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Performance of Thermo Hydraulic Designed Single Pass Earth Air Heat Exchanger

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ABSTRACT

In present study thermo-hydraulic design method by Paepe and Janssens (2003) was illustrated and used for evaluation of single pass Earth- Air Heat Exchanger (EAHE) system. Such designed EAHE was installed at the research field of Soil and Water Engineering Department, Punjab Agricultural University, Ludhiana, India (75°88′E & 30°95′N). It consists of 42 m single PVC pipe of 0.25 m diameter buried at 3.5 m depth. The thermister 2k temperature sensors and Dl2 data logger were used for data recording. The maximum and minimum tube efficiencies were obtained at 2.3 and 24 m/s, respectively. The thermo-hydraulic designed earth air heat exchanger performed well as observed tube efficiency was near to designed efficiency. It was also observed that as velocity increases the tube efficiency decreases. The method proposed by Paepe and Janssens (2003) was simple, fast and reliable for installation of EAHE system in field too.

Highlights

- Owing to high operational cost in heating and cooling of greenhouse, the earth air heat exchanger is gaining popular as it uses the stored energy of deep sub surface soil.
- Various numerical methods for design of earth air heat exchanger are available which is complex but analytical method proposed by Paepe and Janssens (2003) is simple and reliable.
- The pipe length, pipe diameter and flow rate are main three parameters which are to be considered for design of EAHE.

Keywords: Thermo, earth air heat exchanger, thermister, tube efficiency

Greenhouse technology is a breakthrough in the agriculture production technology that integrates market driven quality parameters with production system profits. Compared to open field, very high yields of vegetables have been reported under greenhouse by several workers (Bisht *et al.* 2011; Srivastava and Singh 1997; Parvej *et al.* 2010; Srivastava *et al.* 2011). Extreme high summer temperature and low temperature in winter is a major setback for successful greenhouse crop production throughout year. High temperature and humidity during summer months cause adverse effect on crop production in tropical region (Pek and Hayles 2004). Similarly heating system is required for proper early growth of plants in winter season. Lack of heating/cooling has an important effect on the yield, as well as on the cultivation time and the quality of the products. The availability alternative heating and cooling systems is, therefore, of primary importance. One such system is Earth Air Heat Exchanger (EAHE) which uses the geo-thermal energy of ground. In summers when ambient air is forced through underground earth air pipe system the heat from the air is transferred to the pipe walls by convection, dissipated later to the soil by conduction. The cool delivery air from the earth air heat exchanger system can be passed through greenhouse spaces to create required thermal conditions. In winters, when cold ambient air is passed through same system, the heat is transferred from the surrounding earth to the pipe by conduction and then to air by convection, heating the passing air in process. The hot air from the system can be now used to heat the greenhouse. As a result, greenhouse can be cooled during summers and heated during winters by same system. The use of earth air heat exchangers for heating and cooling of buildings and agricultural greenhouses has gained importance during the last few years. One of the major reasons behind non recognition of EAHE systems even today is lack of knowledge regarding design of efficient system besides the other disadvantages like poor air quality with prolonged use, higher setup cost, growth of harmful microorganisms etc (Bisoniya *et al.* 2014). Therefore, there is need to generalize the use of EAHE systems so that the use of renewable and sustainable energy technologies can be promoted. The amount of heat exchanged between the air and surrounding soil depends on various parameters like the surface area, diameter, length & material of the pipe, soil temperature and air velocity. Pipe length and pipe depth turned out to affect the overall cooling rate of the earth tube, while pipe radius and air flow rate mainly affect earth tube outlet temperature (Mihalakakou *et al.* 1995). Several other papers have been published in which a design method is described. Most of them are based on a descritisation of the one-dimensional heat transfer problem in the tube. Three dimensional complex models, solving conduction and moisture transport in the soil are also found (Boulard *et al.* 1989; Gauthier *et al.* 1997; Kabashnikov *et al.* 2002). Bordoloi and Sharma (2017) developed a 3-dimensional double precision computational fluid dynamics (CFD) model in Ansys FLUENT v15.0 under steady conditions for three different pipe materials and four different pipe geometries. The CFD analysis was also done by Congedo *et al.* (2016) for thermal performance of earth air heat exchanger. A parametric analysis was out carried using numerical analysis taking into account the length and the radius of the pipe and the velocity of the air in the pipe (Belatrache *et al.* 2016). Numerical investigation was also carried out to improve the thermal potential of an Earth-Air Heat Exchanger (EAHE) by Rodrigues *et al.* (2015). TRNSYS 17 was used by Chel *et al.* (2015) to evaluate the dynamic thermal performance of a residential house which was integrated with air-air heat exchanger (AAHE), a water-air heat exchanger (WAHE) coupled with an earth-water heat exchanger (EWHE). Hence, these methods are complex and often not ready for use by designers. A one-dimensional simple analytical method was presented to analyze the influence of the design parameters on thermo-hydraulic performance of the heat exchanger (Paepe and Janssens 2003).

MATERIALS AND METHODS

A relation is derived by Paepe and Janssens (2003) for specific pressure drop, linking thermal effectiveness with pressure drop of the air inside the tube. The relation is used to formulate a design method which can be used to determine the characteristic dimensions of the earth–air heat exchanger in such a way that optimal thermal effectiveness is reached with acceptable pressure loss. The choice of characteristic dimensions becomes thus independent of the soil and climatological conditions. This allows designers to choose the earth–air heat exchanger configuration with the best performance. Therefore, in present study the Paepe and Janssens (2003) method was used for evaluation of EAHE system.

Design of Earth Air Heat Exchanger

Calculation of desire heating load

The naturally ventilated greenhouse of length 16 m, breadth 6 m and height 3.2 m was selected for study. The heating load is the heat that needs to be exchanged from greenhouse to pipe of earth air heat exchanger. It was calculated from exposed surface area of greenhouse, overall heat transfer coefficient, average ambient temperature of the site, and desirable temperature of greenhouse and expressed as:

$$Q = UA\,(T_{greenhouse} - T_{desirable}) \qquad \ldots(1)$$

Where,

A = Total exposed area of green house = 205 m^2

$T_{greenhouse}$ = Greenhouse temperature = 44 ^{o}C

$T_{desirable}$ = Desirable temperature inside green house = 32 ^{o}C

Overall heat transfer co-efficient (U) is the overall transfer rate of a series or parallel combination of convective and conductive walls. The overall heat transfer coefficient is expressed in terms of thermal resistances of each fluid stream. The summation of individual resistances is the total thermal resistance and its inverse is the overall heat transfer coefficient which is expressed as:

$$U = 1/((1/h_o) + x/k + 1/h_i) \quad \ldots(2)$$

Where,

h_o = Ambient air convective heat transfer co-efficient = 35.5 W m^{-2} K^{-1}

h_i = Inside green house air convective heat transfer co-efficient = 30 W m^{-2} K^{-1}

x = Thickness of the green house wall = 0.0002 m

k = Thermal conductivity of green house wall material = 0.3 W m K^{-1}

Therefore, U = 16.1 W m^{-2} K^{-1}

Thus, heating load, Q = 16.1 × 201 × (42-32) = 39608.16 W.

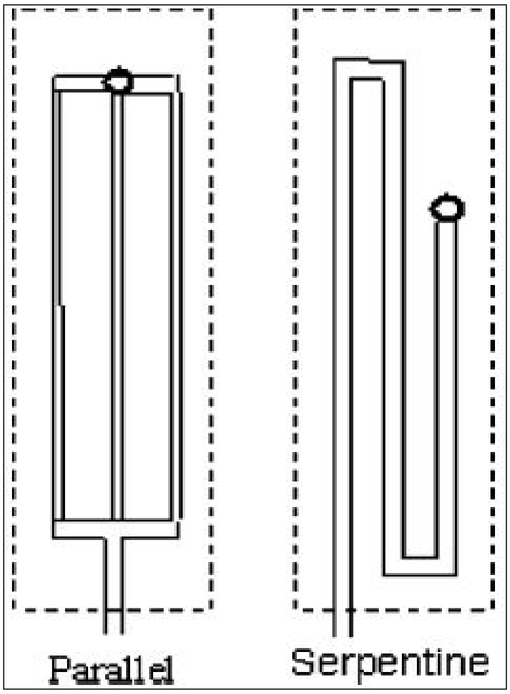

Fig. 1: Layout of EAHE system

Calculation of mass flow rate

The mass flow rate was computed from the calculated heat load, undisturbed soil temperature and specific heat of air. It is expressed as:

$$m = Q/([C_p)(T_{greenhouse} - T_{soil})] \quad \ldots(3)$$

Where, T_{soil} = Temperature of soil at 3.5 m depth = 25.4 °C

C_p = Specific heat value of air = 1007 J kg^{-1} K^{-1}

m = 39608.16 /[1007 (44 – 25.4)] = 2.11 kg s^{-1} = 7088.3 m^3 h^{-1}

Calculation of length of pipe

The length of pipe was computed from mass flow rate (m) and selecting suitable diameter of pipe using Nomograph of Paepe and Jansssens (2003). The layout of EAHE pipe can be done either in parallel or serpentine manner (Fig. 2).

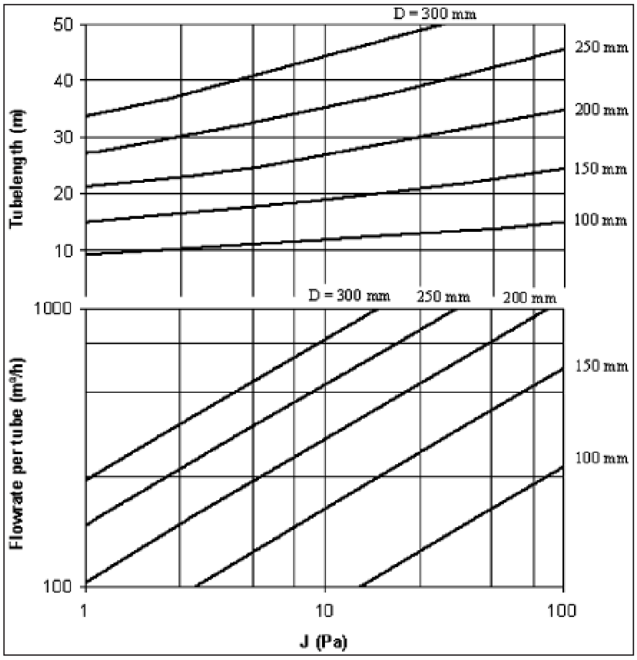

Fig. 2: Design graph for sizing of earth air heat exchanger

Length of Pipe of 0.1 m diameter in parallel manner

Maximum allowable pressure drop (P_{max}) = 100 pa

Tube efficiency = effectiveness (e) = $\Delta T / (T_i - T_s) = 0.65 \quad \ldots(4)$

Where, $\Delta T = T_i - T_o$, $T_i = T_{greenhouse}$, $T_s = T_{soil}$, $T_o = T_{outlet}$

Number of Transfer Unit (NTU) = – ln(1 – e) = 1.03

Specific pressure drop (J) = P_{max}/NTU = 100/1.03 = 96.5 pa

Fig. 3: Digging of soil and fitting EAHE

Using specific pressure drop (J) of 96.5 pa at horizontal axis and pipe diameter of 0.1m from Fig. 2 the flow rate per tube at vertical axis was computed.

So, flow rate per tube = m_t = 260 $m^3 h^{-1}$

Number of parallel pipe required = m/m_t = 7088.3/260 = 27

Using specific pressure drop (J) of 96.5 pa at horizontal axis and pipe diameter of 0.1m from Fig. 2, the length of pipe was determined.

So, length of each pipe = 15 m

Now the air velocity (v) which is to be circulated through each pipe was computed as:

$$v = {}^{M_t}/_{\alpha} \qquad \text{…(5)}$$

Where, a = cross sectional area of pipe of 0.1 m diameter = $\frac{\pi d^2}{4}$ = 0.007 m^2

M_t is mass flow rate per tube in Kg/s and expressed as :

$$M_t = {}^{m_t \rho}/_{3600} \qquad \text{…(6)}$$

ρ is density of air = 1.074 kgm^{-3}

So, v = 9.88 ms^{-1}

Length of Pipe of 0.15 m diameter pipe in parallel manner

Using same nomograph (Fig. 2), specific pressure drop (J), and pipe diameter (0.15 m) the flow rate per tube (m_t) at vertical axis was computed as 590 m^3/h.

Number of parallel pipe required = m/m_t =7088.3 /590 = 12

Consequently, the length of pipe was found to be 26 m using same nomograph (Fig. 2), specific pressure drop and diameter of pipe (0.15 m).

The air velocity (v) (Eq. 5) which is to be circulated through the each pipe was computed as:

v = 9.97 ms^{-1}

Where, cross sectional area of pipe of 0.15 m diameter (a) = 0.0176 m^2

M_t = 0.176 kg s^{-1} (Eq. 6)

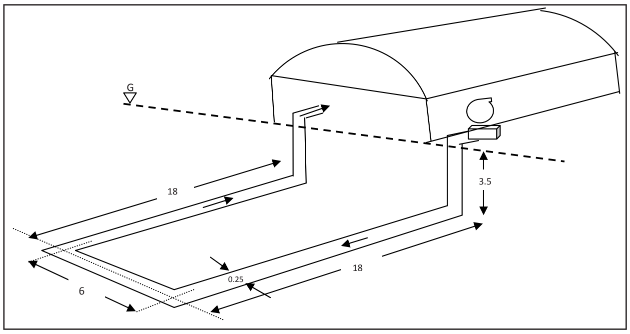

Fig. 4: Schematic diagram of earth air heat exchanger

Fig. 5: Belt driven industrial blower with motor

Length of Pipe of 0.2 m diameter in parallel manner

Using specific pressure drop (J) of 96.5 at horizontal axis and pipe diameter of 0.2 m, the flow rate per tube (m_t) at vertical axis was computed as 1000 m^3/h.

Number of parallel pipe required = m/m_t = 7088.3 /1000 = 7

The length of pipe = 35 m.

The cross sectional area (a) of pipe of 0.2 m diameter = 0.0314 m^2

M_t = 0.24 kg s^{-1}

The air velocity (v) = 9.5 ms^{-1}

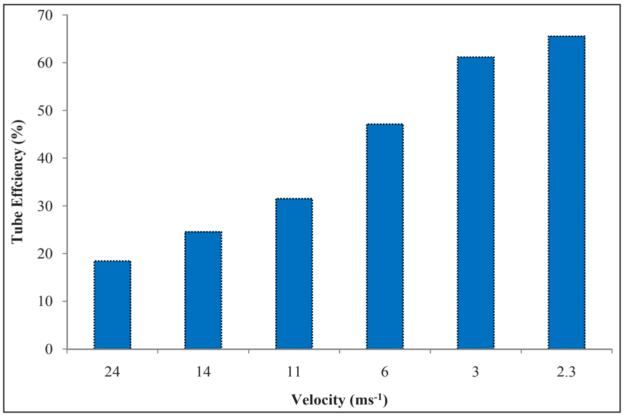

Fig. 6: Variation of tube efficiency with velocity under closed system

Length of Pipe of 0.25 m diameter in serpentine manner

Since it is single pipe in serpentine manner the flow rate per tube is taken as 1000 m^3/h which is maximum value as depicted in Fig. 2.

Now using same Fig. 2 and specific pressure drop and diameter of pipe, the length of pipe was found to be 44 m.

So, the length of pipe = 44 m

The cross sectional area of pipe of 0.25 m diameter (a) = 0.049 m^2

M_t = 0.298 kg s^{-1} (Eq. 6)

Now the air velocity (v) (Eq. 5) which is to be circulated through the single pipe was computed as:

v = 6.08 ms^{-1}

Installation of Earth Air Heat Exchanger

The depth of buried pipe was selected based on one year (April 2013 to March 2014) soil temperature profile. The EAHE pipe was installed at 3.5 m depth where the temperature was maximum and minimum during peak winter and summer, respectively. The combination of different diameter pipes under different EAHE systems layout is

Table 1: Summary of configuration of different EAHE systems layout

Diameter (m)	Length of pipe (m)	Number of pipe	Minimum distance between two pipes (m)	Area require (m^2)	Installation system
0.10	15	27	1	405	Parallel
0.15	26	12	1	312	Parallel
0.20	35	7	1	245	Parallel
0.25	44	1	1	44	Serpentine

Table 2: Tube efficiency (η) of EAHE at different velocities and durations

Velocity, v (ms^{-1})	Duration	ΔT (°C)	T_i-T_s (°C)	η (%)	Velocity, v (ms^{-1})	Duration	ΔT (°C)	T_i-T_s (°C)	η (%)
	24-Apr-15	3.76	29.54	12.7		12-Apr-15	4.10	17.25	23.8
v = 24 ms^{-1}	27-Apr-15	6.1	28.2	21.6	v = 14 ms^{-1}	20-Apr-15	5.86	23.38	25.1
	11-May-15	5.73	27.32	20.9		28-Apr-15	4.35	17.57	24.8
	Mean	5.20	28.35	18.4		Mean	4.77	19.40	24.5
	21-Apr-15	7.76	24.75	31.4		03-May-15	14.10	28.69	49.1
v =11 ms^{-1}	30-Apr-15	8.43	26.63	31.7	v = 6 ms^{-1}	06-May-15	13.40	30.78	43.5
	05-May-15	51.76	28.37	34.3		09-May-15	10.68	21.92	48.7
	Mean	8.64	26.58	32.4		Mean	12.72	27.13	47.1
	22-Apr-15	19.03	30.66	62.0		23-Apr-15	18.45	27.59	66.9
v = 3 ms^{-1}	01-May-15	14.36	23.48	61.2	v = 2.3 ms^{-1}	02-May-15	16.67	25.97	64.2
	10-May-15	45.36	21.12	60.3		08-May-15	57.36	28.55	63.9
	Mean	15.37	25.09	61.2		Mean	17.79	27.37	64.9

summarized in Table 1. The minimum distance to be maintained between two pipes to avoid heat transfer interference under parallel manner is 1 m as reported by Paepe and Jansssens (2003).

The perusal of Table 1 reveals that the minimum area requires beside the existed greenhouse was 245 m^2 and 42 m^2 under parallel and serpentine system, respectively. But, the minimum area required for installation was not available under parallel system. Therefore, the layout of pipe (0.25 m diameter) was carried out under serpentine manner. Moreover, under this system the earthwork require is less which reduces the construction cost of EAHE system. The excavation was initiated in May 2014 with JCB machine upto 3.5 m depth in serpentine manner as shown in Fig. 3. Five 0.25 m diameter PVC pipes with length of 6.09 m along with four elbows were laid down at mentioned depth (Fig. 4). The pipe fittings were made air tight using solvent cement and araldite. The pipe material selected was PVC based on the reviewed literature which reveals that pipe material does not affect the EAHE performance (Spengler and Stombaugh 1983; Bansal *et al.* 2009 and Bansal *et al.* 2010). The schematic view of installed EAHE is presented in Fig. 4. The air was circulated in EAHE with the help of force drive centrifugal industrial blower (radial blade) (Fig. 5). The blower was made belt driven so that air velocity can be increased by reducing the size of pulley. The air velocity was further regulated with the gate valve located at inlet of blower. The blower was driven with 3 phase 10 hp motor with 1440 rpm. The maximum velocity of 14 ms^{-1} was attained at 1440 rpm of motor when size of driven pulley was same as drive (6 inch). The maximum velocity of 24 ms^{-1} was recorded when size of driven pulley was reduced to 3.5 inch. Therefore, EAHE was operated at velocity of 2.3, 3, 6, 11, 14 and 24 ms^{-1} for its thermal performance in heating and cooling mode. The air velocity was measured with digital vane type anemometer having range of 0.2-20 ms^{-1} with 0.1 ms^{-1} resolution. The thermister 2k temperature sensors and Dl2 data logger were used for measuring EAHE inlet & outlet temperature.

RESULTS AND DISCUSSION

The results of tube efficiency of earth air heat exchanger system operated at 2.3, 3, 6, 11, 14 and

24 ms^{-1} are presented in Table 2. The variation of tube efficiency with velocity is plotted. It is clear from Fig. 6 and Table 2 that as velocities increases the tube efficiency decreases as reported by many researcher (Singh and Singh 1994; Ahmad *et al.* 2016). In this EAHE operation the minimum mean tube efficiency was 18.4% when it was operated at 24 ms^{-1}. Similarly, the maximum mean tube efficiency (64.9%) was observed at lowest velocity (2.3 ms^{-1}). The tube efficiency value ranged from 12.7 to 21.6% for 24 ms^{-1}, 23.8 to 25.1% for 14 ms^{-1}, 31.4 to 34.3% for 11 ms^{-1}, 43.5 to 49.1% for 6 ms^{-1}, 60.3 to 62.0% for 3 ms^{-1} and 63.9 to 66.9% for 2.3 ms^{-1}.

The designed single pipe of 0.25 m EAHE in serpentine manner was at tube efficiency of 65% and velocity of 6.08 ms^{-1}. The observed tube efficiency was average 47.1% at 6 ms^{-1} (Table 2).

CONCLUSION

The thermo-hydraulic designed earth air heat exchanger performed well as observed tube efficiency was near to designed efficiency. It was also observed that as velocity increases the tube efficiency decreases. The method proposed by Paepe and Janssens (2003) is simple, fast and reliable for installation of EAHE system in field too.

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