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The Design of Earth Air Tunnel Heat Exchanger System for an Institute Library

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Abstract-In this paper a simple Excel based mathematical model has been developed in order to design the EATHE system for the ground floor of library of the Malaviya National Institute of Technology Jaipur for meeting a given cooling/heating load. This model helps in determining characteristic dimensions, air flow rate, number of pipes, selection of blower and economic investments in an EATHE system. A thermal comfort survey was also conducted to find the thermal comfort temperature inside the library of MNIT, which is approx 28.6 ^{0}C, quiet near to the temperature obtained through this EATHE system.

Keywords:EATHE system, Mathematical model, Performance analysis, Thermal comfort

1. Introduction

Buildings (residential or offices) are major consumer of energy through the use of air conditioner/ heat pump for the comfort of occupants. It has direct or indirect impact on the environment due to CFC's which causes global warming and depletion of ozone layer. For this reason it would be beneficial to adopt passive heating/ cooling systems for providing thermal comfort. Passive heating/ cooling systems consume no or very less energy as compared to active heating and cooling systems. In order to utilize these passive heating/ cooling systems with great heat capacity and high thermal inertia, many techniques have been developed in the last decades such as earth air tunnel heat exchanger.

Earth air tunnel heat exchanger system has ability to provide heating in cold months and cooling during warm months. Hot/cold outdoor air is passed through the pipes laid at 3–4 m depth in the earth called earth air pipes. When air flows through these pipes, heat is transferred from the air to the earth and vice versa depending upon the temperature of air relative to temperature of earth that remains nearly constant at the annual mean temperature of that place. In some cases, the thermal condition of air coming out from the earth air pipes is such that it can be directly supplied to the space connected to it for cooling or heating; whereas in extreme weather conditions, it needs another stage of processing before becoming acceptable for supplying to the connected space.

From summarized literature review presented in table 1, it can be concluded that EATHE system has huge potential of saving electricity (32-50%) and can maintain temperature in the indoor around 29.5-32^{0}C and also smaller diameter pipes not only enhance performance of EATHE but are also cheaper as compared to large diameter pipes. Air flow in the pipe should be around 2-5 m/s and in case of multiple pipe arrangement distance between pipes must be around 5 times the diameter of pipe. Sandy wet clay loam (heavy clay) has higher cooling potential than dry sandy soil. Sandy soil has higher heating potential in desert areas. Pipe material has very little effect on thermal performance.

A field survey has been conducted to determine the thermal set point and estimation of cooling load for the Library of Malviya National Institute of Technology, Jaipur, India. A simple mathematical model has been also developed to design the Earth air tunnel heat exchanger for this building and to support the feasibility of the EATHE system economic analysis was also performed.

Building description

Ground floor of library, Malaviya National Institute of Technology, Jaipur ,India (Fig 1)(Latitude 26^{0} 49'N and 75^{0} 48'E Longitude)consists four rooms which is currently conditioned by split a/c were selected for passive cooling through Earth Air Tunnel Heat Exchanger system. The building dimensions and thermo physical properties of material are shown in Table 1 and 2 respectively.

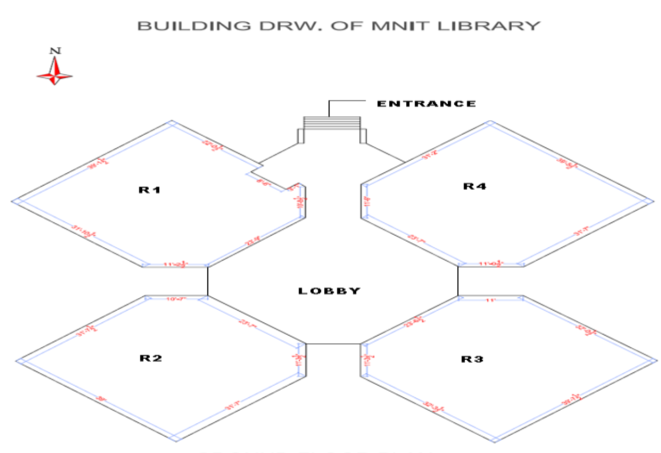

Fig. 1 Ground floor plan of MNIT library

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Table 1 Description of building materials used in library

Components	Material	U Factor
Roof/ Ceiling	6 ’’ concrete 15mm thick plaster	4.0
Exterior Walls	15’’ stone wall 15 mm thick cement plaster	2.61
Window	Clear single pane glass (metal frame)	0.56
Door	Glass door with aluminum frame	5.67
Partition Wall	4 ½ ’’ brick , 15 mm thick cement plaster	2.67

Table 2 Thermo physical properties of building material

Material	Density (Kg/m^3)	Thermal conductivity (W/m K)
Cement	1900	1.73
Brick	2000	1.32
Cement plaster	1885	8.65

2. Cooling load Estimation

Cooling load estimation determines total sensible and latent cooling load separately. Sensible heat load includes Solar and transmission heat gain through walls, glass, walls, ceiling and roof etc, Internal heat gain from people, power, lights, appliances etc, Supply duct heat gain, supply duct leakage loss, Additional heat gain considering safety factor. Room latent heat includes internal heat gain from people, steam, appliances, Supply duct leakage loss, additional heat gain considering safety factor.

Table 3 Cooling load estimation of ground floor of library

Types Of Wall	Quantity	ΔT/Solar Gain	U (W/m^2 K)	Load (W)
N-W Wall	113.6 m^2	13.95 ˚C	2.61	4136
S-W Wall	83.53 m^2	15.05 ˚C	2.61	3281
S-E Wall	91.6 m^2	19.55 ˚C	2.61	4674
N-E Wall	112.1 m^2	18.45 ˚C	2.61	5398
N-W Glass	20.5 m^2	388 W/ m^2	0.56	4454
S-W Glass	15.4 m^2	315 W/ m^2	0.56	2717
N-E Glass	11.2 m^2	38 W/ m^2	0.56	238
S-E Glass	7.3 m^2	38 W/ m^2	0.56	155
Roof	64.4 m^2	17.8 ˚C	4.0	4585
Door	32.4 m^2	8 ˚C	5.67	1470
Occupancy	67 occupant	75 W		5025
Lightning	6 × 40 W, 20 × 12 W	---	---	1920
Fan Load	44×60			2640
Pc Load	45	100 W	0.4	1800
Ups Load	8 KVA	0.9	0.5	3600
Partition Wall	177 m^2, 38.8 m^2	8 ˚C, 8 ˚C	5.67, 2.67	829, 8030
Latent Load	67 occupant	87 W		5829
Total load				**60781 W**

Overall heat transfer coefficient was calculated by given required material composition and thermo physical properties of building material. Total cooling load was around 60.781 kW (Table 3) without considering infiltration load because of positive ventilation inside the room.

3. Survey and Data Collection

Questionnaire based field survey was conducted in summer months of year 2012 to record indoor and outdoor climate condition i.e. Air temperature, Relative humidity, Globe temperature, Outdoor temperature, Air velocity with the help of HT30 heat stress meter and Anemometer instruments.

A total 123 questionnaire forms were filled by surveyor feedback taken from occupants covering thermal responses and the measurement of thermal environment. Regression analysis was done on this survey data. A thermal comfort set point was found to be approx 28.6 ˚C in library of MNIT [Dhaka, 2013].

4. Mathematical modeling

In EATHE systems heat transfer takes place between flowing air and the surrounding soil. This heat transfer includes various heat transfer and fluid flow equation, based on these equations simple Microsoft excel based mathematical program was developed to calculate the length of pipe for a given diameter and velocity of air.

Table 4 shows the thermal and physical properties of soil, air and PVC used in this study.

Table 4 Thermo physical properties of various materials

Material	Density (Kg/m^3)	Specific Heat Capacity (J/Kg K)	Thermal Conductivity (W/m K)
Air	1.15	1005	0.02
Soil	2050	1840	0.52
PVC	1380	900	1.16

Following assumptions are used during modeling of EATHE system:

a) Thermo physical properties of material remain constant and homogeneous.
b) The EATHE system is in steady-state condition.
c) Temperature of subsoil to be around 302.24 ˚K.
d) There is perfect contact between soil and pipe surface.
e) The pipe is of uniform circular cross-section.

4.1 Mathematical modeling for length of pipe of EATHE system

Length of EATHE pipe can be calculated with the help of following fluid flow and heat transfer equation for given pipe diameter, air velocity and effectiveness.

Thermal conductivity of air is calculated from [10] using Eq. (1):

$$K_a = 0.02442 + 10^{-4}(0.06992\, T_a) \quad (1)$$

Kinematic viscosity of air is calculated from [10] using Eq. (2):

$$\upsilon = 10^{-4}\left(0.1335 + 0.000925\, T_a\right) \quad (2)$$

The Reynolds number may be expressed as Eq. (3):

$$\mathrm{Re} = \frac{V \times d}{\upsilon} \quad (3)$$

Where

V = Velocity of air (m/s) d = Diameter of pipe (m) υ = Kinematic viscosity of air (m^2/s)

The Nusselt number for fully developed laminar and turbulent flow in a circular pipe for the ranges $0.5 \le \mathrm{Pr} \le 2000 \quad and \quad 2300 < \mathrm{Re} < 5 \times 10^6$ is proposed by Gnielinski [24] as

$$Nu = \frac{(f/8)(\mathrm{Re} - 1000)\mathrm{Pr}}{1 + 12.7(f/8)^{1/2}\left(\mathrm{Pr}^{2/3} - 1\right)} \quad (4)$$

Here, f is the friction coefficient for smooth pipe and is determined by using Petukhov's relationship [10], which is expressed as

$$f = \left((0.79 \ln \mathrm{Re}) - 1.64\right)^{-2}$$

The convective film coefficient inside the pipe is defined by

$$h = \frac{Nu\, K_a}{d} \quad (5)$$

The pressure drop per unit length in a smooth tube is given by [16]

$$\Delta p / L = \frac{f}{2d} \rho V^2 \quad (6)$$

For all heat exchanger with $C = \frac{C_{min}}{C_{max}} = 0$

Effectiveness of heat exchanger is given by equation (7)

$\varepsilon = 1 - e^{-NTU}$

Where

$$NTU = \frac{UA}{C_{min}} \quad (8)$$

U=overall heat transfer coefficient per unit length

$$NTU = -\ln(1-\varepsilon) \quad (9)$$

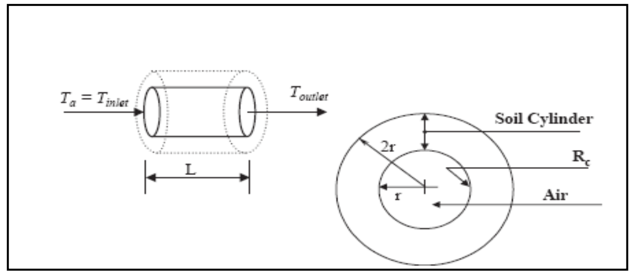

Fig. 2 EATHE system with the layers

Overall heat transfer coefficient per unit length can be written as $U = (R_C + R_P)^{-1}$

Now, length of pipe can be calculated using equation (9) and (10)

$$L = \frac{NTU \times m_a \times C_a}{U \times \pi \times d} \quad (11)$$

Total pressure drop in pipe is given by

$$\Delta P = \frac{\Delta p}{L} \times L \quad (12)$$

Considering leakage and coefficient of friction of material then Total Pressure drop=$\Delta P + \Delta p_{\text{other losses.}}$

$\Delta P <$ Total pressure

Then the length calculated from equation (11) can be taken as a length of pipe. Otherwise length can be calculated from pressure drop equation.

4.2 Mathematical modeling for exit temperature of air

Exit temperature of air mainly depends upon, convective heat transfer between flowing air and pipe inner surface and conduction heat transfer between pipe outer surface and soil annulus.

The heat penetration depth can be written as [20]

$$\delta = \sqrt{\frac{2\lambda_s}{\omega}}$$

Where

$$\lambda_s = \sqrt{\frac{K_s}{\rho_s \times C_s}} \quad \text{And} \quad \omega = \sqrt{\frac{2\pi}{year}} \quad \text{or} \quad \omega = \sqrt{\frac{2\pi}{day}}$$

Here K_s =Thermal conductivity of soil ρ_s =Density of soil C_s = Specific heat of soil

The energy balance for air flowing in a pipe of differential length dx, is given by

$$T_x - T_{us} = dq\sqrt{\frac{R_t}{dx}} \quad (13)$$

(7)

Total resistance of thermal network is given by

$R_t = R_c + R_p + R_s$

R_c is the thermal resistance due to convection current between air and pipe.

$$R_c = \frac{1}{2\pi r L h} \quad (14)$$

Where h is given by

$$h = \frac{Nu\, K_a}{d} \qquad (15)$$

The Nusselt number for laminar flow inside a pipe is:
If Re < 2300 then Nu =3.66 and for turbulent flow in a circular pipe for the
ranges $0.5 \le \Pr \le 2000 \quad and \quad 2300 < \text{Re} < 5 \times 10^6$
Nusselt number is:

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

Here, f is the friction coefficient for smooth pipes and is determined using relationship:

$$f = \left((0.79 \ln \text{Re}) - 1.64 \right)^{-2}$$

Thermal resistance due to pipe thickness is given by

$$R_t = \frac{1}{2\pi K_p L} \ln\left[\frac{r_i + t}{r_i}\right] \qquad (16)$$

Thermal resistance between pipe outer and undisturbed soil is expressed as [21]

$$R_s = \frac{1}{2\pi K_s L} \ln\left[1 + \frac{\delta}{r_i + t} + \sqrt{\left(1 + \frac{\delta}{r_i + t}\right)^2 - 1}\right] \qquad (17)$$

The energy balance of the circulating fluid is given by

$$dq = -mC_a \frac{dT_x}{dx} dx \qquad (18)$$

Equation (13) and (18) gives

$$\frac{dT_x}{dx} + \frac{T_x}{mC_a R_t} = 0 \qquad (19)$$

Initial boundary condition
When x=0, $T=T_x$
The solution equation (19) gives

$$T_x(x) = T_{us} + (T_a - T_{us})\exp\left(-\frac{x}{mC_a R_t}\right) \qquad (20)$$

At x= L, the temperature of air exit from the pipe can be calculated from above equation. Therefore outlet air temperature exit from EATHE system may be given by

$$T_{exit} = T_{x=L} + \frac{\Delta P}{\eta_b \rho_a C_a} \qquad (21)$$

5. EATHE system for MNIT library

Once the cooling demands are known the design parameters i.e pipe burial depth, pipe diameter, air velocity, temperature drop, number of pipes and length of pipe can be find out by using above mathematical equations considering economical and constructional constraints.

5.1 Design parameters

a) Placement depth: Burial depth of pipe should be greater than 3.5 m [27]. It is taken as 4 m due to sandy soil presence in MNIT campus.
b) Pipe diameter: Instead of using large diameter pipe in EATHE system multiple pipes of smaller diameter (4" to 6") is proposed. 6 inch pipe dia. is used in place of 4 inch dia. to avoid more no of pipes.
c) Velocity of air: Velocity of air flowing through pipe for given system is taken as 4m/s.
d) Number of pipes: Total cooling load on ground floor of MNIT library is 77 kW including ventilation load but in EATHE system, there is always a positive pressure inside the rooms so while designing EATHE system it does not include ventilation load. Thus EATHE system is designed for a cooling load of 60781 kW.

Total volume flow rate can be calculated by the following equation:
$Q_c = m_a C_p (T_i - T_{exit})$
$60781 = \dot{m} \times 1.15 \times 1005 \times 11.5$
$\dot{m}$ (Mass flow rate required)=4.57 kg/s
Where m_a is mass flow rate of air
C_p is specific heat capacity of air
Maximum temperature drop was taken as 11.5 ˚C.
Volume flow rate in each 6" pipe at velocity 4 m/s is 0.071 kg/s.
Total number of pipes required (N) = $\frac{\text{Total air flow rate}}{\text{Air flow rate in each pipe}} = \frac{4.57}{0.071}$ ~ 65

Thus 65 no's of pipe are required for meeting above cooling demands.

NTU = -ln (1-ε) = 1.609, ε = 0.80 (considered)

L = $\frac{NTU \times m_a \times c_p}{U \times \pi \times d}$ L = $\frac{1.609 \times 0.081 \times 1005}{3.846 \times 3.14 \times 0.15}$~ 72 m

Conclusion

The national building codes of India specify two narrow range of temperature for winter (21-23˚C) and for summer (23-26˚C). It is very difficult to achieve this temperature with help of EATHE system. Hence, it was aimed to investigate the thermal aspects of thermal comfort in library of MNIT that was achieved through thermal comfort study during summer and thermal comfort set point was found to be 28.6 ˚C which was quiet near to the temperature obtained through EATHE system.

An EATHE system was also designed for ground floor of MNIT library having 60781 kW cooling load. Various important parameters such as diameter, length and velocity have been analyzed using simple mathematical modeling. Proposed EATHE system contains 65 of 6"diameter, 72 meter PVC pipes and 4 m/s air velocity considering maximum temperature drop with in constructional constrains. Total cost of EATHE system was around Rs 11, 49,380 approx with energy efficient blower.

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