**Journal of Mechanical and Construction Engineering, 2023,**
Vol. 03, Iss. 01, S. No. 003, pp. 1-10
ISSN (Online): 2583-0619

# Computational Studies of Earth Air Heat Exchanger using CFD: Parametric Analysis

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**How to cite this paper:** S. Lal, "Computational Studies of Earth Air Heat Exchanger using CFD: Parametric Analysis," *Journal of Mechanical and Construction Engineering (JMCE),* Vol. 03, Iss. 01, S. No. 003, pp. 1–10, 2023.

http://doi.org/10.54060/jmce.v3i1.29

**Received:** 02/01/2023
**Accepted:** 12/03/2023
**Published:** 25/04/2023



## Abstract

*Parametric studies of earth air tunnel heat exchanger (EATHE) using FLUENT 6.3 Computational fluid dynamics (CFD) software have been carried out in this paper. From the parametric analysis it is found that economic analysis of the system is required for the optimization of length, diameter, and depth of buried pipe. For a long earth air tunnel more than 60 m, soil thermal conductivity doesn't give any significant effect. The higher mass flow rate also increases the overall energy conservation potential of the system, but it reduces thermal comfort. So, the mass flow rate also takes to optimize according to the requirement. This study is beneficial to the design and energy researchers of this field.*

## Keywords

*Earth air tunnel heat exchanger, computational fluid mechanics, parametric study*

## 1. Introduction

The highest energy demanding sector is the building sector in the present scenario due to the improvement in the living standard and comfort. And the energy demand in building sector is increasing in developing countries like India in present time. The buildings sector's energy consumption is observed around 40% approximately of global energy use. Indoor thermal comforts are mainly provided by fossil fuels which accounts in the order of 28% of the total global energy consumption [1]. This demand is which realizing indoor thermal comfort has been increased significantly in recent scenario due to economic and infrastructure growth for developing new living standards. This demand may increase greenhouse gas (GHG) emissions and environmental pollution. The fourth IPCC was reported that the GHG emissions in the environment increased by an average increment of 1.6% per year and $CO_2$ emissions at a rate of 1.9% per year [2].

The passive thermal system concepts can provide indoor thermal comfort and it reduces the energy consumption in the buildings. By using this option GHG emissions can also be reduced [2]. The passive concepts for cooling or heating are used to provide indoor thermal comfort by using natural sources of thermal energy. Direct or indirect coupling of buildings with the earth is one of the passive concepts for achieving indoor thermal comfort and one of the ways of reducing energy consumption in HVAC (Heating, Ventilation and Air Conditioning) [3]. EATHE can be adopted as one option for thermal comfort in a building. It is working on the basis of earth to air or air to earth heat exchange process. Sharan and Jadhav studied the subsoil temperature fluctuation with the variation of depth of soil from the earth surface and found the constant or undisturbed earth soil temperature at 3-4 m or more [4]. This undisturbed earth temperature (UET) is unique and observed more than the winter seasonal ambient average temperature (SAAT) and lower than the summer SAAT. The UET can be used to provide indoor thermal comfort by applying the EATHE system. The performance of an earth air tunnel heat exchanger (EATHE) system depends on the UET, ground moisture condition, ground surface condition and the thermal conductivity of the earth soil where EATHE system would be established.

The application of EATHE system is a highly potential option for thermal conditioning of buildings and it will help to reduce energy demand in buildings and adds a root of sustainable development which has added a significant energy saver during the last three decades [5-8].

First scientific study on constructing EATHE was carried out for EATHE installed at Clara Swaine Hospital, Bareilly India. The EATHE coupled with the conventional air conditioner was studied to reduce the cooling load of Air Conditioner (AC) and observed that the effectiveness was substantially increased [9-10] studied a simple theoretical model of EATHE and evaluated the performance. The EATHE system at Mathura consisted of 80 m long and the cross-sectional area was 0.528 $m^2$. It was estimated that the EATHE system of Mathura U.P given 512kWh cooling and 269 kWh heating capacity at an air velocity of 4.89m/s. Singh [11] optimized and analyzed the EATHE system and optimized space cooling based on the room temperature and environmental conditions. An experimental study of EATHE was carried out in France by Trombe and Serres [12]. Santamouris et al. [13] studied the effect on performance of various ground surface conditions for single and parallel EATHE. Another experimental study on EATHE was carried out by Thanu et al. [14] at Gulmohar farmhouse in India and monitored the temperature at inlet and outlet points of the system and relative humidity (RH).

Kumar et al. [15] obtained and presented the heating and cooling potential of a single pass EATHE. Bansal and Mathur [16] observed the effect of evaporative cooling on performance enhancement of EATHE and carried out the parametric study for the illustrated effect of buried pipe length, diameter, and number of pipes, volume flow rate and surface to the volume flow ratio of the exit temperature of EATHE, and the winter performance also analyzed by Bansal et al. [17]. Zukowski et al. [18] observed the main advantages of the EATHE system and 30% energy of conventional AC was saved in the buildings. The PVC pipes were used for the study and observed the reduction in temperature and cooling load by 1.9 ºC and 595kWh respectively. Kaushik et al experimentally studied the EATHE situated at TERI India and presented the energy saving in heating and cooling of building and CO2 mitigation. Many authors have reviewed and analyzed EATHE via experimental and simulation studies [19-24]. It can be used to formulate and design green buildings because much of conventional energy can be saved through this application in residential and commercial buildings [25-26].

The earth air tunnel heat exchanger is a good option for space conditioning of building. It can reduce the energy demand by air conditioners and electrical heaters applied for building space cooling and heating. The study of this technology is also proved its application and benefits. In this communication, parametric analysis of earth air tunnel through computational fluid dynamics software is worked out. It will be beneficial for design and energy researchers of the scientific community.

## 2. Computational fluid dynamic modelling of EATHE

### 2.1. Mathematical Modelling for Earth Air Tunnel Heat Exchanger

The Navier-Strokes equation can be used to govern the unsteady and steady air flow through the earth air tunnel heat exchanger. The continuity, momentum and energy equations for air flow through EATHE are given as follows:

Continuity equation for air flow through EATHE

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \quad (1)$$

X-momentum equation for air flow through EATHE

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial \rho}{\partial x}+\frac{1}{R_{ef}}\left[\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}\right] \quad (2)$$

Y-momentum equation for air flow through EATHE

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=-\frac{\partial \rho}{\partial y}+\frac{1}{R_{ef}}\left[\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}\right] \quad (3)$$

Z-momentum equation for air flow through EATHE

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial \rho}{\partial z}+\frac{1}{R_{ef}}\left[\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}\right] \quad (4)$$

Energy equation for air flow through EATHE

$$\frac{\partial(E_r)}{\partial t}+\frac{\partial(uE_r)}{\partial x}+\frac{\partial(vE_r)}{\partial y}+\frac{\partial(wE_r)}{\partial z}=-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}-\frac{1}{R_{ef}P_{rf}}\left[\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right]+$$
$$\frac{1}{R_{ef}}\left[\frac{\partial(u\tau_{xx}+v\tau_{xy}+w\tau_{xz})}{\partial x}+\frac{\partial(u\tau_{xy}+v\tau_{yy}+w\tau_{yz})}{\partial y}+\frac{\partial(u\tau_{xz}+v\tau_{yz}+w\tau_{zz})}{\partial z}\right] \quad (5)$$

Transport equations for turbulent kinetic energy and turbulent dissipation energy are given as follows:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_j)}{\partial x_j}=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k-\rho\epsilon-Y_M+S_k \quad (6)$$

$$\frac{\partial}{\partial t}(\rho\epsilon)+\frac{\partial}{\partial x_j}(\rho\epsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right]+\rho C_1 S_\epsilon-\rho c_2\frac{\epsilon^2}{k+\sqrt{v\epsilon}}-S_\epsilon \quad (7)$$

Where, the model constants are $\mathbf{P_{k2}}$,, which represents the generation of turbulence kinetic energy due to the mean velocity, the generation of turbulence kinetic energy due to the buoyancy is assumed to be zero. Where, $\boldsymbol{\epsilon}$ is the denoted for dissipation, $\boldsymbol{\mu_t}$ is denoted for eddy viscosity and t represent the turbulent. To solve the above equations the values of some constants are required which are given as follows:

$$\boldsymbol{C_1=1.14, C_2=1.9, \sigma_k=1.0. \sigma_\epsilon=1.2}$$

For the simulation of this mathematical model or computational fluid dynamics model we considering the Realizable k-epsilon model with the steady turbulent flow or constant wall function and the Reynolds-Averaged Navier–Stokes equations (RANS) can be used with $(k - \varepsilon)$ model.

## 2.2. Geometric modelling and meshing

The geometric model of simple earth air tunnel heat exchanger system was prepared using the design modular in the Fluent which is expressed by ANSYS workbench 14.0. The dimensions of the model are similar to the experimental EATHE presented in Mishra et al [27] which is the diameter of the PVC pipe of 100 mm and 60 m long and buried at a depth of 3.7 m. The model is constructed with a sub-soil diameter of 1m around the buried pipe. After that, meshing is carried out of the generated model using Fluent meshing software integrated with the same software (workbench 14.0) as shown in Fig.1.

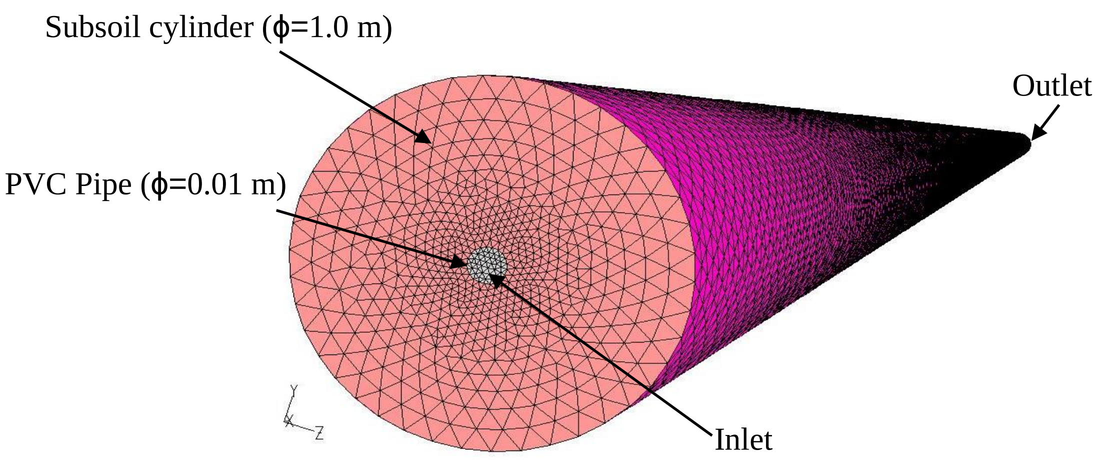


**Figure 1.** CFD geometry and Meshing of EATHE system

The unstructured mesh is used for the meshing because it has the ability to match the boundary shape of CFD solution. The workbench integrated meshing software is optimizing the mesh size and found 1637532 and 3037438 volumes. After meshing the model is forward to the simulation process.

## 2.3. Simulation process in FLUENT

The meshed model is imported in the FLUENT software and checks the model whether it is correct or not. The next step is to define the zones and boundary conditions along with the selection of model. For EATHE simulation k-epsilon realizable turbulent model with constant wall function have used to run the case. The file is heavy, so a parallel processor of 64 GB RAM and 1 TB HDD is used in the DELL workstation to process the data. The fast processor can reduce the simulation time. The basic CFD equation available in FLUENT are processed volume by volume and produced the stable result at particular time in transient analysis.

## 3. Results and Discussions

### 3.1. Model validation

The CFD model is operated in similar to the experimental conditions and yield results are shown in Fig. 3. There is a small difference between experimental and CFD temperatures in buried pipes. The MBE and RMSE are found to be 0.34-0.53 and 0.4-0.61 respectively, the low value of MBE and RMSE are presented the accuracy of the simulated results and said that a good agreement is observed between experimental and CFD results.   Hence the CFD model is validated and can be used for next studies.

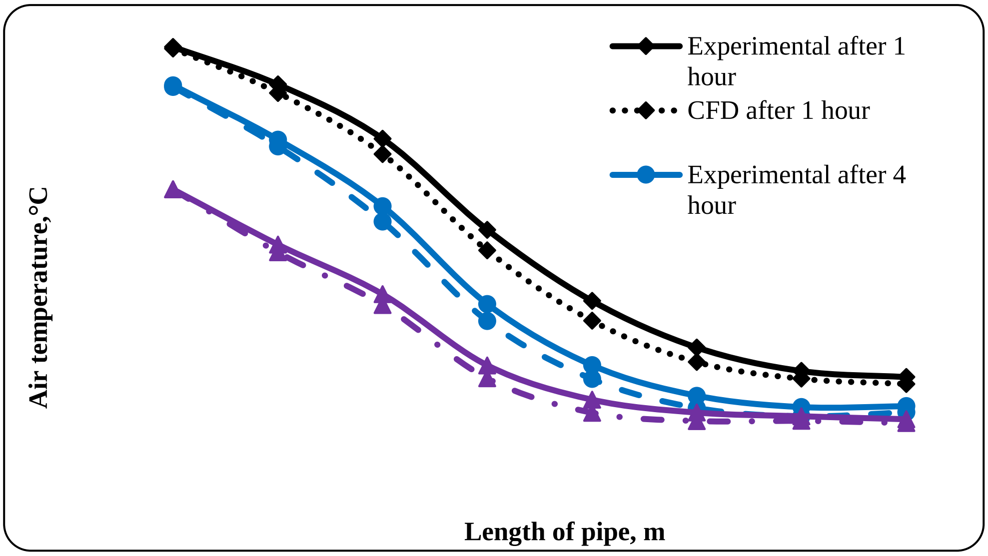


**Figure 3:** Validation of CFD results through experimental

### 3.2. Temperature variation in the buried pipe

The air temperature is reduced when EATHE worked in cooling mode. The reduction of air temperature from inlet to outlet is presented in Fig. 4 and 5 by temperature contour. The outlet temperature is slightly higher than the soil temperature, and maximum lowering up to the soil temperature for infinite long pipe. The cooling capacity depends on the diameter and length of buried pipe, mass flow rate of air and ambient air temperature. The heat transfer from soil surface to the pipe air is shown in Fig. 6&7, it is seen that the temperature is reduced from center to the contact surface of the buried pipe. The maximum temperature observed at the center where mass flow rate is also maximum and the minimum at the wall of pipe.

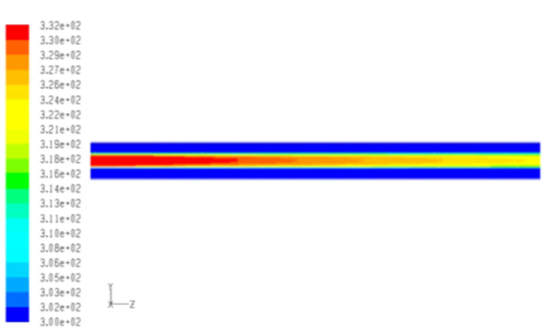

**Figure 4:** Temperature variation contour for Full length of buried pipe

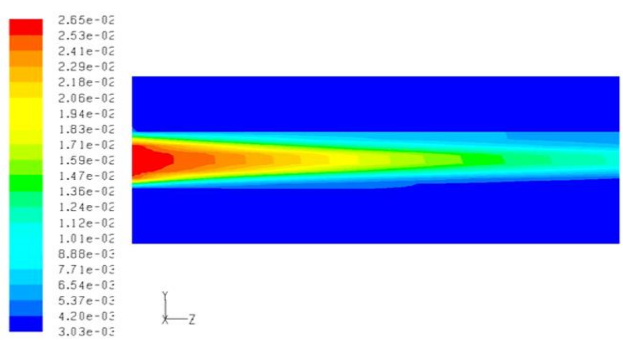


**Figure. 5:** Temperature variation contour in buried pipe

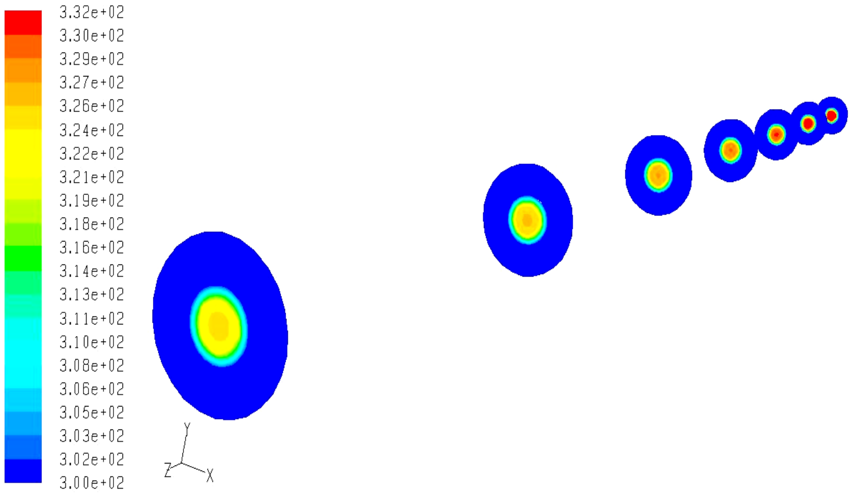


**Figure 7:** Temperature variation circular contour in EATHE model

## 3.3. Effect of running time on performance of EATHE

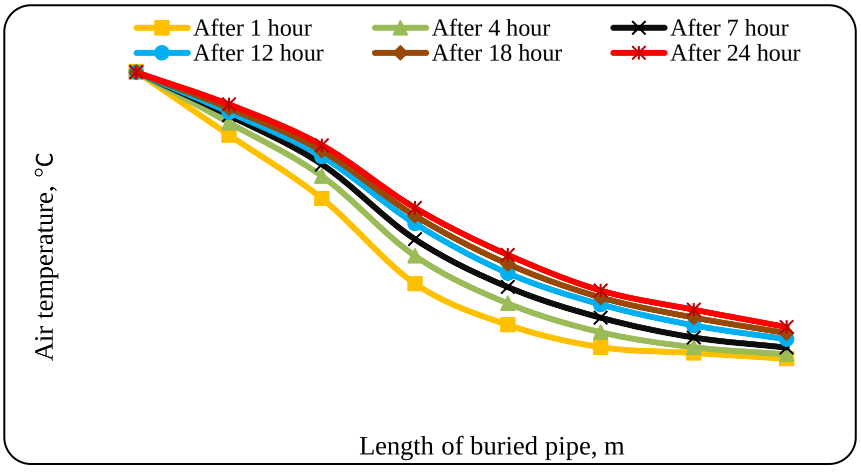


**Figure 8:** Effect of running time on EATHE performance

The soil temperature is constant at the start of the system. After some time, the performance is reduced as shown in Fig. 8. After twenty-four hours it is seen that the air outlet temperature observed more than 34°C and it is not a comfortable temperature. The outlet air temperature increased proportionally to the running time, it is due to the reduction of soil thermal properties, and it is called the derating of soil. The soil required recharging time to find out the initial conditions of the soil.

## 3.4. Effect of soil thermal conductivity on performance of EATHE

The thermal conductivity of soil also affected the performance of the EATHE. Fig. 9, shows the effect of soil thermal conductivity on outlet air temperature when EATHE operated in cooling mode. It is seen that the air outlet temperature decreased with increasing in thermal conductivity of soil. And reverse of that, in heating mode the air outlet temperature increases with increase in the soil thermal conductivity. When length of buried pipe is so longer than optimum length through economic analysis, the thermal conductivity of soil doesn't affect the outlet temperature. As seen from Fig. 9, the outlet temperature gap between two conditions as 0.5 and 2.0 W/m. K, first increased up to 30 m then decreases up to 60 m. And there is no gap at 60 m length of pipe. If the length of pipe (4 inches diameter) is increased more than 60 m, soil thermal conductivity effect isn't considered.

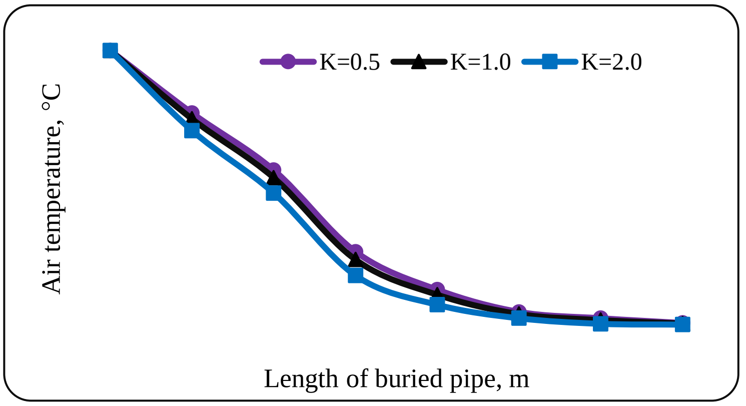


**Figure 9:** Effect of thermal conductivity of soil on performance of EATHE

## 3.5. Effect of mass flow rate on performance of EATHE

The thermal performance of earth air tunnel heat exchanger is also affected by the mass flow rate of working fluid (air). The variation of air temperature at different axial distance in 4-inch diameter EATHE for different mass flow rates (0.02, 0.04, 0.06 kg/s) is shown in Fig. 10. It is found that the outlet temperature augmented with increases in mass flow rate of air. So, the cooling effect decreases. But the outlet temperature increases slightly, and it is difficult to find out the exact mass flow rate for which performance will be maximum. The overall performance may include the economic viability of the EATHE. So, the optimum mass flow rate is defined as the "maximum mass flow rate at which outlet temperature found in comfort acceptable zone by consideration of economic analysis". So, the optimum mass flow rate in for the 4" diameter EATHE is estimated at 1.17-1.19 kg/s.

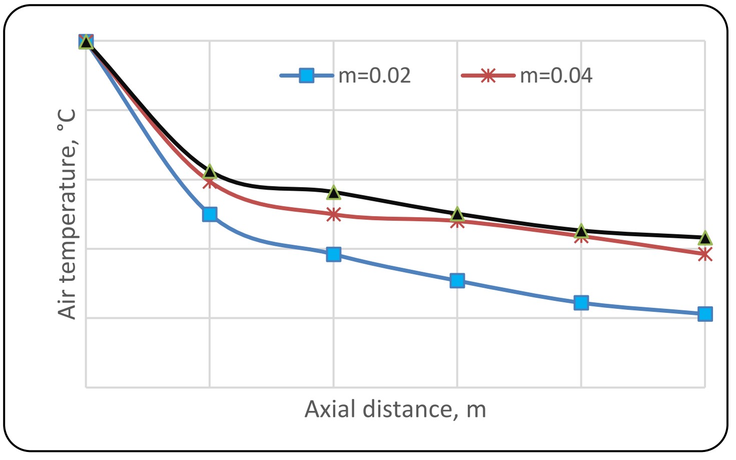


**Figure 10:** Effect of mass flow rate on outlet temperature of EATHE

## 3.6. Effect of pipe dimensions on performance of EATHE

The Diameter and length of buried pipe also affect the heating/cooling potential of the EATHE. Fig. 11 expresses the effect of pipe diameter at different mass flow rates on outlet air temperature when the EATHE is working in cooling mode. The analysis shows that the increased diameter of buried pipe will reduce the cooling effect for same mass flow rate. But if we apply this case for the same velocity definitely increasing diameter will give the higher cooling effects which decided by the outlet temperature.

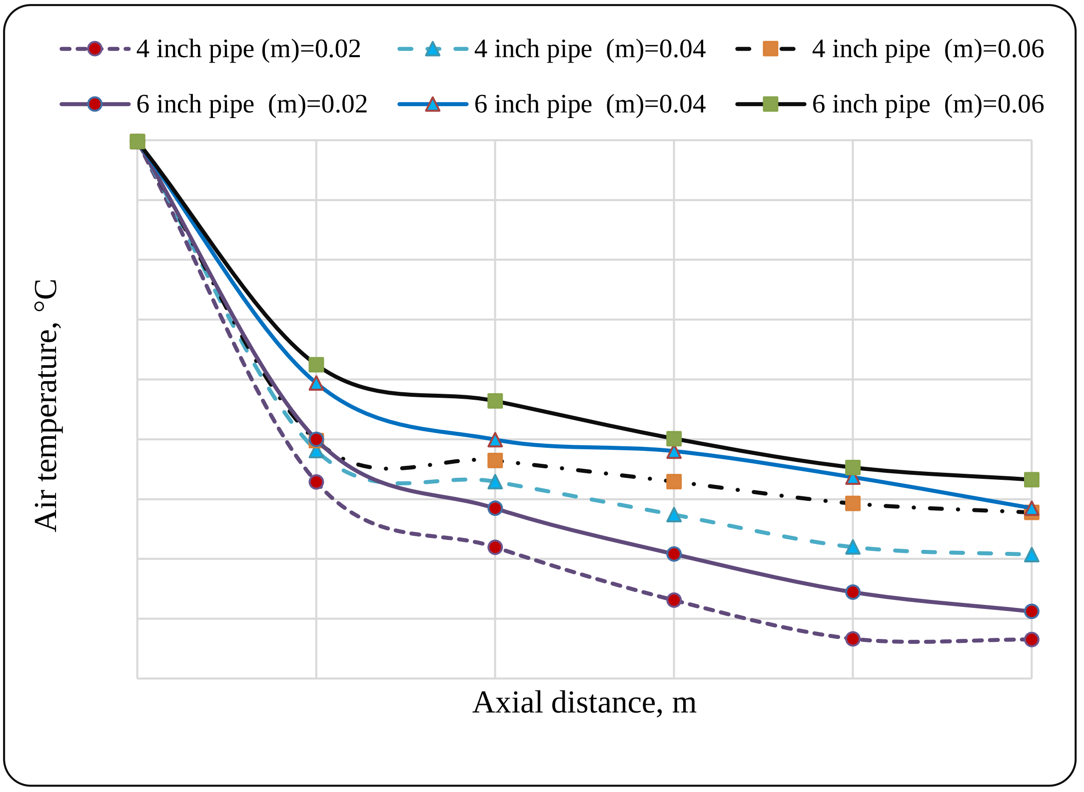


**Figure 11:** Effect of diameter at different mass flow rate on outlet temperature of EATHE

## 4. Conclusions

The earth air tunnel heat exchanger is parametrically studied in this communication. A three-dimensional CFD model is validated through the experimental results of Bansal et al. (2013) and found a good agreement between experimental and CFD results. From the parametric study, it is found that performance of EATHE has been decreased with increasing running time. It is observed that the system required breaking down for 2-6 hours after 12 hours running, to recharge the soil properties. The higher soil thermal conductivity gives a positive response to increasing the EATHE performance, but after 60 m it doesn't affect the performance. For a long EATHE, soil thermal conductivity is not necessary to estimate. Higher diameter and length of EATHE also increased the performance of the system but it is optimized from economic consideration. The mass flow rate is also affecting the performance, but it should be optimized for the comfort condition.

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