A Review – Earth-air Heat Exchanger: Applications, Advances and Challenges

Wael Zeitoun\textsuperscript{1,2*}, Jian Lin\textsuperscript{1} and Monica Siroux\textsuperscript{2}

\textsuperscript{1}ICUBE, IUT Robert Schuman, University of Strasbourg, Strasbourg, France
\textsuperscript{2}INSA Strasbourg ICUBE, University of Strasbourg, Strasbourg, France

*wael.zeitoun@etu.unistra.fr

Abstract. Due to global warming and energy security, renewable energy systems became a subject of interest in research. Earth-air heat exchanger is one of these systems that can decrease the primary energy consumption using shallow layers of the ground as a source or sink of heat. Different configurations and designs of EAHEs were under research to assess their performance and find the optimal designs. It is important to identify and classify these designs to further develop innovative research on this topic. This review sheds light on the different classifications of EAHEs and their applications.

1. Introduction
Following the industrial revolution in the late 18th century, the demand for energy started to significantly increase. Added to the industrialization, the increase in world population and improvement of standards of living resulted in continuous increase in energy consumption from fossil fuels. In addition to causing global warming, fossil fuel quantities are limited and not renewable. Besides that, fossil fuel fields are distributed in certain countries around the world making them susceptible for political and economic conflicts. Due to these harmful effects of using fossil fuels, a series of international conferences (lately in Glasgow, UK, October – November 2021) were held to discuss and adopt policies to reduce the energy consumption and to develop and promote the use of environmentally friendly renewable energy sources.

The energy requirement for space cooling and heating accounts about one-third of the total energy demand [1]. New technologies for heating and cooling were developed to decrease the consumption in buildings’ sector. In this context, the earth-air heat exchanger (EAHE) can decrease the primary energy consumption using the shallow layers of the ground as a heat source/sink. Many experimental and numerical studies showed the advantages of EAHE-based systems in pre-heating/cooling of the air before entering to other air handling units and thus decreasing the use of non-renewable energies.

There are some new reviews done on EAHE. Agrawal et al. [1] focuses in their review on citing different applications of EAHE alone and applications of hybrid coupling between EAHE and other systems as well as mentioning recent research trends about EAHEs. While Soares et al. [2] sheds light on different parameters constraining the performance of EAHE and then reserves an intensive part to review hybrid EAHE systems. Other review by Ahmed et al. [3] focuses on modelling techniques of different EAHE configurations. However, this short review is trying to combine parameters and classifications of EAHEs with a literature review of their uses in a summarized simplified way giving a brief review on this topic.
2. Definition and classification
EAHE is simply an exchanger buried under the ground at a certain depth and configuration where the heat transfer fluid is the air, and the surrounding soil is the heat reservoir. There are other types of this exchanger where the heat transfer fluid is water or another special fluid, and in general, they are called ground-coupled heat exchangers (GCHE) or ground-source heat exchanger (GSHE).

In EAHE, air passes through one-end of the heat exchanger going underground and exchanging heat with the surrounding soil through the pipe, then it is either used directly or processed more in auxiliary systems before using it. The air flow is usually driven by some mechanical devices (such as fans or blowers) or using passive methods to create adequate pressure difference. This makes the EAHE a passive system consuming low amount of energy and reduces CO2 emissions.

The core of an EAHE functioning is the specificity of the ground temperature. Up to 10–15 m deep approximately, ground heat is supplied by the sun and rain, and from there, the underground temperature increases about 3°C per 100 m depth due to the internal thermal energy of the Earth [4]. This makes the soil temperature variations at shallow depths special: in winter (or during night) the underground soil is warmer than ambient air and in summer (or during day) it is cooler. In both cases, the soil temperature tends to reach a relatively constant value at a certain depth throughout the year. To illustrate this, Márquez et al. [4] recorded the distribution of underground temperature in Huelva (southwest of Spain) and the results are shown in figure 1.

The performance of EAHEs is influenced by almost all the surrounding conditions under the ground and above it. It is affected by the structure of the system (pipe-layout, size, depth, spacing of pipes…) and the operation mode. EAHE is also affected by the thermophysical properties of the soil and pipe material (steel, copper, plastic, PVC…), all the characteristics and properties of the flow and the climatic conditions.

EAHEs can be classified according to different design and operation parameters. For simplification, EAHEs are classified based on pipes configuration, circulation and operation modes.

![Figure 1. Behavior of the average monthly temperature regarding soil depth at Huelva [4]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)](image)

2.1. Pipe-layout and design
Different configurations of pipes distribution in the ground are installed in commercial and research projects. Pipes can be either installed horizontally by burying them, or vertically by drilling. Vertical pipes are sometimes used for EAHE especially when the available area is small, but they are most famous for installing GSHP. Horizontal pipes are mostly used in EAHE since their earthworks costs less than drilling vertical boreholes. Pipe-layout could also include single or multilayer configurations with multi or single pipe in each layer. Multilayer uses less space however it could cost more to install
it and the performance of the system is lower than single layer systems. Freire et al. [5] studied a horizontal multi-pipe and multi-layered EAHE. They found that its performance is less than a single layer EAHE, however, the space used was much lower. Multi-pipes could also be arranged in series or in parallel according to the air flow. In either of the cases, the pipes can take different shapes which could enhance the performance of the system such as U-shape, ring-shape, helix, spiral… for the single pipe, and lateral, parallel or radial as a group of pipes [2].

Others proposed different special designs experimenting new ideas. Hsu et al. [6] presented an integrated system consisting of air pipes immersed in the water-filled raft foundation of a high-density residential building. The results indicated that the cooling potential of integrated system was close to the potential of soil based EAHE at 2 m depth or deeper. This study is an example of EAHE installed under the building that can also be applied in soil under it. This helps avoiding extra area and cost since it is done during building construction. Zukowski and Topolanska [7] compared innovative plate exchanger, in which the air is in direct contact with the ground, to a standard EAHE. Results showed that the thermal performance of the plate-exchanger is better than the pipe-exchanger.

2.2. Circulation mode

Two circulation modes can be used in EAHE: closed or open loop. In open-loop systems, the air enters the EAHE from outside ambient environment and then it is blown to the premises being heated or cooled providing fresh air for ventilation purposes and can be even passed through other air processing unit before being blown to the space. However, this sometimes results in water condensation in the pipes which can lead to mould and microbial growth resulting in lower air quality.

Closed-loop systems rely on circulating air from the inside of the premises to the EAHE and then back to the premises which can help reduce moisture problems and condensation in the EAHE [8]. However, open-loop systems are preferred over closed-loop systems to provide fresh air [2] where special treatments could be used to prevent mould and bacterial growth such as adding antimicrobial layer to the inside of the pipe as done by Darkwa et al. [9].

2.3. Operation mode

This is usually determined according to the climatic zone. EAHE is usually for heating in cold regions and for cooling in hot regions. It can be also used in both modes in seasonal regions where heating and cooling is needed. The mode of operation is considered during the design where one can ignore the rain and water infiltration if the system works only during summer for example. In this case, the design of the system limits its functionality to the conditions which the system was designed for. However, limiting the system to one season makes it unfavourable for commercial use where it could become unprofitable. The research challenge nowadays is to optimize the design of the EAHE to satisfy the needs all year round. This optimization becomes more complex since it has multi-objectives. Optimization methods and studies can be found in the literature, for example, Cuny et al. [10] performed a sensitivity analysis to determine the most impactful parameters followed by multi-criteria optimization study to determine the Pareto front.

Other than heating and cooling, the EAHE mode can be classified as in a continuous or intermittent operation. Gao et al. [11] showed that intermittence prolongs the heat transfer in vertical exchangers without reaching an utmost temperature (operation limitation). Xu et al. [12] found that 5-day intermittent operation of horizontal pipes GSHP leads to an increase of 6.41 °C in soil temperature. This shows a significant impact of the operation mode on the thermal performance of the system, but the literature still does not contain many studies in this direction on horizontal systems where there are many on vertical boreholes systems.

Depending on the climatic zone and weather fluctuations, the EAHE can either satisfy the needs alone or must be coupled with other system. The other system could be working on renewable energies, like solar systems, biomass… or other traditional systems like heat pumps, air conditioner… As a standalone system, Sawhney et al. [13] studied an EAHE for cooling of a building in India, they observed that reasonably good thermal comfort conditions can be created in the building with such a system with a COP reaching 3.35. However, in different climate EAHE can only pre-heat and cool the air as showed in a study by Chiesa et al. [14] of an EAHE coupled with an air handling unit (AHU) for
heating and cooling of a school building in Italy. They found that the EAHE is very effective regarding outlet temperature both in pre-heating and cooling ventilation modes, although the treatment of humid air could be needed during summer.

3. EAHE applications

After the positive results of research on EAHE, it was commercialised and has been used in different applications. From building sector to agriculture to industry and others. The use of EAHE reduced the energy bill for heating, cooling and ventilation of buildings, and enhanced the performance of systems in many applications. Below is a brief overview of some applications of EAHE that was under research.

The high energy consumption for heating and cooling in buildings motivated the use of EAHE to reduce the bill and as an environmentally friendly solution. Hsu et al. [15] investigated the performance of an EAHE system for ventilation of a cafeteria in Nantou, Taiwan. They found that the annual COP can reach 27.2 and the annual mean temperature drops from 28.23°C to 24.9°C between inlet and outlet air. Ascione et al. [16] evaluated the performance of a buried EAHE for heating and cooling a building in Italy in different cities. The best energy performances have been obtained for wet/humid soil and for the coldest climates (Milan): maximum energy savings of about 44% in terms of thermal energy and about 37% for primary energy.

In agriculture, EAHE was used to create the suitable air conditions for growing plants in greenhouses and the survival of animals and livestock in their houses in extreme weather conditions. Yang et al. [17] analysed the performance of an EAHE system applied in an agricultural greenhouse temperature-control system. Compared with the traditional heat-pump system, they found that 561.6 kWh can be saved through this EAHE system in summer (operating for 90 days), with an energy-saving benefit of 74.3%, and 177.6 kWh can be saved in winter (operating for 30 days), with an energy-saving benefit of 67.3%. Moreover, the initial equipment costs can be reduced by 35.3%. Deglin et al. [18] studied an EAHE for ambient air conditioning of a livestock building in Tänikon, Switzerland. A parametric analysis was carried out to monitor the effect of different parameters on the thermal efficiency of the system as a step for optimization.

EAHE was also used for cooling of solar photovoltaic (PV) panels where the performance of these panels decreases affected by the increase of their temperature. Elminshawy et al. [22] experimentally studied an EAHE cooling-based system for PV panels in Egypt. They found it possible to decrease the PV module temperature from an average 55 °C to 42 °C by cooled air from the EAHE flowing over the back surface of the PV module. As a military use, Zeng et al. [23] studied the ability of an EAHE to ventilate and cool an underground diesel generator room used in protective engineering. The purpose is to hide the room and the ventilation air from being detected by infrared reconnaissance by enemies. Results showed that the system is suitable for small-scale engineering with high average outdoor temperatures and low temperature difference between day and night.

In industrial sector, the low temperature range of EAHE functioning makes it not so usable as a heat source for industrial processes that need high temperatures. However, there were some attempts for the use of EAHE for cooling purposes in some industrial processes. Barakat et al. [24] investigated the application of an EAHE as an inlet air cooling system on gas turbine. They developed a transient, one-dimensional model for predicting the thermal performance of the EAHE. They found that the output power and thermal efficiency of gas turbine increases by 9% and 4.8%, respectively. Goswami [25] built a model to assess the advantage of cooling the condenser of a solar thermal power plant. Based on his preliminary model, he found that underground-cooling techniques can improve the performance of the overall dry cooled solar thermal power plant by up to 3% at peak dry bulb temperatures.
4. Conclusion
The review showed the different types and configurations of EAHEs classified in groups according to pipe-layouts and design, circulation and operation modes. After the classification, a literature review and examples are mentioned where they showed the main applications of the EAHE and the advantages of using the system from the results found by many researchers. In certain cases, the EAHE can be standalone in satisfying the needs. However, in extreme weather conditions zones, the EAHE usually needs to be assisted by another auxiliary system to reach desired air conditions.

In addition to the studies mentioned in this review, there are a lot more trying to improve the performance of EAHE by investigating the parameters affecting it. At University of Strasbourg, there is an experimental EAHE (figure 2) where the team carried different experiments to see the effect of surrounding soil type on the system and how the moisture affects the properties of the soil [19, 20, 21, 26]. However, there are still more parameters that are not enough investigated in literature, such as, moisture transfer in the soil, condensation inside the EAHE especially in hot and humid climates and heat transfer between the EAHE and the building.

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