CFD Analysis of Earth Air Heat Tunnel using Various Piping Materials

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Abstract - Thermal potential of earth can be effectively used for passive heating/cooling of buildings. The temperature of earth at a depth of about 1.5–2 m remains almost constant throughout the year. This constant temperature (earth's undisturbed temperature) is equal to annual average temperature of a particular place. The earth's undisturbed temperature remains lower than ambient temperature in summer and vice versa in winter. This temperature difference can be used for pre-heating in winter and pre-cooling in summer by installing an Earth Air Heat Tunnel (EAHT) system. Advantages of EAHT systems are high efficiency, stable capacity, good air quality, better thermal comfort, easy control, require simple equipment, low maintenance cost, environment friendly, long term cost effective, tax benefit, and noise free being the underground unit. CFD tools(ANSYS FLUENT software) are used to predict the EAHE performance at various conditions. In this present work an EAHT system is going to be analysed by CFD tool using various piping materials (PVC, concrete, steel). Further the study was extended to analyze the effect of thermal conductivity of soil in EAHE performance.

***Key Words*:** Earth Air Heat Tunnel (EAHT), Computational Fluid Dynamics (CFD), Green buildings

1. INTRODUCTION

Given the importance of energy for the existence of our society as we know, it is imperative and urgent to find alternative sources to replace conventional fuel or at least mitigate its widespread consumption and consequent impact on the environment. The term alternative energy source does not imply only as an efficient option, but is synonymous of clean energy. This kind of energy is, at principle, inexhaustible and can be found and exploited equally well on the planet.

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. EAHE's have been used in agricultural facilities 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. EAHE's have been in use for years in developed countries due to their higher energy utilization efficiencies compared to the conventional heating and cooling systems.

2. EARTH AIR HEAT EXCHANGER

The achievement of indoor thermal comfort whilst minimizing energy consumption in buildings is a key aim in most countries. Generally most people feel comfortable indoors when the temperature is between 22 0C and 27 0C and relative humidity is within the range of 40–60%. In recent times, air conditioning is widely employed not only for industrial productions but also for the comfort of occupants. It can be achieved efficiently by vapour compression machines, but due to depletion of the ozone layer and global warming by chlorofluorocarbons (CFCs) and the need to reduce high grade energy consumption; numerous alternative techniques are being currently explored.

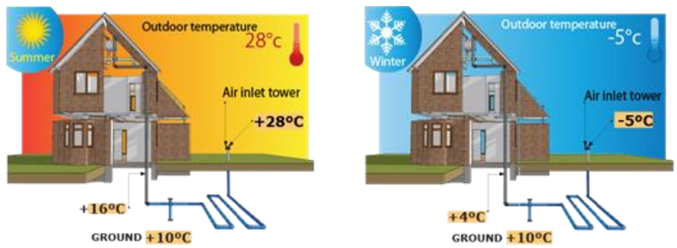

Fig 1: Schematic diagram of Earth Air Heat Exchanger (EAHE)

Thermal potential of earth can be effectively used for passive heating/cooling of buildings. The temperature of earth at a depth of about 1.5–2 m remains almost constant throughout the year. This constant temperature (earth's undisturbed temperature) is equal to annual average temperature of a particular place. The earth's undisturbed temperature remains lower than ambient temperature in summer and vice versa in winter. This constant temperature characteristic is due to high thermal inertia of the soil and as the depth increases, effect of temperature fluctuations of the ground surface is reduced.

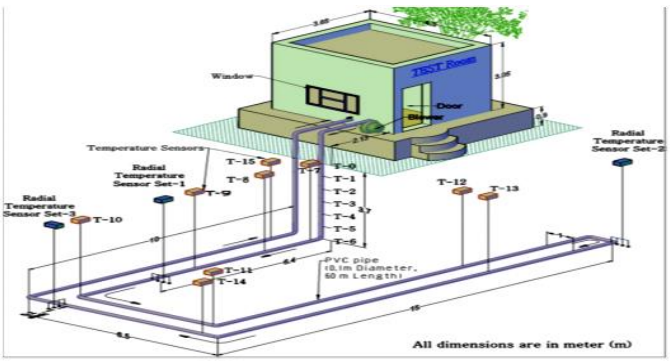

Fig 2: An Earth Air Heat Tunnel Model at Ajmer, Rajasthan

Due to time lag between the temperature variations at the surface of the ground and below the ground, at a sufficient depth, temperature below the ground is always higher than that of the outside temperature of air in winter and is lower in summer. This temperature difference can be used for pre-heating in winter and pre-cooling in summer by installing an Earth Air Heat Exchanger (EAHE) 2 system.Advantages of EAHE systems are high efficiency, stable capacity, good air quality, better thermal comfort, easy control, require simple equipment, low maintenance cost, environment friendly, long term cost effective, tax benefit, and noise free being the underground unit. Drawbacks are higher initial cost, limited availability of trained technicians and contractors. Performance of EAHE systems depends on air/liquid flow rate, depth and length of buried pipe/ tube (sufficient for air / liquid to lose the heat to certain extent), material and diameter of pipe/tube, temperature difference between earth and ambient, initial soil temperature, rating blower fan, and various combinations of pipes.

3. CFD ANALYSIS

Computational Fluid Dynamics (CFD) is the branch of fluid dynamics providing a cost effective means of simulating real flows by the numerical solution of the governing equations. CFD tools are used to predict the EAHE performance at various conditions. The flow characteristics such as pressure, volumetric flow, velocity, temperature at each point can be obtained from CFD tools. As we have a heat exchanger to analyse, it is necessary to use CFD.

CFD procedure requires many assumptions to be made such as number of elements, element types, turbulence model etc., to solve a problem. As no assumption is universal in nature, it is impossible to make an assumption to a problem. Assumptions are selected by trial and error method where the assumptions are varied to match the CFD results with experimental results. This is known as Best practice of CFD. The assumptions which match the CFD results with experimental results are taken as standard for further analyses of optimization. CFD uses numerical methods to solve the fundamental nonlinear differential equations that describe fluid flow (Navier-Stokes and allied equations), for predefined geometries and boundary conditions. The result is a wealth of predictions for flow velocity, temperature, density, and chemical concentrations for any region where flow occurs.

ANSYS FLUENT software is a high-performance, general purpose fluid dynamics program that has been applied to solve wide-ranging fluid flow problems. At the heart of ANSYS FLUENT is its advanced solver technology, the key to achieving reliable and accurate solutions quickly and robustly.

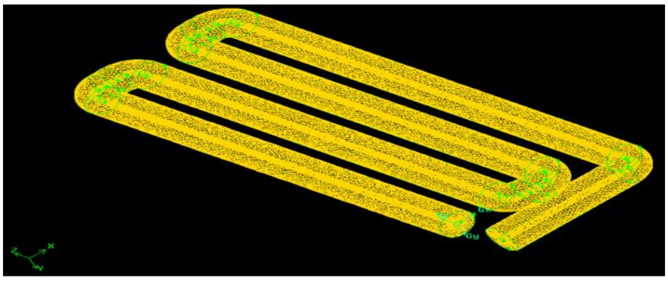

Fig 3 :Meshed domain in GAMBIT 2.4.6 isometric view

4. DESIGN OF EAHE

3.1 Cooling load calculation of the room

- Size = 6 m×3.4m×3m
- Outdoor condition: 38.8°C
- Indoor condition: 27°C
- Effective room sensible heat: 3473.95 W
- Effective room latent heat: 173.25 W
- Grand total heat: 3647.2 W

3.2 Determination of geometric parameters

The geometric sizing parameters of an EAHE are:

D: the diameter of the tube
L: the length of the tube
n: the number of tubes in parallel in the heat exchanger

The total heat transferred from the air when flowing through pipe

$$\dot{Q} = \dot{m}_{air} Cp_{air} (T_{in} - T_{out}) \quad (1)$$

Due to convection between the wall and the air, the trans-ferred heat can be also be written as:

$$\varepsilon = \frac{T_{in} - T_{out}}{T_{in} - T_{wall}} \quad (2)$$

Effectiveness of earth-air heat exchanger can be defined as

$$\dot{Q} = hA\Delta T_{lm} \quad (3)$$

After some mathematical arrangement,

$$\varepsilon = 1 - e^{-(hA/\dot{m}_{air} C_{p,air})} \quad (4)$$

The non-dimensional group is called the number of transfer units (NTU).

$$NTU = \frac{hA}{\dot{m}_{air} C_{p,air}} \quad (5)$$

Then,

$$\varepsilon = 1 - e^{-NTU} \quad (6)$$

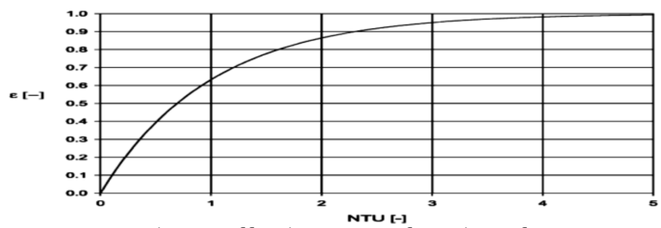

Fig 4 : Effectiveness as function of NTU.

- Increasing NTU increases effectiveness
- But after NTU>3, the relative gain is small
- The convection coefficient inside the tube is, $h = \frac{NuK}{D}$ (7)
- The Nusselt number for flow inside a tube is given by

$$Nu = \frac{f/8(\mathrm{Re}-1000)\,\mathrm{Pr}}{1+12.7\sqrt{(f/8)}(\mathrm{Pr}^{2/3}-1)} \quad (8)$$

- if 2300≤ Re <5×10^6 & 0.5<Pr<10^6
- *f*: friction factor (8.1)
- Re = $(\rho V_{air} D)/\mu$ (8.2)
- Pr = (μC_p) /K (8.3)

Now $$\frac{NTU}{L} = \frac{1}{L}\frac{hA}{\dot{m}_{air} C_{p,air}} \quad (9)$$

Substituting (8) and (7) in (5);

$$\frac{NTU}{L} = \frac{1}{L}\frac{hA}{\dot{m}_{air} C_{p,air}} \quad (10)$$

is the volumetric air flow rate (m^3/s)

The pressure drop in a smooth tube is given by;

$$\frac{NTU}{L} = \frac{1}{L}\frac{hA}{\dot{m}_{air} C_{p,air}} \quad (11)$$

With, f = 64/Re; if Re< 2300

$f = (1.82\log \mathrm{Re} - 1.64)^{-2}$; if Re ≥ 2300

Choose Diameter of pipe as 0.153m (for 16cm thick PVC pipe,3.5 mm will be its thickness)

Velocity of air inside pipe as 5m/s

= $\rho A_c V_{air}$

=1.14585× (π/4×0.153×0.153) ×5

=0. 10533kg/s

Total cooling load for room= 3647.2 W

Daily cooling load for room= (3647.2×24)/1000 kWhr

=87.5328 kWhr

Cooling capacity of a pipe = $\dot{m}_{air} C_{p,air}\ T_{in} - T_{out}$

=0.10533×1006.6×(39-28.5)

=1113.264 W

Daily cooling capacity of tunnel=(1113.264×24)/1000 kWhr

=26.7183 kWhr

The number of tubes = daily cooling load of room/daily cooling capacity of a pipe

= 87.5328/ 26.7183

= 3.27613

~ 4 no's

Now lets take ,

effectiveness of EAHE = 0.972

From equations

- $NTU = 3.57555$
- Re = $(\rho V_{air} D)/\mu$

  Re = 46428.77
- $f = (1.82\log \mathrm{Re} - 1.64)^{-2}$

  f = 0.021289
- Pr = (μC_p) /K

  Pr = 0.785314
- $Nu = \frac{f/8(\mathrm{Re}-1000)\,\mathrm{Pr}}{1+12.7\sqrt{(f/8)}(\mathrm{Pr}^{2/3}-1)}$

  Nu = 105.1461

Substituting these values in equation,

$$\frac{NTU}{L} = \frac{Nu\,\pi K_{air}}{\rho_{air} C_{p,air} \dot{V}_{air}} \quad (10)$$

Length of heat exchanger,

L = 47.422 m

~ 47.5 m

5. BLOWER SELECTION

Pressure drop across pipe, $\Delta p = f\frac{L}{D}\rho\frac{V_{max}^2}{2}$

effective length of the pipe, L = 47.5+ 1.5×2(gap between ground and room)+(3.5+5)[vertical pipes] + (6.096×11)[for drop in elbows]

= 126.056 m

Therefore pressure drop,

$$\Delta p = 0.021289 \times \frac{126.056}{0.153} 1.14585 \times \frac{10^2}{2}$$

= 1004.9052 Pa

Power requirement of blower = [pressure drop× maximum volume flow rate]/ fan efficiency

$$P_f = \frac{1004.905 \times \left[\frac{\pi}{4}\right] \times 0.153^2 \times 10}{0.7}$$

= 263.936 W

= 0.353 hp

Flow rate needed for the process= 0.1053 kg/s

Therefore 0.5 hp, 0.11 kg/s centrifugal blower was selected for the EAHE

Table -1: Material Properties Used

Material	Density (Kg/m^3)	Specific heat (J/kgK)	Thermal conductivity (W/mK)
Air	1.225	1006	0.0242
Soil	2067	1780	1.68
PVC	1380	900	1.16

Table -2: Boundary Conditions

Boundary name	Type
air inlet	Velocity inlet (V=5m/s, T=311.9 K, turbulent intensity[I]= 4%)
air outlet	Pressure outlet (gauge pressure= 0,T= 301.5K, I=4%)
Air soil interface	Coupled boundary(with PVC shell conduction- 0.0035m)
Soil outer surface	Wall (300 K)
PVC	Wall – coupled heat transfer(0.035m)

6. DESIGNED MODEL

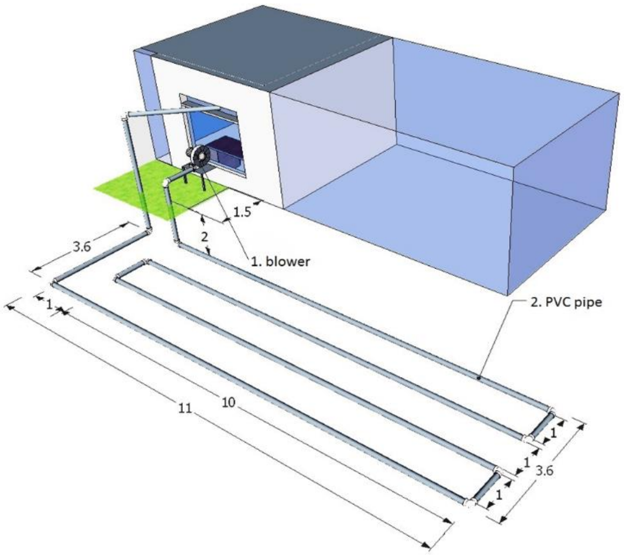

Fig 4 : Schematic of EAHE system

7. RESULTS

Soil	Heat transfer rate (W)
PVC	933.0510
CONCRETE	1104.74
STEEL	1119.78

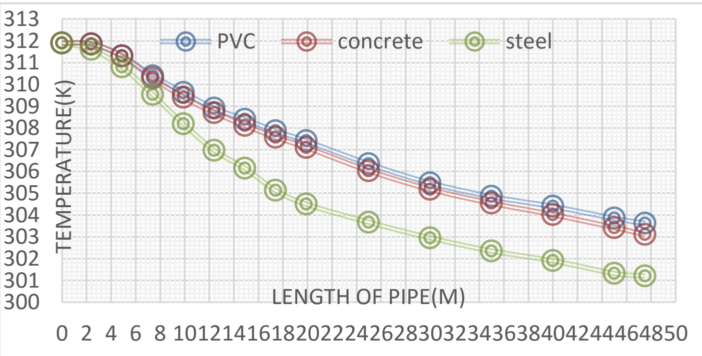

Fig 5: Effect of piping material in temperature drop

3. CONCLUSIONS

- Thermal properties of the soil and temperature distribution with the depth was measured. And feasibility of the project was checked.
- A one dimensional analytic design of the Earth Air Heat Exchanger (EAHE) was done for a room size of 6 m×3.4m×3m room after its cooling load estimation.
- Numerical analysis for the EAHE was done using the commercial package Ansys- Fluent 16. Further the study was extended to analyze the effect of thermal conductivity of soil in EAHE performance.
- Simulation for different pipe material were done at the velocity of 5m/s
- When concrete was used as EAHE pipes, length of the pipe was reduced to 44 m instead of installing 47.5 m. Similarly when steel was used, length of the pipe was reduced to 25 m instead of installing 47.5 m.

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