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 geothermal 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
deepth 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 description
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
design of 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 carried out 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:

\[
Q = UA (T_{greenhouse} - T_{desirable}) \quad \ldots(1)
\]

Where,

- \( A \) = Total exposed area of green house = 205 m²
- \( T_{greenhouse} \) = Greenhouse temperature = 44 °C
- \( T_{desirable} \) = Desirable temperature inside green house
  = 32 °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:

\[
U = \frac{1}{(1/h_o + x/k + 1/h_i)} \quad \ldots(2)
\]

Where,
- \(h_o\) = Ambient air convective heat transfer co-efficient = 35.5 W m\(^{-2}\)K\(^{-1}\)
- \(h_i\) = Inside greenhouse 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, \(Q = 16.1 \times 201 \times (42-32) = 39608.16\) W.

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

Where, \(T_{soil}\) = Temperature of soil at 3.5 m depth = 25.4 \(^\circ\)C

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

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

**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 Janssens (2003). The layout of EAHE pipe can be done either in parallel or serpentine manner (Fig. 2).

**Length of Pipe of 0.1 m diameter in parallel manner**

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

Tube efficiency = effectiveness \((e) = \frac{\Delta T}{T_i - T_s} = 0.65 \quad \ldots(4)\)

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

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

Specific pressure drop \((J) = P_{max}/NTU = 100/1.03 = 96.5\) pa
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 = $m_t = 260 \text{ m}^3\text{h}^{-1}$

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:

$$v = \frac{M_t}{a}$$ \hspace{1cm} ...(5)\]

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

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

$$M_t = \frac{m \rho}{3600}$$ \hspace{1cm} ...(6)\]

$\rho$ is density of air = 1.074 kgm$^{-3}$

So, $v = 9.88 \text{ ms}^{-1}$

**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 = \( \frac{m}{m_r} = \frac{7088.3}{590} = 12 \)

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:
\[
v = 9.97 \text{ ms}^{-1}
\]
Where, cross sectional area of pipe of 0.15 m diameter \( (a) = 0.0176 \text{ m}^2 \)
\[M_r = 0.176 \text{ kg s}^{-1} \text{ (Eq. 6)}
\]

\[\text{Number of parallel pipe required} = \frac{m}{m_r} = \frac{7088.3}{1000} = 7\]

The length of pipe = 35 m.

The cross sectional area \( (a) \) of pipe of 0.2 m diameter = 0.0314 m²
\[M_r = 0.24 \text{ kg s}^{-1}\]
The air velocity \( (v) = 9.5 \text{ ms}^{-1}\)

### 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 m³/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 \( (a) = 0.049 \text{ m}^2 \)
\[M_r = 0.298 \text{ kg s}^{-1} \text{ (Eq. 6)}
\]

Now the air velocity \( (v) \) (Eq. 5) which is to be circulated through the single pipe was computed as:
\[
v = 6.08 \text{ ms}^{-1}
\]

### 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

![Fig. 4: Schematic diagram of earth air heat exchanger](image)

![Fig. 5: Belt driven industrial blower with motor](image)

![Fig. 6: Variation of tube efficiency with velocity under closed system](image)
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 Janssens (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).

### 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$^{-1}$ 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 DI2 data logger were used for measuring EAHE inlet & outlet temperature.
24 m/s 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 m/s. Similarly, the maximum mean tube efficiency (64.9%) was observed at lowest velocity (2.3 m/s). The tube efficiency value ranged from 12.7 to 21.6% for 24 m/s, 23.8 to 25.1% for 14 m/s, 31.4 to 34.3% for 11 m/s, 43.5 to 49.1% for 6 m/s, 60.3 to 62.0% for 3 m/s and 63.9 to 66.9% for 2.3 m/s.

The designed single pipe of 0.25 m EAHE in serpentine manner was at tube efficiency of 65% and velocity of 6.08 m/s. The observed tube efficiency was average 47.1% at 6 m/s (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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