Contents lists available at http://qu.edu.iq

Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: https://qjes.qu.edu.iq

A review on earth tube heat exchanger in heating and cooling systems

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ARTICLE INFO

Article history:
Received 03 January 2023
Received in revised form 21 February 2023
Accepted 05 April 2023

Keywords:
Geothermal
Subsoil
Temperature
Heating
Cooling

ABSTRACT

Systems for heating and cooling that use renewable energy are becoming more popular. One method for lowering ventilation heat losses and enhancing thermal comfort in buildings is the use of earth tube heat exchangers to heat or cool the air. Earth Tube Heat Exchanger is an apparatus that transfers heat from ambient air to underground and vice versa which is used in heating and cooling applications. It started using an Earth tube heat exchanger (ETHE) by relying on the use of sustainable energy sources. Numerous researchers have put many different concepts into practice, carried out studies on ETHE with various parameters based on location, and discovered the best values of parameters for improved performance. This paper reviews ETHE's experimental and numerical research which focuses on its design (Construction materials, distance from the earth's surface, air speed, and pipe length, among other factors). The use of geothermal energy (sustainable energy source) through ETHE leads to meeting energy demand and preserving the environment by reducing carbon dioxide emissions, which in turn affects the ozone.

1. Introduction

In recent times, the consumption of energy raised because of life development and this led to an increase in the energy demands, and this leads to environmental pollution by affecting the ozone layer by increasing carbon dioxide. The solution to this problem is using a sustainable energy source to preserve the environment and meet energy demands. One of the biggest consumers of energy is the heating and cooling systems due to the harsh weather in some areas that requires heating and/or cooling. It can rely on geothermal and solar energy to provide a comfort zone through passive heating and cooling systems. The temperature stability of Earth's interior (undisturbed subsoil temperature) can be exploited at a certain depth throughout the year for heating and cooling purposes to provide a comfort zone. The temperature of the outside air in summer is higher than the temperature of Earth's interior and lower in winter [1,2,3]. ETHE is a device that enables the transfer of heat from ambient air to deeper layers of soil and vice versa [4]. ETHE performance depends on the following factors: pipe dimensions, the number of pipes, the flow rate of the air, pipe depth, soil properties, and surface tube convective heat transfer [5]. Various studies on ETHE have been conducted as of late. **Nasreddine** Sakhri et. all 2022 [6] investigated experimentally in the open-loop horizontal ETHE. ETHE length is 60m, PVC material, a thickness of 0.002m, and a diameter of 0.11m. The buried depth is 1.5m underground in sandy-loam soil. The inlet and outlet pipes are also made of 1.5m PVC material on each side. The results indicated that the annual undisturbed subsoil temperature at depth of 1.5m is equal to 28˚C. The EAHE appears that a cooling capacity of 7°C and a heating capacity of 13°C and a big dependence on local climate conditions. Vasileios K. Firfiris et. all 2022 [7] investigated the

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https://doi.org/10.30772/qjes.v16i2.847

enhancement of the ETHE efficiency. The examination was based on water flow simulation, (water-assisted earth-to-air heat exchanger – WAEAHE) based on double pipe heat exchanger concept. Fins were applied to the internal pipe of ETHE, where the fins and pipes are manufactured from steel. The length of ETHE is 50m, the diameter of the internal pipe of 0.2m, the thickness of 0.01m, the diameter of the external pipe of 0.3m, the volumetric flow of inlet air of 10000 m3/h, and the volume greenhouse of 1721.6 m3. Numerical analysis results show that the presence of an internal water pipe increases the efficiency of the system. Hazim N. Abed and Ahmed Al-Samari 2021[8] investigated experimentally by building a Hybrid system. The temperature difference between ambient and ground during winter and summer seasons is used for heating and cooling applications. The results indicated that the utilization of a geothermal system alone led to decreasing the average indoor temperature by 8˚C within one day. The earth's temperature at depth of 6m is equal to 24˚C throughout the year. Mushtaq I. Hasan and Dhay Mohammed Muter 2021 [9] studied the impact of design parameters numerically on ETHE configuration (overall ETHE performance for poultry houses). ETHE length was 355,370, 385, 395, and 410m respectively. The pipe diameter was 0.0508, 0.0762, 0.1016, and 0.1524 m respectively. PVC was the pipe material and the mass flow rate is equal to 22948.2 kg/s. The results of the simulation showed that the released heat by ETHE reduced with increasing the outside temperature and increased with increasing pipe length. There is a decrease in heat released with the diameter increases and the design of the coil gave a higher value of released heat by ETHE. Dastan Zrar and Younis Khalid 2020[10] studied energy performances experimentally by utilizing ETHE to control the building's air conditioning. Polyethylene was used to make 31 m ETHE long, a thickness of 3mm, a diameter of 10 cm, and a burial depth of 3m. The results showed that the average soil temperature was 21.88°C and ETHE COP was about 3.25 during winter and 1.5 during summer. Mushtaq I. Hasan and Eman Kareem Jabbar 2020 [11] studied experimentally two air conditioning systems types, first one was split-air conditioning (conventional air conditioner, CAC) with a capacity of 12000Btu/h. The length of the condenser pipe was about 13m and the diameter was 6.3mm. The second was a modified air conditioner (MAC). The condenser pipe is buried underground about 3.5m, length 27.5 m and 6.3m in diameter. The systems results showed that the COP of the conventional air conditioner (CAC) was higher than the modified air conditioner (MAC) with values of (6.1-8.48) and (5.5-7.1). Lower electrical energy was consumed by the modified (MAC). Hanin Atwany et. all 2020 [12] studied the horizontal earth tube thermal performance. ANSYS Fluent was utilized to create a 3-D model for studying ground horizontal earth water heat exchangers. The results showed a direct relationship between the heat transfer rate and the thermal conductivity of the soil. Otherwise, there is an inverse relation between the heat exchange rate and the temperature of the ground surface. Nasreddine Sakhria et. all 2020 [13] performed an experimental investigation for ETHE efficiency. Earth tube heat exchanger was made from PVC material with a length of 66m, 0.11m diameter, and 2mm thickness. The buried depth was 1.5m in an agricultural area. The results showed that the undisturbed subsoil temperature at 1.5 m is 28 °C. The relative humidity (RH) for the earth tube heat exchanger was increased by 19 % in the humidification regime. While a 27% decrease in the relative humidity occurred in the dehumidification regime. Devika Padwal et. all 2020 [14] created an analytical model for the Earth Tube Heat Exchanger (ETHE). The experimental set-up included a 21 m long aluminum tube with a 0.15 m diameter that was buried 3.5 m beneath the surface. Theoretical calculations are made using the NTU approach. The findings indicate that the relationship between air velocity and heat transfer rate is inverse. Temperature drop reduces as velocity rises. The ideal ETHE length is 21m. Better cooling and heating results from lower air velocity, although optimal air velocity, which ranges from 2 to 4 m/sec, is needed. The ideal length for ETHE can be calculated using a temperature drop of 10°C. The system's COP is equivalent to 2.9 with a 4 m/sec fluid velocity. Nasreddine Sakhri et. all 2019 [15] introduced an experimental examination into the effectiveness of a coupled system that included a solar chimney and an ETHE. PVC was used to construct pipes for an ETHE in an arid area to the north-west of the Algerian city of Bechar (thickness: 0.002 m, length: 60 m, diameter: 0.11 m), with a thermal conductivity coefficient of 0.2 W m^{-1} K^{-1}. The outcomes demonstrated the system's capacity to raise the outlet air temperature as it leaves the system by 14 °C and generates a heating mode. The system entered a cooling mode by lowering the air temperature by 11.6 °C (from 36.2 °C at the input to 24.6 °C at the exit), as the inlet temperature increased. Jiang Liu et. all 2017 [16] conducted experimental research on the EAHE's winter thermal performance in hot summer and chilly winter regions. For a week, various factors, such as soil temperature, supply air temperature, and external air temperature, were monitored. EAHE was 3.5 meters deep and 40 meters long, with a diameter of 0.3 meters. A fan was added to the pipe's terminus. According to the findings, the undisturbed subsoil temperature at a depth of 3.5 meters is 17.5 C. When the air draws enough heat from the soil, the supply air temperature can rise to the soil temperature around the pipe. The present work, reviews ETHE's experimental and numerical research which focuses on its design (Construction materials, distance from the earth's surface, air speed, and pipe length, among other factors).

2. Working Principle of Earth Tube Heat Exchanger (ETHE)

Since ancient times, the principle of thermal inertia has been used for heating and cooling. The ancient Greeks and Persian used it before the Christian era, and it was also used in modern histories, such as by the Italians who made caves for precooling and preheating. Nowadays, pipes are buried underground and the air passes through them, either for purpose of heating or for cooling, or both. Earth temperature begins to change starting from the surface of the earth until it is fixed at a certain depth, where thermal equilibrium occurs and the temperature of the earth′s interior at that point is called Undisturbed subsoil temperature. At the point where the temperature is fixed, ETHE is placed. The supply air is warm in the winter season because there is a fact of the temperature of the ground that surrounds ETHE is higher than ambient air, while in the summer season, the supply air is cool down because the fact of the ground temperature surrounding the ETHE is lower than ambient air. When air passes into ETHE, heat transfer occurs from/to air through ETHE to the ground. The efficiency of the heat transfer process from/to air depends on the efficiency of ETHE [17]. Thomson suggested the first harmonic model to calculate undisturbed soil temperature in 1826, whereas Kelvin developed this model as follows [17].

$$T_{s(z,t)} = T_{s,average} - \sum_{n-1}^{\infty} e^{-z\sqrt{n\pi/t_p \alpha_s}}\, T_{amplitude,n} * \cos\left[\frac{2\pi n}{t_p}\left[(t - PL_n) - z\sqrt{\frac{n\pi}{t_p \alpha_s}}\right]\right] \quad (1)$$

Where:

$T_{s(z,t)}$: undisturbed subsoil temperature at z m depth and time t sec of the year in ˚C.
$T_{s,average}$: average soil temperature at depth z and time t in ˚C.
$T_{amplitude,n}$: amplitude of the temperature waves at the surface of the ground at z = 0, estimated equal to 0.5 the difference between the maximum and minimum of the average monthly temperature.
z : soil depth in meters.
t : time of the year (in days) that starts on the first of January.
t_p : cycle 365 period of soil temperature, in days.
α_s : thermal diffusivity of the soil in m^2/day.

ASHRAE presented the else sinusoidal model to estimate undisturbed soil temperature as follows [18]:

$$T_{s(z,t)} = T_{s,average-}\sum_{n-1}^{\infty} e^{-z\sqrt{n\pi/t_p\,\alpha_s}}\, T_{amplitude,1} * \sin[\frac{2\pi n}{t_p}[(t - PL'_1) - z\sqrt{\frac{\pi}{t_p\alpha_s}}] \quad (2)$$

$$PL_1 = P'_1 - \frac{t_p}{4} \quad (3)$$

The total energy at the exit of ETHE is estimated as flow:

$$Q_{out} = \dot{m}_{vent} CP_{air}(T_{inlet} - T_{outlet})\, N_{pipe}^2 \quad (4)$$

Where:

$\dot{m}_{vent}$: mass flow rate of ventilation in kg/sec.
CP_{air} : air specific heat = 1.007 J/kg.K.
N_{pipe} : number of pipes.

The coefficient of performance (COP) of the system is calculated as follows:

$$COP = \frac{Q_{out}}{W_{in}} \quad (5)$$

Heat transfer rate is estimated into ways, first is log mean temperature difference (LMTD) and the second is $\varepsilon -$ number of transfer units (NTU) method [19].

LMTD method:

$$Q_h = hA\Delta T_{lm} \quad (6)$$

$$\Delta T_{lm} = \frac{T_{in} - T_{out}}{\ln\frac{T_{in} - T_{wall}}{T_{out} - T_{wall}}} \quad (7)$$

$$T_{out} = T_{wall-}(T_{in-}T_{wall})e^{(hA/\dot{m}\,cp)} \quad (8)$$

NTU method:

$$\varepsilon = \frac{T_{out} - T_{in}}{T_{wall} - T_{in}} = 1 - e^{(hA/\dot{m}\,cp)} \quad (9)$$

$$NTU = \frac{hA}{\dot{m}\,cp} \quad (10)$$

$$\varepsilon = 1 - e^{NTU} \quad (11)$$

Erath tube heat exchanger length (L) and Pressure drop (Δp) calculated based on the NTU method [20] [21]:

- Design requirements:

T $_{air\ out}$ = In-door DBT
T $_{air\ in}$ = Outdoor DBT
T $_{wall}$ = T $_{mean}$

The air kinematic viscosity (ν) is calculated [8] using:

$$\nu = 10^{-4}(0.1335 + 0.000925Ta) \quad (12)$$

- Reynolds's number:

$$R_e = \frac{VD}{vair} \quad (13)$$

- Friction factor:

$$f = (1.82 \log R_e - 1.64)^{-2} \quad (14)$$

- Nusselt number**:**

$$Nu = \frac{\frac{f}{8}(R_e - 1000)P_r}{1 + 12.7\sqrt{\frac{f}{8}}\,(P_r^{\frac{2}{3}} - 1)} \quad (15)$$

- Heat transfer coefficient (h):

$$h = \frac{NuKair}{D} \quad (16)$$

- Calculation of NTU:

$$\varepsilon = 1 - e^{-NTU} \quad (17)$$

- Overall heat transfer coefficient (U) Calculation**:**

The radius of the soil domain (r_2) is assumed as twice the radius of the pipe [20] and pipe thickness is neglected, the thermal resistance:

$$R_{th} = \frac{1}{h} + \frac{rln\frac{r_1}{r}}{k_{air}} + \frac{r_1 ln\frac{r_{12}}{r_1}}{k_{soil}} \quad (18)$$

$$U = \frac{1}{R_{th}} \quad (19)$$

- And finally, Length Calculation:

$$NTU = \frac{U\pi DL}{m_{air}\,cp_{air}} \quad (20)$$

- Pressure drop (Δp) Calculation**:**

The pressure difference and the power required to pump the air through the earth air heat exchanger is given by [22]:

$$\Delta p = f(\frac{m_{air}}{\rho_{air}})(\frac{L}{D})^3 \quad (21)$$

3. Classifications of ETHE

3.1 Classification of ETHE According to The Passage of Air Flow:

i. In an open system, ambient air is preheated or precooled by underground tubes before being heated or cooled by a traditional air conditioner before entering the structure. Open loop as shown in Fig. 1-a.

ii. In this instance, heat exchangers are positioned underground, either horizontally, vertically, or obliquely, and heat is transferred from the earth to a heat pump or vice versa by the circulation of a heat carrier medium within the heat exchanger. Closed loop as shown in Fig. 1-b.

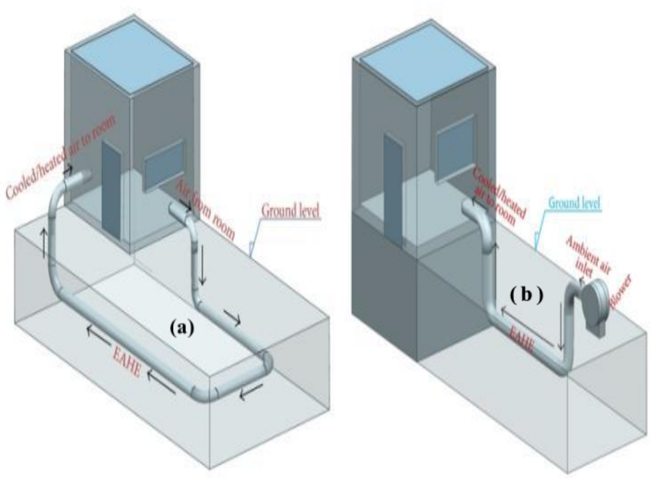

Figure 1. EAHE: (a) open loop and (b) closed loop [23]

iii. The hybrid system, and conventional air conditioning systems combined with ETHE for decreasing the energy consumption and improving the performance factor of the system. Also, renewable techniques integrated with EAHE such as the solar chimney, wind tower, etc.

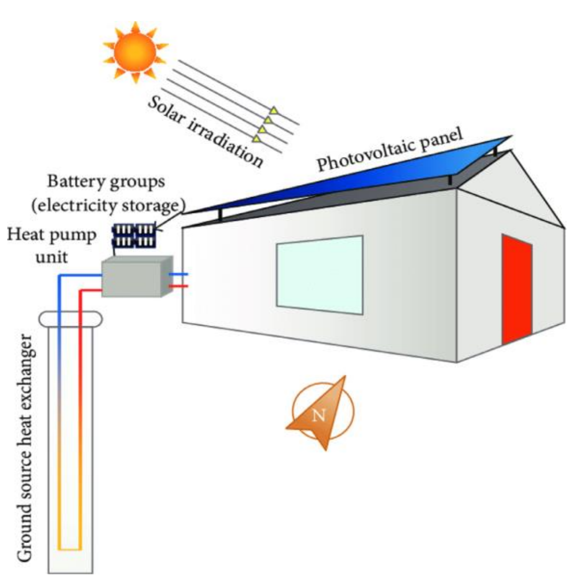

Figure 2. Solar-assisted ground source heat pump [24]

3.2 ETHE Classified according to buried tubes configuration.

1. The single tube is shown in Fig. 3-a.
2. multi-tubes as shown in Fig. 3-b.

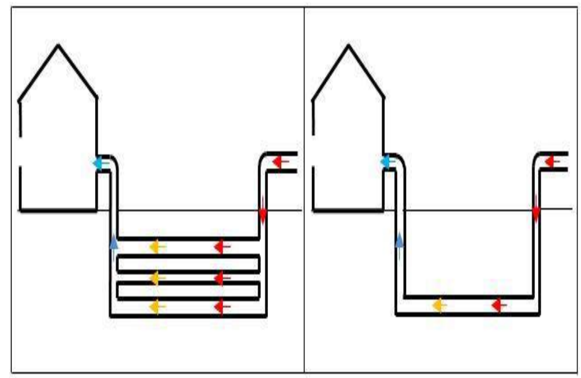

Figure 3. (a) Single tubes and (b) multiple tubes ETHE [25]

3.3 ETHE classified according to the buried tubes assortment:

1. Vertical ETHE as shown in Fig. 4-a.
2. Horizontal ETHE as shown in Fig. 4-b.

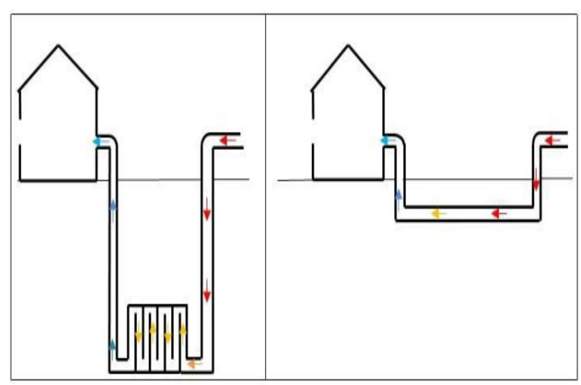

Figure 4. (a) Vertical and (b) horizontal ETHE [23]

4. Advantages and disadvantages of ETHE

The earth tube heat exchanger has the following benefits:

- Can work with a different type of soil.
- For fully buried ETHE, the outlet air temperature relies on the inlet air temperature only.
- The simplicity of and installation.
- Air is used as a working fluid.
- Requires less maintenance with lower costs.
- In case of high wind speed, does not need for its operation.
- As a result of the absence of any combustion source, no pollution or greenhouse gases [25].

Although of these benefits, it has the following disadvantages:

- The cost of installation is high.
- Decreased indoor air quality due to the phenomenon of condensation inside the heat exchanger in addition to the possible development of micro-organisms.
- Non-uniform outlet air temperature; and
- The thermal performance of ETHE is directly affected by local climatic conditions in presence of the upper parts of the heat exchanger on the surface of the earth [25].

5. Operative Conditions and Optimization Parameters

When designing the ETHE, it is analysed influential parameters on heating and cooling processes like the length of ETHE, diameter, air velocity, and burial depth of ETHE. These parameters affect:

- Outlet air temperature.
- The absolute difference in temperature between outlet and inlet of ETHE.
- ETHE efficiency, is the ratio between span ETHE temperature and ideal temperature difference.

6. Factors Affecting the ETHE Systems Thermal Performance

- Airflow.
- Site characteristics.
- Soil characteristics.
- Geographic location.
- Climatic conditions.
- Relative humidity [26].
- Pipe Materials: for manufacturing ETHE pipes, steel was used at the beginning. After experiments and research were found that PVC gives good performance with low cost and long use [26,27]. Despite the high thermal conductivity of steel as compared to PVC, the difference in outlet air temperature is small. So, it can be concluded that heat transfer by convection does not play a substantial role in conduction.
- Tube Length: the length of the ETHE tube is important and it must determine the effective length, where the short length isn′t give the required performance that increasing the length after a certain length is not give improvement. According to researchers [28] length of about 10 m is unsatisfying and a length over 70 m isn't give important benefits for all climates.
- Burial depth: soil temperature is varied with weather fluctuations, but it is fixed at a certain depth throughout the year (undisturbed subsoil temperature). After 1.5 m depth, the soil temperature is start to stable, so the burial depth taken must be more than that.
- The velocity of Air inside Pipe: according to researchers [26,27] increasing the velocity from 2 to 5 m/s led to an increased heat transfer coefficient of about 2.3 times, while the duration of air contact with the ground is reduced by 2.5 times.

7. Conclusions

It is necessary to move towards clean energy sources to meet the demand for energy and preserve the environment. ETHE can be used in heating and cooling for residential applications, greenhouses poultry houses and in desert areas, etc. Earth tube heat exchanger is an environmentally, sustainable, and passive technique that doesn't consume energy employed for about 3000 years B.C for conditioning arid regions [29]. ETHE is based on renewable energy sources, which means reducing carbon dioxide emissions that affect the ozone layer which results from the utilization of conventional air conditioning systems. ETHE is a simple device and have good efficiency for heat transfer for heating and cooling purpose. It can be concluded that the good design of ETHE gives to reach better cooling and heating efficiency. Undisturbed subsoil temperature is an important parameter for the installation of ETHE. Length, diameter, the material of pipes, thermal properties of the material, burial depth, and soil characteristics are other important ETHE parameters. After 1.5 m depth, the soil temperature is start to stable, so the burial depth taken must be more than that. The length of the ETHE tube is important and it must determine the effective length, where a short length isn’t giving the required performance and increasing the length after a certain length isn’t given improvement. length of about 10 m is unsatisfying and a length over 70 m isn’t given important benefits for all climates. The velocity from 2 to 5 m/s leads to an increase in heat transfer coefficient of about 2.3 times, while the duration of air contact with the ground is reduced by 2.5 times. It can be also concluded that heat transfer by convection does not play a substantial role as conduction.

Authors’ contribution
All authors contributed equally to the preparation of this article.

Declaration of competing interest
The authors declare no conflicts of interest.

Funding source
This study didn’t receive any specific funds.

Acknowledgements

The authors wish to express their appreciation to Mustansiriyah university college of Engineering Mechanical department and Al-Qadisiyah university for their support of scientific research efforts.

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