Design Optimization and Performance Prediction of Earth Pipe Heat Exchanger in Cooling Mode

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Abstract— In this study, theoretical models for earth-tube heat exchanger have been developed and effects of various design and operational parameters on cost – benefit ratio in cooling mode of operation have been investigated. The results are presented in various design curves, which will be helpful for the users to select appropriate designs according to utility. The results revealed that about 8-10°C drop was achieved for L=50m and different values of m, D and t_{op}. The optimum values of 'm' were found to be 0.075, 0.1 and 0.125m^3/s respectively for corresponding values of D=0.1, 0.15 and 0.2m at t_{op}=4.00h.

Key words: Earth Pipe Heat Exchanger, Design, Mathematical Models, Performance, CBR

I. INTRODUCTION

Soil temperature at about 2m depth exists relatively stable which may be considered as an annual average temperature ±1.5°C. An earth pipe heat exchanger is a system consisting of a long pipe buried in the ground at desired depth. If ambient air is passed through the pipe, it will either be heated or cooled depending upon the ambient air temperature. Thus conditioned air may be obtained and can be utilized for various purposes like crop and livestock production, conditioning residence and agricultural processing and storage space etc. The hybrid system like an earth pipe heat exchanger is now preferred due to the concept of energy conservation and utilization of alternate energy sources. The system provides a high level of air conditioning often higher than conventional methods (Ewen et al, 1980). The applicability of an earth pipe heat exchanger, however depends on two major factors i.e. performance and cost. Therefore, one has to make an effort to reduce the cost and simultaneously improve the performance of the system. The performance of earth pipe heat exchanger can be improved by increasing the air flow rate and increasing the pipe length. However, pumping cost and material cost also increases with increase in length/diameter of pipe. An ideal way to overcome this problem is to optimize the design and operational parameters by keeping the cost-benefit aspect in view.

In the present study efforts were made to develop the mathematical models for predicting the techno-economic performance of the earth pipe heat exchanger and to optimize design and operational parameters.

II. METHODOLOGY

Fig. 1 Shows the schematic view of the system to study the effect of various design and operational parameters i.e. air flow rate (m), pipe geometry (pipe length, L & diameter, D) and operating time (t_{op}) on techno-economic performance i.e. outlet air temperature and pipe surface temperatures, effectiveness, coefficient of performance and cost-benefit ratio of the earth pipe heat exchanger consisting of a 50m long pipe buried at 2m depth in soil.

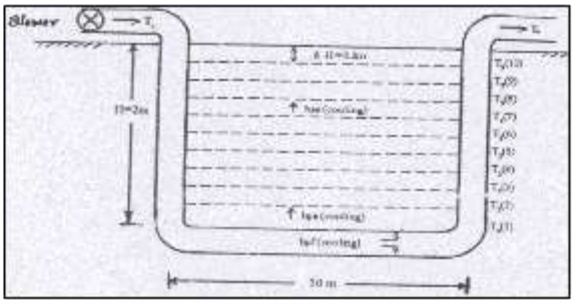


Fig. 1: Schematic View of A Typical Earth Pipe Heat Exchanger System Showing Heat-Transfer Coefficients

A. Mathematical Modeling:

The theoretical models were developed by writing the energy balance equations for various components of the system and solving it by using the finite difference technique. The finite elements of time and distance were considered as 0.1sec and 5m for pipe and 20cm for soil profile respectively.

B. Energy Balance Equations:

Energy balance equations for different components are given below for air flowing through pipe

$$A\,\rho_f\,C_f\,(\partial T_f/dt) + \rho_f\,m\,C_f\,(\partial T_f/dl) = P\,h_{pf}\,(T_p - T_f) \quad (1)$$

for pipe surface

$$M_pC_p\,(\partial T_p/dt) = h_{pf}\,(T_p - T_f) - h_{ps}\,(T_p - T_s) \quad (2)$$

for soil layers

$$\rho_s\,C_s\,(1 - \epsilon)\,\partial T_s/dt = [\partial\,(K_s\,(\partial T_s/dh))/dh] \quad (3)$$

The temperature of soil layers adjoining to the heat exchanger were determined as

$$T_s(1) = \sum_{L=0}^{L=50} T_p\,(L, t) / L \quad (4)$$

C. Boundary Conditions:

$T_f\,(L, 0) = T_i\,(T_a)$
$T_f\,(L, t) = T_o\,(T_f)$
$T_p\,(L, 0) = T_s\,(0, 0) = T_{av} - 1.5°C$
$T_s\,(0, 0) = T_a$

D. Performance Analysis:

1) Temperatures:

Hourly variation in outlet air (T_f) and pipe surface (T_p) temp. at different locations of the system for various input design and operational parameters were calculated by using the equations 1 to 4.

Efficiency- $\eta = [(T_f(1)–T_f(L))/(T_f(1)–T_s(2))] \times 100$ (5)

2) *Coefficient of performance:*

$$COP = E / P_{kW} \quad (6)$$

where, $E = m\, \rho_f\, C_f\, (T_i – T_f)$ and P_{kW} was calculated as per equation (14)

3) *Cost Analysis:*

$$HC=HCS+HMC+HPC–HSV \quad (7)$$

In above equation, cost parameters are calculated as given below

4.1 Hourly cost of the system**:** $HCS = ACS/(200\, t_{op})$ (8)

where, $ACS = CRF\ (CI)$ (9)

$CI = PC + CINS + CBLOW$ (10)

$CRF = i\, (i+1)^n / [(i+1)^n – 1]$ (11)

Here, PC = 1000 L D; CINS = 15 L and CBLOW = Rs. 3000/- (12)

4.2 Hourly maintenance cost (HMC) **:** considered as 10 % of the HCS

4.3 Hourly pumping cost **:** $HPC = P_{kW}\, CE$ (13)

where, $P_{kW} = m\, \Delta P / \eta_{blower}$ (14)

$\Delta P = 0.022243\ m\ L^{1.852} / (1000\ D^{4.973})$ (Arora, 1988) (15)

and CE = Rs.5/kWh

However, the minimum capacity of the blower was considered as 0.25 hp (186.5W). The efficiency of blower (η_{blower}) was considered to be 50 %.

4.4 Hourly salvage value**:** $HSV = SFF\ (SV) / (200\, t_{op})$ (16)

where, $SFF = 1 / [(i+1)^n – 1]$ and $SV = 0.1\ (CI)$

4.5 Cost – benefit Ratio: $CBR = HC / TR$ (17)

where, TR = 3.5 E and HC was calculated by using equation (10).

4) *Heat Transfer Coefficients*

The various heat transfer coefficients were calculated by using relationship given by Duffie and Beckman (1980). The HTC between air and pipe surface was calculated as

$$h_{pf} = Nu\ K / D \quad (18)$$

where, $Nu = 0.023\ Re^{0.8}\ Pr^{0.3}$

$Re = \rho\, v\, D / \mu = 4\, m\, \rho / \pi\, D\, \mu$

$$H_{ps} = h_{ss} = K_s / H \quad (19)$$

5) *Input Parameters:*

1) Weather Data:

The hourly ambient inlet air temperatures for typical summer day at Junagadh (21°36'N, 71°26'E) considered for numerical calculations are given in Table 1.

Time (h) / Temperature (°C)					
9.0	10.0	11.0	12.0	13.0	14.0
36.0	39.0	40.0	42.0	42.0	41.0
Time (h) / Temperature (°C)					
15.0	16.0	17.0	18.0	19.0	
41.0	39.5	37.0	34.0	31.0	

Table 1: Hourly Ambient (Inlet) Air Temperatures For Typical Summer And Winter Days For Junagadh

2) Soil Parameters:

The variation in physical and thermal properties of black clay loam soil with respect to soil moisture content for Junagadh are given in Table 2.

Moisture content (θ)	Specific Heat (C_s) J/kg°C	Thermal conductivity (K_s), W/m°C	Porosity (∈), %	Bulk density (ρ_s) kg/m³
10	1300	0.50	38	1400
15	1500	1.15	33	1450
20	1700	1.38	28	1500
25	1900	1.45	23	1550
30	2100	1.50	18	1600

Table 2: Variation In Physical & Thermal Properties Of The Soil With Respect To Soil Moisture Content

3) Design And Operational Parameters:

L=0-50m with 5m interval; D= (A) 0.1, (B) 0.15 and (C) 0.2m; m=0.025, 0.05, 0.075, 0.1, 0.125 and 0.15 m^3/s; θ= 15% and t_{op}=9h (9.00h to 18.00h).

III. RESULTS AND DISCUSSION

A. *Temperature Pattern:*

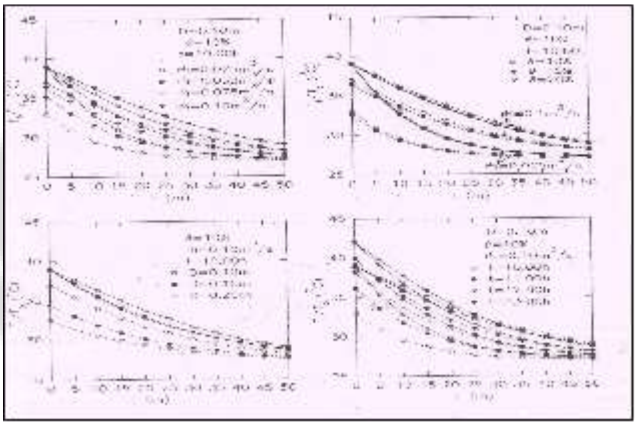
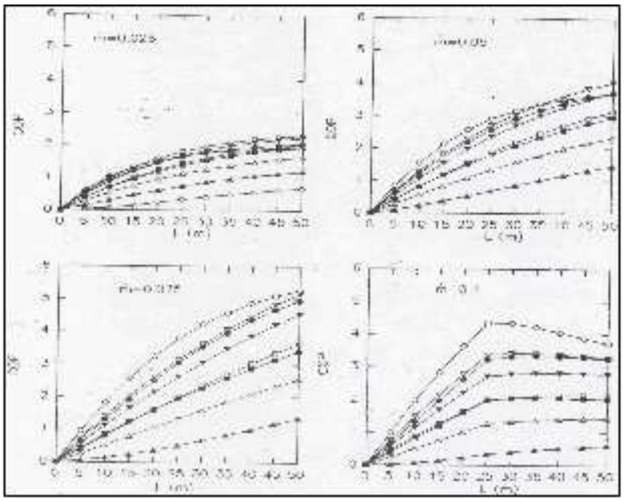


Fig. 2: Variation in Tf and Tp with respect to different operational parameters in cooling mode

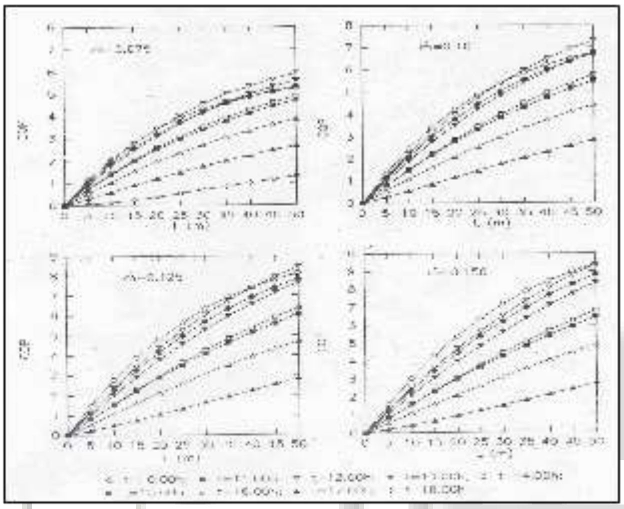
The effect of D on T_f for any fixed value of m and t_{op} revealed that, T_f increases with increase in D (Fig.2). For lower values of m and t_{op} and higher values of D, L=30-35 m is sufficient to achieve the desired reduction in T_f. The optimum t_{op} for any combination of m and D are first four hours i.e. from 9.00h to 13.00h after that the cooling effect decreases due to decrease in T_a after 13.00h. For L = 50m about 10-12°C drop (ΔT_f) in T_f was achieved for lower values of m and any value of D whereas, for higher values of m, the ΔT_f was found to be 6-10°C.

B. *Coefficient of Performance of the System:*

The results on COP are presented in Fig. 3. It shows that except for m = 0.1 m^3/s and D = 0.1 m i.e high flow rate at small D, the COP increases with increase in both L and m



(A)



(B)

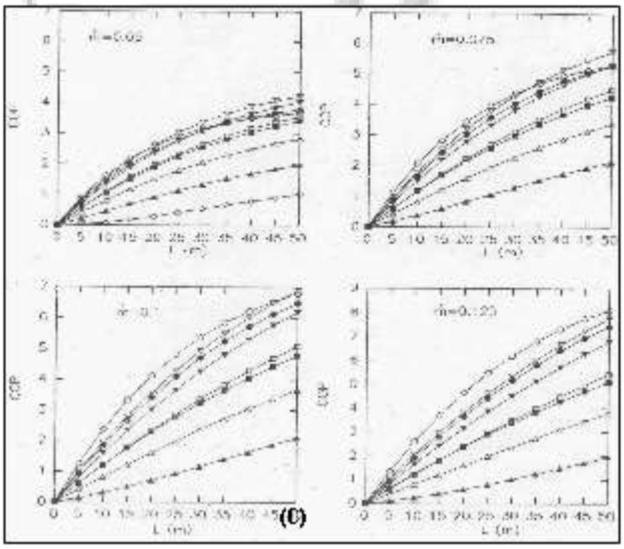
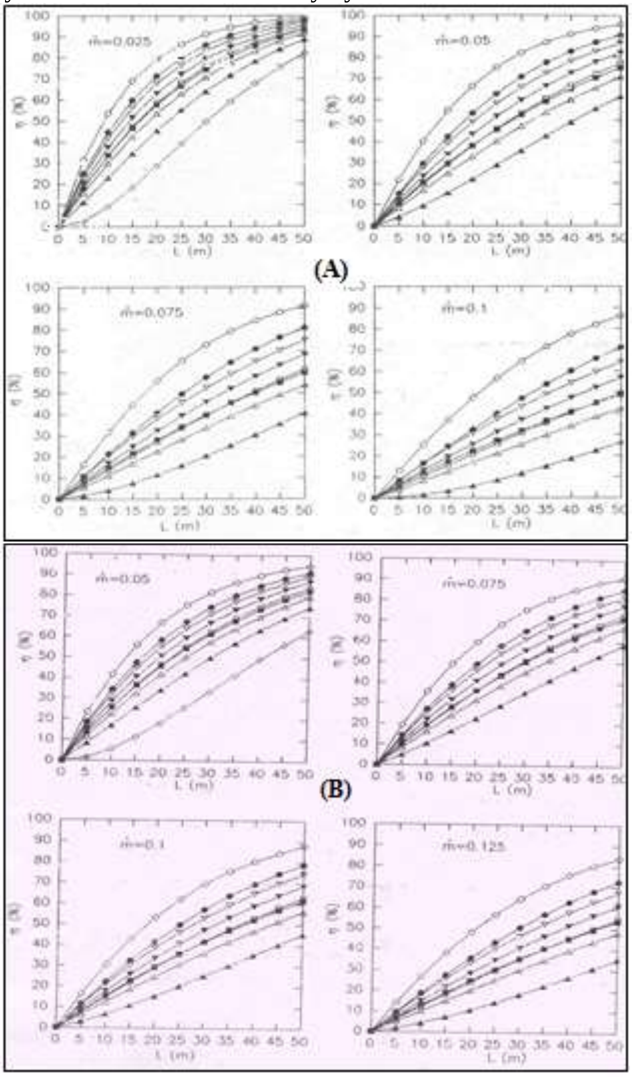


Fig. 3: Variation in COP With Respect To L for Different D, M And Top In Cooling Mode

For different values of D. The effect was found to be more prominent for m as compared to L. The effect of D on COP revealed that for any fixed value of m and L, COP increased with enlargement of D, because of better heat transfer between soil and pipe surface and pipe surface and flowing air for larger D. For D = 0.1m and m = 0.1 m^3/s, the COP first increases and then decreases during first hour of operation while, for remaining period of operation, COP first increases and then remained constant at higher duct lengths. This was due to the fact that at small D and high m, the pumping power increased due to higher-pressure drop. The COP of the system was found to be as high as 9.5 for m = 0.15 m^3/s and D = 0.2m and as low as 1.0 for m = 0.025 m^3/s and D=0.1m for first and eighth hour of operation respectively.

C. Effectiveness of the System:

The efficiency of the system was predicted for different variables considered for the study and results in the form of design curves are presented in Fig. 4. The maximum efficiency of the system (as high as 98 %) was obtained for lower values of m, D and t_{op} and extreme values of L. The efficiency of the system was found to be greatly influenced by the m and L and moderately by D.



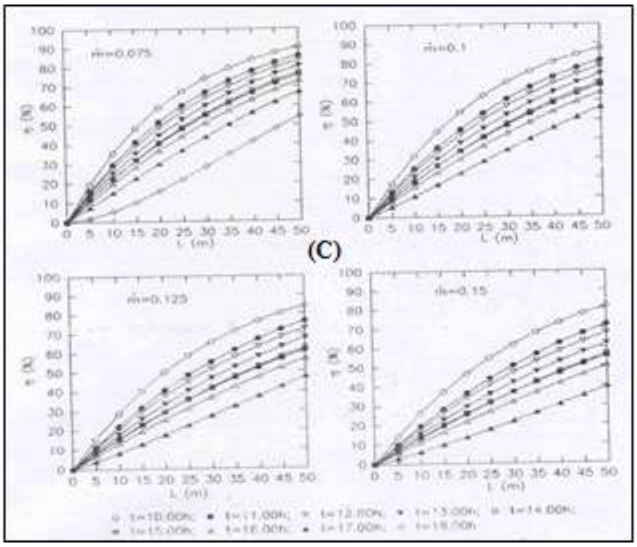
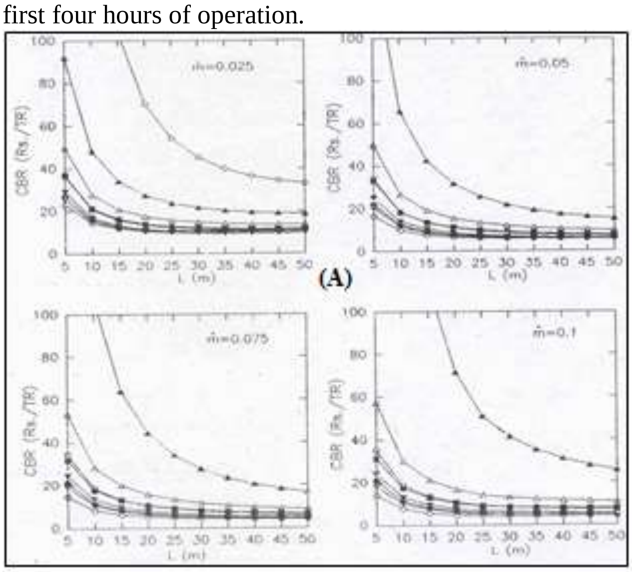
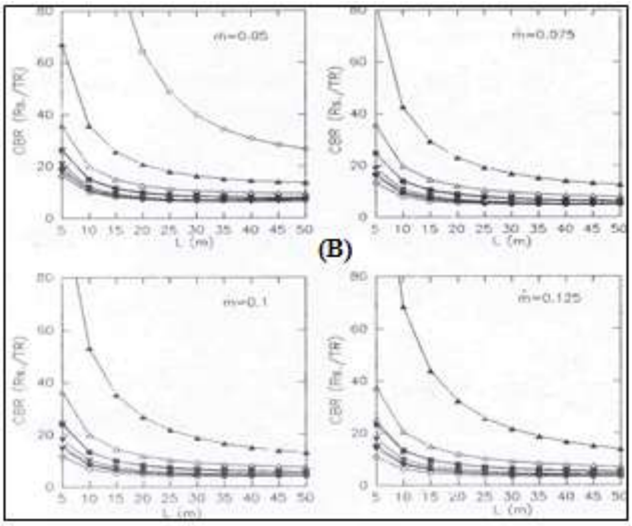


Fig. 4: Variation in Efficiency With Respect To L for Different D, M And Top In Cooling Mode

D. Cost-Benefit Ratio:

Figure 5 illustrate the hourly cost of cooling capacity (Rs./TR) plotted as a function of L for different values of m and D. From all figures it can be seen that, irrespective of variation in D, at all values of m, the cost-benefit ratio decreases first sharply up to a length of 25m and then slowly with further increase in L. The effect was found to be more prominent for higher values of m and smaller D, due to higher pressure drop and hence, more pumping cost. The effect of t_{op} revealed that the CBR increases with increase in t_{op} and was found to be exceptionally high for last hour of operation at all L. The CBR decreases with increase in D for all duct lengths at any fixed value of m. The CBR was found to be minimum for t_{op} = 4 hours (i.e. from 9.00 to 13.00h) for all L and different combinations of D and m. For lower values of D, the respective values of m can be selected as 0.075 m^3/s to obtain maximum cooling capacity at minimum cost. Similarly, for D=0.15 m and D=0.2 m, the minimum CBR was obtained for m = 0.1 and m = 0.125 m^3/s, respectively. For the above design and operational values, the CBR was observed as less than Rs.10/TR for first four hours of operation.





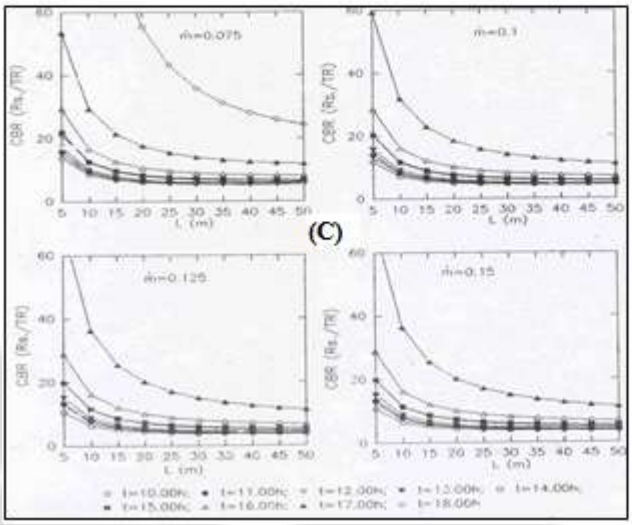


Fig. 5: Variation in CBR with respect to L for different D, m and t_{op} in cooling mode

E. Selection of Design and Operational Parameters:

The selection of optimum design and operational parameters based on various design curves of techno-economic performance of the system are presented here in tabular form.

θ (%)	D (m)	m (m^3/s)	L (m)	top (h)	Max.Δ T_f (°C)	Max. COP	Max. η (%)	Min. CBR Rs/TR
15	0.10 0.15 0.20	0.075 0.10 0.125	50 50 50	4 4 4	8-10 8-10 8-10	4.5-5.1 6.2-6.9 7.6-8.5	68-92 68-88 68-84	5 5 5

Table 3: Summary of best techno-economic performance of the system for different optimum values of θ, D, m, L and t_{op}

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IV. NOMENCLATURE

C	Specific heat, J/kg °C
CBLOW	blower cost, Rs.
CE	cost of energy, Rs./kWh
CI	capital investment, Rs.
CINS	installation cost, Rs.
CRF	capital recovery factor
h	heat transfer coefficient, W/m^2°C
HC	hourly cost, Rs.
i	rate of interest, per cent
k	Thermal conductivity, W/m°C
M	mass, kg/m^2
m	flow rate, m^3/s
N	life of system, years
Nu	Nusselt number
P	circumference, m
PC	pipe cost, Rs.
P_{kW}	power, kWh
Pr	Prandtl Number
Re	Reynolds Number
SFF	salvage fund factor
SV	salvage value
T	temperature, °C
t	time, s, h
TR	tonnes of refrigeration
V	Velocity, m/s
Greek	
ρ	density, kg/m^3
∈	porosity, decimal
ΔH	spacing between two successive soil layers, m
ΔP	pressure drop, Pa
μ	viscosity, kg/m-s
Subscript	
a	ambient
f	fluid (air)
i	inlet
o	outlet
op	operational
p	pipe
pf	pipe-fluid
ps	pipe-soil