Optimizing the length of Earth Air Tunnel Heat Exchanger based on CFD analysis

<u>Thesis by</u>

Saikot Mahmud

ID: 141456

Sami Hamid

ID: 141467

Index

SUBMITTED TO THE DEPARTMENT OF

MECHANICAL AND CHEMICAL ENGINEERING

ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

Accepted by. . . . .

Dr. Arafat Ahmed Bhuiyan

Assistant Professor, Islamic University of Technology (IUT)

Thesis Supervisor

Professor Dr. Md Zahid hossain

Head of Dept. of MCE

Islamic University of Technology (IUT)

Title

Optimizing the length of Earth Air Tunnel Heat Exchanger based on CFD analysis.

Abstract

Thermal performance of Earth Air Tunnel Heat Exchanger (EATHE) under steady operating conditions has been carried out considering in hot and dry region of Bangladesh using Computational Fluid Dynamics modeling. Effect of soil thermal conductivity and by changing air velocity operation of EATHE on thermal performance has been evaluated for different pipe length of EATHE using experimentally validated CFD. Simulation Results show that the steady thermal performance of EATHE is significantly dependent on thermal conductivity of the soil and velocity of air. Results show that the increase in flow velocity leads to change in thermal behavior of the pipe.

The effect of soil thermal conductivity of EATHE on thermal performance has been also carried out for different pipe length of EATHE using experimentally validated CFD simulation. Maximum air temperature drop of 15.6, 17.0 and 17.3 K are observed for soil thermal conductivities of 0.52, 2 and 4 W m1 K1 respectively for 60 meter pipe. The thickness of the soil annulus beyond which no significant rise in temperature of soil observed is equal to the pipe diameter.

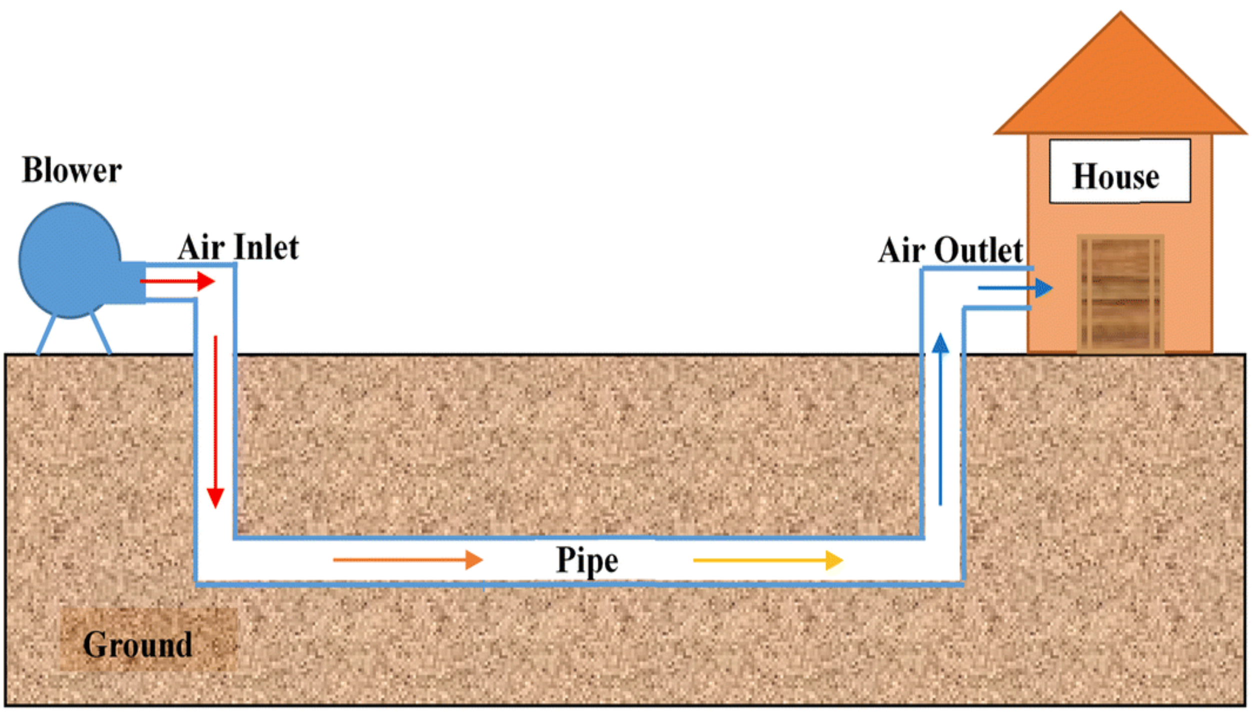
Mainly in this paper, the effect soil thermal conductivity has been compared with different pipe length considering also the change in velocity of air. The optimization of pipe length has been also carried out from the experimental analysis based on validated CFD analysis.

Introduction

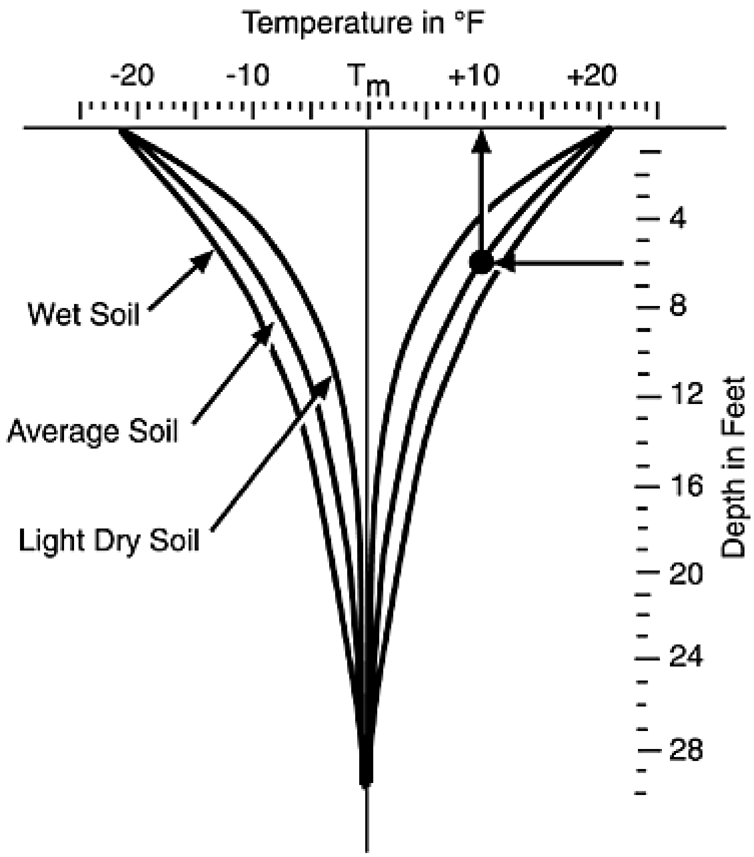
By evaluating the energy crisis over the world and the importance of energy for the existence of our society, it is urgent to save energy and improve overall energy efficiency. Passive heating and cooling systems are known for their advantage of consuming no or very less energy as compared to active heating and cooling systems. Earth–Air–Tunnel Heat Exchanger (EATHE) is one of the various passive heating and cooling systems, having the relative advantage over most passive systems due to its ability to provide both the effects: heating in cold months and cooling during warm months. Earth behaves as a huge -storage medium for heat and can be used as daily or seasonal thermal storage medium. Ground possesses many advantages due to its high heat capacity as well as its insulation potential. Similarly the thermal capacity of the earth is such that the diurnal variations of the surface temperature do not penetrate much deeper than 0.5 m, and seasonal variations beyond a depth of about 3 m. Below this depth, the earth's temperature, therefore, remains constant and the value of this temperature is usually equivalent to the annual mean of the sol air temperature of its surface. Therefore, at a sufficient depth, the ground temperature is always higher than that of the outside air in winter and is lower in summer. The earth's thermal potential can be exploited using Earth Air Tunnel Exchanger system (EATHE) as shown in. Over the decades many researchers concentrated on the development of EATHEs to improve and enhance its thermal performance. Most of the research has been carried out using various experimental, analytical, numerical, and hybrid models to estimate the heat transfer in and around EATHE pipes.

The utilization of geothermal energy to reduce heating and heating needs in buildings has received increasing attention during the last several years considering the installation cost and the use of renewable energy. An Earth Air Tunnel Heat Exchanger (EATHE) consists of a long underground metal or plastic pipe through which air is drawn with the help of blower. As air travels through the pipe, it gives up or receives some of its heat to/from the surrounding soil and enters the room as conditioned air during the cooling and heating period. Thermal performance of the

EATHE is evaluated as the temperature drop of air obtained due to steady heat transfer between the air and the soil surrounding the EATHE pipe based on CFD analysis. Effect of thermal conductivity of soil on the thermal performance of EATHE system has also been studied by varying the thermal conductivity of soil. Effect of pipe length, pipe diameter, and pipe design are also obtained by changing the geometry of the EATHE. Results of the CFD model analysis can be used to predict the steady temperature of the air outlet flowing through the pipe and soil surrounding it.



At a sufficient depth, the ground temperature is always lower in summer. The earth's thermal potential can be exploited using Earth Air Tunnel Heat Exchanger system (EATHE).



Nomenclature

- EATHE= Earth Air Tunnel Heat Exchanger
- PVC= Poly Vinyl Chloride
- RPM= Revolutions per Minute
- CFD =Computational Fluid Dynamics

A brief scenario of EAHE systems in the world

A ground-coupled heat exchanger is an underground heat exchanger that can capture heat from and/or dissipate heat to the ground. They use earth's temperature which is generally low due to water layer, they utilize this low temperature for transferring heat from air to soil. Air from buildings is blown through the heat exchanger for heat recovery ventilation, they are called earth tubes (also known as earth cooling tubes or earth warming tubes) in Europe or earth–air heat exchangers (EAHE or EAHX) in North America. Earth 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/or heating of facility ventilation air.

The idea of using earth as a heat sink was known in ancient times. In about 3000 B.C., Iranian architects used wind towers and underground air tunnels for passive cooling. Earth–air heat exchangers have been used in agricultural facilities (animal buildings) and horticultural facilities (greenhouses) in the United States over the past several decades and have been used in conjunction with solar chimneys in hot arid areas for thousands of years, probably beginning in the Persian Empire. Underground air tunnel (UAT) systems, nowadays also known as earth to air heat exchangers (EAHEs), have been in use for years in developed countries due to their higher energy utilization efficiencies compared to the conventional heating and cooling systems. Implementation of these systems in Austria, Denmark, Germany, and India has become fairly common since the mid-1990s, and is slowly being adopted in North America. Earth–air heat exchangers are one of the fastest growing applications of renewable energy in the world, with an annual increase in the number of installations with 10% in about 30 countries over the last 10 years. With the exception of Sweden and Switzerland, the market throughout Europe but is likely to grow with further improvements in the technology and the increasing need for energy savings. From the middle of the 20th century, a number of investigators have studied the cooling potential of buried pipes. Since that time, a number of experimental and analytical studies of this technique have appeared in the literature. Till 2001, about 1000 passive house units have been built in Germany and this amount sensibly doubles every year. In Europe, already more than 5000 passive house units have been successfully built and completed

Physical model

According to research paper, the experimental test set up comprises of 60 m long horizontal PVC pipe of inner diameter 0.10 m, buried in flat land with dry soil at a depth of 3.7 m. Inlet end of EATHE pipe is connected through a vertical pipe to a 0.75 kW, single phase, variable speed motorized blower (maximum flow rate of 0.0945 m3/s and maximum speed of 2800 rpm). Ambient air was forced through the earth air pipe system with the help of blower and air flow velocity was changed with the help of an auto transformer (single phase, 0–270 V, 2 A maximum current, with a least count of 1 V). Seven RTD (Pt-100) temperature sensors viz. T0–T6 were mounted at a depth of 0 m, 0.62 m, 1.24 m, 1.86 m, 2.48 m, 3.10 m and 3.7 m respectively from the ground surface on inlet vertical pipe to measure soil temperatures at different depths. One additional temperature sensor was inserted at a distance of 10 m away from the EATHE system at a depth of 3.7 m in the ground to measure the undisturbed soil temperature. Nine RTD (Pt-100) temperature sensors viz. T7–T15 were also inserted at the center of EATHE pipe along the length at a horizontal distance of 0.2 m, 1.7 m, 4.7 m, 9.3 m, 15.1 m, 24.2 m, 34.0 m, 44.4 m and 60.0 m respectively from the upstream end to measure air temperature. A group of four RTD (Pt-100) temperature sensors at axial distance of 6.4 m, 27.4 m and 48.8 m from the inlet of EATHE were also provided to measure the temperature of pipe-soil interface, temperature of soil at a distance of 0.2 m, 0.4 m and 0.6 m from pipe surface respectively. Properly calibrated, digital temperature display devices (accuracy of ±0.1 C and resolution 0.1 C) have been used. Dry bulb temperature and relative humidity of ambient air were recorded hourly using RTD (Pt-100) temperature sensor and capacitive transducer mounted on weather station. Temperature and relative humidity of air inside the test room were also measured accurately with the help of calibrated thermo hygrometer (make – Fluke-971, temperature accuracy of ±0.1 C, temperature resolution of 0.1 C and relative humidity resolution of 0.1%). Air flow velocity is measured with the help of a vane probe type anemometer (make – Lutron, model-AM-4201, range 0.4 to 30.0 m/s and least count of 0.1 m/s). Electrical energy consumed by the centrifugal blower was measured with the help of calibrated digital energy meter (make – Power tech measurement system, type – PTS-01, least count of 0.1 kWh and an accuracy of ±0.1 kWh). dimensions of research room is 4.3 m 3.8 m 3.05 m, having two windows (1.52 m 1.22 m each, located on east and north facing walls respectively) and a door (1.82 m 0.91 m, located on west facing wall.

Description of the simulation model

In this investigation a three-dimensional numerical simulation of heat transfer is conducted using the ANSYS FLUENT 16. It uses finite volume method to convert the governing equations into numerically solvable algebraic equations.

To predict the turbulence inside the pipe Realizable k-ε model with standard wall treatment was used. The numerical investigation was based on the assumption that thermo-physical properties of solids and fluids remain constant over the range of soil and air temperature during operation. It has also been assumed that air is incompressible and soil is homogeneous. Fluid zone-soil interface in the CFD simulation has been considered as a coupled boundary so that heat can be transferred from air to the soil through pipe. The outer surface of soil cylinder has been treated as an adiabatic wall. Pipe inlet was given the 'velocity-inlet' boundary condition and outlet as 'pressure outlet'. The SIMPLE pressure-velocity coupling algorithm, the standard pressure, and the second order upwind discretization scheme for momentum, energy, turbulent kinetic energy and dissipation energy are employed in the model. The convergence criterion of 10-3 is chosen for all calculated parameters except for the energy where a value of 10-6 is used.

Geometry: The model of EATHE bend pipe were designed in SolidWorks and later imported on Ansys 16. We used three different pipe of length 60 meter, 50meter, and 40 meter. The dimension of PVC pipe as follow: inner diameter 0.10 meter, outer diameter 0.12 meter. Following some previous researches no heat dissipation occur after radius of four time of inner diameter of pipe. So the soil layer were taken of diameter 0.4 meter.

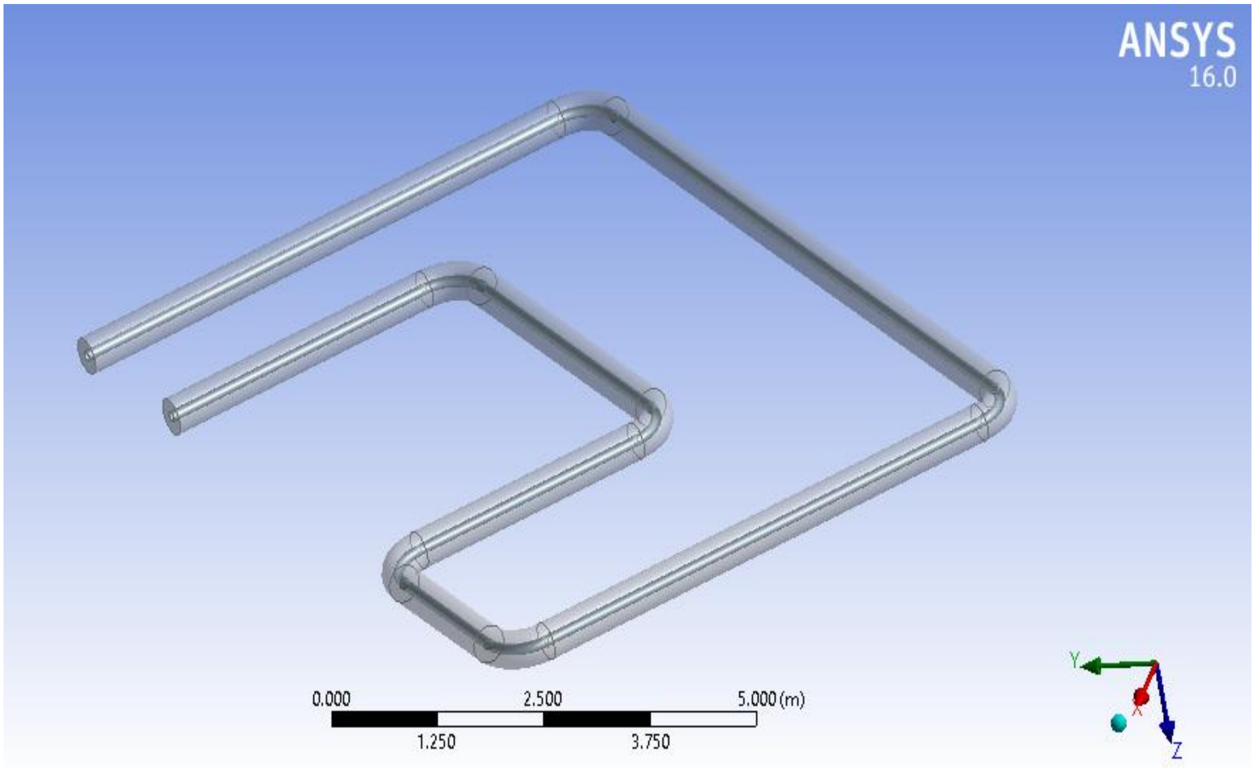


Fig: 40 meter long bend pipe

The diameter of pipe and soil layer were same for all three pipe of different lengh. The soil layer were considered as wall and the layer between PVC pipe and soil were coupled thermally.

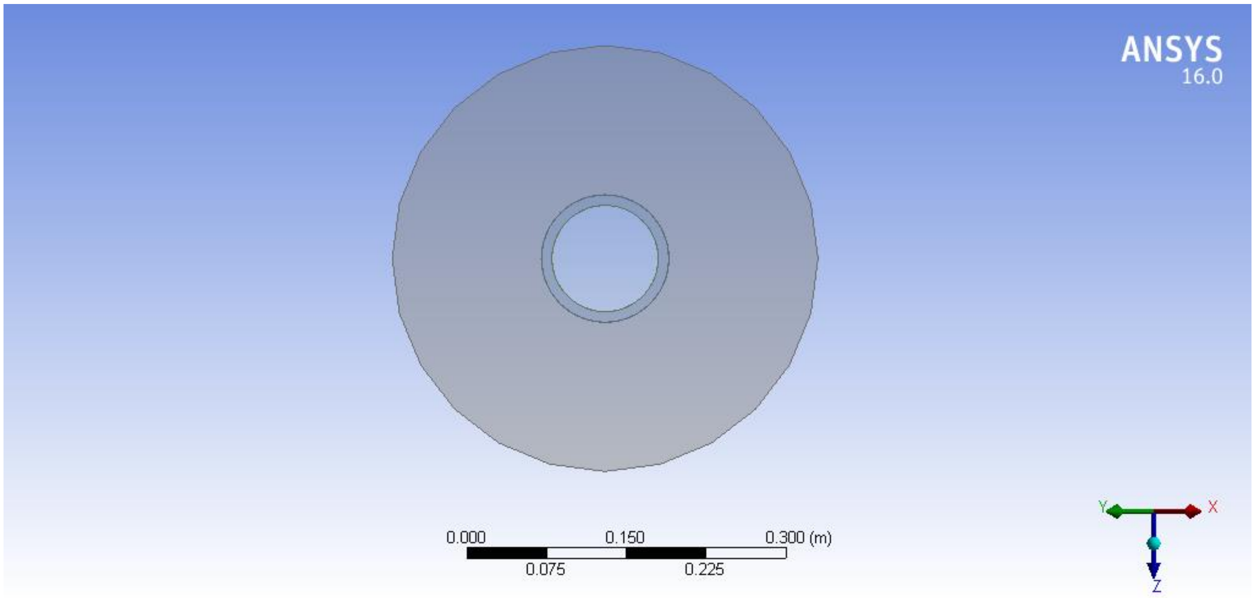


Fig: Face view of PVC pipe, Soil layer and air inlet.

Meshing: After completion of Geometry the next preprocess step is generation of Mesh. Good quality of meshing is important for getting desired result and it depends on edge sizing, inflation and size of element. The tetrahedral meshing were used for all three pipes with different edge sizing of 25 for 60 m long pipe, 20 for 50 m long pipe and 18 for 40 m long pipe. No of node and elements were 745584 and 712353 respectively for 60 m pipe where for 50 m and 40 m pipe, node 585995 elements 3391134 and node 465455 elements 2693764 respectively were found.

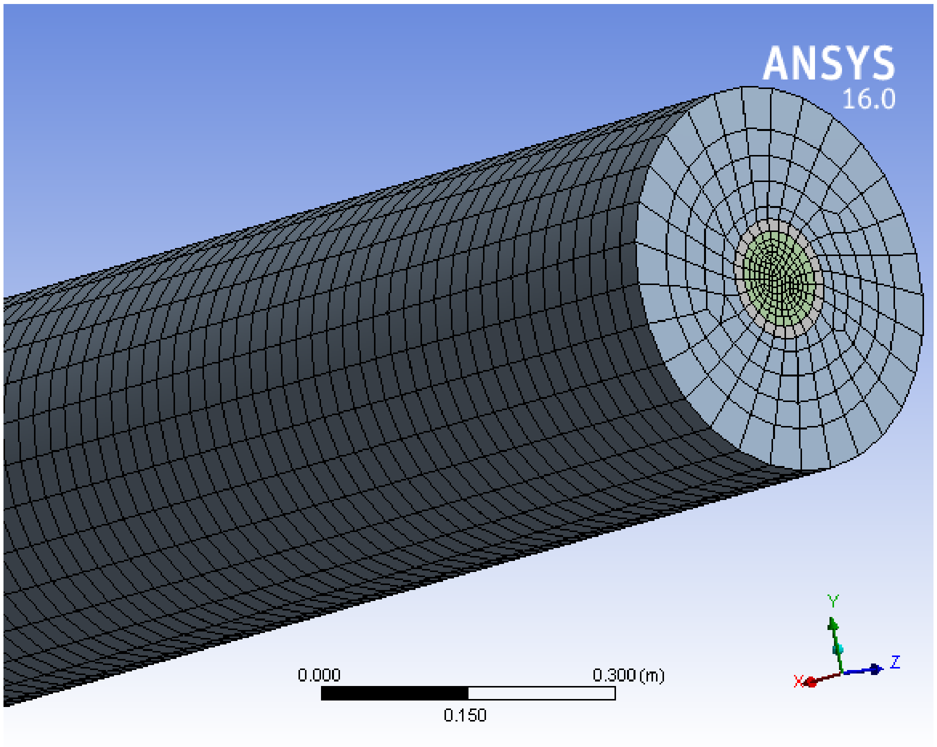


Fig: Meshing of the EATHE model.

Some characteristics shows the quality of meshing like Orthogonal quality which ranges from 0 to 1 and the value close to 0 correspond to low quality, Ortho skew which ranges from 0 to 1 where the value close to 1 correspond to low quality. In this setup minimum orthogonal quality were 6.66268e-02 and maximum ortho skew were 9.33373e-01. Maximum aspect ratio were 4.26286e+01.

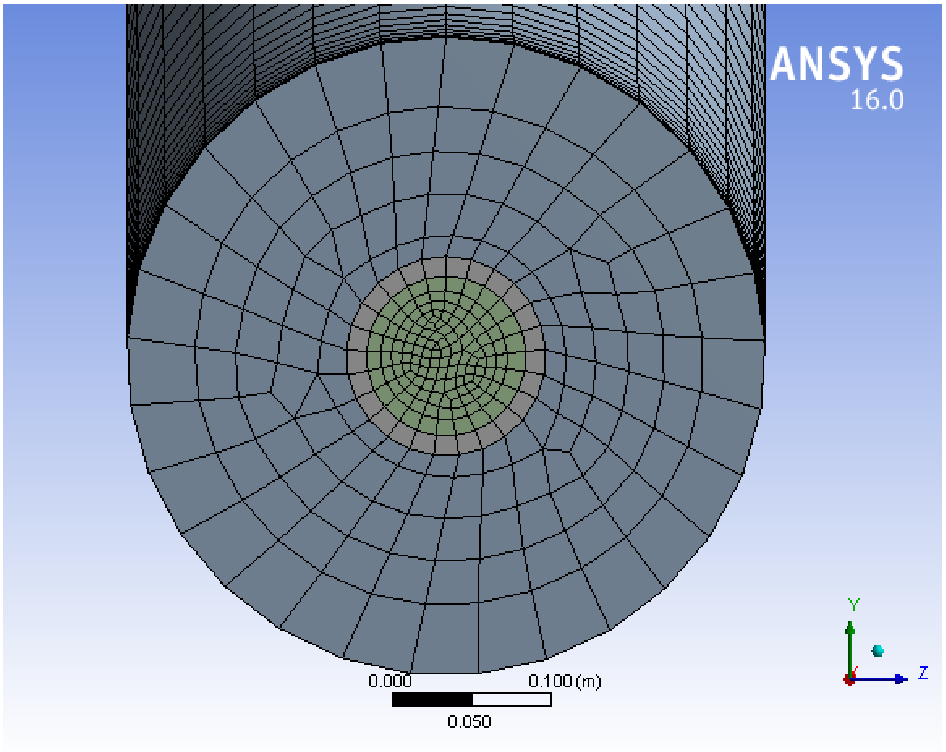


Fig: Meshing of the EATHE model.

The generation of mesh ere done after selecting the Relevance 0, Relevance Centre to coarse, Medium smoothing and Slow transition. The minimum element size and maximum element size both are set to 5.34 mm and 683.85 mm respectively.

Solution setup: Generation of mesh were done on CFD for setting up the data to run the calculation. Single precision and pressure based calculation were solved while the time set was steady. Model for the CFD solver is K-epsilon (standard). The physical properties were chosen from table below and for three different sample of soil CFD analysis were done after defining the materials.

Material	Density (kg/m3)	Specific heat (J/kgK)	Thermal conductivity (W/mK)
Air	1.225	1006.43	0.0242
Soil 1	2050	1840	0.52
Soil 2	2050	1840	2
Soil 2	2050	1840	4
PVC	1380	900	1.16

Table: Physical properties of materials

The model constants value for the simulation has been taken as values which are as inbuilt in the set up file.

BOUNDARY CONDITIONS

Inlet boundary

As for the boundary values of this set up ,the inlet air is taken as velocity inlet .The velocity of inlet has been varied from 3ms^-1 to 5ms^-1 to acquire the best results. The direction is normal to the opening at inlet.

Outlet boundary

The outlet boundary region was considered as pressure outlet .The pressure was acted in the vertical direction of soil face. Heat flux is considered as zero.

Far boundary of the soil

Outer surface of the soil cylinder (4 times the pipe diameter) surrounding the EATHE pipe was assumed to be at constant temperature of 300K. A trial simulation was carried out on EATHE model of 60 m pipe length, 0.1 m pipe diameter and radius of soil surrounding the pipe as 20 times the pipe radius. It was observed that penetration of heat in radial direction at inlet section was not beyond 4 times the pipe diameter. Hence, in further simulation on large scale model having 60 m pipe length and 0.1 m diameter, outer diameter of soil cylinder surrounding the EATHE pipe was taken equal to four times the pipe diameter in order to save the iteration time.

Inlet and exit faces:

At inlet and exit faces of EATHE, heat flux was taken to be zero. Since the area of inlet and exit faces of EATHE are almost negligible compared to the lateral area of EATHE pipe through which the heat gets transferred into soil domain.

Soil pipe interface

At soil pipe interface coupled heat transfer condition was taken. No-slip conditions for velocity and steady temperatures are applied at the duct surfaces. In fluid dynamics, the no-slip condition for viscous fluids states that at a solid boundary, the fluid will have zero velocity relative to the boundary. Particles close to a surface do not move along with a flow when adhesion is stronger than cohesion.

Governing equations

The following set of governing equations is used to perform simulation in FLUENT software to describe the heat and mass transfer and flow of fluid within any systems.

.

Law of mass conservation:

The equation for mass conservation law or continuity equation is written as:

$\partial u/\partial x+\partial v/\partial y+\partial w/\partial z=0\partial u/\partial x+\partial v/\partial y+\partial w/\partial z=0$ (1)

Law of energy conservation:

The first law of thermodynamics or law of energy conservation stated as neither the energy can be created nor destroyed, it only changes its form in nature. The equation can be written as follows:

$u\partial T\partial x+v\partial T\partial y+w\partial T\partial z=\alpha[\partial 2T/\partial x2+\partial 2T/\partial y2+\partial 2T/\partial z2]u\partial T/\partial x+v\partial T/\partial y+w\partial T/\partial z=\alpha[\partial 2T/\partial x2+\partial 2T/\partial y2+\partial 2T/\partial z2]$ (2)

Law of momentum conservation (Navier–Stokes equation, also known as Newton’s second law):

The equation for momentum conservation is as follows:

X-momentum equation:

$U\partial u/\partial x+v\partial u/\partial y+w\partial u/\partial z=-1\rho\partial p\partial x+\vartheta[\partial 2u\partial x2+\partial 2u\partial y2+\partial 2u\partial z2]u\partial u\partial x+v\partial u\partial y+w\partial u\partial z=-1\rho\partial p\partial x+\vartheta[\partial 2u\partial x2+\partial 2u\partial y2+\partial 2u\partial z2]$ (3a)

Y-momentum equation:

$u\partial v\partial x+v\partial v\partial y+w\partial v\partial z=-1/\rho(\partial p/\partial y)+\vartheta[\partial 2v/\partial x2+\partial 2v/\partial y2+\partial 2v/\partial z2]u\partial v/\partial x+v\partial v/\partial y+w\partial v/\partial z=-1/\rho(\partial p/\partial y)+\vartheta[\partial 2v/\partial x2+\partial 2v/\partial y2+\partial 2v/\partial z2]$ (3b)

Z-momentum equation:

$u\partial w/\partial x +v\partial w/\partial y+w/\partial w$
$\partial z=-1/\rho(\partial p/\partial z)+\vartheta[\partial 2w/\partial x2+\partial 2w/\partial y2+\partial 2w/\partial z2]u\partial w/\partial x+v\partial w/\partial y+w\partial w/\partial z=-1/(\rho\partial p/\partial z)+\vartheta[\partial 2w/\partial x2+\partial 2w/\partial y2+\partial 2w/\partial z2]$ (3c)

In the above Eqs. (1–3), *u*, *v*, and *w* are the velocity components in *x*-, *y*-, and *z*-directions, and *T* and *p* are the temperature and pressure of the flowing air, respectively.

Turbulence model description:

In the simulation, the pressure-based Navier–Stokes algorithm has been adopted and SIMPLE scheme was selected for solving pressure–velocity coupling. The pressure gradients are solved by second order and LSCB (least square cell-based), respectively. Second-order upwind for the kinetic energy of turbulence and second-order upwind for turbulent momentum were taken. During simulation, the far-field boundaries were treated as an adiabatic wall, and EATHE pipe wall and surrounding soil temperatures were initialized at 27 °C as the average sub-soil temperature (at 3–4 m depth) remains 27 °C throughout the year in Ajmer, India. Air is treated as an incompressible ideal gas and the viscous *k*-epsilon (*k*-*ε*) realizable turbulence model with standard wall function is applied. The constants in the viscous model are as follows: C1∈C1∈ = 1.44; C2C2 = 1.9; σkσk = 1.0; σ∈σ∈ = 1.2, and $Pr_{wall}$and Pr_{energy} are 0.85. The viscosity of air was kept constant as 1.78 e−05 kg/m-sec.

Result analysis

As the topic is based on optimization of pipe length of EATHE, this paper has been designed based on the characteristics of obtaining the lowest temperature at the outlet corresponding to the pipe length.

As from the graphical analysis, it has been seen that almost 18 degree Celsius (ΔT=17.986) temperature difference has been found from 60 meter pipe length for air velocity=5 ms^-1 and soil thermal conductivity

k=4wk^-1m^-1.But the same temperature drop (ΔT=17.915) can be obtained from 50 meter pipe also. To obtain this result .the air velocity should be minimized to V=4ms^-1 for k=4wk^-1m^-1. And almost same temperature (ΔT= 17.872) can be obtained from 40 m pipe.
For K=2 wk^-1m^-1 maximum temperature drop is found ΔT=17.960 when the air inlet velocity was V=3 ms^-1 in 60 meter long pipe. Close to this result were also found for 50 meter long pipe (ΔT=17.913) for same condition where for 40 meter long pipe it has been found ΔT=17.773

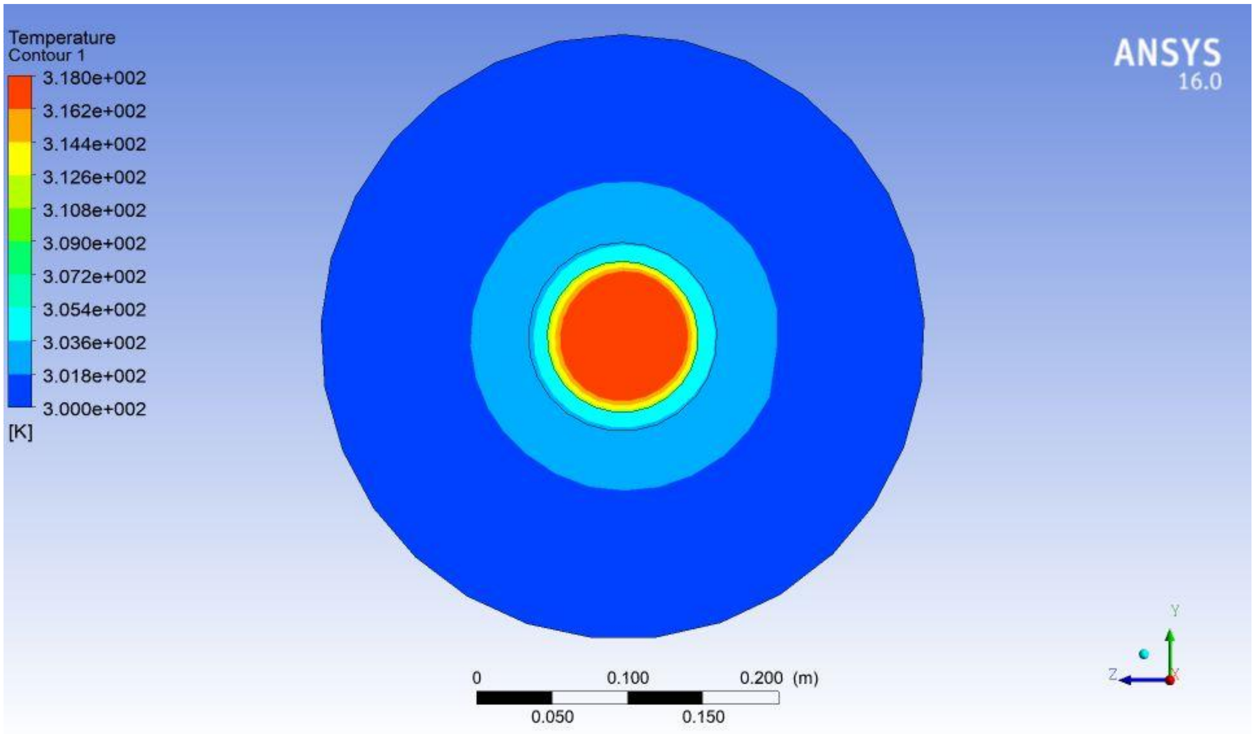
When the K=0.52 and V=3 maximum temperature drop was ΔT=17.096 for 60 meter long pipe and the same result ΔT=17.014 were found for 50 meter long pipe.

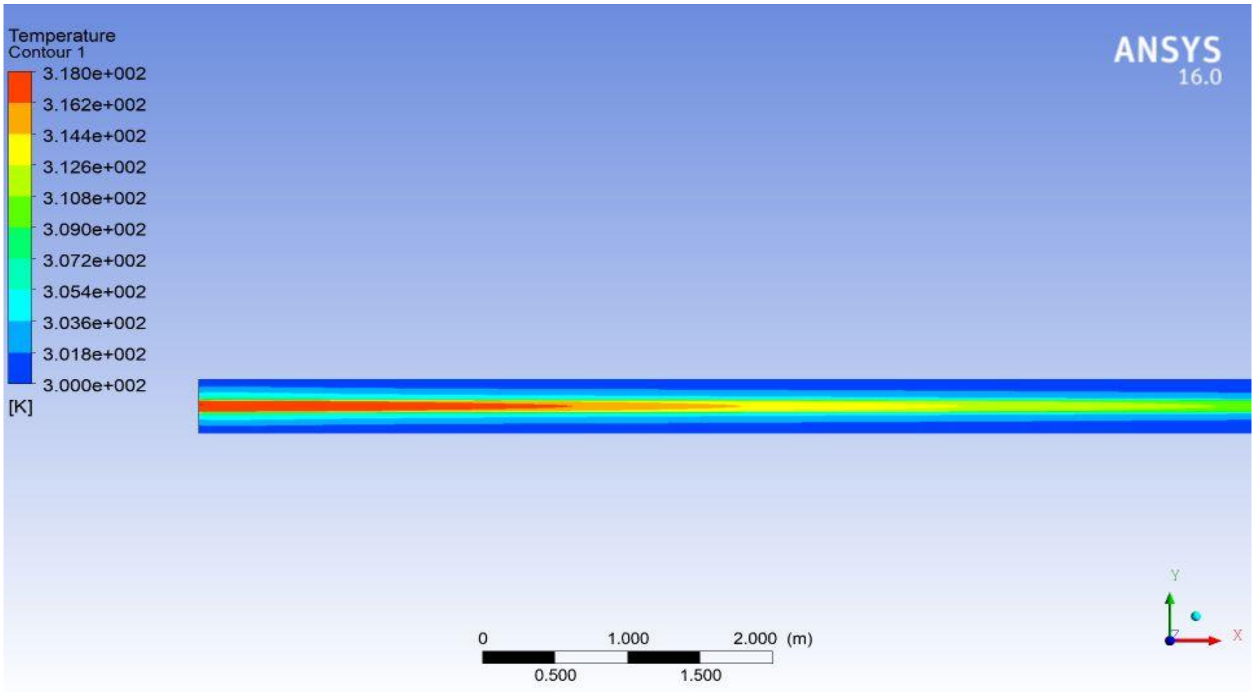
• **Pipe length**	• **Temperature Drop ΔT**		
	Thermal conductivity of soil, k=0.52		
	Velocity=3 m/s	**Velocity=4m/s**	**Velocity=5m/s**
40m	**ΔT= 16.185**	**ΔT= 15.753**	**ΔT= 14.112**
50m	**ΔT= 17.014**	**ΔT= 16.217**	**ΔT= 15.411**
60m	**ΔT= 17.096**	**ΔT= 16.784**	**ΔT= 16.112**
	Thermal conductivity of soil, k=2		
	Velocity=3 m/s	**Velocity=4m/s**	**Velocity=5m/s**
40m	**ΔT= 17.737**	**ΔT= 17.534**	**ΔT= 17.205**
50m	**ΔT= 17.913**	**ΔT= 17.794**	**ΔT= 17.645**
60m	**ΔT= 17.96**	**ΔT= 17.898**	**ΔT= 17.807**
	Thermal conductivity of soil, k=4		
	Velocity=3 m/s	**Velocity=4m/s**	**Velocity=5m/s**
40m	**ΔT= 17.872**	**ΔT= 17.623**	**ΔT= 17.587**
50m	**ΔT= 17.965**	**ΔT= 17.915**	**ΔT= 17.852**
60m	**ΔT= 17.986**	**ΔT= 17.962**	**ΔT= 17.926**

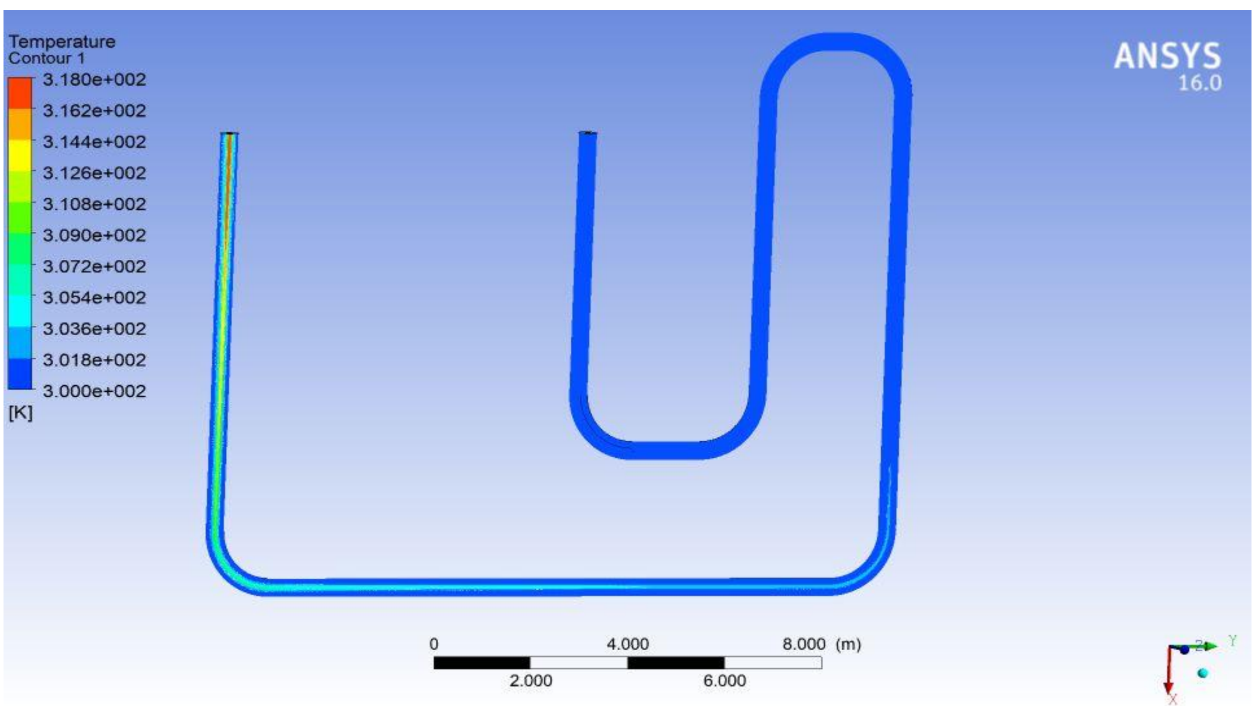
Result

Total 27 Simulation were conducted at different condition of varying in velocity of inlet air, the thermal conductivity of soil for three different length of pipe. The analysis of result were represented graphically. The temperature difference were calculated with respect to inlet air and outlet air. It has been found that air temperature were converged earlier than outlet. Later the results were represented in Microsoft excel 2013.

Graphical Animation of Result

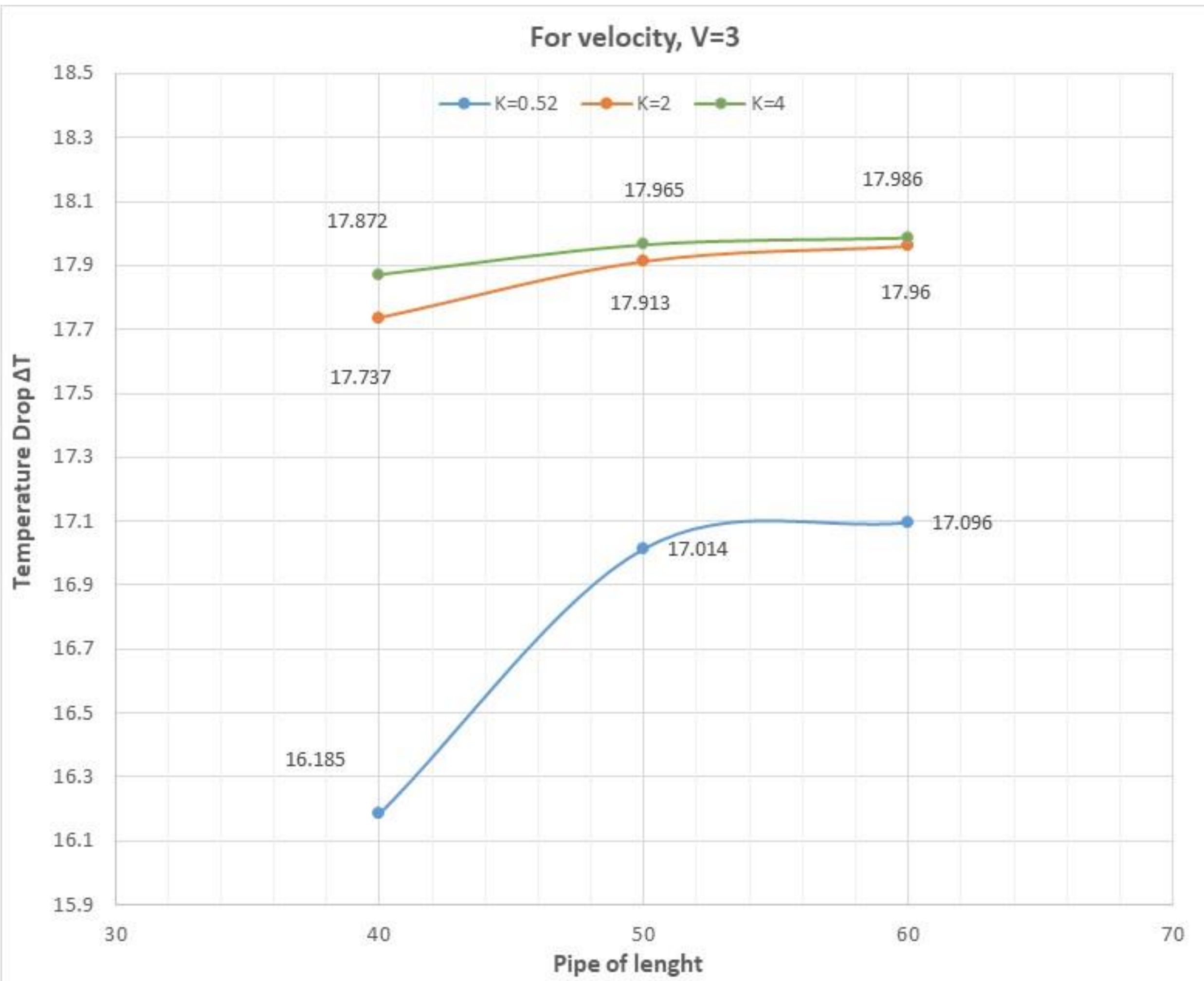


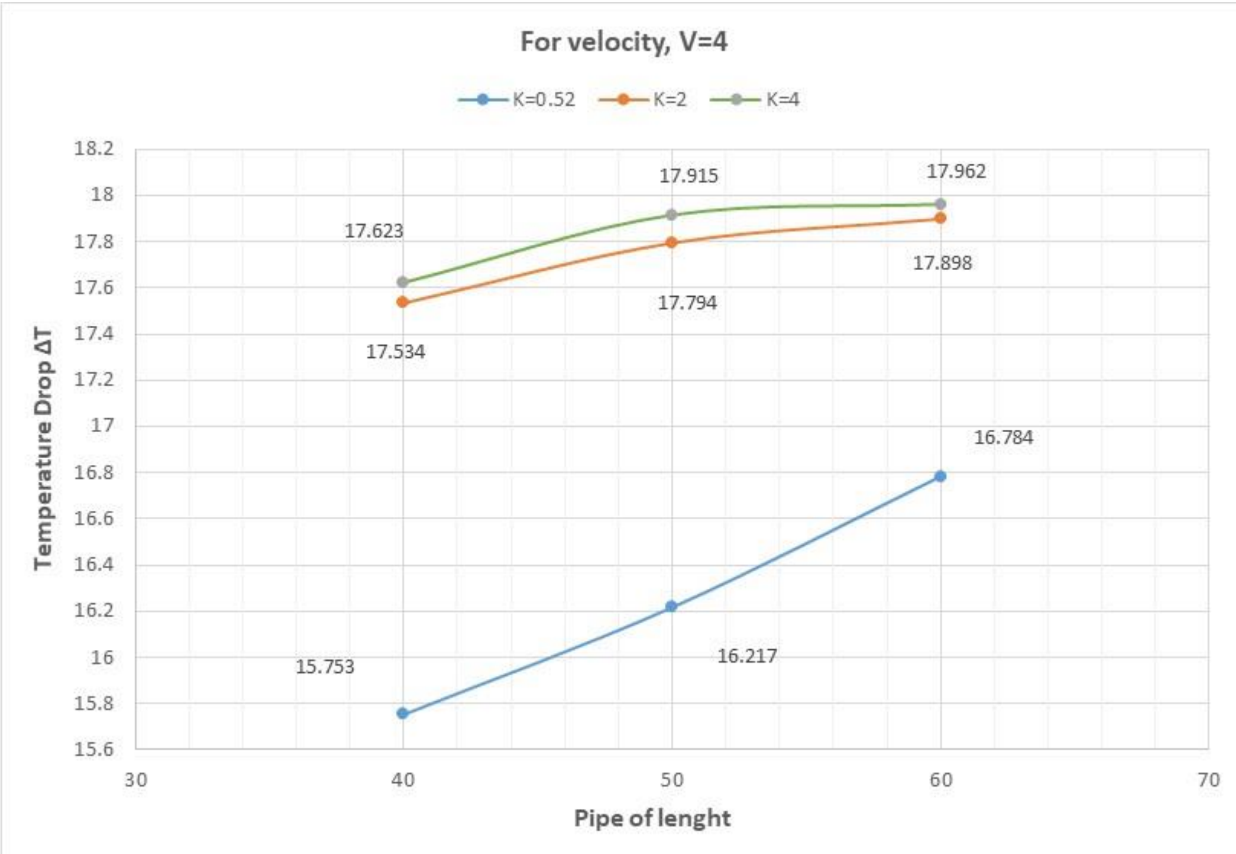

Temperature
Contour 1
3.180e+002
3.162e+002
3.144e+002
3.126e+002
3.108e+002
3.090e+002
3.072e+002
3.054e+002
3.036e+002
3.018e+002
3.000e+002
[K]
ANSYS
16.0
0
1.000
2.000 (m)
0.500
1.500
Y
X

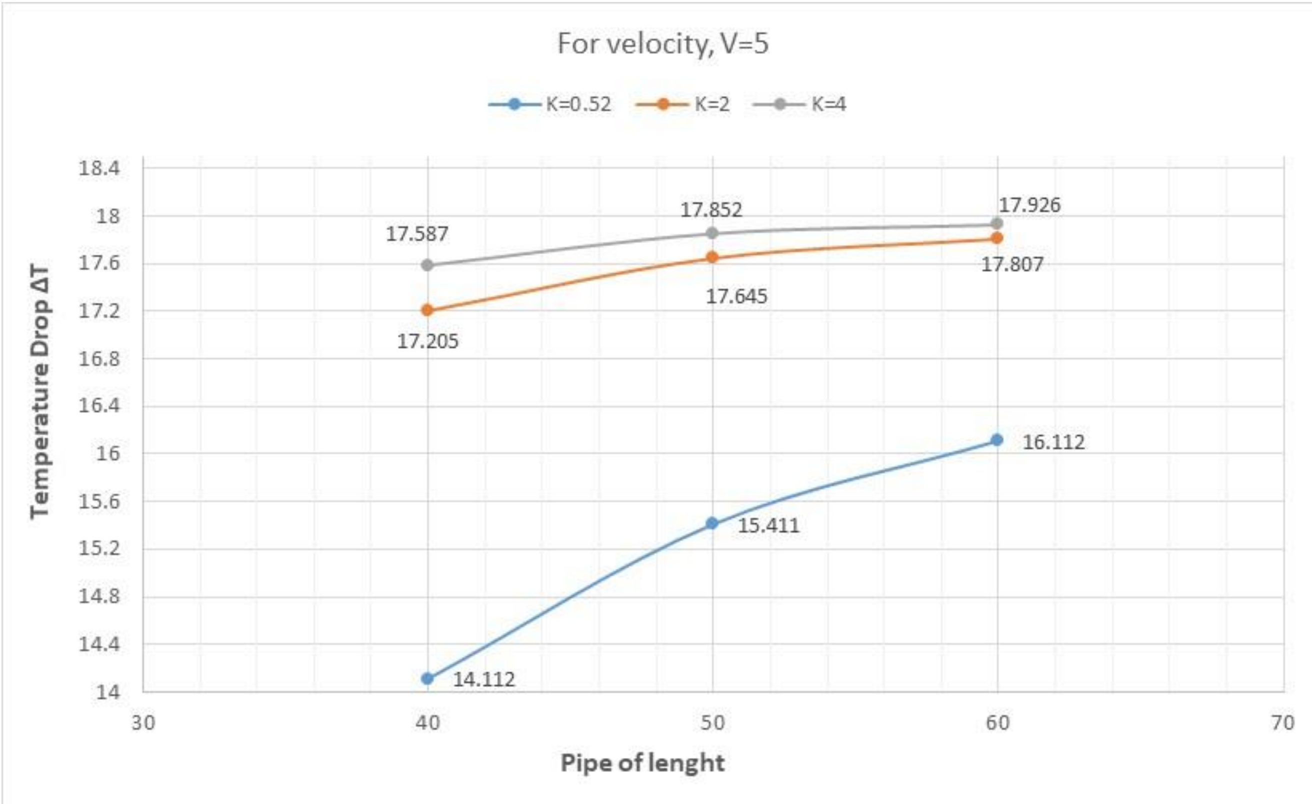

Temperature
Contour 1
3.180e+002
3.162e+002
3.144e+002
3.126e+002
3.108e+002
3.090e+002
3.072e+002
3.054e+002
3.036e+002
3.018e+002
3.000e+002
[K]
ANSYS
16.0
0
4.000
8.000 (m)
2.000
6.000
Y
X

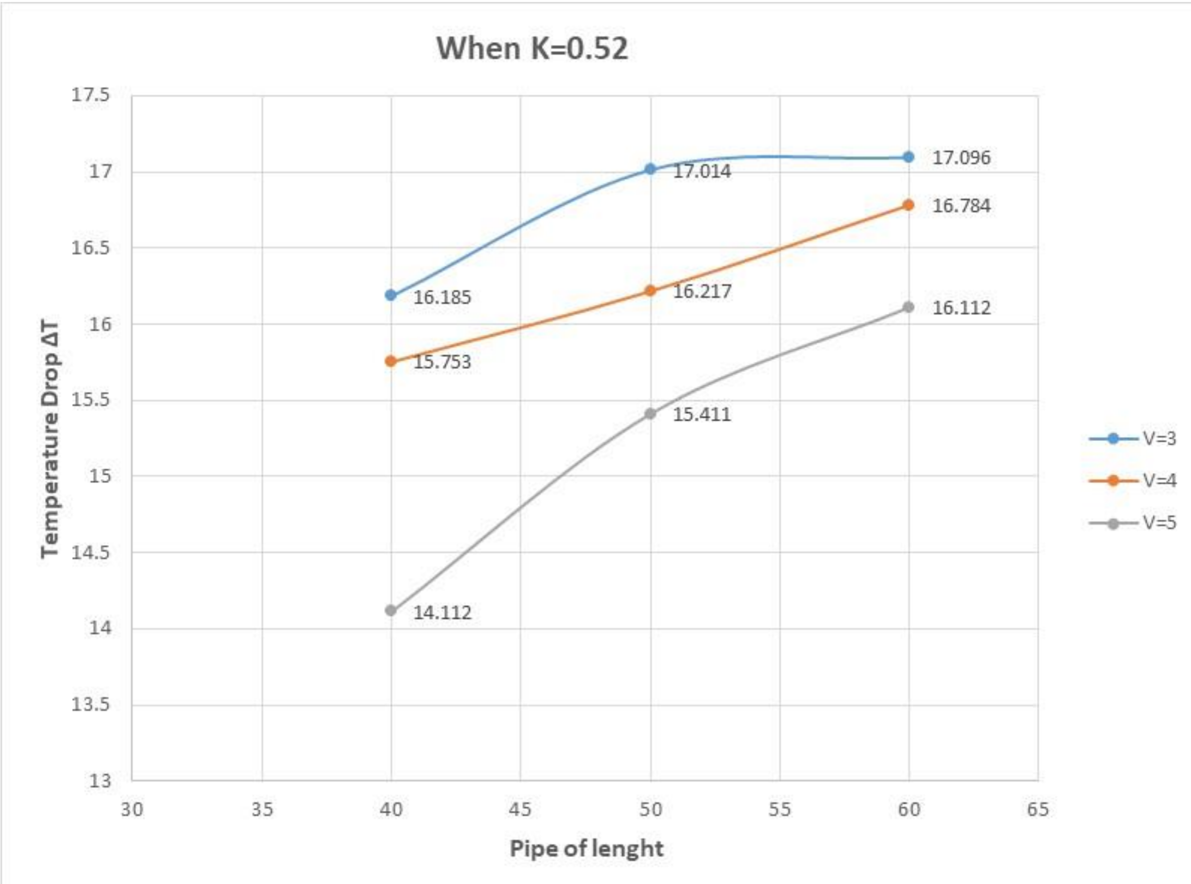
As the topic is based on optimization of pipe length of EATHE, this paper has been designed based on the characteristics of obtaining the lowest temperature at the outlet corresponding to the pipe length.

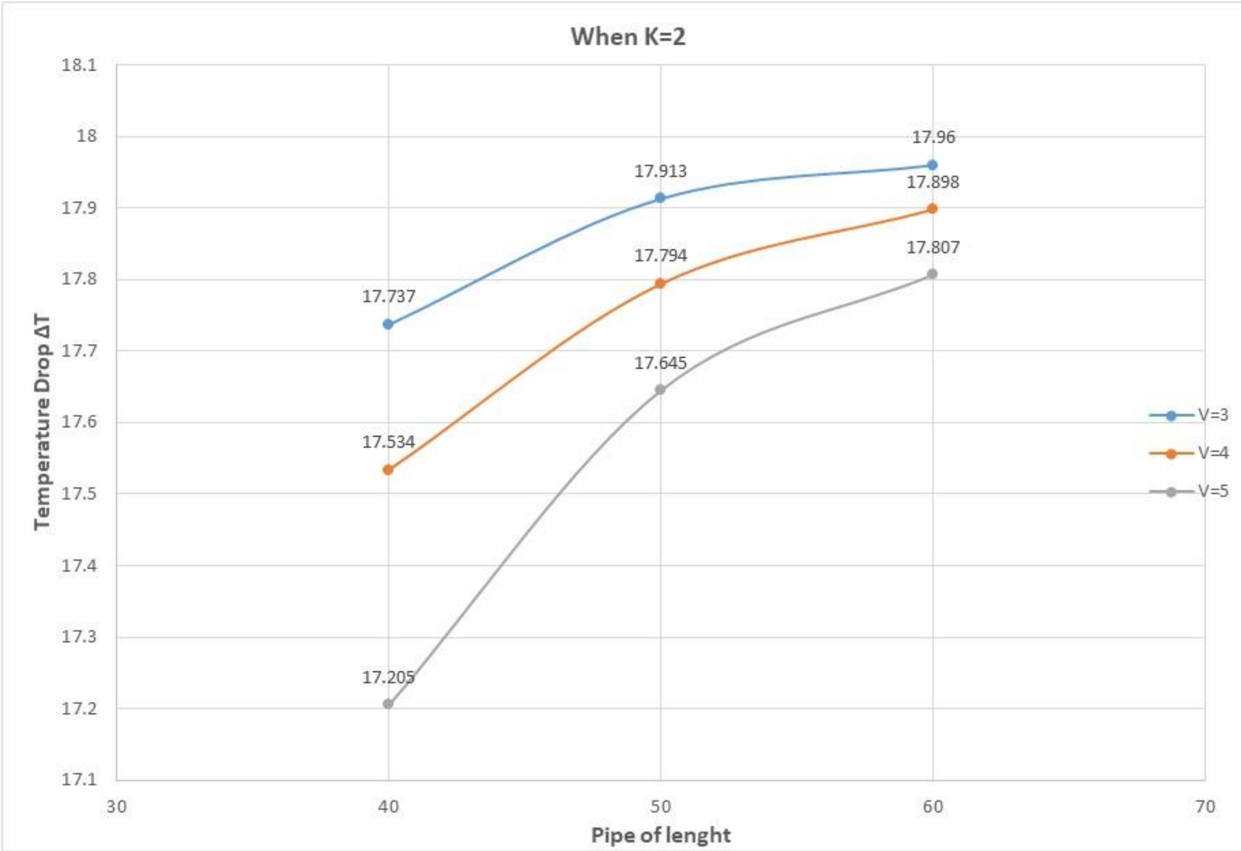
Graph presenting Temperature drop vs. Pipe length



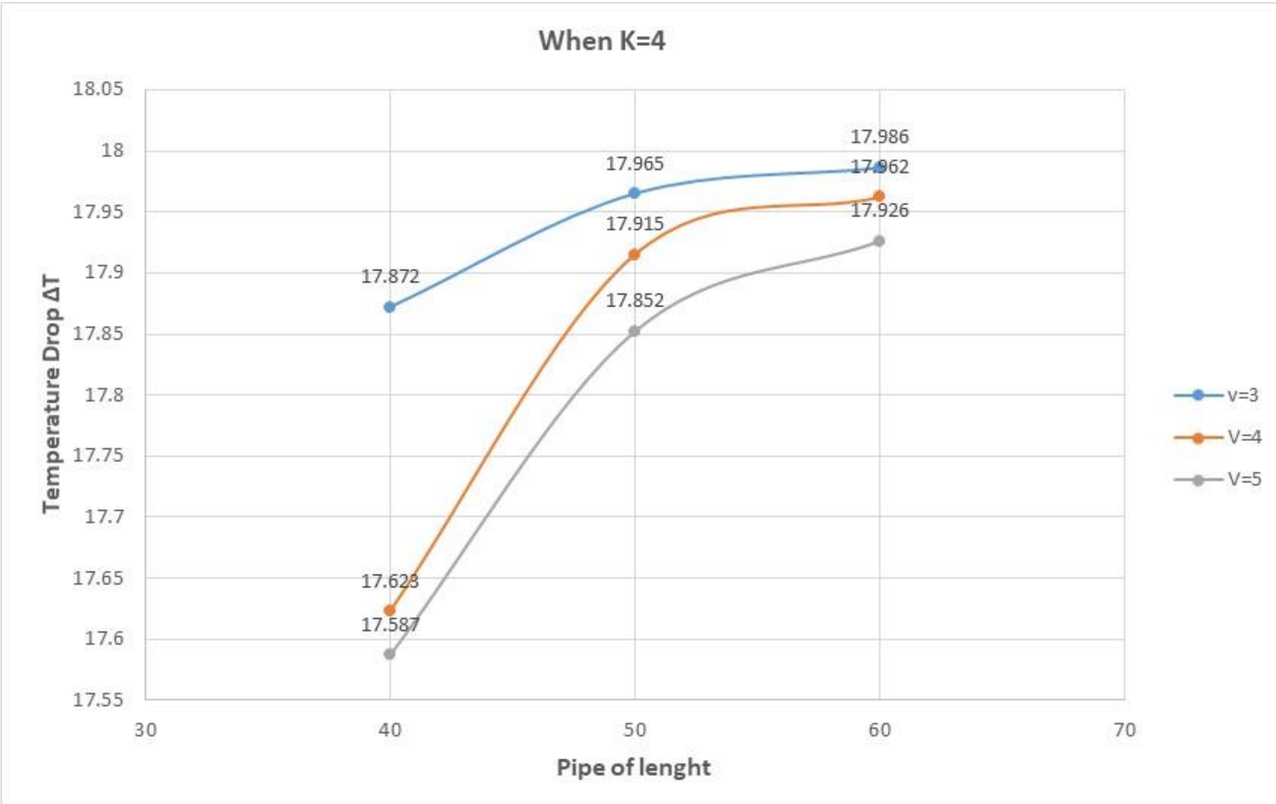

For velocity, V=4
K=0.52
K=2
K=4
18.2
18
17.8
17.6
17.4
17.2
17
16.8
16.6
16.4
16.2
16
15.8
15.6
Temperature Drop ΔT
17.915
17.962
17.623
17.898
17.794
17.534
16.784
16.217
15.753
30
40
50
60
70
Pipe of lenght


For velocity, V=5
K=0.52
K=2
K=4
Temperature Drop ΔT
Pipe of lenght
18.4
18
17.6
17.2
16.8
16.4
16
15.6
15.2
14.8
14.4
14
30
40
50
60
70
17.587
17.852
17.926
17.807
17.645
17.205
16.112
15.411
14.112


When K=0.52
Temperature Drop ΔT
Pipe of lenght
17.5
17
16.5
16
15.5
15
14.5
14
13.5
13
30
35
40
45
50
55
60
65
17.096
17.014
16.784
16.185
16.217
16.112
15.753
15.411
14.112
V=3
V=4
V=5



When K=2
Temperature Drop ΔT
Pipe of lenght
18.1
18
17.9
17.8
17.7
17.6
17.5
17.4
17.3
17.2
17.1
30
40
50
60
70
17.96
17.913
17.898
17.794
17.807
17.737
17.645
17.534
17.205
V=3
V=4
V=5


When K=4
Temperature Drop ΔT
Pipe of lenght
18.05
18
17.95
17.9
17.85
17.8
17.75
17.7
17.65
17.6
17.55
30
40
50
60
70
17.872
17.965
17.986
17.962
17.915
17.926
17.852
17.623
17.587
v=3
V=4
V=5

Conclusions

At a depth of about 1.5 to 2 m the temperature of ground remains almost constant. This constant temperature is called earth's undisturbed temperature. The earth's undisturbed temperature remains always higher than that of ambient air temperature in winter and vice versa in summer. To utilize efficiently the heat capacity of earth EAHE system is to be designed. The outlet of EAHEs can be connected to conventional air-conditioning unit, if cooling or heating achieved is not sufficient. The use of green and clean energy in order to minimize CFC emissions and to minimize conventional energy consumption is in prime focus everywhere. The EAHE systems can play a vital role in minimizing energy consumption by preheating air for heating of different types of buildings in winter and vice versa in summer. Therefore, design optimization, modeling and testing of EAHE systems is very essential. In the literature several calculation models are found to simulate the thermo-physical behavior of earth–air heat exchangers. A well designed EAHE can reduce electricity consumption of a typical house by 30%. EAHE systems offer reductions in heating/cooling load of buildings, power consumption, CFC and HCFC consumption and greenhouse gas emissions, and have been extensively used for years. Commonly, the thermal performance of EAHE system increases with increase in length and depth of burial of pipe while the decline in performance is observed with increase in pipe diameter and air velocity. United States and Europe are world leaders in the use of EAHE systems. The hybrid systems of EAHE and renewable energy sources like solar and wind energy can further improve performance of EAHE system. It may be concluded that efficient use of EAHE systems in combination with sustainable energy sources and latest technology will play an important role in saving energy consumption and environment not only in India but at world level. In this view, it is anticipated by authors that this review paper will be very useful to researchers and scientists working in the field of passive heating/cooling of buildings mainly with the use of EAHE systems

References

[1] Bansal Vikas, Misra Rohit, Agrawal Ghanshyam Das, Mathur Jyotirmay. Performance analysis of earth–pipe air heat exchanger for winter heating. Energy and Buildings 2009;41:1151–4.
[2] Bansal Vikas, Misra Rohit, Agrawal Ghanshyam Das, Mathur Jyotirmay. Performance analysis of earth–pipe air heat exchanger for summer cooling. Energy and Buildings 2010;42:645–8.
[3] Bansal NK, Sodha MS, Bhardwaj SS. Performance of earth–air tunnel system. Energy Research 1983;7(4):333–41.
[4] Bharadwaj SS, Bansal NK. Temperature distribution inside ground for various surface conditions. Building and Environment 1983;16(3):183–92.
[5] Santamouris M, Argiriou A, Vallindras M. Design and operation of a low energy consumption passive solar agricultural greenhouse. Solar Energy 1994;52(5):43–9.
[6] Kumar Rakesh, Kaushik SC, Garg SN. Heating and cooling potential of an earth-to-air heat exchanger using artificial neural network. Renewable Energy 2006;31:1139–55.
[7] Sodha MS, Sharma AK, Singh SP, Bansal NK, Kumar A. Evaluation of an earth–air–tunnel system for cooling/heating of a hospital complex. Building and Environment 1984;20(2):115–22.
[8] Milun Stanko, Klic Tomislav, Bego Ozren. Measurment of soil thermal properties by spherical probe. IEEE transactions on instrumentation and measurement 2005;54 (3).
[9] Kersten MS Laboratory research for the determination of the thermal properties of soils, Bulletin No. 28. Minneapolis, MN: Engineering Experiment Station, University of Minnesota; 1949.
[10] de Vries DA. Thermal properties of soils. In: van Wijk WR, editor. Physics of plant environment. Amsterdam: North-Holland Publishing Company; 1963.

[11] de Vries DA. Heat transfer in soils. In: de Vries DA, Afgan NH, editors. Heat and mass transfer in the biosphere. Washington, DC: Scripta Book Co.; 1975. p. 5–28.
[12] Hillel D. Introduction to soil physics. San Diego, CA: Academic Press; 1982.
[13] Nofziger DL Soil temperature changes with time and depth: theory. /http:// soilphysics.okstate.edu/software/SoilTemperature/document.pdfS.
[14] Becker BR, Misra A, Fricke BA. Development of correlations for soil thermal conductivity. International Communications in Heat and Mass Transfer 1992;19:59–68.
[15] Chen Y, Shi M, Li X. Experimental investigation on heat moisture and salt transfer in soil. International Communications in Heat and Mass Transfer 2006;33(9):1122–9.
[16] Yu ZMX, Peng F, Li XD, Fang ZH. A simplified model for measuring thermal properties of deep ground soil. Experimental Heat Transfer 2004;17:119–30.
[17] Ozgener Leyla. A review on the experimental and analytical analysis of earth to air heat exchanger (EAHE) systems in Turkey. Renewable and Sustainable Energy Reviews 2011;15(9):4483–90.
[18] Scott NR, Parsons RA, Kochler TA. Analysis and performance of an earth–air heat exchanger, ASAE Paper No. 65–840 (1965).
[19] Goswami DY, Ileslamlou S. Performance analysis of a closed loop climate control system using underground air tunnel. Solar Energy Engineering 1990;112:76–81.
[20] Lund J, Sanner B, Rybach L, Curtis G, Hellstro€m G. Geothermal (ground-source) heat pumps—a world overview, GHC Bulletin, September, 2004.
[21] Sanner B. Current status of ground source heat pumps in Europe, Futurstock, Warsaw, 2003.
[22] Hubner H, Hermelink A. Mieter im passivhaus-nutzungsorientierte gestal- ¨ tung als voraussetzung funachhaltiges wohnen. In: Schrader U, Hansen U, ¨ editors. Nachhaltiger Konsum. Frankfurt, Germany: Campus Forschung; 2001. p. 137–48 [in German].
[23] Badescu V. Economic aspects of using ground thermal energy for passive house heating. Renewable Energy 2007;32:895–903.
[24] Pfafferott Jens. Evaluation of earth-to-air heat exchangers with a standardised method to calculate energy efficiency. Energy and Buildings 2003;35:971–83.
[25] D'Accadia MD, de Rossi F. Thermo-economic optimization of a refrigeration plant. International Journal of Refrigeration 1998;21(1):42–54.
[26] Tzaferis A, LIParakis D, Santamouris M, Argiriou A. Analysis of the accuracy and sensitivity of eight models to predict the performance of earth to air heat exchanger. Energy and Buildings 1992;18:35–43.

[27] Mihalakakou G, Santamouris M, Asimakopoutos D. Modeling the thermal performance of the earth to air heat exchanger. Solar Energy 1994;53(3): 301–5.
[28] Bojic M, Trifunovic N, Papadakis G, Kyritsis S. Numerical simulation, technical and economic evolution of air to earth heat exchanger coupled to building. Energy 1997;22(12):1151–8.
[29] Gauthier C, Lacroix M, Bernier H. Numerical simulation of soil heat exchanger storage system for greenhouse. Solar Energy 1997;60(6):333–46.
[30] Hollmiller P, Lachal B. Cooling and preheating with buried pipe systems: monitoring, simulation and economic aspects. Energy and Building 2001;33(5): 509–18.
[31] Wu H, Wang S, Zhu D. Modeling and evaluation of cooling capacity of earth–air–pipe systems. Energy Conversion and Management 2007;48:1462–71.
[32] Aslam Bhutta Muhammad Mahmood, Hayat Nasir, Hassan Bashir Muhammad, Rais Khan Ahmer, Naveed Ahmad Kanwar, Sarfaraz Khan. CFD applications in various heat exchangers design: a review. Applied Thermal Engineering 2012;32:1–12.
[33] Abdelkrim Sehli, Abdelhafid Hasni, Mohammed Tamali. The potential of earth–air heat exchangers for low energy cooling of buildings in South Algeria. Energy Procedia 2012;18:496–506.
[34] Cucumo M, Cucumo S, Montoro L, Vulcano A. A one-dimensional transient analytical model for earth-to-air heat exchangers, taking into account condensation phenomena and thermal perturbation from the upper free surface as well as around the buried pipes. Heat and Mass Transfer 2008;51: 506–16.
[35] Badescu V. Simple and accurate model for the ground heat exchanger of a passive house. Renewable Energy 2007;32:845–55.
[36] Mihalakakou G, Santamouris M, Asimakopoulos D, Tselepidaki I. Parametric prediction of the buried pipes cooling potential for passive cooling applications. Solar Energy 1995;55(3):163–73.
[37] Lee Kwang Ho, Strand Richard K. The cooling and heating potential of an earth tube system in buildings. Energy and Buildings 2008;40:486–94.
[38] Kabashnikov VP, Danilevskii LN, Nekrasov VP, Vityaz IP. Analytical and numerical investigation of the characteristics of a soil heat exchanger for ventilation systems. International Journal of Heat and Mass Transfer 2002;45: 2407–18.
[39] Tittelein P, Achard G, Wurtz E. Modeling earth to air heat exchanger behavior with the convolutive response factor methods. Applied Energy 2009;86: 1683–91.
[40] De Paepe M, Janssens A. Thermo-hydraulic design of earth–air heat exchangers. Energy and

Buildings 2003;35:389–97.
[41] Leyla Ozgener, Onder Ozgener. An experimental study of the exergetic performance of an underground air tunnel system for greenhouse cooling. Renewable Energy 2010;35:2804–11.
[42] Onder Ozgener, Leyla Ozgener. Determining the optimal design of a closed loop earth to air heat exchanger for greenhouse heating by using exergoeconomics. Energy and Buildings 2011;43:960–5.
[43] Ajmi FAl, Loveday DL, Hanby V. The cooling potential of earth–air heat exchangers for domestic buildings in a desert climate. Building and Environment 2006;41:235–44.
[44] Woodson Thomas, Coulibaly Ye´zouma, Traore´ Eric Seydou. Earth–air heat exchangers for passive air conditioning: case study Burkina Faso. Journal of Construction in Developing Countries 2012;17(1):21–33.
[45] Khalajzadeh Vahid, Farmahini-Farahani1Moien, Heidarinejad Ghassem. A novel integrated system of ground heat exchanger and indirect evaporative cooler. Energy and Buildings 2012;49:604–10.
[46] Pfafferott J. Evaluation of earth-to-air heat exchangers with a standardized method to calculate energy efficiency. Energy and Buildings 2003;35(10): 971–83.
[47] Thiers S, Peuportier P. Thermal and environmental assessment of a passive building equipped with an earth-to-air heat exchanger in France. Solar Energy 2008;82:820–31.
[48] Hollmuller Pierre, Lachal Bernard. Cooling and preheating with buried pipe systems: monitoring, simulation and economic aspects. Energy and Buildings 2001;33:509–18.
[49] Hamada Yasuhiro, Nakamura Makoto, Saitoh Hisashi, Kubota Hideki, Ochifuji Kiyoshi. Improved underground heat exchanger by using no-dig method for space heating and cooling. Renewable Energy 2007;32:480–95.
[50] Breesch H, Bossaer A, Janssens A. Passive cooling in a low-energy office building. Solar Energy 2005;79:682–96.