International Review of Applied Engineering Research.
ISSN 2248-9967 Volume 4, Number 3 (2014), pp. 211-220

http://www.ripublication.com/iraer.htm

Parametric Study and Computational Fluid Dynamics Analysis of Earth to Air Heat Exchanger

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Abstract

ABSTRACT: The article presents the performance analysis of earth to air heat exchanger, which is capable of providing higher temperature at the required cold domain consistently for the winter season and providing lower temperature at the required hot domain in summer. Simulation of EAHX is done with the help of ANSYS Fluent 14.0. The article describes the various temperatures and heat transfer rates for the flowing air through earth to air heat exchanger pipe, for time duration of 24 hours (a standard day). Study includes both steady and transient analysis of earth to air heat exchanger. Effects of the operating parameters (i.e. the pipe material, air velocity, soil conductivity) on the thermal performance of earth to air heat exchanger systems are studied. The 30m long EAHX system discussed in this paper gives heating in the range of 4^0C-9^0C for the flow velocities 2–5 m/s. Investigations on aluminium and PVC pipes have shown that performance of the EAHX system is not significantly affected by the material of the buried pipe. Velocity of air through the pipe is found to greatly affect the performance of EAHX system. Conductivity of soil is also found to greatly affect the performance of EAHX. In This paper the scope of hybridization of EAHX when coupled with HVAC and Solar Air Heater respectively for summer and winter air-conditioning applications to increase the cooling or heating capacity of EAHX is also discussed.

Keywords: Earth to air heat exchanger; soil; temperature; PVC pipe; solar air heater.

1. Introduction

The utilization of geothermal energy to reduce heating and heating needs in buildings has received increasing attention during the last several years. An Earth Air Tunnel Heat Exchanger (EATHE) consists of a long underground metal or plastic pipe through which air is drawn. As air travels through the pipe, it gives up or receives some of its heat to or from the surrounding soil and enters the room as conditioned air during the heating and heating period. In the past over 30years, researchers have actively considered using soils for thermal energy storage applications e.g., [1–8]. The nearly constant ground temperature at a certain depth has been regarded by several researchers as a passive means for heating and cooling of buildings. Depending mainly on the ambient air temperature, shallow soils could be the unique heat source or sink needed for heating or cooling purposes, for considerable periods of time throughout the year. Hence, soil temperature is an important parameter in solar and geothermal energy applications such as the passive heating and cooling of buildings and agricultural greenhouses [4]. In many engineering applications it is necessary to know the soil temperature at different levels in order to determine the system design parameters. Although soil temperature is considered to be constant at certain depths, it varies especially near surface levels. It is well known that in system such as EAHEs. The depth at which they are installed has vital importance on dimensions, performance and installation costs of the system. In many cases a detailed investigation of the soil properties and long term soil temperature measurements as a function of time at different depths of the research area are needed in order to deter- mine design parameters and feasibility of a system. However, researchers are in the need of more practical tools as obtaining a detailed site survey is not always possible. Despite its importance in scientific research and operations, relatively few data are available on soil temperature. Even when available, the data are often scattered and incomplete. These problems could be attributed to the substantial investment of money and time, and relatively large network of data acquisition system needed for detailed characterization of soil temperature at different depths and times. This study focused on utilizing easily accessible data such as annual daily average air temperatures to predict daily soil temperatures depending on depth and time.

2. Earth to Air Heat Exchanger

Schematic diagram of the earth to air heat exchanger is shown in Fig. 1(a). It consists of a 30 meter length pipe which is buried at some depth inside the earth. Since earth is a semi-infinite body and according to principle of heat transfer in a semi-infinite body. Theoretical equations are shown on next page.

Case 1 Constant Surface Temperature: $T(0,t) = T_s$

$$\frac{T(x,t) - T_s}{T_i - T_s} = erf\left(\frac{x}{2\sqrt{\alpha t}}\right), \qquad q_s''(t) = \frac{k(T_s - T_i)}{\sqrt{\pi \alpha t}}$$

Case 2 Constant Surface Heat Flux: $q_s'' = q_o''$

$$T(x,t) - T_i = \frac{2q_o''(\alpha t/\pi)^{1/2}}{k} \exp\left(\frac{-x^2}{4\alpha t}\right) - \frac{q_o'' x}{k} erfc\left(\frac{x}{2\sqrt{\alpha t}}\right)$$

Case 3 Surface Convection: $-k \left.\frac{\partial T}{\partial x}\right|_{x=0} = h[T_\infty - T(0,t)]$

$$\frac{T(x,t) - T_i}{T_\infty - T_i} = erf\left(\frac{x}{2\sqrt{\alpha t}}\right) - \left[\exp\left(\frac{hx}{k} + \frac{h^2 \alpha t}{k^2}\right)\right]\left[\mathrm{erfc}\left(\frac{x}{2\sqrt{\alpha t}} + \frac{h\sqrt{\alpha t}}{k}\right)\right]$$

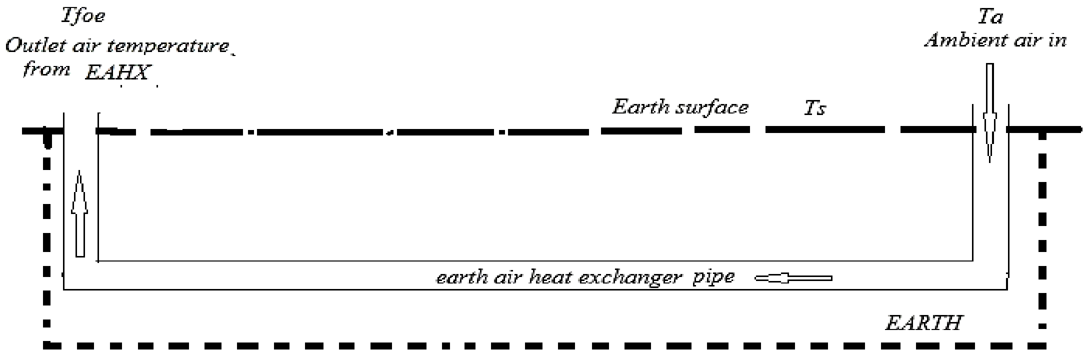


fig 1.(a) Schematic of EAHX

3. Description of CFD Model

To examine the complicated airflow and heat transfer processes in an EATHE system, CFD software FLUENT 14.0, was used in this study. In the present analysis, CFD simulations have been performed using an unstructured grid. CFD software FLUENT is employed to resolve the transient temperature field around the horizontal buried pipe of EATHE. A transient and implicit numerical model based on coupled simultaneous heat transfer and turbulent flow was developed to predict the thermal performance and evaluate the heating capacity of Earth Air Tunnel Heat Exchanger system. The model incorporates the effect of turbulent air flow on the thermal performance. The element type and the grid density were selected to be variable according to the sensitivity of temperature quantity, so that the calculation can adapt to the actual situation and reach a high level of accuracy. Because the temperature changes more sharply around the pipe wall, the grid is designed to be more dense in that area, while it is more sparse farther away from the pipe wall. In the present study it has been assumed that air is incompressible and the soil is homogeneous and its physical properties are constant. It was also assumed that the property of the pipes and ground materials do not change with temperature and engineering materials used in the CFD model are isotropic and homogeneous. It was also assumed that the material of pipe and soil is same to ease the complications in modelling and simulation. The fundamental equations of fluid flow and heat transfer have been used in the analysis. The geometric modelling and meshing have been prepared using ANSYS meshing tool. The main objective of the CFD study was to investigate the transient behavior of simple EATHE system used in continuous heating mode and compare its thermal performance with EATHE operating under steady state condition (assuming that the temperature of soil surrounding the pipe remains constant). Schematic of the numerical model of EATHE used for CFD simulation is shown in Fig. 2. The physical and thermal parameters of different engineering materials used in the simulation are listed in Table 1.

Table 1: Thermal properties of materials.

Material	Density (kg m−3)	Specific heat	Thermal
Air	1.225	1006	0.0242
Soil (SL1)	2050	1840	2
PVC	1380	900	1.16

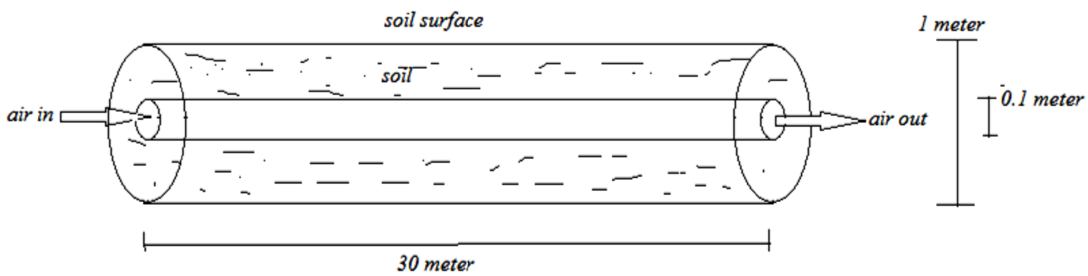


Fig. 2: Schematic diagram of EAHX

4. Governing Equations

The governing transport equations in 3D Cartesian coordinates for the fluid flow, heat and mass transfer are given below

4.1 Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

X-momentum equation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+v\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right]$$

Y-momentum equation

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+v\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right]$$

Z-momentum equation:

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+v\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right]$$

Energy equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right]$$

In the above equations, u, v and w are the velocity components in x, y and z directions, p and T are the pressure and temperature of the flowing air.

Transport equations for the Realizable $k-\varepsilon$ model

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

And

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

Where $C_1=\max\left[0.43,\frac{\eta}{\eta+5}\right]$, $\eta=S\frac{k}{\varepsilon}$, $S=\sqrt{2S_{ij}S_{ij}}$

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, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, C_2 and $C_{1\varepsilon}$ are constants. σ_k And σ_ε are the turbulent Prandlt numbers for k and ε, respectively. S_k And S_ε are user-defined source terms.

The eddy viscosity is computed from $\mu_t=\rho C_\mu\frac{k^2}{\varepsilon}$

The model constants are $C_{1\varepsilon}=1.44, C_2=1.9, \sigma_\varepsilon=1.2$

5. Boundary Conditions

(a) 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 3 m/s. Turbulence parameters at the inlet are defined using turbulence intensity (assuming 5%) and inlet characteristic length (hydraulic diameter) as 0.1 m. **(b)** Far boundary of the soil: outer surface of the soil cylinder (10 times the pipe diameter) surrounding the EATHE pipe was assumed to be at constant temperature of 300.2 K.

(c) Inlet and exit faces: at inlet and exit faces of EATHE, heat flux was taken to be zero. **(d)** 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. Zero diffusion flux of all flow variables in the direction normal to the outlet is used.

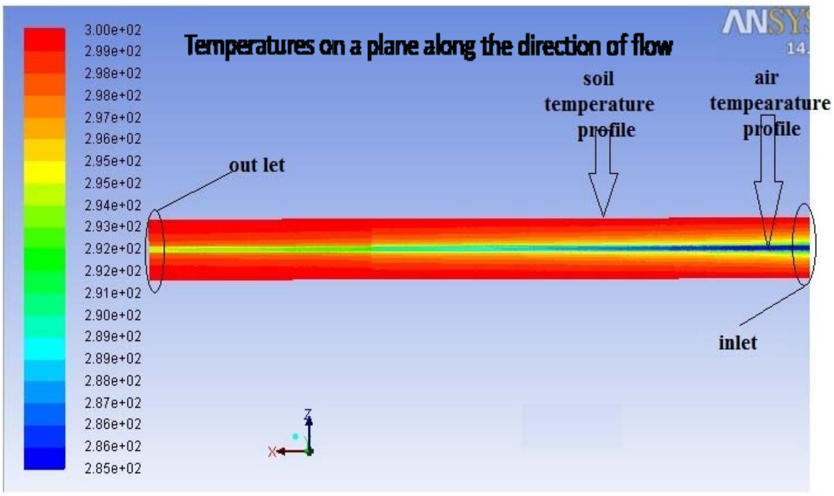
6. Solution Technique

This study used a fully unstructured finite-volume CFD solver, Fluent 14.0, 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.

7. Results

Table 2: Steady state and Transient performance of EATHE system in continuous operation:

Time(hrs)- L (m)	0 hr	1 hr	2 hr	4 hr	6 hr	8 hr	10 hr	12 hr	14 hr	16 hr	18 hr	20 hr	22 hr	24 hr
0 m	285.1	285.1	285.1	285.1	285.2	285.1	285.1	285.1	285.1	285.1	285.1	285.1	285.1	285.1
5 m	289.5	289.5	289.3	289.1	289.0	288.9	288.8	288.7	288.7	288.5	288.5	288.5	288.5	288.5
10 m	292.0	292.0	291.8	291.5	291.3	291.2	291.1	291.0	290.9	290.9	290.8	290.7	290.7	290.7
15 m	294.0	294.0	293.8	293.4	293.2	293.1	293.0	292.9	292.8	292.7	292.7	292.6	292.5	292.5
20 m	295.5	295.5	295.2	294.9	294.7	294.6	294.4	294.3	294.3	294.2	294.1	294.1	294.0	294.0
25 m	296.6	296.6	296.3	296.0	295.8	294.7	295.6	295.5	295.4	295.3	295.3	295.2	295.1	295.1
30 m	297.4	297.4	297.2	296.9	296.7	296.6	296.5	296.4	296.3	296.3	296.2	296.1	296.1	296.1



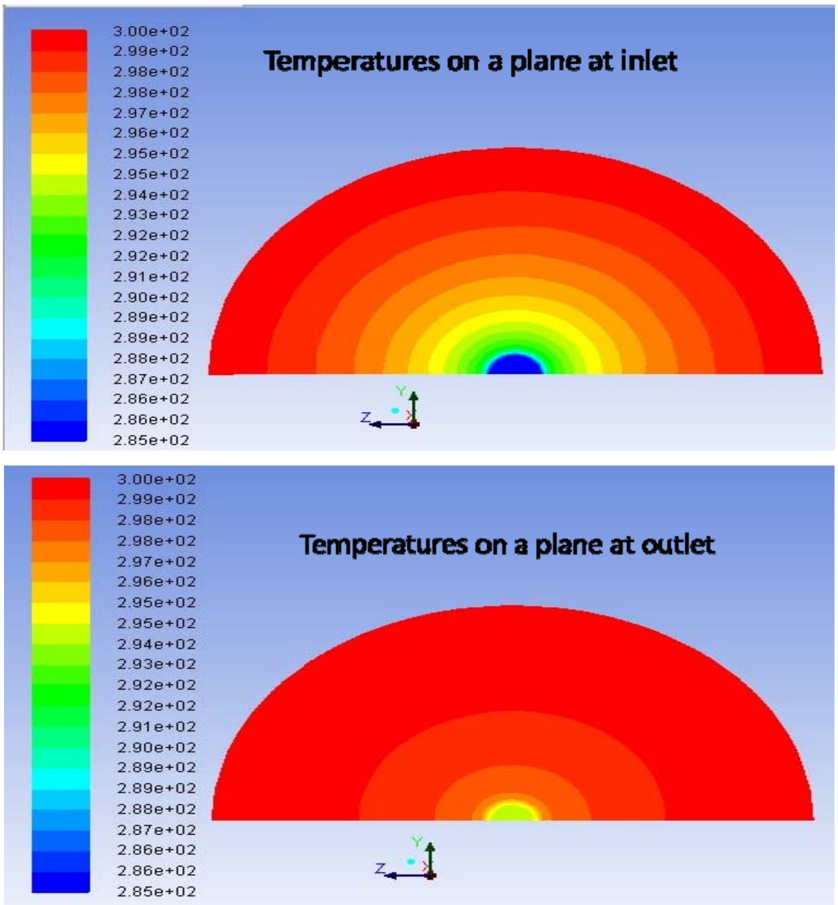


Fig. 3: Temperature profiles on various planes of an Earth to Air Heat Exchanger.

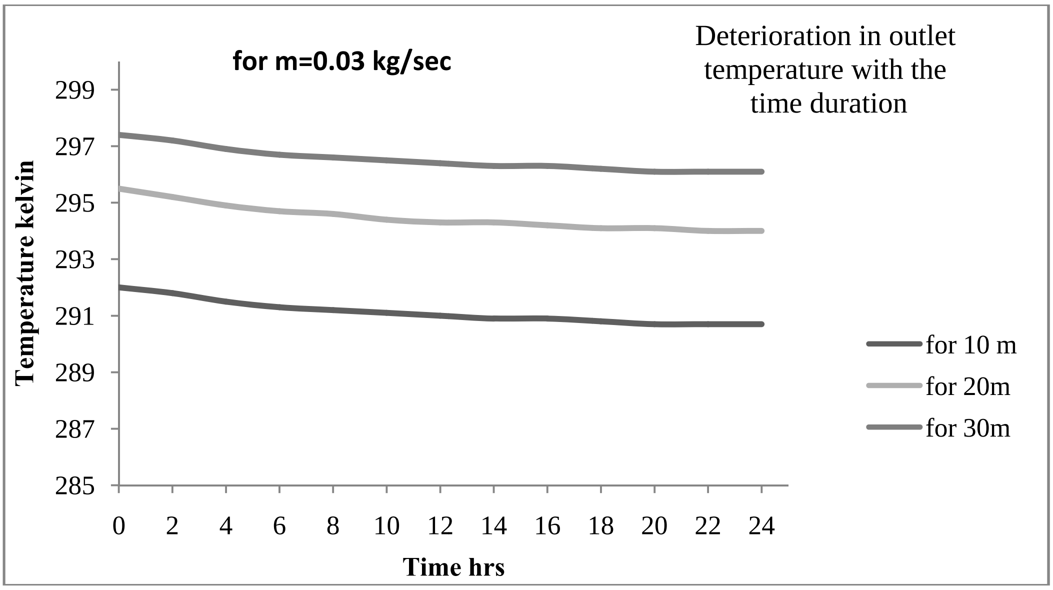


Fig. 3(a): Outlet temperature of an Earth to Air Heat Exchanger for pipe lengths of 10m,20m,30m.

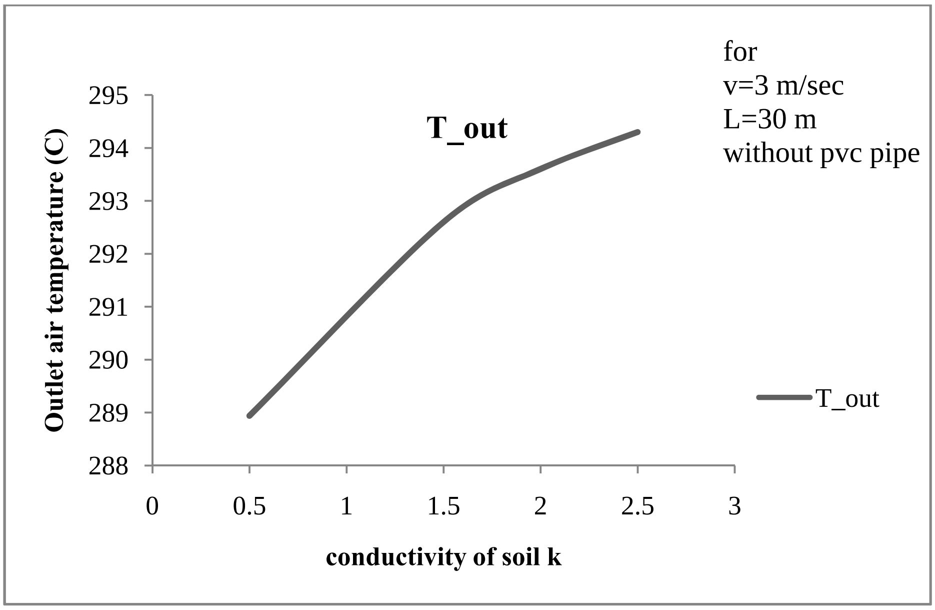


Fig. 3 [b]: Variation of outlet air temperature of an EAHX corresponding to increase in soil-conductivity.

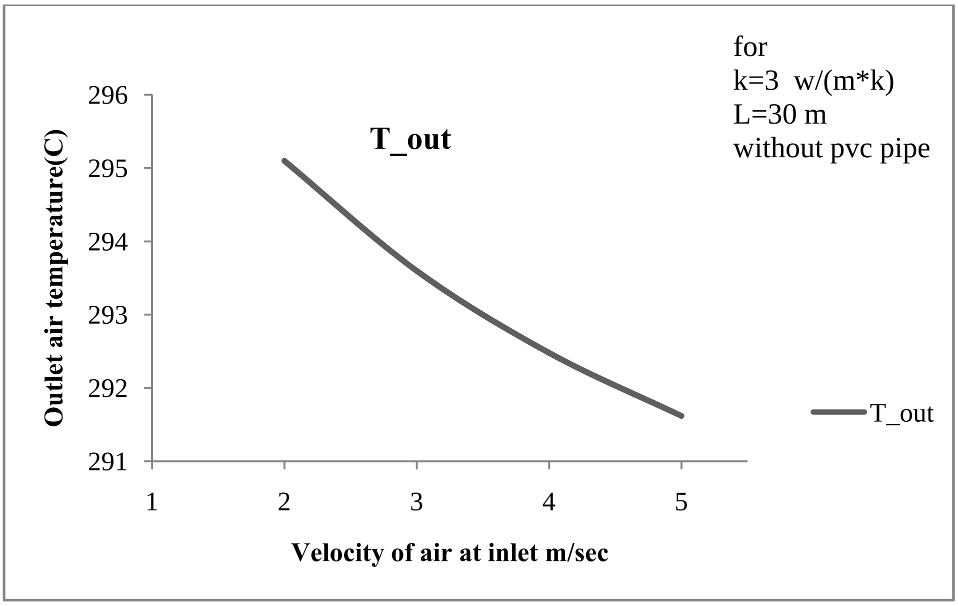


Fig. 3[c]: Variation of outlet air temperature of an EAHX corresponding to increase velocity of inlet air.

8. Scope of Hybridization of EAHX

There is a wide scope of hybridization of EAHX when coupled with HVAC and Solar Air Heater respectively for summer and winter air-conditioning applications to increase the cooling or heating capacity of EAHX. “An Stand alone photovoltaic (PV) integrated with earth to air heat exchanger (EAHE) for space heating cooling of adobe house in New Delhi (India)" [7], shows that a realistic source of cooling source for summer season or heating source for winter season can be developed when PV is integrated with EAHX. And "Performance Potential of Flat Plate Solar Air Heaters in Tehran"[8], shows the effect of increasing the inlet air temperature of a solar air heater results in a desirable effect on outlet air temperature. The fig.[] shows that if the hot air obtained from EAHx in winter season is be used at inlet of solar air heater then a realistic heating source can be achieved however no work has been done on this innovative idea.

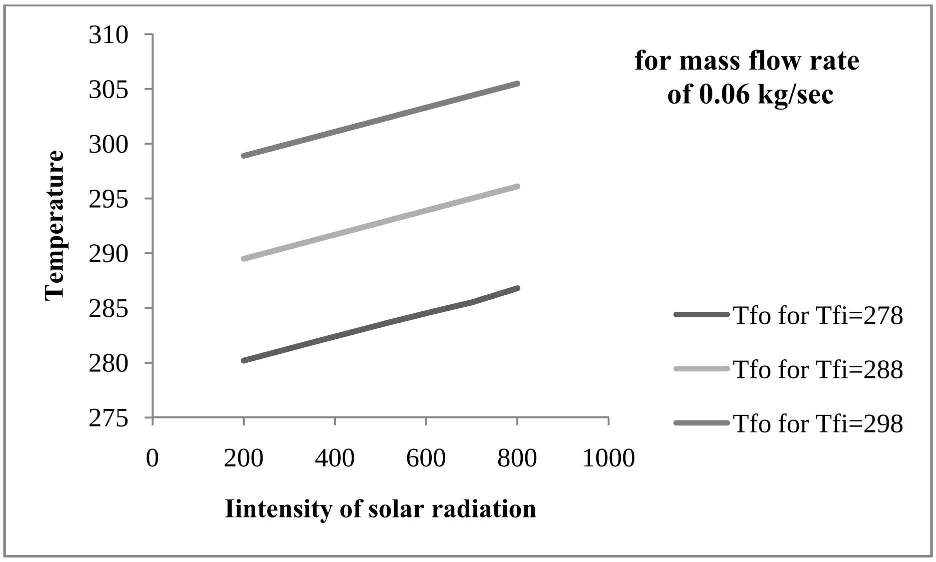


Fig. [4]: Variation of outlet air temperature of a solar air heater corresponding to increase in air inlet temperature.

9. Conclusions

When an EAHx works continuously for a long time its performance deteriorates. Performance of EAHx is better when it is installed in the soil with better conductivity. As the length of the pipe is increased the outlet air temperature goes up, but after 30 meter of length increase in outlet air temperature is not economical because the most of temperature gain has been done and after 30 meter of length heat transfer rate is very poor. The performance of EAHx deteriorates with increasing the air velocity at inlet of earth air pipe. To get realistic heating source hybridization should be preferred.

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