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3D NUMERICAL ANALYSIS OF THE EFFECT OF VARIOUS GEOMETRIC PARAMETERS OF EATHEs UNDER STEADY OPERATING CONDITIONS

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DECLARATION

I hereby declare that thesis entitled “**3D NUMERICAL ANALYSIS OF THE EFFECT OF VARIOUS GEOMETRIC PARAMETERS OF EATHEs UNDER STEADY OPERATING CONDITIONS”** is an authentic report of our study carried out as requirement for the award of degree B.Sc. (Mechanical Engineering) at Islamic University of Technology, Gazipur, Dhaka, under the supervision of Dr. Arafat Ahmed Bhuiyan during January 2018 to October 2018.

The matter embodied in this thesis has not been submitted in part or full to any other institute for award of any degree.

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3D NUMERICAL ANALYSIS OF THE EFFECT OF VARIOUS GEOMETRIC PARAMETERS OF EATHEs UNDER STEADY CONDITION.

ABSTRACT

Space heating and cooling is a comfort requirement which results in a significant amount of energy consumption. EATHE (Earth Air Thermal Heat Exchanger) is one of the passive ways of space heating and cooling that can reduce the energy consumption notably. In this paper, the effect of different geometric parameters; cross section of the pipe, inclusion of fins on the pipe, pitch of multiple pipe arrangements on the thermal performance of EATHEs under steady and transient conditions were analyzed. Since, the performance deteriorates over the continuous operation of the EATHEs, their performance under periodic operations were studied. A validated three-dimensional, transient numerical model was used to carry out the analysis. The governing equations, based on the k–$\mathcal{E}$ model and energy equation were used to describe the turbulence and heat transfer phenomena. The results are compared in terms of the outlet temperature of air and heat transfer rate.

1. INTRODUCTION

In recent years, the energy demands on buildings have increased significantly due to the growing population and better levels of life. The cooling and heating space use approximately 33% of the total energy consumption worldwide [1,2]. For heating and cooling of spaces, conventional air conditioning systems that consume a lot of energy and are harmful to the environment are used. Various alternative passive systems are being researched to meet the cooling and heating requirements and minimize primary energy consumption.

NOMENCLATURE

EATHE	Earth Air Tunnel Heat Exchanger
GHE	Ground Heat Exchangers
GSHP	Ground Source Heat Pump
PVC	Poly Vinyl Chloride
CFD	Computational Fluid Dynamics
RPM	Revolutions Per Minute
DBT	Dry Bulb Temperature

These passive alternatives use natural sources of energy, except for a few conventional energy inputs (usually to operate a small fan for air). Geothermal energy has been made one of the promising sources for heating and Cooling buildings through different means and is being used for a long time. It mainly started three decades after 1973's oil crisis [3]. Mainly, the different approaches made so far to utilize the geothermal energy are, i.e. (i) Earth air tunnel system (EATs) or Earth-air heat exchanger system (EAHEs) [4-6]; (ii) direct integration of the building envelope [7,8]; and finally (iii) Ground source heat pumps (GSHP) [9,10]. These are used to exploit the thermal energy of the earth for heating and Cooling applications. In a typical Earth air tunnel heat exchanger, the air is blown through the tunnel/pipes buried in the ground and forced to exchange heat with the soil and thus the air becomes heated/cooled depending on the difference in temperature between air and soil. This heated/cooled air is used directly/indirectly to produce indoor thermal comforts in indoor spaces. In the second option, the buildings themselves exchange heat with the soil through its total or partially underground construction

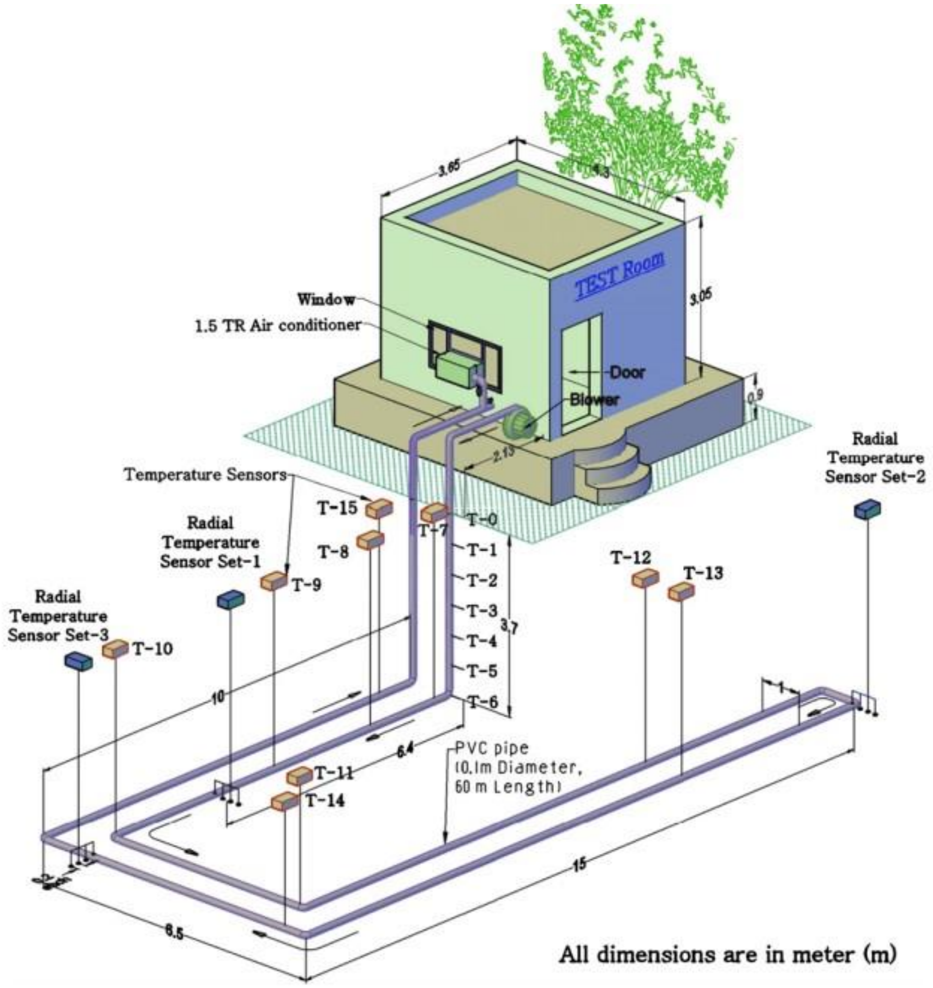


Figure 1:Schematic of room integrated EATHE system [42]

[11,12]. But this option needs large works of soil excavation and significantly increases the cost. In a third system, the soil heat exchanger is used side by side with a closed circuit GSHP system that consists of long tubes (usually PVC) buried in the ground. The extracted soil heat is used to heat/cool indoor spaces and also used in domestic application [13-16], to melt snow or, ice accumulated on the pavement or on bridge surfaces in winter [17,18].

The aforementioned systems have proved their worth by providing reduced condensation temperature in the summer season and a higher evaporation temperature in the winter season [19]. Among these, the Earth Air Tunnel (EATHE) Heat Exchangers are simple in design and comparatively less expensive as it uses air as a working fluid and require a tiny amount of electric power to operate.

An EATHE system consists of one or several pipe/pipes in a certain arrangement placed at a certain depth in the floor and normally a blower to blow the air through the pipe (s). The air blown in the pipes exchange heat with the adjacent soil layers and finally is delivered to the space occupied in the building. The temperature of the subsoil, which varies with depth and becomes almost constant at a depth of 4 m or more [20]. The special feature about this constant temperature is that, it is lower than the average summer seasonal temperature and higher than the average seasonal temperature in the winter [21]. EATHEs use thus difference between the subsoil and ambient air temperature to heat the air in winter and to cool the air in summer season.

Many researchers have reported progress in the different aspects of EATHEs, while some of them had recommended it as a feasible and effective alternative source of passive energy for space heating/cooling [22-24]. Many scientists had carried out extensive researches on different aspects of EATHEs. Recently, Leyla Ozgener [25], Bisoniya et al. [26], Peretti et al. [27] and Kaushal [28] have published thorough reviews on EATHEs.

An important factor to consider while studying EATHEs is the soil properties. Soil's performance is based on input temperature that varies seasonally, and the temperature of the earth, as well as the distribution of moisture within the soil [29]. Various statistical characteristics of surface temperatures of soil at various depths were studied and analyzed by Jacovides et al. [30]. Puri [31] studied a pipe buried under soil, carrying a hot fluid while focusing on the factors; diameter of the pipe, initial soil moisture concentration, temperature and temperature of the fluid tube interface. Bojic et al. [32] and Krarti et al. [33] used different mathematical models to evaluate the technical and economic performance of an Earth air tunnel heat exchanger. To study the effects of different soils and pipes, the velocity of air of the performance of the EATHE, a 3-D non-steady state flow model was introduced by, Deglin et al. [34]. To reduce the energy consumption in the building heating and cooling, a technical solution was put forward by Thiers and Peuportier [35]. Different other researchers based their experimental studies on the effects various parameters like material, length, diameter, thickness, number, and spacing of the buried pipes, soil type, depth of the pipes under the soil, inlet air velocity etc. Bansal et al. [36,37] found the great resemblance of simulated data with the experimental ones and found that the COP of the EATHE system increases with the increase of velocity. On further research, Bansal et al. [38,39] stated that higher soil thermal conductivity always results in a better thermal performance of the EATHE. He also found that under continuous operation, EATHE loses its performance. Bansal et al. [39] also studied about the thermal influence zone and concluded that the temperature rise of soil layers is larger for the initial length of the pipe than the succeeding length of the pipe. Performance of a solar PV assisted EATHE was investigated by Yildiz et al. [40] by exergetic analysis based on parameters like climatic condition, sand condition etc. Misra et al. [41-43] mentioned in their study that, derating factor can be as high as 64% and thus put emphasis on the fact that, while designing an EATHE, derating factor must be taken into consideration. They also found that derating factor is a function of soil thermal conductivity, duration of cont. operation and pipe length. The deteriorating performance of EATHEs with the increased pipe diameter and increased flow velocity was shown by Misra et al. [42]. Li et al. [44] coupled an earth to air heat exchanger with a solar chimney and found out promising performance. Simulation results carried out by Ajmi et al. [45] showed that the EATHE can provide a reduction of as high as 1700W in the peak cooling load. Longer pipes and higher depths of burial for obtaining a better performance from the EATHEs was recommended by Wu et al. [46]. Mathur et al. [47] concluded that the deteriorating performance of EATHEs due to continuous operations can be compensated by increasing the pipe length. On a different study, Mathur et al. [48] compared the performance between EATHEs having straight and spiral pipes and stated that spiral pipe's performance is comparable to that of the straight ones while having a lower aspect ratio. Few researchers [49-52] investigated the arrangements of multiple buried pipes. Misra et al. [49] concluded that the thermal influence zone has a conical shape (narrower towards the end) and thus suggested that the spacing between the buried pipes should be gradually decreased along the pipe length. Kabashnikov et al. [51] developed a mathematical model in the form of Fourier integral and found that the efficiency of the EATHe decreases with the decrease in the spacing between the buried pipes. Sodha et al. [52] analyzed the performances of the parallel pipes with respect to each other. A few other [53-55] researcher discussed an alternative to the continuous operation; intermittent operation of the EATHE system. It was recommended by Mathur et al. [53] that, in the intermittent mode, the soil temperature and the cooling capacity can recover during the OFF period. Mathur et al. [54] suggested running the EATHE in winter days/night mode to get a better performance in the following summer as it will reduce the soil saturation. It was shown by Mathur et al. [55] that, intermittent operation (60 min ON and 20 min OFF) increases the heat transfer rate by 1.81% in terms of the outlet temperature.

In our study, the effect of soil thermal conductivity and various geometric parameters like pipe length, pipe thickness etc. on the thermal performance of the EATHEs has been analyzed. A validated three-dimensional, transient numerical model was used to carry out the analysis. The transient analysis was carried out using ANSYS FLUENT 12. The performance is analyzed based on the outlet air temperature. The results are validated against experimental data and can be utilized in any study regarding EATHEs and most importantly to design EATHEs in real life.

Material	Density (kg m^{-3})	Specific heat capacity (J kg^{-1} K^{-1})	Thermal conductivity (W m^{-1} K^{-1})
Air	1.225	1.006	.024
PVC	1380	900	1.16
Soil-1	2050	1840	.65
Soil-2	2050	1840	1.25
Soil-3	2050	1840	3.5

Table. 1. *Physical and thermal properties of the different materials used in simulation*

2. SYSTEM DESCRIPTION AND SIMULATION SEUP

Thermal analysis of an EATHE system (under transient conditions) has been evaluated in order to analyze the thermal performance. Numerical simulations were performed using the Computational Fluid Dynamics software package, ANSYS FLUENT v. 12. It has the ability to predict the compressible, incompressible, laminar and turbulent fluid flow, along with fluidity and compressibility phenomena. FLUENT turbulence models can reflect the turbulence behavior near wall using extended wall functions [56].

2.1. Physical model

he physical geometry of EATHE systems, including the PVC pipe and surrounding soil, has been

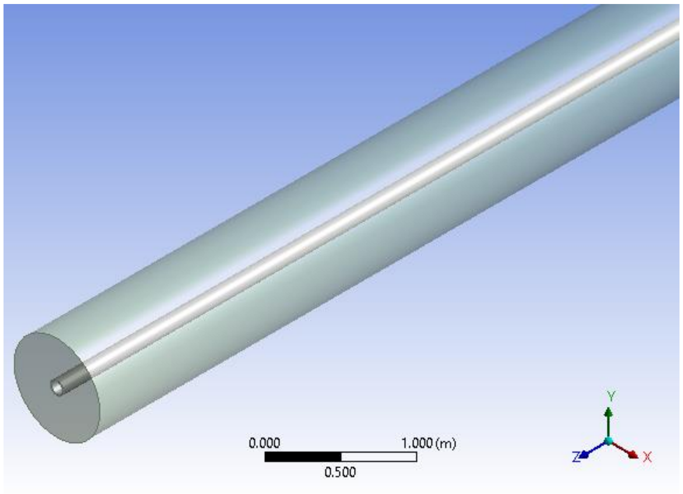


Figure 2:Modeling of the EATHE

modeled (*Figure 1).* All the geometric parameters are the same as in the existing experimental setup (*Table* 1) using ANSYS's workbench platform, that is, ANSYS DESIGN MODEL.

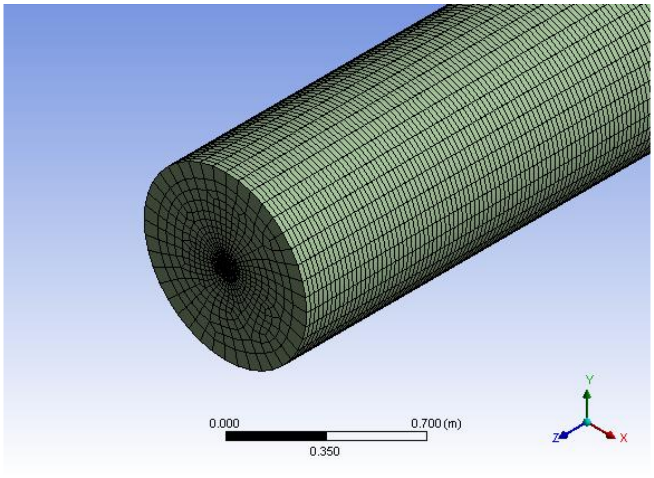


Figure 3: Meshing (side view)

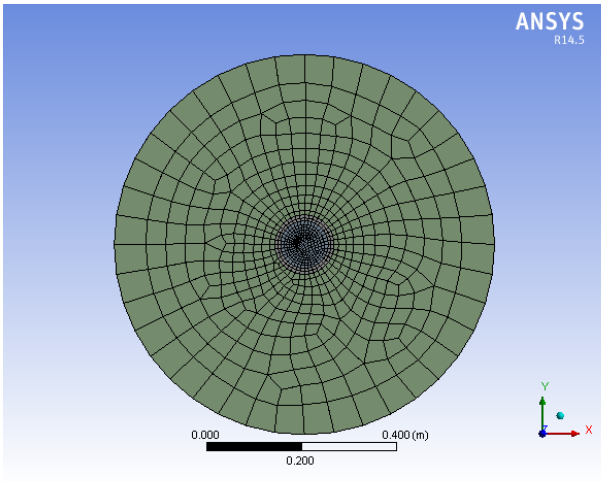


Figure 3: Meshing (front face)

The physical model of the straight EATHE system is meshed using 3D hybrid (hexahedral and tetrahedral) mesh networks (*Fig. 2*) consisting of a total of 23,26,116 cells (elements) with ANSYS's workbench MESHING.

2.2. Simulation model

ANSYS FLUENT v 12 was used in the study which uses the finite volume method to convert the governing equations into numerically solvable algebraic equations. The numerical solutions are based on the following assumptions:

i. Thermo-physical properties of soil, PVC pipe and air remain constant during the operation.
ii. The vertical pipes are well insulated and do not affect the temperature of the air due to the change in soil temperature around it.
iii. There is no effect of moisture on heat transfer.
iv. Thermal contact between ground and buried pipe is perfect.
v. Initially, soil and PVC pipe’s temperatures are considered equal and undisturbed.
vi. Air within an EATHE mix evenly within each segment next to the tube without stratification.

2.2.1. Governing equations

The current numerical model consists of continuity equation, momentum equation, energy equation and realizable k-ε equation and these equations can be expressed in the following conservative form [56,57]

$$\varDelta \equiv \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad or \qquad \varDelta \equiv \frac{\partial u_i}{\partial x_i} = 0 \qquad \text{---continuity equation---} \qquad (1)$$

$$\partial\rho/\partial t + \nabla \cdot (\rho \rightarrow v) = S_m \qquad (2)$$

Where; ρ is the density of the fluid (kg m^{-3}) and → v is the velocity vector of the flow (m/s). The source term S_m is the mass added or removed by the continuous phase dispersed phase or any other source (kg m^{-3} s^{-1}).

$$[u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}] = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \vartheta[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}] \qquad \text{\_\_\_Momentum equation-X\_\_(3.1)}$$

$$[u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}] = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \vartheta[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}] \qquad \text{\_\_\_Momentum equation-Y\_\_(3.2)}$$

$$[u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}] = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \vartheta[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}] \qquad \text{\_\_\_Momentum equation-Z\_\_ (3.3)}$$

In energy equation (Eq. (4)), the terms on the left correspond to the local variation of energy and the advective transport of energy, respectively. The first three terms on the right side represent the energy transfer due to heat diffusion, mass diffusion and viscous dissipation, respectively. The last term, S_h (W m^{-3}), takes into consideration any source or sink of heat by conversion of any mode of energy (electrical, chemical) in thermal energy [31].

$$\partial/\partial t\ (\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot (Keff\ \nabla T - \rightarrow \sum h_j \rightarrow J_j + (\bar{\bar{\tau}}_{eff} \cdot \vec{v} + S_h)$$

$$\text{---energy equation---} \qquad (4)$$

$$E = h - p/\rho + v^2/2, \qquad h = \sum_j Y_j h_j + \frac{p}{\rho}, \quad h_j = \int_{T_{ref}}^{T} C_{pj}\, dT$$

where E is the specific energy (J kg^{-1}), h is the sensible enthalpy (J kg-1), Y_j and h_j are the mass fraction and the enthalpy of species j, respectively, C_{pj} is the specific heat of species j (J kg^{-1} K^{-1}), T_{ref} is a reference temperature (298.15 K), k_{eff} is the effective conductivity ($Wm^{-1}K^{-1}$) given by $k + k_t$ being k_t the turbulent thermal conductivity defined according to the turbulence model adopted and → J_j is the diffusive flux of species j (kg m^{-3} s^{-1}).

To predict the turbulence inside the pipe, pressure based realizable k-ε model with enhanced wall treatment and energy equation is also solved with ANSYS [56] since the computations included heat transfer. The k-ε model is one of the most common turbulence models, which is built in FLUENT and gives good results for bounded wall and internal flows with small mean pressure gradients

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}\left(\rho k u_j\right) = \frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j} + G_k + G_b - \rho\varepsilon - Y_M + S_k \qquad (5)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}\left(\rho \varepsilon u_j\right) = \frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j} + \rho C_1 S_{k\varepsilon} - \rho C_2 \frac{\epsilon^2}{k+\sqrt{(v\varepsilon)}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \qquad (6)$$

Where,

$C_1 = \max 0.43, \frac{\eta}{\eta+5}, \quad \eta = S\frac{k}{\varepsilon}, \quad S = \sqrt{2S_{ij}S_{ij}}$

In these equations, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to buoyancy. G_m represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. C_1 and $C_{1\varepsilon}$ are constants. S_k and S_ε are user-defined source terms.

The molecular Prandtl number P_r, turbulent kinetic energy k and turbulent dissipation rate ε are calculated by FLUENT automatically according to the physical parameter and flow velocity.

The eddy viscosity is computed from,

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon}$$

Different model constants are,

$C_{1\varepsilon}=1.44, \quad C_2=1.9, \quad \sigma_k = 1.0, \quad \sigma_\varepsilon = 1.2$

2.2.2. Boundary and Initial conditions

The far-field soil environment was treated as fixed temperature areas. Moreover, the soil conditions are treated as constant. In the worst case, it had been observed by different simulations [47, 58] that, the ground temperature at a distance from more than 10 times pipe diameter of the pipe does not change significantly and can therefore be neglected. In this study a PVC pipe with an inlet diameter of .1m and thus a control volume of 1.1 m has been considered as the control volume. Modelling was done in this control volume for the analysis.

The pipe wall and surrounding soil layer was "Coupled" to so that they could initiate heat transfer and initial conditions are set as shown in the *table. 02*.

Input parameters	Values
Pipe Diameter (m)	.1
Pipe length (m)	60
Air velocity (ms^{-1})	5
Surrounding soil temperature (K)	300.2
Soil thermal conductivity ($W\ m^{-1}\ K^{-1}$)	1.25
Soil thermal diffusivity (m^2s^{-1})	0.00232

Table. 02. *Input parameters for competitive validation*.

The boundary conditions that are imposed for the analysis are as follows-

i. Inlet boundary: At the inlet of EATHE uniform velocity is used and the direction is normal to the opening at inlet, velocity along the x-axis was taken as 5 m/s. Turbulence parameters at the inlet are defined using turbulence intensity (assuming 5%) and inlet characteristic length (hydraulic diameter) as 0.1 m.

ii. Soil far boundary: Outer surface of the soil (10 times the pipe diameter) surrounding the EATHE pipe was assumed to be at constant temperature of 300.2 K.

iii. Inlet & exit face: Zero heat flux condition is assumed at both of the inlet and outlet face of the EATHE pipe

iv. Soil-pipe interface: As already said, coupled heat transfer is assumed at the soil-pipe interface. No-slip conditions for velocity and steady temperatures are applied at the duct surfaces. Zero diffusion flux of all flow variables in the direction normal to the outlet is used.

2.2.3. Solution technique

This study used a fully unstructured finite-volume CFD solver, Fluent 12, for simulation. The SIMPLE algorithm is applied for the pressure–velocity coupling in the segregated solver. A second order upwind scheme is adopted for the discretization of the governing equations. The convergence criteria for all variables were set to be 10^{-6}.

3. VALIDATION

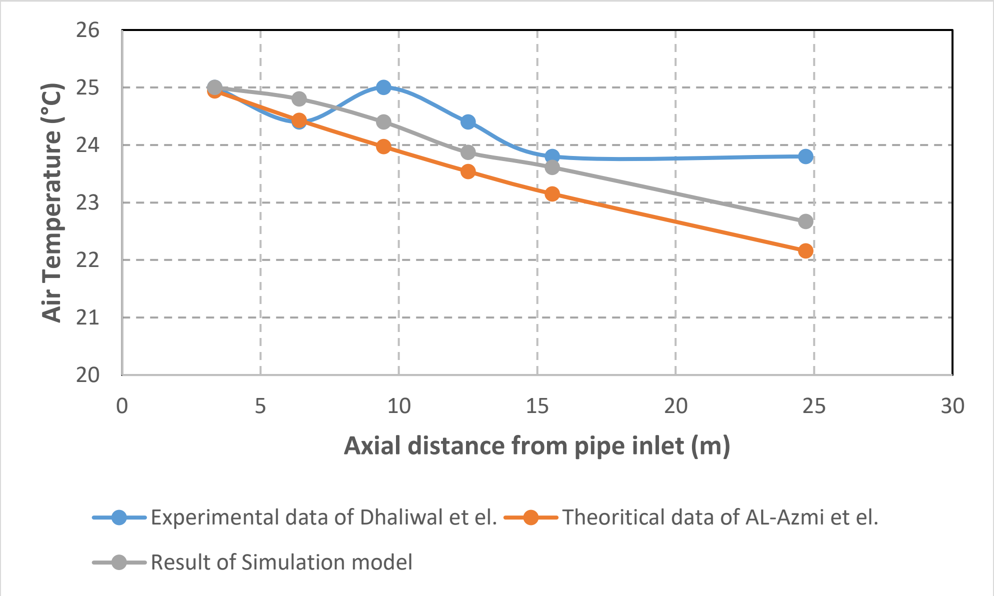


Figure 5: Validation against experimental/theoretical data of Dhaliwal experimental/theoretical data of Dhaliwal et al. and AL-Azmi et al. [59,45]

CFD based modeling of EATHE cooling system had been validated for summer weather conditions by Mishra et el. [42] with data from the experimental set-up as shown in *Fig. 1* for the month of June, 2011at Ajmer (Western India). For validation of EATHE model, pipe diameter of 0.1 m and pipe length of 60 m was prepared. The outer diameter of the soil cylinder surrounding the EATHE pipe has been taken as ten times the pipe diameter. In this validation exercise, inlet condition of air in CFD simulation was kept same as measured at the experimental set-up. When the comparison to experimental results were done, the model developed in the previous section was validated against both theoretical model and experimental data of other researchers also. The theoretical model for the comparison was developed by Al-Ajmi et al. [45], which was validated against relevant experimental and theoretical studies. The experimental study was carried out by Dhaliwal and Goswami [59] at North Carolina under the configuration of a pipe diameter of 30 cm, a pipe length of 24.7 m, and a pipe depth of 1.7 m.

4. GRID INDEPENDENCY TEST

A grid-independency test was carried out to check the effect of mesh size on the accuracy of the solution as shown in *Fig. 5*. Mesh size varies from 0.015 m to 0.075 m from pipe surface to soil

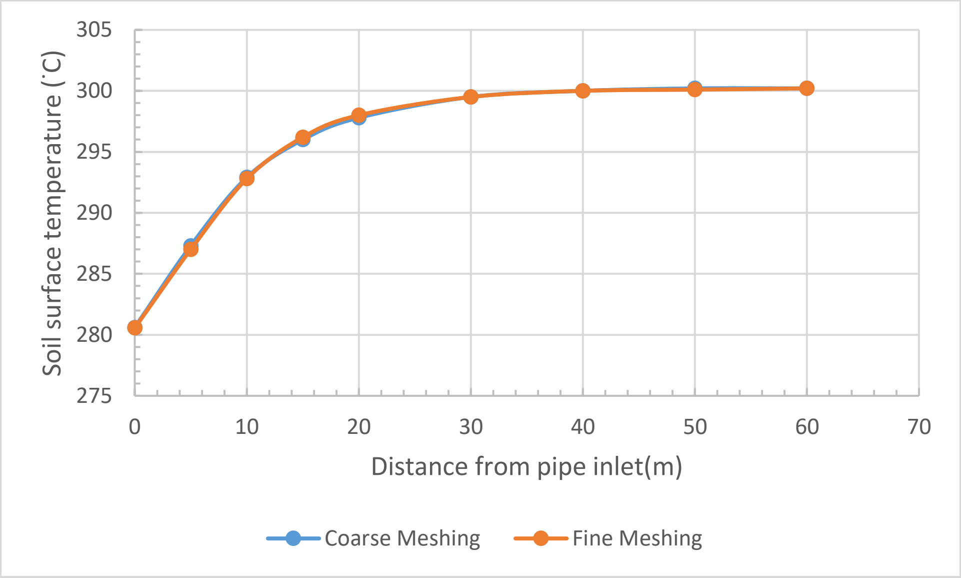


Figure 6: Grid independency test with soil surface temperature vs distance from pipe inlet for different meshing

outer layer. The independent grid size was determined by successive refinements, increasing the number of elements from 23,26,116 (Coarse mesh) to 34,17,234 (Fine mesh).

5. STEADY STATE PERFORMANCE OF EATHE SYSTEM

3-D simulations were carried out with the help of k-epsilon model and the performance of EATHEs are measured in terms of the temperature drop found at the outlet section of the EATHE. i.e. The more the temperature drop, the better the performance of EATHE.

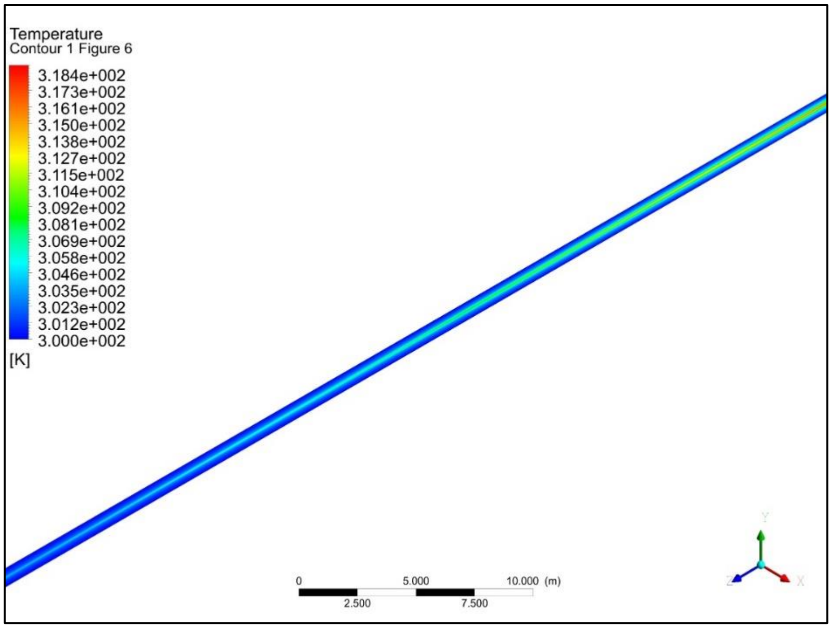
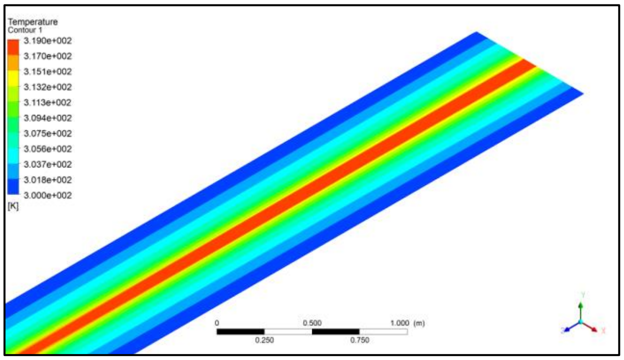
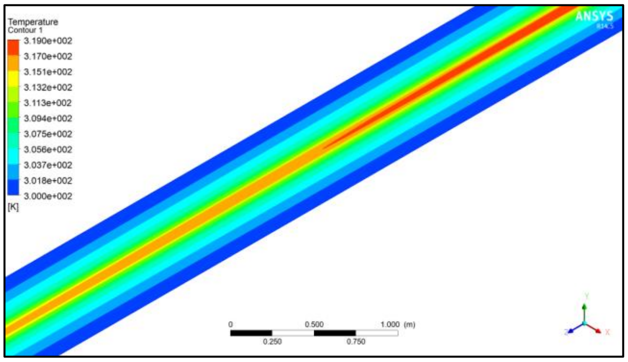
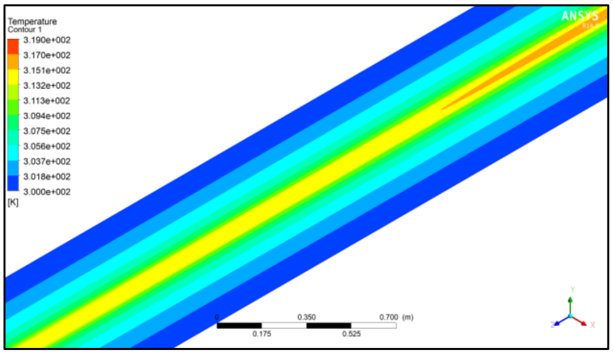
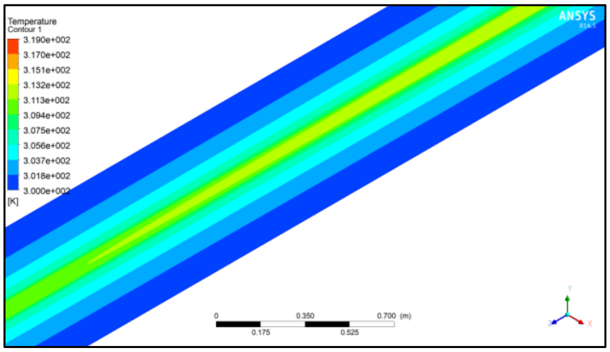


Figure 7: Temperature Profile of the model.









Here, the effects of soil thermal conductivity, velocity of air entering the EATHE (inlet air velocity) and thickness and the length of the PVC pipe on the thermal performance of the EATHEs has been studied.

Analysis was done in terms of the thermal performance based on three different soil samples each having a different thermal conductivity value. Sample1, 2 and 3 has, thermal conductivity, K_1=.65 $Wm^{-1}K^{-1}$, K_2=1.25 $Wm^{-1}K^{-1}$, K_3=3.5 $Wm^{-1}K^{-1}$. The soil temperature at a depth of 3.7m was found to be 300.24K and it was assumed to be constant [38] during the whole operation of the EATHE. It is known as the undistributed soil temperature, as it remains unaffected by the environmental temperature above the soil surface. Although, for soils with low thermal conductivity, there will be heat generation and the temperature will not remain constant anymore yet, we assumed it to remain constant. This heat generation in case of soil with low thermal conductivity will result in a deteriorated thermal performance.

In this study, different velocities were also considered for the air entering the EATHE ranging from 3 ms^{-1} to 7 ms^{-1}. And the effect of change of air velocity on the thermal performance of the EATHE is also analyzed and summarized.

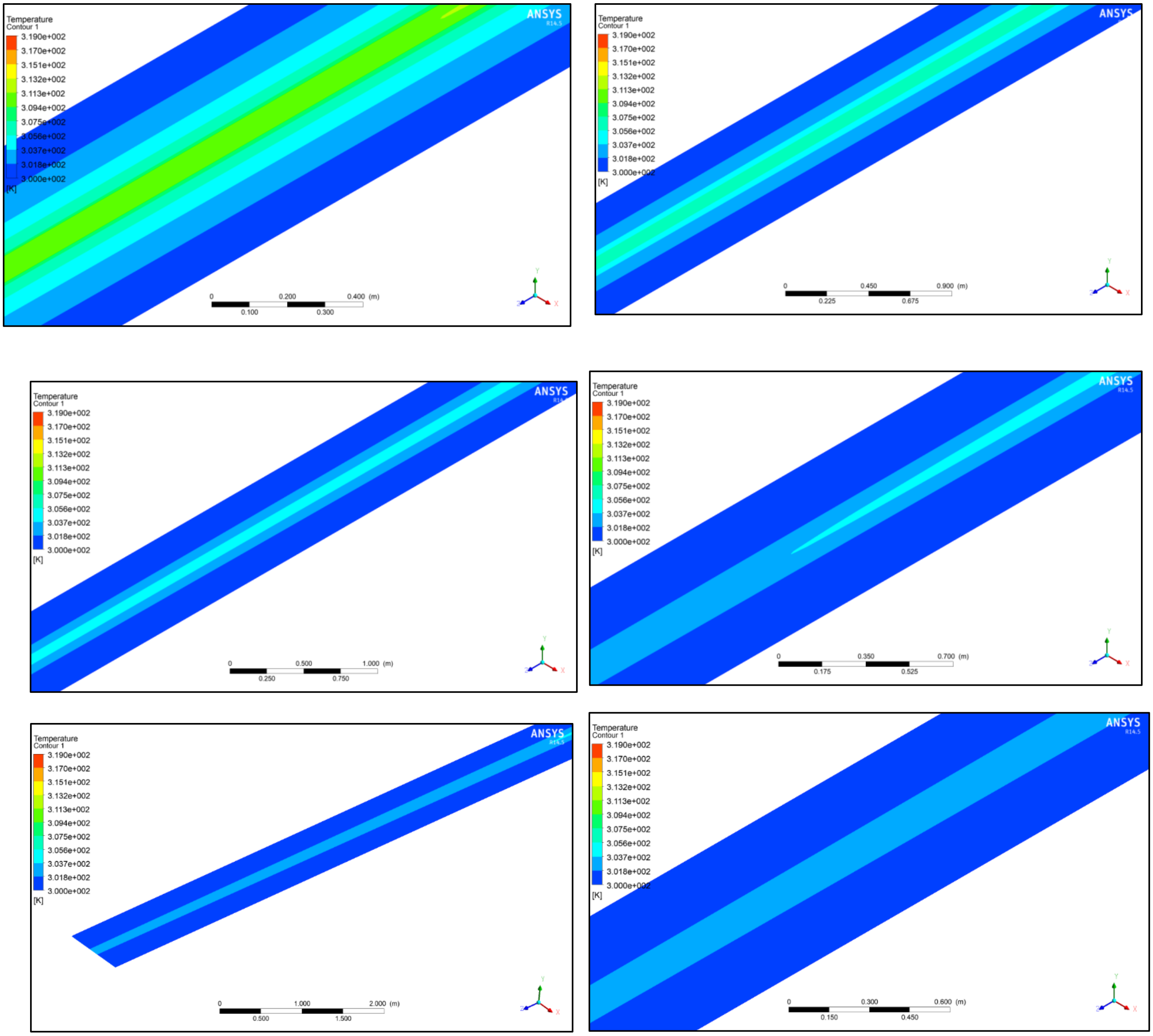


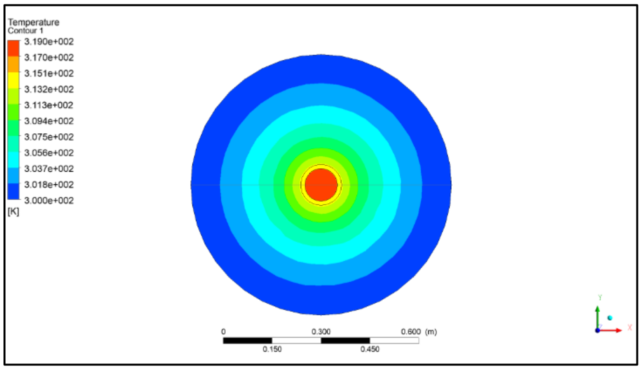
Figure 8: Temperature profile along the length of the pipe.

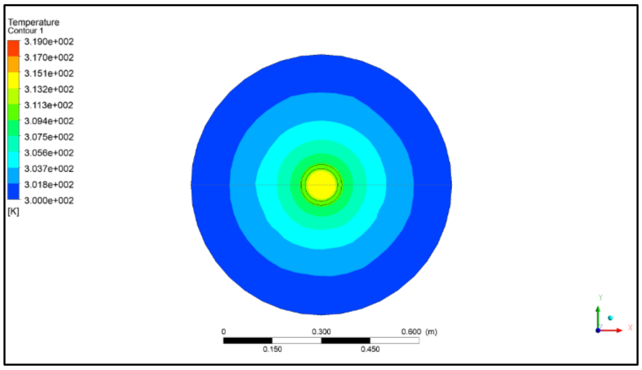
It is also studied that, how the thickness of the PVC pipe effects the thermal performance, as it is an important parameter for the economic consideration. Another parameter related to the economic operation is the length of the PVC pipe. Initially, all the simulations are carried out with a pipe length of 60m. Further simulations were carried out to show that, how smaller the pipe can be without deteriorating its thermal performance. As it is mentioned earlier that the simulations were carried out with three different soil samples (K_1=.65 $Wm^{-1}K^{-1}$, K_2=1.25 $Wm^{-1}K^{-1}$, K_3=3.5 $Wm^{-1}K^{-1}$). In *table-3*, the results found from the simulations are tabulated by putting the temperature drops against different thermal conductivities under different operating conditions (Inlet velocity, V).

V=3 (ms^{-1})		V=4 (ms^{-1})		V=5 (ms^{-1})		V=6 (ms^{-1})	
Conductivity ($Wm^{-1}K^{-1}$)	Temperature Drop(ΔT)	Conductivity ($Wm^{-1}K^{-1}$)	Temperature Drop(ΔT)	Conductivity ($Wm^{-1}K^{-1}$)	Temperature Drop(ΔT)	Conductivity ($Wm^{-1}K^{-1}$)	Temperature Drop(ΔT)
0.65	17.706	0.65	16.769	0.65	15.818	0.65	14.903
1.25	18.627	1.25	18.24	1.25	17.771	1.25	17.268
3.5	18.948	3.5	18.879	3.5	18.772	3.5	18.641

Table 03*: Variation of temperature drop under different velocities.*

It is clearly visible that, in the bottom row of the table, there remains the higher values of temperature drops. And it is highest on the left side while gradually decreasing towards the right and top side of the table. i.e. Soil thermal conductivity is directly proportional to the temperature drop. As the conductivity of soil increases, the temperature drops increase. This is due to the fact that, soils having lower thermal conductivity tend to diffuse heat at a slower rate resulting in heat generation around the EATHE pipe and thus the performance of the EATHE gets deteriorated. From the *table-03* it is also clear that, velocity of the incoming air has also got something to do with the EATHE performance. With increasing velocities of the inlet air, the thermal performance hence, the temperature drops decrease. We get a maximum temperature drop of 18.948 K with a soil having thermal conductivity of 3.5 $Wm^{-1}K^{-1}$, and air having inlet velocity of 3 ms^{-1}. But as the velocity is increased, the temperature drops go down accordingly to 18.879 K, 18.772 K, 18.641 K for velocities 4,5 and 6 ms^{-1} respectively.





Everything that had been said so far, will be easier to grasp if a closer look is taken at *figure-10*. It can be seen that; lower velocities of air have the higher temperature drops comparing to the higher velocities. At the same time, temperature drops are increasing with thermal conductivity of the soil. But, this trend of increasing temperature drop with thermal conductivity does not remain for too long. As we can see from *figure-10*, up to certain values of thermal conductivities, the curves have a comparable slope. But, after that, the curves tend to get horizontal, thus stating the fact that,

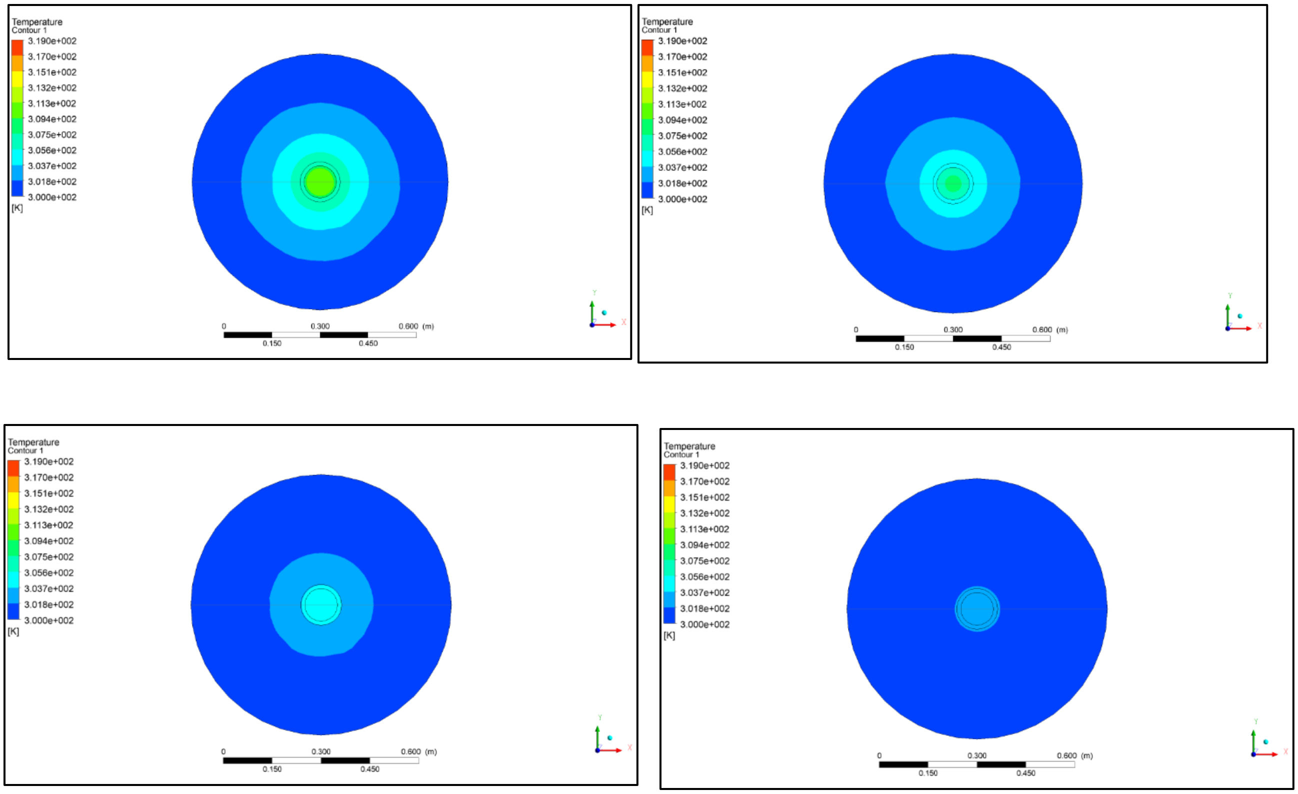


Figure 9: Cross-sectional view of the temperature contour along the length at inlet, 10m, 20m, 30m, 40m,60m

temperature drops become independent of the thermal conductivity of the soil for higher values of "K". Another fact from *figure-10* is that, the dependency of the temperature drops on soil thermal conductivity is higher for higher inlet velocities of air.

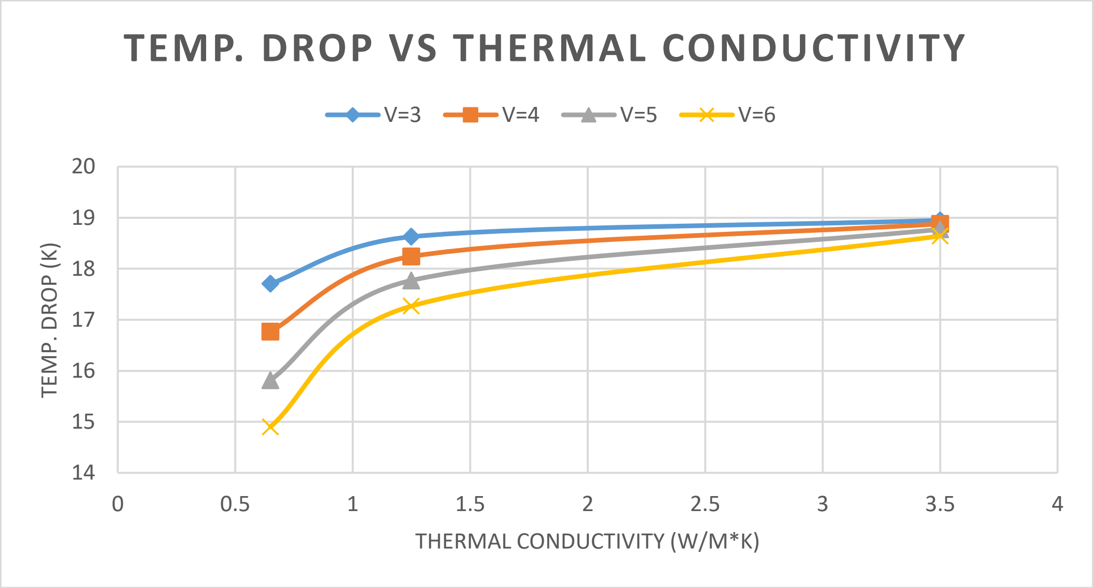


Figure 10: Graphical representation of the change in temperature drops at the outlet section of the tube under varying inlet velocity.

K=.65 ($Wm^{-1}K^{-1}$)				K=1.25 ($Wm^{-1}K^{-1}$)				K=3.5 ($Wm^{-1}K^{-1}$)			
Inlet Temperature	Outlet Temperature	Inlet Velocity (V, ms^{-1})	Temperature Drop (ΔT)	Inlet Temperature	Outlet Temperature	Inlet Velocity (V, ms^{-1})	Temperature Drop(ΔT)	Inlet Temperature	Outlet Temperature	Inlet Velocity (V, ms^{-1})	Temperature Drop(ΔT)
319	301.294	3	17.706	319	300.373	3	18.627	319	300.052	3	18.948
319	302.231	4	16.769	319	300.76	4	18.24	319	300.121	4	18.879
319	303.182	5	15.818	319	301.229	5	17.771	319	300.228	5	18.772
319	304.097	6	14.903	319	301.732	6	17.268	319	300.359	6	18.641

Table 04: *Data representing the temperature drops at the outlet section of the EATHE pipe, under different soils with different soil conductivities.*

Table-04 and *figure-10* is just the re-confirmation of the things that had already been said. From *table-04* it is visually clear that, no matter what, higher soil thermal conductivities always result in higher temperature drops while increasing inlet air velocities deteriorate the performance, i.e. decrease the temperature drop. The highest temperature drop found from *table-04* is 18.948 K for K=3.5 $Wm^{-1}K^{-1}$ and V=3 ms^{-1} while the lowest one is 14.903 K for K=.65 $Wm^{-1}K^{-1}$ and V=6 ms^{-1}. That is, the difference is huge.

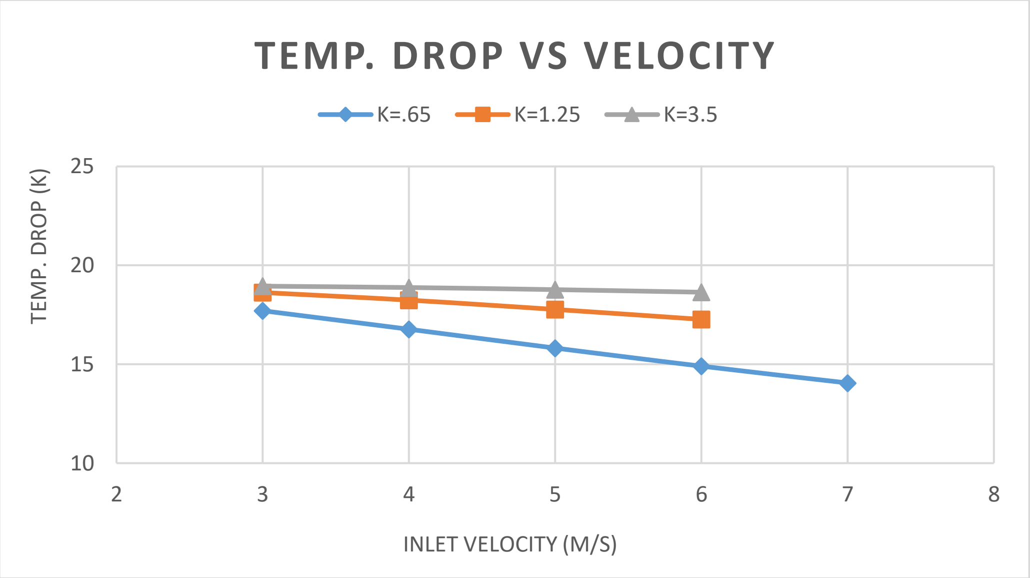


Figure 11: Graphical representation of change in temperature drops w.r.t change in inlet velocity under different soil thermal conductivities.

For better visualization, the data from *table-04* were plotted to get the curves of *figure-11*. *Figure-11* shows that, there is a decreasing linear relationship of temperature drops with increasing velocity. From the higher slopes of the lines for lower thermal conductivities state that the effect of velocity on temperature drop is more for the soils having lower thermal conductivities

K=3.5 $(Wm^{-1}K^{-1})$			K=1.25 $(Wm^{-1}K^{-1})$		
Thickness of pipe (mm)	Outlet temp.	Temperature drop	Thickness of pipe (mm)	Outlet temp.	Temperature drop
2.5	300.052	18.948	2.5	300.373	18.627
7.5	300.051	18.949	7.5	300.382	18.618
10	300.052	18.948	10	300.376	18.624

Table 05*- Change in the temperature drops at the outlet section due to change in the thickness of the EATHE pipe.*

In order to grasp the effect of the pipe thickness on the thermal performance of the EATHE, simulations were also carried out with different pipe thickness. The results are tabulated in *table-05*. It is pretty much a straightforward observation from the *table-05* that, there is hardly any change in the temperature drops for change in the pipe thickness.

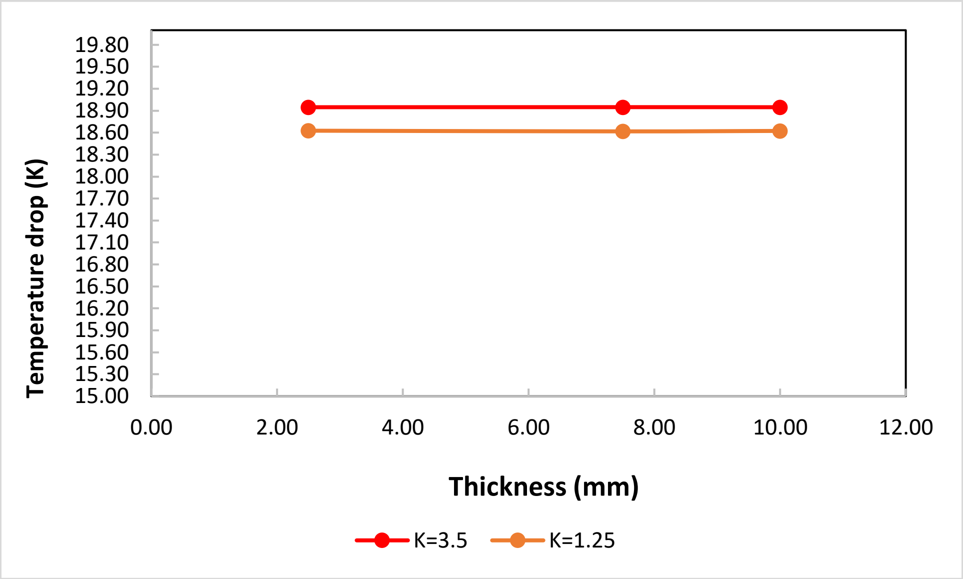


Figure 12: Linear relation between the thickness of the EATHE and the corresponding temperature drops

Thus, it can be concluded that, the effect of pipe thickness on the thermal performance the EATHEs is negligible. That's why, we end up with straight lines in *figure-12*.

6. CONCLUSION

The results of the simulation model indicate prime movers of the thermal performance of an EATHE. The outlet temperature of air is dependent on the pipe length up to a certain length around 40m. After this length, the drop-in temperature is negligible. The thickness of the pipe affects the time to obtain a certain temperature drop for a fixed length of pipe. The inlet velocity of the air is also important as it determines the possibility of the air elements being obstructed in the pipe wall. Temperature drop decreases with higher inlet velocities. The most prominent parameter of this study is the thermal conductivity of the soil. With increasing soil thermal conductivity, the ability of absorbing heat increases.

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