CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 3

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Heiselberg, P. K. (Ed.) (2016). *CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 3*. Department of Civil Engineering, Aalborg University.

Case study of earth tube system performance with design variable variation of residential house in Korea

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Abstract

In this study, a case review was conducted through simulations for reduction in heating energy consumption when the earth tube system was installed in Changwon, South Korea. Six design variables of earth tube systems in residential house were chosen such as underground depth, underground length, tube thickness, tube thermal conductivity, soil conditions, and fan types. And the effects of changes in the values of the six variables on earth tube zone inlet temperatures and heating energy consumption were examined through Energyplus simulations.

Keywords – Earth tube; Energyplus; Building energy

1. Introduction

Earth tube system is an underground duct(or pipe) through which outside air is drawn into the building. Earth tube system is considered as a passive heating and cooling technique that uses the relatively constant temperature of the earth to preheat in the winter and to precool in the summer by passing the air through earth tube buried underground before bringing it inside the building. Therefore, earth tube system is considered as an alternative of low cost solutions to reduce the cost of heating and cooling energy in buildings.

Earth tube systems can be designed many ways with several variables of earth tube system. However, performance data of earth tube system is still lacking and they are empirically installed with rules of thumb in Korea until now.

In this study, a case review was conducted through simulations for reduction in heating energy consumption when the earth tube system was installed in Changwon, South Korea. Six design variables of earth tube systems in residential house were chosen such as underground depth, underground length, tube thickness, tube thermal conductivity, soil conditions, and fan types. And the effects of changes in the values of the six variables on earth tube zone inlet temperatures and heating energy consumption were examined through Energyplus simulations.

2. Equations of earth tube system[1]

The earth tube in Energyplus adopted a simple earth tube model that uses a complex ground heat transfer model to find out the soil temperature at the concerned depth of the earth tube.

Under the assumption of a homogeneous soil of constant thermal diffusivity, the soil temperature at any depth z and time t can be estimated by the following Equation (1).

$$T_{z,t} = T_m - A_s exp\left[-z\left(\frac{\pi}{365\alpha_s}\right)^{1/2}\right]\cos\left\{\frac{2\pi}{365}\left[t - t_0 - \frac{z}{2}\left(\frac{365}{\pi\alpha_s}\right)^{1/2}\right]\right\} \quad (1)$$

Where,
t : time elapsed from beginning of calendar year
t_0 : phase constant of the soil surface (days)
α_s : soil thermal diffusivity (㎡/days)

Regarding the heat transfer between soil and earth tube system, thermal conductivity of air, k_{air} and kinetic viscosity of air, υ are calculated with equation (2) and (3).

$$k_{air} = 0.02442 + (10^{-4}(0.6992T_a)) \quad (2)$$

$$\upsilon = (10^{-4}(0.1335 + 0.000925T_a) \quad (3)$$

With k_{air} and υ, the convective heat transfer coefficient at the inner pipe surface, h_c can be calculated. It is a function of Reynolds number, Re and Nusselt number, Nu.

Where,

$$h_c = \frac{Nuk_{air}}{2r_1} \quad (4)$$

$$\mathrm{Nu} = \frac{(f_a/2)(Re-1000)Pr}{1+12.7(f_a/2)^{1/2}(Pr^{2/3}-1)} \quad (5)$$

$$f_a = (1.58InRe - 3.28)^{-2} \quad (6)$$

$$\mathrm{Re} = \frac{2r_1 V_a}{v} \quad (7)$$

$$\mathrm{Pr} = \frac{v}{\alpha_{air}} \quad (8)$$

Where,
r_1 : inner pipe radius (m)
V_a : average pipe air velocity (m/s)

The heat transfer between the soil and the air inside the pipe is calculated with equation (9) and (10).

$$U_t\left[T_a(y) - T_{z,t}\right]dy = -m_a C_a[dT_a(y)] \quad (9)$$

$$U_t = \frac{1}{R_t},\ R_t = R_c + R_p + R_s \quad (10)$$

Where,
U_t : heat transfer coefficient of the whole earth tube system (W/㎡℃)
T_a *(y)*: air temp of the pipe at the distance y from the pipe inlet (°C)
m_a : mass flow rate of ambient air through pipe (kg/s)
C_a: specific heat of air (J/kg℃)
R_t : total thermal resistance between pipe air and soil (㎡℃/W)

3. Comparison of experiment and energyplus simulation results

An experimental earth tube system was installed underground in the campus of a university located in Changwon (latitude 35.2° , longitude 128.7°) located in the southern region of South Korea as shown in Table 1 and Fig. 1 to compare the results with the results of prediction of earth tube zone inlet temperatures by Energyplus simulations to verify the differences.

The comparison period was from October 14, 2015 to November 14, 2015 (32 days) and Fig. 2 shows the average monthly outdoor air temperature, outdoor air humidity, and solar radiation data for Changwon, South Korea where the earth tube system was installed. And the results of comparison are as shown in Fig. 3.

The range of actually measured earth tube zone inlet temperatures was 16.8℃~20.6℃ with an average value of 18.6℃ and the range of earth tube zone inlet temperatures obtained through Energyplus simulations in the same period was 18.1℃~19.7℃ with an average value of 18.8℃ indicating that the earth tube zone inlet temperatures obtained by actual measurement and those obtained through simulations were almost the same.

Table 1. Specification of earth tube system installed

Items	Earth tube	Items	Fan
Material	PVC	Blower type	Intake
Diameter	0.1m	Frequency / RPM	60Hz, 2,590
Thermal heat conductivity	200W/m·K	Air volume	8.2CMH
Length	60m	Air pressure	36mmAq
Underground depth	3m	Efficiency	0.9

(a) Earth tube inlet (b) Earth tube zone inlet

Fig. 1 Installed earth tube system

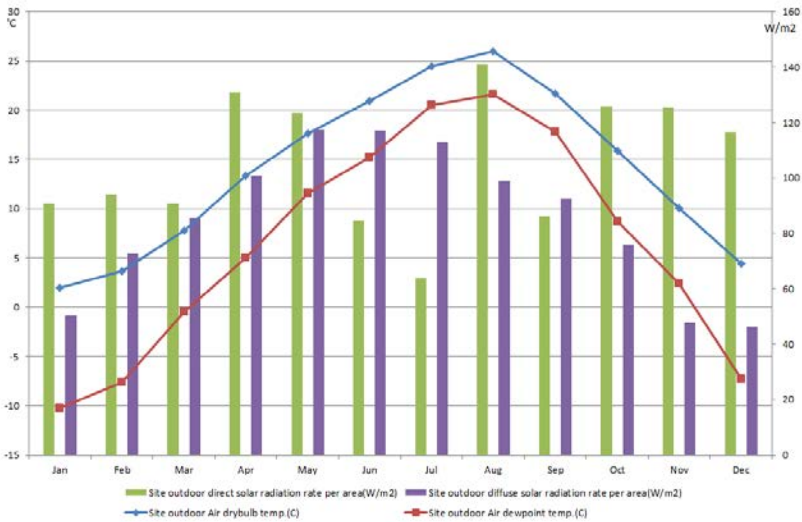


Fig. 2 Monthly site outdoor data(air temperature and solar radiation) of Changwon, Korea

Fig. 3 Comparison with experiment and simulation results of earth tube zone inlet temperature

4. Review thermal performance with design variable variation of earth tube system

Six design variable conditions were chosen as shown in Table 2; underground depth, underground length, tube thickness, tube thermal conductivity, soil conditions, and fan types and the effects of changes in the values of the six variables under the reference conditions on average earth tube zone inlet air temperatures (℃) and outdoor air heat transfer rates were examined using the Energyplus program.

In this case, air volume and wind velocity conditions of the earth tube were maintained at 0.03317697 ㎥/sec and 0.169m/s respectively.

When the earth tube was installed under the reference conditions during the heating period(Dec 1 Mar 31), the average zone inlet air temperature and the average outdoor air heat transfer rate under were shown to be 8.2℃ and 158.8W respectively.

Changes in earth tube zone inlet temperatures resulting from changes in underground depth (1～3m), underground length(10～30m), tube thickness (0.01～0.03m), tube thermal conductivity(100～300W/m℃), soil conditions, and fan types among the earth tube design variables were shown to be in ranges of 7.1～9.9℃, 6.7～9.2℃, 8.1～8.2℃, 8.2～8.2℃, 8.0～8.2℃, and 7.8～8.2℃ respectively.

Therefore, on reviewing the average earth tube zone inlet air temperatures during the heating period, among six variables, earth tube length and length were shown to be the largest effects followed by the effects of soil conditions and the effects of fan types in order of precedence. On the other hand, variables such as tube thickness and tube thermal conductivity had almost no effect.

Table 2. Simulation results of earth tube design variable values on average earth tube zone inlet temp and outdoor air heat transfer rate

Earth tube variables	Values	Heating Period (Average outdoor temperature 4.5℃)	
		Earth tube Zone Inlet Air Temperature (℃)	Earth Tube Outdoor Air Heat Transfer Rate (W)
Tube depth (m)	1	7.1	115.2
	1.5*	8.2	158.8
	3	9.9	232.8
Tube length (m)	10	6.7	97.6
	20*	8.2	158.8
	30	9.2	205.0
Tube thickness (m)	0.01	8.1	158.2
	0.02*	8.2	158.8
	0.03	8.2	159.3
Tube thermal conductivity (W/m·℃)	100	8.2	158.7
	200*	8.2	158.8
	300	8.2	158.8
Soil condition	Heavy&Damp	8.0	154.1
	Heavy&Dry*	8.2	158.8
	Light&Dry	8.1	157.3
Fan type**	Exhaust	7.8	142.2
	Intake*	8.2	158.8

* reference condition of earth tube system

** Fan intake type : the additional heat due to the fan is included or not in the inlet air temp.

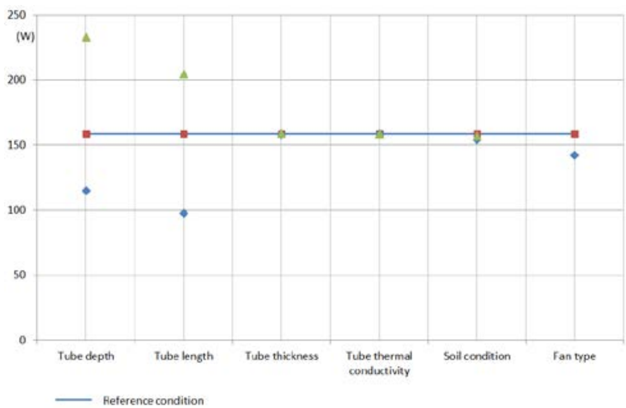


Fig. 4 Average earth tube outdoor air heat transfer rate by variable change compared to reference condition

As set forth above, the most important elements were shown to be the depth and length of earth tube systems.

Therefore, average earth tube zone inlet air temperatures and earth tube outdoor air heat transfer rates were reviewed when the depth and length of earth tube systems were changed in more subdivided steps, that is, the depth in a range of 1～5m(1m intervals) and the length in a range of 10～60m(10m intervals).

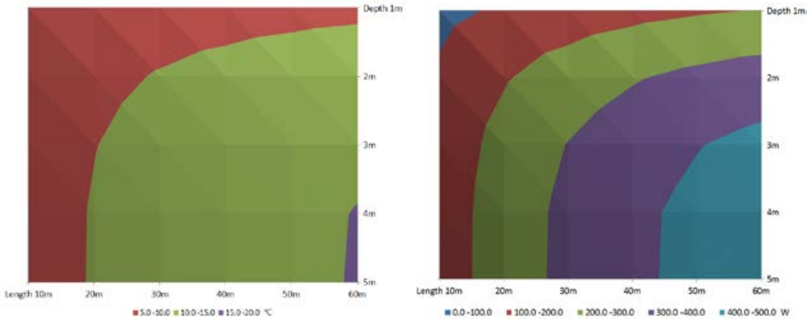
According to the results, as shown in Table 3, Fig. 5, the ranges of average earth tube zone inlet air temperatures and average earth tube outdoor air heat transfer rates during the heating period(December 1～March 31) were shown to be 6.2～15.2℃(average 15.2℃) and 72.7～458.1W(average 275.0W) respectively.

During heating, as the length of the earth tube system installed increased, the average earth tube zone inlet air temperature and outdoor air heat transfer rate increased. Also, the depth of the earth tube system installed increased, the average earth tube zone inlet air temperature and outdoor air heat transfer rate increased, indicating that the earth tube system should be placed as deeply as possible. However, the underground trenching cost and other economic factors should be considered when installing earth tube system.

The depth and length conditions of earth tube systems necessary to maintain 15.0℃ or higher average temperatures during the heating periods were shown to be at least 4m and 60m respectively and those necessary to maintain average temperatures between 10℃ and 15℃ were shown to be depths 2m and 3m with lengths not shorter than 30m and depths 4m and 5m with lengths not shorter than 20m.

Table 3. Influence of earth tube depth and length on average earth tube zone inlet air temperature and outdoor air heat transfer rate (average outside air temp 4.5℃)

	Earth Tube Zone Inlet Air Temperature (℃) / Outdoor Air Heat Transfer Rate (W)					
length / depth	10m	20m	30m	40m	50m	60m
1m	6.2 / 72.7	7.1 / 115.2	7.9 / 147.3	8.4 / 171.5	8.9 / 189.9	9.2 / 203.8
2m	7.2 / 116.6	8.9 / 192.1	10.3 / 249.2	11.3 / 292.3	12.0 / 324.9	12.6 / 349.5
3m	7.7 / 139.8	9.9 / 232.8	11.5 / 303.1	12.8 / 356.2	13.7 / 396.3	14.4 / 426.6
4m	7.9 / 148.6	10.3 / 248.3	12.0 / 323.6	13.3 / 380.5	14.3 / 423.4	15.1 / 455.9
5m	8.0 / 149.3	10.3 / 249.5	12.1 / 325.2	13.4 / 382.3	14.4 / 425.5	15.2 / 458.1



(a) Earth tube zone inlet air temp (b) Earth tube outdoor air heat transfer rate

Fig. 5 Influence of earth tube depth and length on average earth tube zone inlet air temperature and outdoor air heat transfer rate during heat season (average outside air temp 4.5℃)

Next, two story residential house located in the southern region of South Korea(north latitude 35.2°, longitude 128.6°) was selected to examine changes in ventilation loads between when the earth tube system was applied and when the earth tube system was not applied on the building energy consumption. The architectural scheme of the subject house for implementation of simulations is as shown in Table 4.

For comparison, the existing system installed in one of the subject house was set to have a ventilation rate of 1.0 ACH. In the case of the house where the earth tube system was installed, a 6m long earth tube was installed 3m underground so that air for ventilation would flow into the building through the earth tube.

(a) Perspective (b) Heating system diagram

Fig. 6 House perspective and heating system diagram

When the average earth tube zone inlet air temperature was maintained at 13.7℃ during the heating period that showed an average outdoor air temperature of 4.5℃, the heating energy consumption of the house with the existing system was shown to be 23.8MJ and that of the house installed with the earth tube system was shown to be 11.4MJ indicating a reduction of heating energy consumption by 52.1%.

Table 4. Summary of Model residence building

<table>
<tr><th colspan="2">Category</th><th>Value</th><th colspan="2">Category</th><th>Value</th></tr>
<tr><td rowspan="8">Building & Plant System</td><td>Gross floor area</td><td>132.29 ㎡ (GF : 88.66 ㎡, 2F : 43.63 ㎡)</td><td rowspan="8">Earth tube system</td><td>Tube length</td><td>50m</td></tr>
<tr><td>Structure</td><td>Reinforced Concrete</td><td>Tube depth</td><td>3m</td></tr>
<tr><td>Wall Materials</td><td>DRY VIT (U value 0.340W/㎡·℃)</td><td>Tube thickness</td><td>0.02m</td></tr>
<tr><td>Roof Materials</td><td>Reinforced Concrete + Roof tile (U value 0.220W/㎡·℃)</td><td>Tube thermal conductivity</td><td>200W/m·K</td></tr>
<tr><td>Floor materials</td><td>Floor heating (U value 0.347W/㎡·℃)</td><td>Soil condition</td><td>Heavy & Dry</td></tr>
<tr><td>Window Materials</td><td>Low-E Clear 3mm+Argon 6mm+Clear 3mm (U value 2.012W/㎡·℃)</td><td>Fan type</td><td>Intake</td></tr>
<tr><td>Heat and cooling system</td><td>Heating : gas boiler
Cooling : PTAC(Package terminal air conditioner, cooling DX Cooling Coil, air cooled)</td><td>Fan efficiency</td><td>0.7</td></tr>
<tr><td>Heating and cooling period</td><td>Heating season : Dec 1～Mar 31</td><td>Inlet air flow rate</td><td>ventilation rate 1.0 air change/hr</td></tr>
</table>

5. Conclusion

In this study, a case review was conducted through simulations for reduction in heating energy consumption when the earth tube system was installed in Changwon, South Korea and major results of the study are as follows.

1. Using the Energyplus program, the effects of changes in the design conditions of earth tube system on heating energy consumption were examined. Six design variables comprising underground depth, underground length, tube thickness, tube thermal conductivity, soil conditions, and fan types were chosen as shown in Table 2 and the effects of change in the six variable values under the reference condition on average earth tube zone inlet air temperatures (℃) and outdoor air heat transfer rates(W) were examined.

2. Among six variables earth tube length and length of earth tube system were shown to be the largest effects followed by the effects of soil conditions and the effects of fan types in order of precedence. On the other hand, variables such as tube thickness and tube thermal conductivity had almost no effect.

3. When the earth tube system was applied to a selected residential house with a 6m long and 3m deep underground, heating energy consumption decreased from 23.8MJ in the case of existing to 11.4MJ with a rate of decrease of 52.1% indicating that the earth tube system is sufficiently applicable to the southern region of South Korea.

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