Techno-Economic Analysis of Earth Air Heat Exchanger System for Building Cooling in Hot and Dry Climate of Rajasthan (India)

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Abstract

The earth air heat exchanger (EAHE) system is a promising passive technique which can be used effectively to reduce dependency on conventional air conditioning system with significant energy saving and reduction in emission of CFC gases. In the present study, an earth-air heat exchanger (EAHE) system has been considered for the cooling of an office room in a hot and dry climate of Jaipur (India). For the present study, the hottest day of the summer season (i.e. 21 June) has been taken for calculating the cooling load of the office building and according to which the cooling load of office room of floor area 16.73 m^2, was 4233 Watts. To yield this cooling load, an EAHE system is designed for an office room. For the parametric study, three different diameter pipes (0.1 m, 0.15 m and 0.2 m) were considered with four different air flow velocities (2 m/s, 3 m/s, 4 m/s and 5 m/s). It was observed that an EAHE system with 0.2 m diameter pipe and 3 m/s air flow velocity is the best combination to produce desired cooling load with the Internal Rate of Return (IRR) of 5% and the payback period of 6.35 years. Moreover, the net present value (NPV) for a 20-year operating period is approximately nearby 91450 rupees at the market discount rate of 5 %.

Keywords: Passive-cooling system; EAHE system; Techno-economic analysis; Cooling potential; Energy savings; Pay-back period.

1. Introduction

In the last few years, the use of air conditioning systems is drastically increased not only in industries but also for the comfort of peoples, and the demand of air conditioning systems will increase in the near future. This high demand for air conditioning system will increase energy load and will make energy crisis and environmental issues more critical. Hence, there is need of new promising energy sources or technology which are environment-friendly and can reduce the energy load of air-conditioning. There are some environment-friendly and economically feasible methods for air-conditioning such as solar air-conditioning, fuel cell powered air conditioning, and ground-coupled air-conditioning system. In ground coupled air-conditioning system, earth-air heat exchanger (EAHE) system is a promising and low-cost system. In EAHE system, underground soil act as a heat source or sink and air as the heat transfer medium for space heating/cooling in winter/summer. When air flows in pipes, heat transfer takes place between the earth and the air. As a result, the air temperature at the outlet of the pipes is much higher than that of the ambient in winter and lower in summer. The schematic diagram of an EAHE is shown by Figure 1.

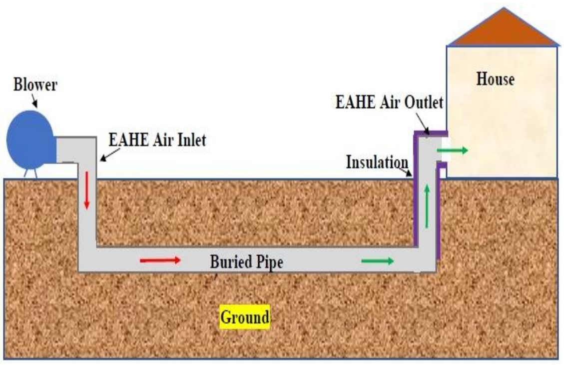

Fig.1: Schematic diagram of the EAHE system

In the literature, plenty of parametric studies are available which evaluated the impact of various parameters on the performance of EAHE system but here are very few studies available which considered an economic analysis of EAHE system.

Laknizi et. al.[1] has carried out an energy performance analysis of EAHE system for a Poultry House in Morocco and calculated the energy saving through heating and cooling by EAHE system. Also, recommended that an EAHE system of PE material with the diameter of 100 mm and length of 30 m, operating at a velocity of 2 m/s. The annual heating and cooling demand are 418.38MWh and 104.46MWh, while the use of EAHE can satisfy energy demand 146.38 MWh in summer and 104.30MWh in winter.

In 2017, Ghaith et. al.[2] has proposed EAHE system integrated with Vapour Compression Cycle (VCC) for a villa in Dubai and done cost analysis with payback period. The proposed EAHE system for the villa of 360m^2, this system has 55 m length with a flow rate of 7500 CFM. The total expenditure of the EAHE installation is about 26840 AED (521235 Rupees) and payback period for EAHE with R22 Air Conditioning (AC) system and EAHE with R410a AC system are 2.43 and 2.23 years.

Life cycle cost analysis of EAHE system integrated with adobe building done by Chel et. al. [3], and energy balance equation solved by using fourth order Runge–Kutta numerical technique. The system consists of six pipes of 11 m in length and 6 cm in diameter. The installation cost of the EAHE system is €314.17, which resulted in the total annual energy saving potential of the adobe house is 10321 kWh/ year. The payback period for EAHE with adobe house is less than 2 years for the interest rate of 16%.

The Techno-economic analysis of an EAHE system was done by Shukla et al. [4], on the basis of comparing operating hours and energy saving between air-conditioner with/without EAHE and also by payback period. In this EAHE system, there are three lanes of 11m× 0.6m and Poly- vinyl chloride (PVC) pipe of the length 78m and 0.06m diameter is buried in these three lanes. The initial investment in the EAHE system was 6000 rupees and payback period for this EAHE system were 2.48 years.

Cui et. al. [5] carried out Life cycle cost analysis and techno-economical evaluation for the Ground-Coupled Heat Pump (GCHP) system. The system consists of 21 energy pile, every pile has pipe of diameter 0.032m and depth of every energy pipe is about 10m. Total capital investment for ground-coupled heat pump system is £28663.53. NPV of the GCHP system is £26,095.41 at the market discount rate of 8.75% for a 20-year operating period and payback period for the GCHP system is approximately 4.31 years.

Bansal et. al. [6] done the economic analysis on the basis of energy consumption of blowers and calculated the IRR of the integrated Earth Air Tunnel Heat Exchanger (EATHE) system with evaporative cooling. The EATHE comprises of a horizontal cylindrical pipe of 0.15 m inner diameter with buried length of 23.42 m. Three types of blowers are used in the EATHE systems viz Energy efficient blower, Standard blower, and Inefficient blower. The total investment is $452, $402 and $352 for simple EATHE system with energy efficient, standard and inefficient blower. IRR of simple EATHE system varies from 52.31% to 5.05% for residential electric tariff and 169.49% to 23.71% for commercial electric tariff when energy efficient blower is used and the payback period is 2 years.

In this study, one office room is taken which are situated in Jaipur, Rajasthan. The office room is in use for 8 hours a day for 5 days of the week. The cooling load of office room is 4233W and this full load is taken by 1.5 Ton 5 star rated window AC, but it consumes about 1677 Wh of energy per hour and produces chlorofluorocarbons (CFC) gases which increase global warming effect. For this office room EAHE system selected above another type of AC system because EAHE system has very less maintains and operating cost.

2. Building Description and System Parameters

In the present study, the cooling load of an office room is calculated and then an EAHE system is proposed for providing thermal comfort condition in the office room.

Following assumptions has been considered for the present analysis:

- The pipe along its distance is uniform with constant thermal properties and geometry.
- The properties of soil are constant throughout the pipe length.
- The EAHE is on steady-state conditions with its surrounding.
- The ambient temperature is 43°C for day 21st Jun of the year [19].
- The soil temperature of the underground soil is nearly 26°C [7].
- The output temperature from EAHE system is 30°C.

2.1 Description of office room

An office room (dimension: 5.53m × 3.02m × 3.17m) of mechanical workshop of MNIT Jaipur is considered for the passive cooling through EAHE system. The office room is currently conditioned by a 5-star rated window AC of capacity 1.5 TR (make: Voltas). Description of different materials used for the construction of the room are presented in Table 1.

Table 1: Description of material used for room

Components	Material	U-factor (W/m²-k)
East and North wall	0.38 m Stone wall (including 1.25cm plaster)	2.5
West wall (shaded)	0.18 m concrete wall (including 1.25cm plaster)	3.19
South wall	0.18 m concrete wall (including 1.25 cm plaster)	2.42
Windows	Clear single glass with metal frame	5.15
Door	Half portion made of glass and other half of Wood	0.64
Roof/ Ceiling	4 cm Asbestos cement board	2.24

2.2 Cooling load estimation

In order to carry out the techno-economic analysis of EAHE system integrated with an office, the cooling load of an office room (total floor area of 16.73 m^2) located in Mechanical workshop, MNIT Jaipur (India), is calculated by using a standard method as given by Arora [9]. Table 2 shows, the estimated sensible load of the office room.

Table 2: Sensible cooling load of Room

Serving Area	Quantity	ΔT (°C) or Sun gain	U-factor (W/m²-°C)	Cooling load (W)
East wall	17.58m²	17.65	2.49	774.16
West wall (shaded)	12.2 m²	13.25	3.19	516.56
North wall	9.59 m²	10.15	2.49	243.02
South wall	9.59 m²	0	2.42	0
Roof-shaded	16.53m²	9.66	2.24	358.1
Doors	1.88 m²	16	0.64	19.26
All glass	8.58 m²	16	5	686.4
Floor (ground)	16.53m²	2.5	0.75	31.0
People	4 people	-	75	300
Lights	72 w	-	1.25	90
Applications	415 w	0.33	0.85	116.4
Total sensible heat				**3134.9**

The total infiltration heat gain is 675.71W and internal latent heat gain is 220W. Therefore, the total cooling load of the room is 4233 Watts (±5%).

3. Design of EAHE system for office

If the cooling load is known of any building, an EAHE system can be designed for that building [5], [7], [10], [11]**.** For the design of any EAHE system, the following parameters have been decided.

(a). **Pipe diameter:** The pipe diameter should not be very large or small, because in small pipe diameter pumping power is increases while in large pipe diameter, the interaction between soil and air is decreases. Therefore for the present study, three different pipes of medium size pipe diameter (0.1 m, 0.15 m and 0.2 m) are considered as suggested by Agrawal et al.[12].

(b). **Depth of buried pipe**: The depth of pipe should such that the ambient environment not disturbed the soil temperature. For the present study, pipe depth is considered 3m as suggested in the literature [6], [13], [14].

(c). **Air velocity:** Four different velocity of air (2m/s, 3 m/s,4 m/s and 5 m/s) are considered for EAHE system [6], [12], [15].

(d). **Number of Pipes:** The required number of pipes are depends on total air flow required and the total air flow required is depends on the volume of building and air change per hours required for a building. In the present study, the volume of office room is 56 m^3 and Air change per hour (ACH) is considered 4 [16].

Hence, Total air flow required = Volume of room × ACH

$$= 56 \times 4 = 224 \frac{m^3}{hour} = 0.062 \frac{m^3}{sec}$$

Therefore, Required number of pipes $= \frac{\textit{Total Air flow}}{\textit{Air flow rate in single pipe}}$ (1)

(e). **Length of pipe**: The length of EAHE pipe can be calculated by using following equations

$$L = \frac{NTU \times m_a \times C_a}{U \times \pi \times d} \quad (2)$$

Number of transfer unit for ground heat exchanger,

$$NTU = -ln\,(1 - \varepsilon) \quad (3)$$

Effectiveness,

$$\varepsilon = \frac{T_{ai} - T_{ao}}{T_{ai} - T_{w,in}} \quad (4)$$

Overall Heat transfer Coefficient per unit length of pipe

$$U = (R_C + R_P)^{-1} \quad (5)$$

$$U = \left(\left(\frac{1}{2\pi r_i L h} + \frac{\ln(r_o/r_i)}{2\pi k_p L}\right)\right)^{-1} \quad (6)$$

$$U/_L = \left(\left(\frac{1}{2\pi r_i h} + \frac{\ln(r_o/r_i)}{2\pi k_p}\right)\right)^{-1} \quad (7)$$

Convective film coefficient (W/m^2-k) inside the pipe

$$h = \frac{Nu\, k_a}{d} \qquad (8)$$

Nusselt Number, $Nu_s = 3.66$,

$$if\ \ Re < 2300 \qquad (9)$$

$$Nu_s = \frac{\left(\frac{f_s}{8}\right)(Re - 1000)\, Pr}{1 + 12.7\left(\frac{f_s}{8}\right)^{1/2}(Pr^{2/3} - 1)} \qquad (10)$$

Reynolds Number,

$$Re = \frac{\rho_a v D}{\mu} \qquad (11)$$

Friction factor,

$$f_s = (1.82\, log\, Re - 1.64)^{-2} \qquad (12)$$

if, $2300 < Re < 5 \times 10^6$ and $0.5 < Pr < 10^6$

Prandtl number for flow in the circular pipe is

$$\text{Pr} = \frac{\mu C_p}{K_a} \qquad (13)$$

For the present study, the ambient temperature is taken as 43 °C and that thermal conductivity is 0.024 W/m-k, kinematic viscosity as 1.7235 × 10^{-5} m^2/s and Prandtl number 0.841.

(f). Energy saving by using EAHE system: It is as the difference between energy consumed by AC and energy consumed by EAHE integrated AC system.

Energy consumption by 5-star, 1.5 TR air conditioner:

This AC provides cooling of 5200 watts and consumed 1677 Watts power, however, in the present study, cooling load is 4233 Watts, and therefore power consumption will be 1365 watts in one hour (1.365 kWh).

Energy consumption by EAHE integrated AC system:

Cooling provided by a single EAHE pipe is

$$q = \dot{m}c_p\,(T_{inlet} - T_{outlet})$$

Total cooling provided by EAHE system (Q) = q × Number of pipes

Remaining cooling load will be provided by AC and it will be

= 4233 - Q

Therefore, energy savings in EAHE integrated AC system

$$= \frac{4233 - cooling\ provided\ by\ EAHE\ system}{3.1}$$

Total energy saving (w) = 1365 - Energy consumption by AC with EAHE system

The Energy consumption by EAHE integrated AC includes energy consumption by AC and blower of EAHE system.

3.2 Change in the design parameters

By using above design methodology of EAHE system, the total energy saving calculated for different pipe diameters (0.1m 0.15m and 0.2 m) with different air flow velocities (2 m/s, 3 m/s, 4 m/s, and 5 m/s). For all the cases total air flow rate was constant as 0.062 m^3/s. Table 3 represents the effect of pipe diameter and air flow velocities on energy savings by EAHE system.

Table 3: Effect of pipe diameter and air flow velocity on energy savings

Pipe diameter (m)	Air velocity (m/s)	Mass flow rate of air in a pipe (Kg/s)	Air flow rate in a pipe (m^3/s)	Total air flow rate required (m^3/s)	No. of pipes required	Convective H.T. coefficient (w/m^2-k)	Overall H.T. coefficient per unit length(w/m^3-k)	Length of pipe (m)	Energy saving per day with EAHE (kW)
0.1	2	0.018	0.015	0.062	4	9.09	2.46	33.88	2.45
	3	0.028	0.023	0.062	3	12.56	3.28	38.19	2.70
	4	0.037	0.031	0.062	2	15.75	3.98	41.99	2.37
	5	0.047	0.039	0.062	1.5	18.76	4.59	45.44	2.19
0.15	2	0.042	0.035	0.062	2	8.37	3.48	36.02	2.82
	3	0.063	0.052	0.062	1	11.51	4.62	40.67	2.11
	4	0.084	0.070	0.062	1	14.42	5.61	44.67	2.79
	5	0.105	0.088	0.062	1	17.17	6.49	48.25	3.44
0.2	2	0.075	0.062	0.062	1	7.87	4.41	37.84	2.53
	3	0.113	0.094	0.062	1	10.81	5.87	42.70	3.77
	4	0.150	0.125	0.062	0.5	13.54	7.14	46.83	2.52
	5	0.188	0.157	0.062	0.5	16.13	8.27	50.49	3.13

4. Results and Discussion:

In the present study three different diameter pipes (0.1m, 0.15m and 0.2m) are considered with four different air flow velocity (2 m/s, 3 m/s, 4 m/s and 5 m/s) and based on these parameters the required number of pipes, length of pipe and energy saving are calculated.

Figure 2 shows, the effect of air flow velocity on number of pipes of different diameters. From figure 2, it was observed that by increasing air flow velocity, the required number of pipes is decreases. Due to the increase in air flow velocity, the volume flow rate of air increases which decreases required number of pipes.

Figure 3 shows, the effect of air flow velocity on the required length of pipe of different diameters. From figure 3, it was observed that by increasing air flow velocity, the required length of pipe increases. The length of pipe and air flow velocity are directly proportional to each other because due to increase air flow velocity, the contact time between air particles and pipe surface decreases which decreases total heat transfer between air and soil.

Figure 4 represents, the impact of air flow velocity on per day energy savings (8 hours of operation). The energy saving is mainly decided by cooling capacity and power consumption of EAHE system. The power consumption and cooling capacity of EAHE system depend on pipe diameter, and air flow velocity. It shows that the maximum energy saving per day is 3.77 kW for the pipe of 0.2 m diameter at flow velocity of 3 m/s. Therefore this case is further considered for the economic analysis of EAHE system.

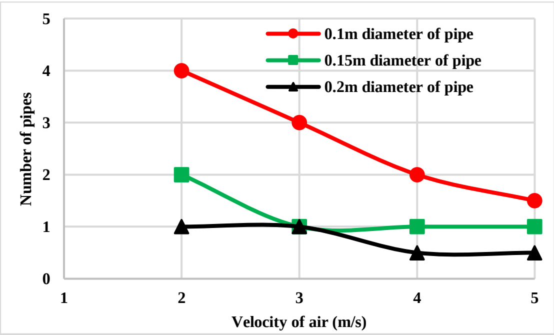

Fig. 2: Effect of air flow velocity on required number of pipes of different diameters

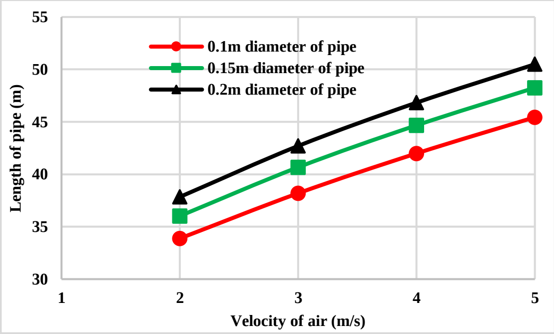

Fig. 3: Effect of air flow velocity on required length of pipe of different diameters

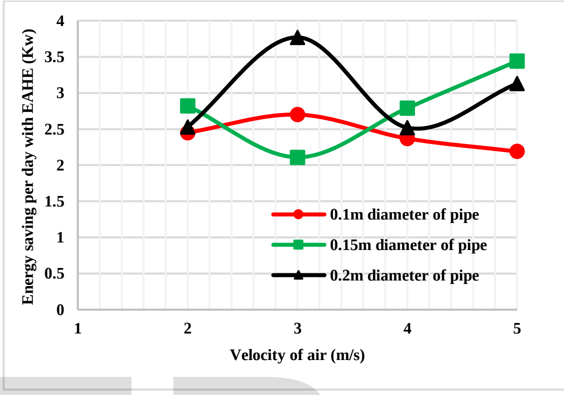

Fig. 4: Effect of air flow velocity on energy savings of different diameters

5. Economic Analysis

For the economic analysis, pipe of 0.2 m diameter with 3 m/s air flow velocity is considered, because it was showing maximum energy savings. Total energy saving with EAHE integrated AC is 1018.26 kW/Year, as compared without EAHE integrated AC system (i.e. with AC alone). The total cost of EAHE system (installation cost and operating cost) is estimated as per the Indian market [17],[19]. The installation cost (i.e. capital cost) of EAHE system is presented in Table 4.

The economic viability of any project or system is judged on the basis of the internal rate of return (IRR) and its payback period (PBP). IRR represents the level of financial return on the investment.

Table 4: Capital cost for installation of EAHE system

Item description	Specifications	Quantity	Rate	Cost (Rs)
PVC pipe	0.2 m diameter and 43 m length	1	Rs. 490.73/meter	21101.39
Blower	6000 CFM, 1.5kW, 2 HP	1	Rs. 10054/Piece	10054
Pipe Elbow (90°)	0.2 m size	4	Rs.350/ piece	1400
Excavation and backfilling (l x b x h)	Excavation of 32.25 m3 of soil volume (43 m x 0.25 m x 3m) by JCB machine	8 hours	Rs. 800/hr.	6400
Miscellaneous & labour	-	-	5% of total cost	1947.76
Total Cost (Rs)				**40903.15**

The Payback Period helps to determine the time required to recover the initial investment for the installation of the EAHE system.

For the present study, it was considered that the cooling is required for 270 days in a year and in a day cooling system is operated for 8 hours. The electricity tariff is considered as Rs.7/kWh [8] and the cost of electricity increases by 5% every year. The operating and maintenance cost of the system is considered as 2% of the total installation cost of EAHE system.

Based on these assumptions the payback period at 5% discount rate is found to be 6.3 years. This payback period is beneficial because the life of EAHE system is more than the ten years. Moreover, if the life of EAHE system is considered as 20 years, then the IRR of the system came out to be 20.5%.

6. Conclusion:

In the present study, an EAHE system is designed for an office room which have cooling load of 4233 Watts. For the designing EAHE, three different diameters (0.1 m, 0.15 m and 0.2 m) with four different air flow velocity were considered. Based on these parameters, the required length of pipe and number of pipes are determined and then per day (8 hours of operation) energy saving in each case is calculated. Based on energy saving, a combination of pipe diameter and air flow velocity is decided for the economic analysis. Maximum energy saving was found for pipe of 0.2m diameter at air flow velocity of 3 m/s, therefore this case is selected for economic analysis.

For the economic analysis of the selected case, 9 months of duration is considered and it was observed that the payback period of EAHE system is about 6.35 years with the total initial investment of Rs. 40903. The payback period is mainly depends on operating hours of the system, therefore if operating hours is more, total energy saving due to EAHE will be more and thus it's payback period will be reduced. For the present case, if the life of EAHE system considered to be 20 years then the IRR of the EAHE system will be 20.5%.

Based on the economic analysis, it is observed that the proposed EAHE system is economically feasible. It is concluded that the use of an EAHE along with an air-conditioner unit, reduces the cooling load and running time of AC unit significantly, which leads to saving of energy and consequently proves the economic viability of an EAHE system. Hence, the use of EAHE system with AC can be recommended for cooling of small and medium size residential buildings in Rajasthan.

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