Analysis of working parameters affecting the performance of Earth-air tube heat exchanger (EATHE): A review

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Abstract – *One of the major concerns of an ideal air conditioning system is to provide enough comfort levels within the building. Moreover, the last few years have been an explicit example of the increased per capita energy consumption. This significant plunge has not only added to improved living standards but it also threatens the subsistence of human resources due to heavy reliance on conventional sources of energy to meet the regular energy demands. Hence it becomes crucial to explore and utilize nonconventional energy resources which prove to be clean, inexhaustible, easily exploitable and most importantly sustainable. Thus, several methods of passive air conditioning being developed in the present era such as ground cooling, nocturnal radiative cooling(NRC) prove to be an efficient as well as economic solution to the persisting problem of limited conventional energy resources. Moreover, earth as a heat source and heat sink is a well studied subject and is one of the fastest growing applications of renewable energy in the current worldwide scenario. Hence the aim of this study is to investigate the effect of various working parameters such as pipe length, material, depth of burial, air flow rate and several other factors that contribute to the proper functioning of an earth air tube heat exchanger and to bring in light the further advancements that could be made to enhance the thermal performance of EATHE systems.*

***Key Words*: EATHE, conventional energy resources, passive air conditioning, NRC, thermal performance**

1. INTRODUCTION

With regards to the continuous depletion of nonconventional energy resources and the excessive rate of greenhouse gas emissions, it has become imperative and urgent to look out for alternative sources to mitigate the widespread use of conventional fuel. This diversification of energy resources has captured the attention of many researchers and scholars to contribute towards development of much cleaner and sustainable energy sources. Earth air tube heat exchanger is one such major outcome.

Earth air tubes are often a viable and economical alternative or supplement to conventional central heating or air conditioning systems since there are no compressors, chemicals or burners and only blowers are required to move the air. These are used for either partial or full cooling and their use can help building meet passive house standards. In the case of cooling a building, the ground is the heat sink, and the building to be cooled acts as heat source. In the case of heating, these functions are reversed-the ground becomes the heat source and the building heat sink. Heat is extracted from or rejected to the ground by means of buried pipe, through which a fluid flows. This buried pipe is commonly called ground loop heat exchanger [1].

The basic principle behind the functionality of EATHE system is the "near constant" ground temperature which is achieved at certain depth of the earth's surface. Because of the relatively high thermal inertia of the ground, temperatures in the ground lag those at the surface, and their fluctuations decrease with depth below grade; moreover, soil temperature gets closer to the mean annual ambient air temperature with increasing depth. This raises the possibility of using the ground for heating air when ambient temperatures are lower than the ground temperature and cooling air when they are higher. However, such systems have faced many restrictions, when the consumers reject more heat than they extract over the annual cycle and hence the size of the ground heat exchangers is increased. To avoid the problem of oversized EATHE setup and to increase their efficiency, a hybrid ground-coupled cooling system can also be used.

2. Types of Earth air tube heat exchangers

There are two general types of earth air heat exchangers: open and closed. In open systems, ambient air passes through tubes buried in the ground for preheating or pre-cooling and fresh fluid is circulated through the ground loop heat exchanger. This system provides ventilation while hopefully cooling or heating the building's interior. In closed systems, both the ends of the pipe are kept inside the control environment, which can be a room in case of air and a tank in case of water, the system is said to be closed loop because the same fluid is passed continuously over and over through the loop [1]. The subsections provided below briefly discuss the highlights of both open and closed EATHE systems:

2.1 Open-loop system:

This type of system uses wells or surface body water as the heat exchange fluid which circulates directly through the ground heat pump (GHP) system. Once it has circulated through the system, the water returns to the ground through the well, a recharge well, or surface discharge. This option is practical only where there is an adequate supply of relatively clean water, and all local codes and regulations regarding groundwater discharge are met. This system is usually used for larger installations.

2.2 Closed-loop system:

This type of system uses heat exchangers that are located underground, either in horizontal or vertical position and a heat carrier medium is circulated inside the heat exchanger within a closed loop. It transfers heat from the ground to a heat pump or vice versa [2]. The following figures illustrate the above mentioned EATHE systems:

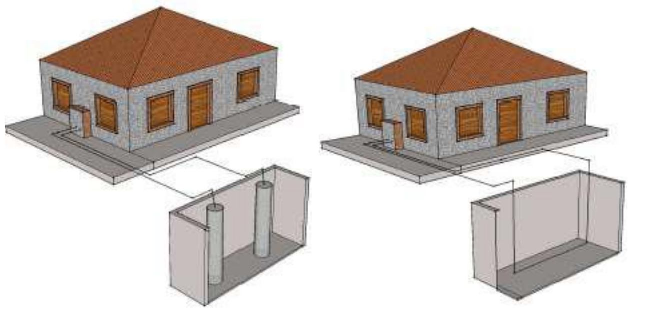

Fig.1 An open loop EATHE setup and a closed loop EATHE setup

3. EATHE systems and the related models

The temperature distribution of earth is divided in three zones the ground, the first zone is surface zone (up to a depth of approximately 1m), the second zone is shallow zone (ranging from 1m to 20m) and the third zone is the deep zone (beyond 20m) having constant temperature around the year [3]. It is suggested that for effective utilization of heat capacity of the earth we need to design a heat-exchanger system which comprises of an array of pipes vertically buried in deep zone and running along the length of the building. Hence, several calculation models are discussed for ground heat exchangers. One-dimensional models were devised in the first stages which during the nineties were replaced by two dimensional models. In the recent researches three-dimensional systems are being considered and are even worked on. Sodha et.al. [4] have carried out rigorous experimental studies with a large earth-to-air heat exchanger system situated at Mathura, India. These models were based on several assumptions such as axially symmetric flow, constant pipe wall temperature, negligible humidity variations etc. Moreover, earth-air heat exchanger in these studies was analysed independent of the effects of variations in ground temperature.

Mihalakakou et.al. [5] presented a complete model for the prediction of the daily and annual variation of ground surface temperature. The model used a transient heat conduction differential equation and an energy balance equation at the ground surface to predict the ground surface temperature. The energy balance equation involved the convective energy exchange between air and soil, the solar radiation absorbed by the ground surface, the latent heat flux due to evaporation at the ground surface as well as the long-wave radiation. The model was validated against 10 years of hourly measured temperatures for bare and short-grass covered soil in Athens and Dublin. The results were compared with the corresponding results of models using Fourier analysis. Furthermore, a sensitivity investigation was performed to investigate the influence of various factors involved in the energy balance equation at the ground surface on the soil temperature profile.

Bojic et al. [6] developed a model in which the soil was divided into horizontal layers with uniform temperature. All the pipes were placed in one layer at the same depth and parallel to each other. The heat was transported to the soil by convection from the air and the solar radiation was calculated. Moreover, an equation describing the heat flow between the air flow in the pipe and the neighbouring soil layer was used. All equations used for the soil layers in each time step, were steady state energy equations. This model was a 2-dimensional model therefore the influence that pipes had on each other was not evaluated.

Fabrizio Ascione et al. [7] conducted experiments at three different cities of Italy and evaluated the performance for ground heat exchanger in both summer and winter seasons. He concluded that the ground heat exchanger placed in the wet soil gave the better results than the other two. He used different materials like PVC, metal and concrete for tube construction and concluded that material type has no effect on the performance of the ground heat exchanger.

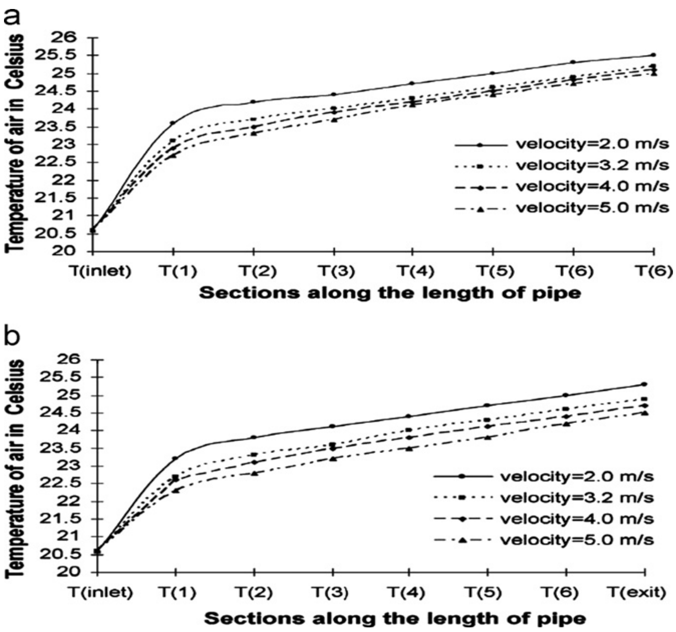

Fig.2. Simulated temperatures along the length of the pipe for various exit velocities for (a) steel pipe and (b) PVC pipe

Manoj Kumar Dubey et.al. [8] performed experiments on earth air heat exchanger system and investigated the results for parallel connection in the summer climate. The experimental result indicated that the temperature difference between inlet and outlet of the pipe at a depth of 1.5 m varied from 8.6 to 4.18 °C at a velocity of 4.1 to 11.6 m/s. He also found that the COP in the parallel connection varied from 5.7 to 2.6 for velocity of 4.16 to 11.2 m/s respectively.

Trilok Singh Bisoniya et.al. [9] had developed a quasi-steady state, three-dimensional model for simulation of earth-air tube heat exchanger (EATHE) system. CFD platform CFX 12.0 was thereby used for development of the simulation model of EATHE system. The simulation results were compared against experimental results obtained from experimental set-up installed at Bhopal (Central India) where a good agreement was found between simulation and experimental results. Thus, he carried out a detailed analysis to examine the effect of length of pipe, radius of pipe, mass flow rate of air and burial depth on the performance of earth air heat exchanger system for summer cooling. He buried a longer pipe of smaller diameter at higher depth and having lower mass flow rate of air which resulted in decrease in outlet air temperature of EATHE system. It was found that the outlet air temperature decreased at faster rate for first 10m length of pipe and became constant afterwards. So, it was concluded that increasing the pipe length more than 20-30m did not cause any significant increase in performance. The results also clearly portrayed the fact that burial depth of pipe and mass flow rate of air have more influence on thermal performance of EATHE system than pipe diameter and length.

Ozgener and Ozgener [10] reported the exergetic performance characteristics of an underground air tunnel system for greenhouse cooling. The data used were obtained from the measurements made in a system, which was designed and installed in the Solar Energy Institute of Ege University, Izmir, Turkey. Ozgener and Ozgener [11] also determined the optimal design of a closed loop EATHE for greenhouse heating by using exergoeconomics. The results so obtained displayed that the losses in blower and heat exchanger are primarily responsible for exergy destructions in the system. The values of COP and exergy efficiency were found 10.51 and 89.25%, respectively, which were determined to improve the system performance. It is shown in the paper that how the use of simple thermoeconomic optimization methodologies can contribute to find out the accurate design of new equipment.

Ajmi et al. [12] studied the cooling capacity of earth–air heat exchangers for domestic buildings in a desert climate. A sub-soil temperature model adapted for the specific conditions in Kuwait was presented and its output was compared with measurements in two locations. Simulation results showed that the EATHE could provide a reduction of 1700W in the peak cooling load, with an indoor temperature reduction of 2.81°C during summer peak hours (middle of July).

Khalajzadeh et. al. [13] carried out thermal performance analysis of ground heat exchanger and evaporative cooler hybrid system in summer conditions of Tehran, Iran. It concluded that the hybrid system gives cooling effectiveness more than unity and causes significant reduction in air temperature well below the ambient wet-bulb temperature. The hybrid system is thereby capable to replace the conventional air-conditioner effectively.Pfafferott.et.al [14] presented a study about evaluation of earth-to-air heat exchangers with a standardized method to calculate energy efficiency. The author studied about temperature behaviour, energy gain, general efficiency and thermal efficiency.

On basis of extensive monitoring and simulation work, Hollmuller and Lachal [15] examined the fundamental difference between winter preheating and summer cooling potential of buried pipe systems under Central European climate, from an energetic as well as an economic point of view. Hamada et al. [16] described experiments and analysed on an improved underground heat exchanger by using a no-dig method for the purpose of the cost reduction of a space heating and cooling system using underground thermal energy.

Breesch et al. [17] presented that in office buildings, the use of passive cooling techniques combined with a reduced cooling load may result in a good thermal summer comfort and therefore save cooling energy consumption. This was verified in the low-energy office building SD Worx in Kortrijk (Belgium), in which natural night ventilation and an earth-to-air heat exchanger were applied. He evaluated that passive cooling has an important impact on the thermal summer comfort in the buildings. Furthermore, natural night ventilation appears to be much more effective than an earth-air heat exchanger to improve comfort.

4. Factors affecting thermal performance of EATHE systems

The performance of earth-air tube heat exchanger is predominantly governed by various factors such as pipe length, pipe diameter and its material, depth of pipe burial, air flow velocity, site location and soil characteristics. The EATHE system if properly designed can be feasible and economical option to replace conventional air-conditioning systems. Hence, appropriate information of physical and thermal properties of soil (diffusivity, density, thermal conductivity, etc.), depth of bedrock, type of soil and other parameters is crucial as well as primary as it guides the designer in choosing correct type of EATHE system and in the design of that system. The subsections provided below discuss the major parameters which largely influence the thermal functioning of heat exchangers:

4.1 Design and geometric blueprint of pipe material:

Over the years various analytical and numerical models of varying complexity have been developed and used as design and research tools. Among other things, they can be used to predict the heat transfer mechanism inside a borehole, the conductive heat transfer from a borehole and the thermal interferences between boreholes. Some of the most noteworthy numerical models include the work of Eskilson and Claesson (1988), Muraya (1994), Zeng et al. (2003) and Al-Khoury et al. (2005; 2006).

Misra et al. [18] developed a transient and implicit numerical model based on coupled simultaneous heat transfer and turbulent flow, to conduct the study on the effect on time duration of continuous operation, thermal conductivities of soil pipe diameter and flow velocity on thermal performance of earth air tunnel heat exchanger (EATHE) system. Three different pipe diameters were chosen; 0.10m, 0.15m, and 0.20m and the air flow velocity was kept constant to investigate the effect on transient performance of EATHE system to work in long continuous operation. Based on the result, thermal performance of EATHE system with larger pipe diameter had dropped faster after 24h of continuous operation especially the pipe length which are 20m or less from the inlet. Other than that, pipes with smaller diameter and pipe length are beyond 30m experiencing less deterioration in thermal performance.

Pohstiri et al. [19] had developed a mathematical model based on energy conservation equations and solved by iterative method to study the capability of the solar chimney and earth air heat exchanger system to meet the thermal needs of individuals and also the dependence of the system performance on environmental and geometrical issues. Based on the results, EATHE pipe lengths of less than 35m should be used to provide a better thermal comfort condition. Other than that, the result of the effect of EATHE pipe diameter on system performance reveals that the increase of the EAHE diameter up to 0.5m does not increase the room air temperature.

Ahmed et al. [20] developed a thermal model to compare the earth pipe cooling performance between two different piping systems for a hot and humid subtropical climatic zone in Queensland, Australia using ANSYS Fluent. Vertical earth piping cooling VEPC system and horizontal earth piping cooling HEPC systems were laid in the ground in order to compare the cooling performance. The developed model was validated at the pipe inlet and different points of the room with the measured data. The inlet air velocity and air temperature were set at the pipe inlet to predict their effect on the room temperature. The simulation result led to results that the minimum temperature reductions of approximately 1.82 °C and 1.02 °C in the modelled room of vertical and horizontal earth pipe cooling system, respectively. Based on the results, the vertical earth pipe cooling system was better than the horizontal earth pipe cooling system even though there were no large temperature reductions found for both systems.

Recent studies have shown that increasing the depth of burial of the EATHE pipes makes the outlet air temperatures of EATHE systems to increase in winter and decrease in summer whereas for the pipe diameter, an increase in diameter resulted in lower thermal performance in the EATHE systems. This is caused by the decrease in the heat transfer from earth or lower convective heat transfer coefficient due to increase of pipe surface and slower air flow. However, the increase of pipe length does increase the thermal performance of EATHE system only until certain length of the pipe.

4.2 Pipe material

One of the major factors affecting the performance of EATHE is the material of so chosen pipe. Usually the pipe material is selected based on availability and cost. The materials of higher thermal conductivity have higher heat transfer rate, and therefore can reduce the buried pipe outlet temperature more efficiently.

Bansal et al. [21] studied the EATHE system performance during winter in Ajmer (Western India). The pipes were buried at a depth of 2.7m in a flat land with dry soil. They experimented on steel and PVC pipe materials with the air velocity ranging from 2-5m/s which flowed through 23.42m length of 150mm diameter pipe. The result showed that the system gives heating in the range of 4.4-4.8°C. In another study, Bansal et al. [25] further analysed the EATHE system performance using CFD simulation during summer with similar parameters and showed that the system gives a cooling range of 8-12.7°C in reduction compared to the ambient temperature. He concluded that the performance of EATHE system is not affected by the material, therefore the cheaper material may be used to construct the pipe.

Hatraf et al. [22] investigated the parameters influencing the performance of earth to air heat exchanger through modelling and experimentation. They did the calculation using a simple model the distribution of the air temperature and varied several parameters such as nature of the ground and the ground depth diameter of the duct. One of their finding was that the pipe material has no effect on the performance of the heat exchanger, which was in agreement with previous results.

Aliyah et al. [23] studied the materials for the EATHE system using computer simulation to find the best pipe material for the same for the hot and humid climate in Malaysia. The study utilized the Energy Plus environmental simulation program to investigate the performances of three pipe materials system; which includes single pipe material, hybrid pipes (combination of pipe materials) and insulated hybrid pipes system (combination of pipe materials with insulation). It was found that for single pipe material polyethylene (PE) had the maximum temperature reduction followed by steel (St), copper (Cu) and polyvinyl chloride (PVC). Through an exhaustive enumeration process, the study found that the insulated hybrid pipes system gave the best temperature reduction. It also concluded that the choice of the pipe material does not have any significant consequence on the temperature reduction by the EATHE system in hot and humid climate.

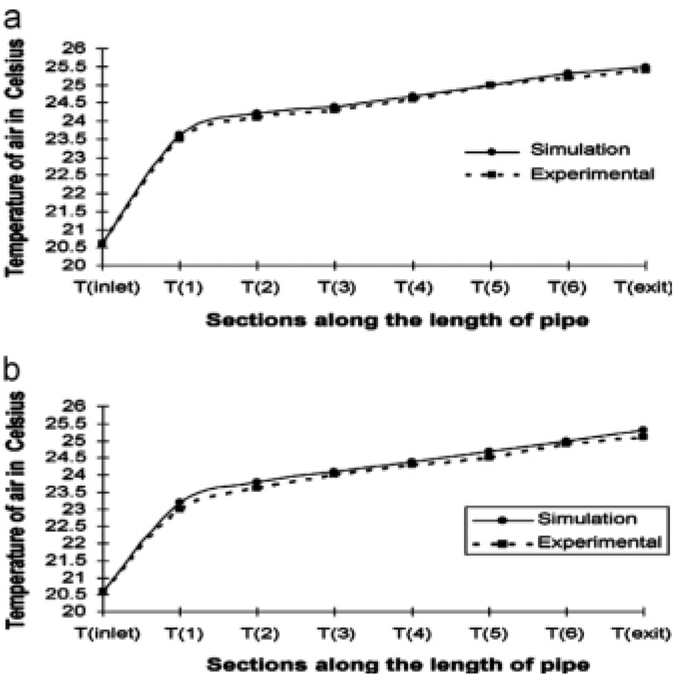

Fig.3 Temperature distribution along the length of the pipe for exit velocity 2.0 m/s for (a) steel pipe and (b) PVC pipe.

Serageldin et al. [24] studied the thermal performance of an earth air heat exchanger (EATHE) used for heating and cooling under the Egyptian weather conditions. They had developed a mathematical model based on unsteady, one-dimensional, quasi-state for energy conservation equation, and also a three dimensional, steady and double precision Computational Fluid Dynamics(CFD) ANSYS Fluent simulation model that was established to predict the air and soil temperature. A parametric study was done to investigate the impact of different parameters such as pipe diameter, pipe material, pipe space, pipe length and flowing fluid velocity. Three different types of pipe materials were used, namely PVC, steel and copper. The outlet air temperature was 19.7°C in PVC pipe, and 19.8°C for both steel and copper respectively. Therefore, it was concluded that the change in outlet air temperature for various pipe material is too small and hence negligible.

4.3 Air flow

The impact of different air velocities was analysed through a number of studies whose results have been summarized below.

It is found that the increase in mass flow rate of air leads to the decrease and increase of the greenhouses air temperature in the winter and summer, respectively. This may be caused by the air that has a shorter time in contact with the soil, causing lower thermal exchange rate between soil and air.

Misra et al. [25] developed a transient and implicit numerical model based on coupled simultaneous heat transfer and turbulent flow to conduct the study on the effect on time duration of continuous operation, thermal conductivities of soil pipe diameter and flow velocity on thermal performance of earth air tunnel heat exchanger EATHE system. Three different velocities were chosen; 2.0m/s, 5.0m/s, and 8.0m/s and the pipe diameter were kept at 0.1m for all different flow velocities to investigate the effect on transient performance of EATHE system to work in long continuous operation. From the result, the increase in flow velocity caused the thermal performance of EATHE system to deteriorate. This is because when the flow velocity increases, the amount of heat is transferred to the soil from air per unit time also increases.

Comparison of experimental and simulated temperature at different sections along the length of steel pipe.

Section	Air velocity = 2 m/s			Air velocity = 3 m/s			Air velocity = 4 m/s			Air velocity = 5 m/s		
	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.
T_{inlet}	43.7	43.7	0.00	43.5	43.5	0.00	43.1	43.1	0.00	43.6	43.6	0.00
T_1	36.2	35	3.31	37.1	35.9	3.23	38.2	36.5	4.45	38.8	37.4	3.61
T_2	34.7	33.1	4.61	35.5	33.9	4.51	36.7	34.3	6.54	37.3	35.2	5.63
T_3	33.6	32	4.76	34.5	32.8	4.93	35.5	33.3	6.20	36.5	34.1	6.58
T_4	32.8	31.1	5.18	33.7	31.9	5.34	34.4	32.4	5.81	35.5	33.1	6.76
T_5	32	30.4	5.00	33	31.1	5.76	33.7	31.6	6.23	34.6	32.1	7.23
T_6	31.4	29.3	6.69	32.4	29.9	7.72	33	30.3	8.18	34.1	31	9.09
T_{exit}	31	28.6	7.74	32	29.2	8.75	32.5	29.5	9.23	33.7	30.2	10.3

Comparison of experimental and simulated temperature at different sections along the length of PVC pipe.

Section	Air velocity = 2 m/s			Air velocity = 3.0 m/s			Air velocity = 4 m/s			Air velocity = 5 m/s		
	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.
T_{inlet}	43.4	43.4	0.00	42.5	42.5	0.00	42.3	42.3	0.00	42.2	42.2	0.00
T_1	37.4	35.8	4.28	38	36	5.26	38.2	36.5	4.45	39.3	37	5.85
T_2	35.8	34.1	4.75	36.5	34.7	4.93	36.8	35.4	3.80	37.9	35.9	5.28
T_3	35	33	5.71	35.7	33.7	5.60	35.8	34.4	3.91	37	34.9	5.68
T_4	34.3	32	6.71	34.8	32.8	5.75	34.9	33.5	4.01	36.1	34.1	5.54
T_5	33.7	31.2	7.42	33.7	32	5.04	34	32.7	3.82	35.3	33.3	5.67
T_6	33.3	30	9.91	33.3	30.7	7.81	33.7	31.4	6.82	34.8	32	8.05
T_{exit}	33.1	29.3	11.4	33.1	29.7	10.2	33.5	30.6	8.66	34.2	31.1	9.06

Based on the recent studies conducted on the effect of air flow velocity in EATHE systems, it is found that the increase of air velocity leads to the decreasing thermal performance. This is caused by the shortened time in contact between air and the ground where the heat from the air has not enough time to achieve thermal equilibrium with the ground.

4.4 Nature of Soil

The performance EATHE is based upon the seasonally varying inlet temperature, and the tunnel-wall temperature which further depends on the ground temperature. Hence thermal performance of EATHE system indirectly depends upon the temperature and moisture distribution in the ground, as well as on the surface conditions.

Soils saturated in water are better from a thermal point of view; greater depths are thus preferable since they provide higher temperatures in winter and lower temperatures in summer; smaller pipes are more thermally efficient, i.e. they result in a higher heat exchange per unit volume of air; however, they cause greater pressure losses and require larger installations.

Bansal et al. [26] conducted study on the effect of thermal conductivity of soil on thermal performance of earth air tunnel heat exchanger under transient operating conditions in predominantly hot and dry climate of Ajmer (India) using experimental and computational fluid dynamics modelling with FLUENT software. From the result, maximum air temperature drops obtained under steady state operation of EATHE for pipe length 100m was 18.4°C, 18.7°C and 18.4°C for soil thermal conductivity of 0.52, 2.0 and 4.0Wm-1K-1 respectively. However, the maximum air temperature drops under transient conditions for 24 hours of operation varied between 18.3°C and 14.0°C, 18.3°C and 17.2°C and 18.6°C and 18.0 °C for soil thermal conductivity of 0.52, 2.0 and 4.0Wm-1 K-1 respectively.

This was due to higher soil thermal conductivity which resulted into better thermal performance of EATHE system under transient conditions, even after longer period of operation.

Ahmed et al. [27] conducted an experimental study of thermal and moisture behaviours of dry and wet soils heated by buried capillary plaits. A prototype, which was similar to an agricultural tunnel greenhouse was used to carry out the experiment. There were three different operational conditions of the capillary plaits: heating at 70°C, heating at 40°C and without heating in summer, in order to understand the greenhouse climate effect on soil behaviour. It was revealed that, in unsaturated moist soils the transport of heat was complicated by the fact that heat and mass transfer is a coupled process. It was found that the surface temperature amplitude was higher in wet soil compared to dry soil during the daily soil temperature variation. Even though thermal diffusivity in wet soil was higher than in dry soil, the wet soil surface temperature was higher during daytime.

The above studies show that thermal conductivity of soil generally affect the outlet air temperature of EATHE system. Thus, higher the thermal conductivity of soil higher will be the thermal performance of EATHE system.

5. CONCLUSIONS

This paper provides a review describing the utility of earth-air tube heat exchangers. Different models such as one, two and three-dimensional models can be found in the paper that simulate the heat transfer process. Various mathematical models or simulation may be used for sizing and predicting the performance of earth-air tube heat exchangers. It can be concluded through many studies mentioned in the paper that that pipe material doesn't affect the performance of EATHE much whereas the air flow rate and ambient air temperature affect the performance of EAHE greatly.

One of the major reasons behind no recognition of EATHE systems even today is lack of knowledge of how to design an efficient system besides the other related disadvantages like poor air quality with prolonged use, higher setup cost, growth of harmful microorganisms, and so forth. Hence, the need of the hour is to generalize the use of EATHE systems so that the use of renewable and sustainable energy technologies can be promoted.

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