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Transient effect of soil thermal diffusivity on performance of EATHE system

Anuj Mathur[a,*], Ayushman Srivastava[b], Jyotirmay Mathur[a], Sanjay Mathur[a],
G.D. Agrawal[a]

[a] *Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur-302017, India*
[b] *Civil Engineering Department, Malaviya National Institute of Technology, Jaipur-302017, India*

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ABSTRACT

This paper presents effect of thermo-physical properties of soil on performance of an Earth Air Tunnel Heat Exchanger (EATHE). The analysis has been carried out using a validated three-dimensional, transient numerical model for three different types of soil. The governing equations, based on the k–ε model and energy equation were used to describe the turbulence and heat transfer phenomena, are solved by using finite volume method. Comparisons were made in terms of temperature drop, heat transfer rate and COP of the EATHE system by operating it continuously for 12 h duration. The study reveals that each soil exhibits different rate of heat dissipation and thermal saturation over a period of continuous operation, which adversely affects the performance of EATHE. Dissipation of heat from the EATHE pipes to its surrounding soil and subsequently to the outer subsoil region is mainly found to be depending upon the thermal conductivity of soil; even of their thermal diffusivity is of different order.

1. Introduction

Passive heating/cooling systems consume no or very less energy as compared to active heating and cooling systems. In order to utilize these passive heating/cooling systems with great heat capacity and high thermal inertia, many techniques have been developed in the last decades such as earth air tunnel heat exchanger. The earth air tunnel heat exchanger system is one of the important energy efficient ways to provide both space heating and cooling because of very small variation of soil temperature viz-a-viz ambient air temperature throughout the year. This facilitates extraction or rejection of heat from the building space to the subsoil region.

Over the last decade, a number of performance analyses on earth air tunnel heat exchanger systems have been carried out to improve and enhance its thermal performance, either using numerical modeling or via experiments. Thermal performance of earth air heat exchanger system were studied (Bansal et al., 1985; Ajmi et al., 2006; Thanu et al., 2001) to provide thermal comfort inside the buildings in India using ground as heat source and sink. Study conducted by Santamouris et al. (1995) revealed that increment in the length of buried-pipe and soil height above the pipes resulted in an increase in the system cooling capacity. An EATHE system integrated with evaporative cooler (Bansal et al., 2012) and air conditioner (Said et al., 2010) provides 4500 MJ of cooling effect during summer months and 18.1% (Mishra et al., 2012) reduced power consumption of air conditioner respectively. It can be concluded from previous studies that EATHE systems have a potential to provide cooling effect.

Due to the improvement in numerical technique various researchers tried to explore the effect of various design, operating and geographical parameters on to the thermal performance of EATHE, such as effect of the pipe length, radius, depth and air flow rate (Huijun et al., 2007), installed depth variation (Cucumo et al., 2008). Further, effects of ground temperature gradient, surface conditions, moisture content, have also been identified as important design aspects of earth air tunnel heat exchanger (Kumar et al., 2003), along with effect of length, radius of pipe and air mass flow rate (Sodha et al., 1993) on the cooling potential of an underground air pipe system.

Study on the effect of soil thermal conductivity (Bansal et al., 2013) on to the thermal performance of EATHE system revealed that thermal performance of the system influenced by the thermal conductivity of the system but author assumes thermal conductivity values taking specific heat and density same for

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[*] Corresponding author.
E-mail address: anujmathur89@yahoo.com (A. Mathur).

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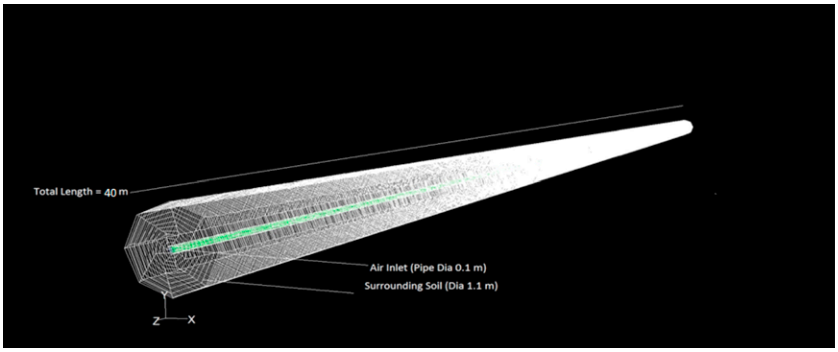

Fig. 1. CFD model of EATHE.

all three cases of soil. An improved theoretical model (Ozgener et al., 2013) that includes short term weather variations, seasonal variations, moisture content and thermal conductivity of soil was presented to predict the daily soil temperatures variation with depth and time. A three dimensional numerical model (Eicker and Vorschulze, 2009) was used to analyze the influence of soil properties and operation strategies. Numerical results of this study suggest that the heat dissipation mostly depends upon the soil thermal conductivity.

However, it may be noted that despite having same thermal conductivity, soils may have different thermal diffusivity due to change in density and specific heat.

This paper presents analysis carried out on three different soils with different thermal diffusivity values. Out of the three, two soils were having very close values of thermal conductivity but significantly different thermal diffusivity values. Three dimensional simulation software package, FLUENT 6.3, was used to analyze the thermal performance of EATHE. Evaluation has been carried out through studying the temperature drop of air, heat transfer rate and COP for the EATHE system.

2. System description and simulation setup

The CFD simulations were performed with the commercial CFD code Fluent 6.3 and the use of preprocessor Gambit 2.2 for the geometry and 3D mesh creation to investigate the effect of thermal diffusivity on to the thermal performance of EATHE system.

2.1. *Physical model*

Description of the geometrical configuration of earth air tunnel heat exchanger and surrounding soil is presented in Table 1. Physical geometry (Fig. 1) of the EATHE system consists of 40 m long HDPE pipe with 0.1 m outer diameter. The control volume was defined through creating a cylinder volume of soil around the EATHE pipe. Diameter of soil cylinder was kept 1.1 m, geometry was created using Gambit (version 2.2.3) as preprocessor. Structured hexahedral meshing (Fig. 1) was used. Numerical simulations were tested by varying the number of elements of mesh and stability of convergence of the model was achieved for all the meshes.

2.2. *Simulation model*

FLUENT (version 6.3) software was used in this study that uses finite volume method to convert the governing equations to numerically solvable algebraic equations. As the flow is turbulent, k–ε model is selected as turbulent model for analysis of the problem. Energy equation is also kept ON as a heat transfer model. This numerical investigation was based on the following assumptions:

1. Thermal–physical properties of solids and fluids remains constant over the range of soil and air temperature during operation.

Table 1
Geometrical and simulation parameters.

Parameters	Unit	Value
EATHE pipe length	m	40
Pipe Outer diameter	m	0.1
Surrounding soil diameter	m	1.1
Air density	$(\mathrm{kg\ m^{-3}})$	1.225
Air thermal conductivity	$(\mathrm{W\ m^{-1}\ K^{-1}})$	0.02
Air specific heat capacity	$(\mathrm{J\ kg^{-1}\ K^{-1}})$	1006
HDPE Pipe density	$(\mathrm{kg\ m^{-3}})$	940
HDPE thermal conductivity	$(\mathrm{W\ m^{-1}\ K^{-1}})$	0.4
HDPE specific heat capacity	$(\mathrm{J\ kg^{-1}\ K^{-1}})$	2000
PVC pipe density	$(\mathrm{kg\ m^{-3}})$	1380
PVC thermal conductivity	$(\mathrm{W\ m^{-1}\ K^{-1}})$	1.16
PVC specific heat capacity	$(\mathrm{J\ kg^{-1}\ K^{-1}})$	900
Soil density	$(\mathrm{kg\ m^{-3}})$	2050
Soil specific heat	$(\mathrm{J\ kg^{-1}\ K^{-1}})$	1840
Soil thermal conductivity	$(\mathrm{W\ m^{-1}\ K^{-1}})$	0.52

Table 2
Boundaries conditions.

Boundaries	Unit	Value
Initial soil temperature	°C	27
Initial pipe temperature	°C	27
Air inlet velocity	$\mathrm{m\ s^{-1}}$	5
Air inlet temperature	°C	46.2

2. Inlet air velocity was constant throughout the operation of tunnel.

The far-field boundaries were treated as adiabatic wall and EATHE pipe wall and surrounding soil temperatures were initialized with 27 °C as shown in Table 2. Velocity inlet boundary condition was specified for the inlet air velocity i.e. 5 m/s and a ‘pressure outlet’ condition for the outlet for the air.

3. Grid independence test

Grid independence test (Fig. 2) was to be conducted to assess the quality of developed CFD model. If the mesh is refined (i.e. the cells are made smaller in size hence larger in number), then the behavior observed by the post processing should remain unchanged if the solution is grid-independent. To have grid independent solution, simulations are run for two grid sizes i.e. 0.04 m and 0.03 m taking operating parameters same for both cases.

It can be concluded from Fig. 2 that there is no or minimum effect on the operating parameters when we change the grid size from 0.03 m to 0.04 m. Therefore, 0.04 m element size was chosen as the model grid size as it gives better accuracy and lesser computational time.

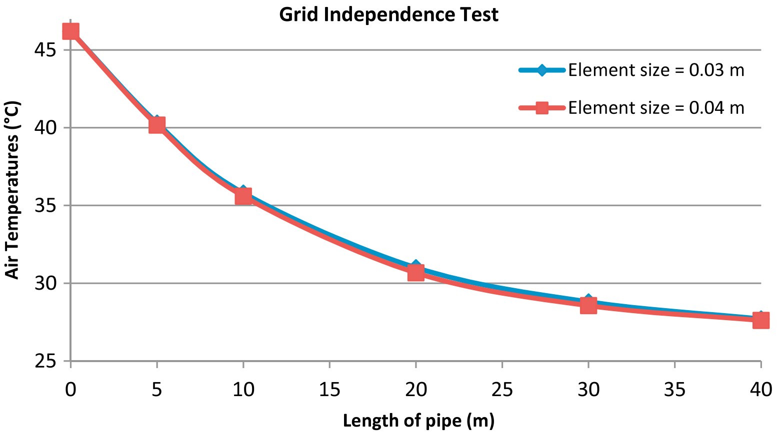

Fig. 2. Grid independence test.

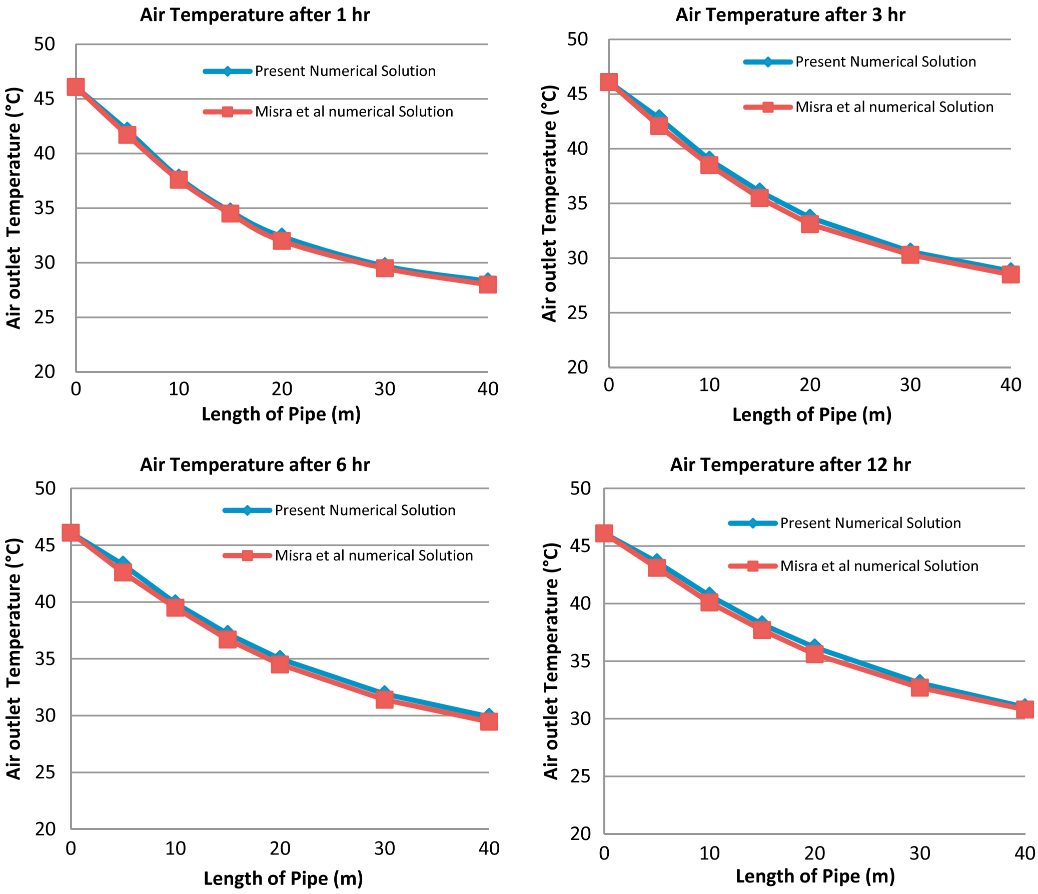

Fig. 3. Air outlet temperature comparison between numerical solutions.

4. Validation of CFD model

The developed CFD model was validated against the numerical solution obtained by Mishra et al. (2013), which were experimentally verified and reported. Maximum difference in temperature at various points in the two studies was found to be 0.72 °C, whereas, for most of the points, temperatures were having same value as shown in Fig. 3. This shows good agreement between the two numerical solutions.

5. Selection of soil for analysis

Three soils were selected with significant difference in their soil thermal diffusivity as mentioned in Table 3. Soil 'J' and 'F' were selected for significantly different thermal diffusivity and very close thermal conductivity. This was done to investigate role of thermal diffusivity as well as thermal conductivity on performance of EATHE.

6. Results and discussion

Thermal performance of EATHE was numerically investigated for three different soils to examine the effect of thermo-physical properties of soil on to its thermal performance respectively. Performance was evaluated through examining the drop in air temperature, heat transfer rate, soil temperature and COP of EATHE system.

Table 3
Soil properties.

Soil	Location	Density (kg m^{-3})	Specific heat capacity (J kg^{-1} K^{-1})	Thermal conductivity (W m^{-1} K^{-1})	Thermal diffusivity (m^2/s)	Reference
Soil A	Ajmer (India)	2050	1840	0.52	1.37×10^{-7}	Bansal et al. (2013)
Soil J	Jodhpur (India)	1470	1553.14	1	4.37×10^{-7}	Chandra et al. (0000)
Soil F	Presles (France)	1500	880	1.280	9.69×10^{-7}	Boithias et al. (2009)

Table 4
Hourly variation in air temperature along the pipe length for three types of soil.

Length of pipe (m)	Air temperature (°C)											
	1 h			3 h			6 h			12 h		
	A	J	F	A	J	F	A	J	F	A	J	F
0	46.20	46.20	46.20	46.20	46.20	46.20	46.20	46.20	46.20	46.20	46.20	46.20
10	37.42	36.49	36.49	38.5	37.51	37.45	39.27	38.17	38.01	39.98	38.75	38.51
20	32.46	31.48	31.48	33.64	32.52	32.45	34.56	33.24	33.07	35.49	33.83	33.51
30	29.84	29.09	29.09	30.79	29.85	29.80	31.59	30.40	30.26	32.43	30.79	30.52
40	28.46	27.96	27.96	29.12	28.43	28.4	29.73	28.76	28.66	30.33	28.98	28.81

Table 3 shows that all the three soils were having different combinations of density, specific heat and thermal conductivity leading to significant difference in their thermal diffusivities. The thermal diffusivity values for the three soils have been calculated as 1.37×10^{-7} m^2/s, 4.37×10^{-7} m^2/s and 9.69×10^{-7} m^2/s.

Table 4 shows the variation in air outlet temperature at different sections along the pipe length for three different types of soil for continuous 12 h operation. It can be observed that the air outlet temperature was getting affected due to gradual heat accumulation and thermal saturation of soil.

For soil A, that has least thermal diffusivity, the air temperature at a section of 10 m from inlet increases by 2.56 °C after 12 h of continuous operation. This is because of continuous heat transfer from air to soil (through the pipe) is faster as compared to transfer of heat in the sub-layers of soil. This difference results into higher subsoil temperature surrounding the pipe as compared to the sub soil temperature to the beginning, thereby, reducing the heat transfer from air to soil in subsequent hours.

For Soil J and F, air temperature at 10 m length increases by 2.26 °C and 2.02 °C respectively after continuous 12 h operation. The increase in temperature is lesser for soil having higher thermal conductivity, due to lesser difference between the rate of heat transfer between the air to soil and rate of heat transfer in sub-layers of soil.

Hence it can be clearly concluded that the performance of EATHE gets deteriorated during continuous running operation mainly due to saturation of nearby situated subsoil. This deterioration was less pronounced in soil having higher thermal conductivity because it provides faster heat dissipation from the soil layers situated in the immediate vicinity of EATHE pipe to the sub-soil layers situated away from the pipe in the radial direction.

Tables 5–7 show the temperature variation of the soil at 10, 20 and 30 m lengths and at 0.05 and 0.25 m away from the pipe after different time period of continuous operation.

It can be noticed that the penetration of heat because of heat transfer between the air and surrounding soil depends upon the thermal conductivity of soil. Penetration of heat into the surround soil was more with soil J and F because of higher thermal conductivity and can only penetrate maximum up to 0.25 m away from the EATHE pipe with 12 h continuous running operation. Beyond this distance from the pipe, no significant rise in soil temperature was observed.

Similarly, for soil having lesser thermal conductivity i.e. soil A, this penetration of heat was restricted to even lesser radial distance from pipe surface for same operating conditions and duration. This suggests that penetration of heat into the soil is mainly influenced by the thermal conductivity of soil.

Table 5
Hourly temperature variation of soil layers at section 10 m length from inlet.

Time (h)	Soil Temperatures (°C) at various radial distances from pipe surface					
	0.05 m			0.25 m		
	A	J	F	A	J	F
1	28.46	28.81	29.21	27.00	27	27.01
3	30.07	30.15	30.46	27.00	27.06	27.29
6	31.34	31.09	31.25	27.00	27.29	27.75
12	32.61	31.95	31.88	27.01	27.65	28.15

Table 6
Hourly temperature variation of soil layers at section 20 m length from inlet.

Time (h)	Soil Temperatures (°C) at various radial distances from pipe surface					
	0.05 m			0.25 m		
	A	J	F	A	J	F
1	27.76	27.81	27.99	27.00	27.00	27.00
3	28.72	28.59	28.72	27.00	27.00	27.10
6	29.60	29.18	29.24	27.00	27.08	27.28
12	30.53	29.58	29.49	27.00	27.15	27.36

Table 7
Hourly temperature variation of soil layers at section 30 m length from inlet.

Time (h)	Soil Temperatures (°C) at various radial distances from pipe surface					
	0.05 m			0.25 m		
	A	J	F	A	J	F
1	27.35	27.36	27.43	27.00	27.00	27.00
3	27.90	27.76	27.84	27.00	27.00	27.00
6	28.44	28.04	28.06	27.00	27.00	27.03
12	28.98	28.21	28.17	27.00	27.00	27.05

Hence, it can be concluded that the EATHE system with higher thermal conductivity soil gives better thermal performance even after prolonged continuous operation. The phenomenon of better thermal performance of EATHE with higher thermal conductivity occurs due to better dissipation of heat from the soil layers situated in the immediate vicinity of EATHE pipe to the soil layers situated away from the soil pipe interface in the radial direction.

It can also be noticed that as the distance from inlet increases, the effect of heat accumulation reduces. This leads to a conclusion, that the effect of soil saturation on continuous operation, and with soil of low conductivity, can be offset by providing extra length of pipe.

Table 8
Hourly variation of heat transfer rate through EATHE pipe.

Type of soil	Average heat transfer rate through EATHE pipe surface after different hours of operation (W/m^2)			
	1 h	3 h	6 h	12 h
Soil A	44.50	43.98	43.45	42.92
Soil J	44.92	44.68	44.49	44.36
Soil F	44.92	44.69	44.54	44.45

Table 9
Hourly variation in COP of EATHE system.

Type of soil	COP after different hours of operation			
	1 h	3 h	6 h	12 h
Soil A	4.29	4.13	3.98	3.83
Soil J	4.41	4.29	4.21	4.16
Soil F	4.41	4.30	4.24	4.20

Hourly variation of heat transfer rate from EATHE pipe to soil and COP of EATHE system with different hours of operation are presented in Tables 8 and 9 respectively.

It can be observed in Table 8 that average rate of heat transfer through EATHE pipe surface to surrounding soil decreases with continuous running operation because of accumulation of heat nearer to the pipe surface but this decrement in rate of heat transfer was less pronounced with soil having higher thermal conductivity. Higher thermal conductivity soil transferred more amount of heat through EATHE pipe surface to nearby subsoil. Therefore, higher thermal conductivity of soil nearer to the EATHE pipe surface provides better thermal performance of the EATHE system.

It can also be concluded from Table 9, that EATHE system with higher thermal conductivity soil could be used continuously for longer time of operation as compared to soils having lesser conductivity. Coefficient of performance (COP) of the system can be evaluated from the following expression:

$$\mathrm{COP} = \frac{\dot{m} C_d c_p (T_{\mathrm{inlet}} - T_{\mathrm{exit}})}{Q_i} \quad \text{(Bansal et al., 2010)}$$

where $\dot{m}$, mass flow rate of air through the pipe $= 0.048$ kg/s; c_p, specific heat of air $= 1005\ \mathrm{J\ kg^{-1}\ K^{-1}}$; C_d, coefficient of discharge of the pipe $= 0.6$; T_{inlet} & T_{exit}, EATHE inlet & outlet temperature, Q_i, theoretical blower input power $= 120$ W.

7. Conclusion

Thermal performance of EATHE systems were investigated considering three different soil thermal diffusivity in terms of temperature drop, heat exchange rates and COP using commercial CFD software FLUENT. The numerical results showed reasonable agreement with the experimental results. Small differences between the numerical and experimental were caused by several uncertain factors such as local ground thermal properties, boundary and initial conditions, etc.

Some conclusions drawn from this study are as follows:

1. Performances of EATHE with soil J and F were very close to each other even after continuous 12 h of operation because of very close soil thermal conductivity. So it can be concluded that soil thermal conductivity plays a vital role which influenced the thermal performance of EATHE. Therefore, maximum air temperature drop and heat transfer achieved with higher thermal conductivity soil.
2. Soil with higher thermal diffusivity has higher rate of heat transfer and can transfer more amount of heat through the nearby soil to the outer subsoil quickly. Therefore higher temperature observed in subsoil layer at 0.25 m away from the EATHE pipe.
3. Thermal performance of EATHE deteriorates after continuously operated for long time. This deterioration was more observed with least thermal conductivity of soil because of saturation of soil situated nearby to the EATHE pipe.
4. Effect of thermal saturation on continuous operation of EATHE especially for soil of low conductivity, can be compensated by providing extra length.

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