climate.	Jakhar et al. (Jakhar et al., 2018)
	- Thermal performance investigation of the integrated system.	The energy cost was improved by 12% that assisted in reducing CO_2 emissions of around 13896 g in the summer.	Building cooling	Heat transfer between the adjacent zones, surface phenomena, and occupancy level variations should be addressed.	Elminshawy et al. (Elminshawy et al., 2019)
EAHE + PCM	- Performance assessment of the EAHE-PCM system.	The hybrid technique reduced about 47% of temperature swings.	Building cooling and heating	Validation is one of the most important parts to develop a model.	Rodrigues and Gillott (Rodrigues and Gillott, 2015)
	- The cooling and heating potentials of the PCM assisted the EAHE system.	Maximum cooling capacity was enhanced by 28.55%−39.74% using the hybrid technique.	Building cooling and heating	The cost-efficiency of the system must be investigated to show the reliability of the model.	Zhou et al. (Zhou et al., 2020)
EAHE + Ventilated roof	- Energy-saving potential of the EAHE -Ventilated roof coupled system.	Optimizing air a substantial amount of energy savings can be attained in a warmer environment.	Building energy savings	A numerical model can also be developed to compare its results with the theoretical and experimental ones.	Serres et al. (Serres et al., 1997)
EAHE + Solar air heater	- Predict the heating performance of the hybrid system in winter using a CFD model.	Heating capacity of an additional 1217.63–1280.75 kWh was achieved using the solar air heater assisted EAHE system.	Building heating	The model was developed for assessing only the heating performance of the hybrid system.	Jakhar et al. (Jakhar et al., 2015)
	- Heating performance measurement of the EAHE-Solar air heater system.	Temperature differences between the pipe inlet and outlet were found as a maximum of 14.4 K and 49.83 K for the simple and hybrid EAHE respectively.	Building heating	The hybrid model cannot assess the cooling performance using an air heater.	Kaushal et al. (Kaushal et al., 2015)
EAHE + air conditioner	- Calculate the cooling performance of the EAHE-air conditioner (AC) system.	The EAHE assisted the air conditioner to reduce energy consumption by 18.1%.	Building energy savings	More energy can be consumed by the hybrid system integrating a passive (EAHE) with an active strategy (AC).	Misra et al. (Misra et al., 2012)

low prediction capacity.

To overcome the shortcomings issues found in the physical models, hybrid models are appropriate to develop. The hybrid models offer numerous advantages, for example, minimal computational cost, high accuracy, less complexity, better control performance, and simple generalization ability. These models are considered more effective than physical models as it gives high accuracy in prediction. The main benefits of the two studied modelling techniques related to the EAHE studies are pointed below:

- All the influential parameters that affect the EAHE performance were taken into account in some models, and consequently, these models were capable to effectively identify the disturbances and uncertainties in system dynamics and substantially provided more information over the dynamic behaviors of the EAHE system.
- Most of the hybrid models performed better compared to physical models because of the integration of two or more passive and/or active heating and/or cooling systems such as EAHE coupled with the other systems.

The most important features of the two modelling techniques are tabulated in Table 5 based on their performance and available studies of the EAHE system.

5.2. Challenges of the modelling techniques

To develop physical models by considering all the EAHE components is quite complicated. In addition, these models cannot perform as expected from their design. This is because the physical models are constructed based on some particular assumptions which affect their prediction accuracy. It is essential to comprehend the EAHE operational methods and physical behavior of the EAHE components in developing the physical models. Therefore, the physical models were described in this study based on the different designs of the EAHE system as these models are more about the design aspects rather than the piping alignments and installation process. For insufficient medium training data, the hybrid model is found reliable in prediction. However, the hybrid models suffer from complexity during the model development as its structures are quite complex due to the involving several physical components. Since the hybrid model comprises two or more integrated physical systems consisting of a good number of governing equations and/or massive data set, additional work is needed to construct the model. The major challenges of the modelling techniques are summarized below:

Physical models:

- Most of the physical models developed for the EAHE system were single-input–single-output types which cannot characterize interactive phenomena of the multivariable commonly used in the EAHE system.
- The models constructed in a significant number of studies are inadequate as a result of not considering some effective parameters for the EAHE system.
- The physical models were identified as complex during the execution, and are not practically affordable to implement.
- Some of the models were not validated, and consequently, the results' accuracy is questionable and unreliable.
- The prediction accuracy of some models was found very poor because of the inclusion of excessive assumptions, and therefore, the resultant design could not show actual performance as per the model.
- Underground soil properties were not taken into account in the CFD domain in some of the models, and thus those models were unable to accurately estimate the temperature loss below the ground.
- Fan power was not considered in most of the models, and consequently, the model cannot provide trustworthy performance.

Hybrid models:

- The development of the hybrid models is comparatively complex than the physical models.
- A good number of assumptions were made in developing hybrid models that cannot be reachable in a real system.
- Some developed models were single-input–single-output type which is not capable of signifying multivariate interactions.
- A few models only considered most of the parameters/variables that influence EAHE performance, and therefore sufficient information was obtained to understand system dynamic characteristics. However, there are a significant number of models did not consider some influential parameters that cannot be recognized as complete models.
- Sometimes the models did not provide good prediction accuracy because of the inappropriate designs in the coupling systems.
- Almost in every model, the fan used in the hybrid EAHE system was not taken into account during model development, and therefore, those models are not realistic.
- To avoid the complexity of the models, the computational domain did not include underground soil, as a result, the models could not accurately predict soil temperature loss with respect to time.

6. Conclusion and future recommendations

The Selection of an appropriate and suitable modelling technique is much important to enhance the energy efficiency of a building. However, it is very challenging as so many factors are involved in this. To select the appropriate modelling technique, detailed knowledge of the advantages, disadvantages, applications, performances, recent advancements, and challenges of the modelling strategies utilized in the EAHE system is essential. Therefore, this study investigated those through a comprehensive literature survey. At the very beginning of this study, different types of EAHE systems were introduced and described. After that, the basic and common two modelling techniques, namely physical, and hybrid models used in measuring the EAHE performance were comprehensively reviewed along with their features and applications. How much these modelling approaches are practically applicable and suitable was exposed through this critical review. The benefits and challenges of these modelling techniques were finally identified based on the critical literature review.

A comparison was made between the two models based on their performances where both negative and positive characteristics were found in each of them during the model development. a major and/or minor weaknesses are found in most of the modelling techniques. These are produced from either any disturbances or uncertainties or substantial assumptions made in system dynamic characteristics. By overcoming all of these weaknesses, it is not an easy task to develop a suitable and energy-efficient model for the EAHE system. However, it is doable if the model constraints are properly known and conduct further research to minimize those. For instance, a hybrid model provides more prediction accuracy while the physical model gives less accuracy as it

Table 5
Performance comparison between two modelling techniques.

Modelling techniques	Generalization ability	Prediction accuracy	Complexity	Data requirement	Reference
Physical	H	L	H	L	(Afram and Janabi-Sharifi, 2015; Okochi and Yao, 2016)
Hybrid	M	H	H/M	M	

Note: The letters L, M, and H represents Low, Medium, and High.

comprises a good number of assumptions. Overall the hybrid model gives better performance compared to the physical model as tabulated in Table 5. The main constraint of this model is the complexity during the model development. Considering all these issues in selecting the appropriate modelling technique, some directions have been made as a guideline to minimize the constraints, overcome the shortcomings, and conduct further research in the future.

Physical model:

- The model must be a multiple-input-multiple-output type so that the dynamic characteristics of the EAHE system can be properly and easily understandable.
- The number of assumptions should be minimized as much as possible during model development.
- Attention should be given not only to the EAHE outlet temperature to reduce room energy consumption but also to indoor air quality and relative humidity to make the indoor environment comfortable.
- The main important and effective parameters that affect EAHE performance must be considered while developing the model.
- The model should be developed in such a way that it can be applicable and efficiently operated in our real system.

Hybrid model:

- Attention must be given to the hybrid designs while coupling two physical systems, for example, EAHE is coupled with the other systems.
- The model should be assumption-free although in some cases, it is not possible due to unavailable data in the EAHE system.
- To avoid the complexity of the hybrid models, the coupled system can be modeled separately and then integrated. However, extra care must be taken to minimize the uncertainties that may occur during the model development of the integrating system.
- Major influential parameters that affect any of the physical components of the coupling system should be taken into consideration.
- If a hybrid model involves two or more physical systems, the energy consumption of the hybrid system would be more compared to the other models. Therefore, the payback period of the hybrid model must not be too long to implement it practically.

The recommended guidelines will help the energy consumers, EAHE engineers, policymakers, government, scientists, building occupants, especially the energy executives, and building and energy research community in adopting the most appropriate modelling technique in their climates.

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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