IMPLEMENTATION OF AN EARTH TUBE SYSTEM INTO ENERGYPLUS PROGRAM

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ABSTRACT

A new module was developed for and implemented in the EnergyPlus program for the simulation of earth tubes. This paper describes the basic concepts, assumptions, and algorithms implemented into the EnergyPlus program to predict the performance of an earth tube. Using the new module, a parametric analysis was carried out to investigate the effect of pipe radius, pipe length, air flow rate and pipe depth on the overall performance of the earth tube under various conditions. Pipe length, air flow rate and pipe depth are predicted to have more influence on the performance than pipe radius. In addition, 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 inlet temperature.

INTRODUCTION

The utilization of geothermal energy to reduce heating and cooling needs in buildings has received increasing attention during the last years. An earth tube is a long, underground metal or plastic pipe through which air is drawn. As air travels through the pipe, it gives up or receives some of its heat to/from the surrounding soil and enters the room as conditioned air during the cooling and heating period.

Due to the significance of earth tube system, numerous research studies have been performed by Krarti at al. (1995), Puri (1986), Labs at al. (1989), and Schiller (1982). Recently, a sophisticated model describing the complex mechanisms of simultaneous heat and mass transfer occuring around the earth tube has been developed and integrated into TRNSYS by Mihalakakou et al. (1994).

Nevertheless, those research studies have focused either on heat transfer to/from the surrounding soil or on the prediction of soil temperature separately. To date, a detailed algorithm calculating the soil temperature variation around the earth tube directly from weather data files has not been encoded within the existing simulation tools. Since an accurate ground temperature prediction is also an essential factor for the simulation of an earth tube, both the heat transfer occuring around the earth tube and the soil temperature should be modeled together in an earth tube model.

Before calculating the soil temperature, the ground surface temperature above earth tube should be predicted by taking into account several mechanisms occuring on the ground surface. Based on the calculated ground surface temperature, the temperature of the soil surrounding the earth tube and heat transfer rate can be predicted.

The objective of this paper is to discuss the development and implementation of a new module handling both heat transfer and soil temperature algorithms into the EnergyPlus program for the simulation of earth tubes. Also, using the new model, the effects of four parameters, pipe radius and length, air flow rate and pipe depth under the ground surface on the overall performance of the earth tube were quantitatively assessed. Preliminary testing and parametric analysis results will also be discussed in this paper.

EARTH TUBE MODEL DESCRIPTION

The simulation program in which the earth tube module was implemented is EnergyPlus. The integrated solution manager in EnergyPlus consists of three managers: the surface heat balance manager, the air heat balance manager and the building systems simulation manager. Among them, an earh tube module is implemented at the air heat balance manager level.

Due to the complex mechanisms occuring around the earth tube, several simplyfying assumptions were made and are described below:

- Convection flow inside the pipe is hydrodynamically and thermally developed.
- Soil temperature in the pipe vicinity can be calculated using the soil model discussed below

beyond a particular distance from the center of the pipe (thickness of the annulus).

- The temperature profile in the pipe vicinity is not affected by the presence of the pipe. As a result, the pipe surface temperature is uniform in the axial direction.
- The soil surrounding the pipe is homogeneous and has a constant thermal conductivity.
- Pipe has an uniform cross sectional area in the axial direction.

Soil temperature calculation

Prior to the calculation of soil temperature around earth tube, the ground surface temperature straight above earth tube should be predicted. According to Kusuda and Achenbach (1965), the ground surface temperature satisfies the following expression.

$$T_{sur} = T(0,t) = T_m + A_s \operatorname{Re}(e^{iwt}) \tag{1}$$

where $T(x,t)$ is the soil temperature profile as a function of depth x and time t. T_m and A_s are annual mean value and amplitude of the ground surface temperature variation respectively, which should be calculated by considering the convective heat transfer between the air and ground, the solar radiation absorption by the ground, the long-wave radiation emitted from the soil, and the latent heat loss due to the moisture evaporation at the ground surface.

Regarding convective heat transfer, it can be calculated from the following expression.

$$E_{conv} = h_s (T_a - T_{sur}) \tag{2}$$

According to McAdams(1954) the convective heat transfer coefficient at the soil surface (W/m^2°C), h_s, can be approximated by the following correlation:

$$h_s = 5.7 + 3.8u \tag{3}$$

Wind velocity (m/s), u, is the annual average value.
The air temperature variation is approximated by the following equation

$$T_a(t) = T_{ma} + T_{va} \operatorname{Re}[e^{(iwt+\phi_s)}] \tag{4}$$

The annual angular frequency, w, is equal to 1.992 x 10^{-7}rad/s. The amplitude of the air temperature (°C), T_{va}, can be evaluated by dividing the difference between the maximum and minimum air temperature value of the whole year by two. The phase angle between the insolation and the air temperature (rad), φ_I, is calculated by subtracting the insolation phase angle from air temperature phase angle. The phase angle of insolation and air temperature is the point from the beginning of the year at which the insolation and air temperature, respectively, each reaches its minimum value among in the year.

Regarding solar radiation absorption by the ground, it can be estimated from the following equation (Krarti et al. 1995):

$$E_{solrad} = \beta S \tag{5}$$

The absorption coefficient, β, depends on the soil absorptance and shading condition. The coefficient β is approximately equal to one minus the soil surface albedo. Albedo depends on soil cover and moisture content (Krarti et al. 1995).
In a similar way to air temperature, horizontal solar radiation is approximated by the following equation

$$S(t) = S_m + S_v \operatorname{Re}[e^{(iwt+\phi_s+\phi_I)}] \tag{6}$$

The amplitude of the solar radiation (W/m^2), S_v, can also be determined from weather data by dividing the difference between the maximum and minimum solar radiation value of the entire year by two.

Regarding the long-wave radiation emitted from the ground surface, it can be approximated by the expression (Krarti et al. 1995):

$$E_{longrad} = \varepsilon \Delta R \tag{7}$$

The appropriate value of hemispherical emittance of the ground surface, ε, is 0.93~0.96. The radiation constant (W/m^2), ΔR, depends on soil radiative properties, air relative humidity, and effective sky temperature. An appropriate value of ΔR is 63 W/m^2 (Krarti et al. 1995).

Finally, regarding the latent heat loss due to the evaporation, it can be evaluated by the following expression:

$$E_{latent} = 0.0168 f h_s [(aT_{sur} + b) - r_a (aT_a + b)] \tag{8}$$

where a = 103 Pa/°C, b = 609 Pa
Fraction of evaporation rate, f, depends on the soil cover and the soil moisture level and h_s can be approximated by Eq. (3).

By considering all the four mechanisms described above, the heat transfer rate on the ground surface can be estimated by the following equation:

$$-k_s \left.\frac{\partial T}{\partial x}\right|_{x=0} = E_{conv} - E_{longrad} + E_{solrad} - E_{latent} \qquad (9)$$

where, k_s is thermal conductivity of soil (W/m°C).
Now, T_{sur} in Eq. (2) and Eq. (8) can be replace by the value for this parameter as shown in Eq. (1), and T_a in Eq. (2) and Eq. (8) can also be replaced by Eq. (4). Similarly, S in Eq. (5) can be replaced by Eq. (6). T_m is a constant (annual mean value) and is not a function of depth x and time t. Therefore, by using Eq. (2), (5), (7) and (8) in Eq. (9) and by only considering the terms that are not a function of t in Eq. (9), the following equation can be obtained:

$$\begin{aligned} &h_s(T_{ma} - T_m) - \varepsilon\Delta R + \beta S_m \\ &- 0.0168 f h_s (aT_m + b - ar_a T_{ma} - r_a b) = 0 \end{aligned} \qquad (10)$$

After the rearrangement to solve for T_m, the annual mean ground surface temperature, T_m, can be estimated as follows:

$$T_m = \frac{1}{h_e}\left[h_r T_{ma} - \varepsilon\Delta R + \beta S_m - 0.0168 h_s f b\left(1 - r_a\right)\right] \qquad (11)$$

where

$$h_e = h_s\left(1 + 0.0168af\right)$$
$$h_r = h_s\left(1 + 0.0168ar_a f\right)$$

The amplitude of the soil surface temperature variation (°C), A_s, the phase constant of the soil surface (sec), t_0, and phase angle difference between the air and soil surface temperature (rad), φ_S, can be determined as follows (Krarti et al. 1995):

$$A_s = \left\| \frac{h_r T_{va} - \beta S_v e^{i\phi_I}}{\left(h_e + \delta k_s\right)} \right\| \qquad (12)$$

$$t_0 = t_{0a} + \frac{\phi_s}{w} \qquad (13)$$

$$\phi_s = -Arg\left[\frac{h_r T_{va} - \beta S_v e^{i\phi_I}}{\left(h_e + \delta k_s\right)}\right] \qquad (14)$$

It should be noted that in Eq. (12) and (14) that the symbols || || and Arg are used to signify the modulus and the argument of a complex number, respectively.

The phase constant of the air (sec), t_{0a}, is the time elapsed from the beginning of the year at which the air temperature reaches the minimum value in the year, and dampening depth (m), D, is calculated from the following equation:

$$D = \sqrt{\frac{2\alpha_s}{w}} \qquad (15)$$

The value of δ is evaluated as follows.

$$\delta = \frac{1+i}{D} \qquad (16)$$

Assuming a homogeneous soil of constant thermal diffusivity, the temperature at any depth z and time t can be finally estimated by the following expression (Labs et al. 1989).

$$T_{z,t} = T_m - A_s \exp\left[-z\left(\frac{\pi}{365\alpha_s}\right)^{1/2}\right]\cos\left\{\frac{2\pi}{365}\left[t - t_0 - \frac{z}{2}\left(\frac{365}{\pi\alpha_s}\right)^{1/2}\right]\right\} \qquad (17)$$

Heat transfer and earth tube inlet air temperature calculation

In order to calculate the heat transfer between the earth tube and the surrounding soil, the overall heat transfer coefficient should be determined using the following three thermal resistance values:

$$R_c = \frac{1}{2\pi r_1 h_c} \qquad (18)$$

$$R_p = \frac{1}{2\pi k_p}\ln\frac{r_1 + r_2}{r_1} \qquad (19)$$

$$R_s = \frac{1}{2\pi k_s}\ln\frac{r_1 + r_2 + r_3}{r_1 + r_2} \qquad (20)$$

where R_c is thermal resistance due to convection heat transfer between the air in the pipe and the pipe inner surface (m°C/W), R_p is thermal resistance due to conduction heat transfer between the pipe inner and outer surface (m°C/W), and R_s is thermal resistance due to conduction heat transfer between the pipe outer surface and the undisturbed soil (m°C/W). The thickness of the annulus, r^3, is taken as being equal to the radius of the pipe.
The convective heat transfer coefficient at the inner pipe surface (W/m^2°C), h_c, is a function of Reynolds

number, Re, and Nusselt number, Nu and can be evaluated by the following expressions:

$$h_c = \frac{Nuk_{air}}{2r_1} \tag{21}$$

$$Nu = \frac{(f_a/2)(\mathrm{Re}-1000)\,\mathrm{Pr}}{1+12.7(f_a/2)^{1/2}(\mathrm{Pr}^{2/3}-1)} \tag{22}$$

$$f_a = (1.58\ln \mathrm{Re} - 3.28)^{-2} \tag{23}$$

Using the three thermal resistance values, R_c, R_p and R_s, overall heat transfer coefficient of earth tube can be estimated as follows.

$$U_t = \frac{1}{R_t} \tag{24}$$

$$R_t = R_c + R_p + R_s \tag{25}$$

Now, the heat transfer between the soil and the air inside the pipe is equal to the amount of heat losses as air flows along the pipe (Mihalakakou et al. 1989).

$$U_t dy\left[T_a(y) - T_{z,t}\right] = -\dot{m}_a C_a \left[dT_a(y)\right] \tag{26}$$

The earth tube outlet air temperature is finally evaluated by solving the heat transfer equation above. The inlet air temperature of air entering the earth tube (where y = 0) is equal to the ambient air temperature since outdoor air initially enters the earth tube.

By integrating the both sides of Eq. (26), the following expression can be obtained:

$$U_t y = -\dot{m}_a C_a \ln\left|T_a(y) - T_{z,t}\right| + C \tag{27}$$

From the boundary condition:

$$T_a(0) = T_{am} \tag{28}$$

The constant C can be determined from Eq. (27) at the soil surface where y = 0:

$$C = \dot{m}_a C_a \ln\left|T_{am} - T_{z,t}\right| \tag{29}$$

By solving for air temperature inside the pipe, $T_a(y)$, the following outlet air temperature can be finally obtained.

In case $T_{am} > T_{z,t}$

$$T_a(L) = T_{z,t} + e^A \tag{30}$$

In case $T_{am} = T_{z,t}$

$$T_a(L) = T_{z,t} \tag{31}$$

In case $T_{am} < T_{z,t}$

$$T_a(L) = T_{z,t} - e^A \tag{32}$$

where

$$A = \frac{\dot{m}_a C_a \ln\left|T_{am} - T_{z,t}\right| - U_t L}{\dot{m}_a C_a} \tag{33}$$

Table 1 Description of simulation conditions

	CONDITIONS
Location	Spokane, WA - mild and dry Peoria, IL - mild and wet Phoenix, AZ - hot and dry Key West, FL - hot and wet
Run period	Summer Design Day
Variables	Pipe radius : 0.05m, 0.075m, 0.1m 0.15m, 0.2m Pipe length : 10m, 30m, 50m, 70m, 90m Air velocity : 2m/s, 5m/s, 8m/s, 11m/s, 14m/s Pipe depth : 1m, 2.5m, 4m, 5.5m, 7m

PARAMETRIC ANALYSIS

Using the newly developed earth tube model, user can predict the performance of an earth tube under various circumstances by changing each possible inut parameter such as the schedule of earth tube operation, volumetric air flow rate, radius, thickness, length, depth and thermal conductivity of the pipe.

Parametric studies were carried out to determine the effect of four important variables influencing the earth tube outlet air temperature: pipe radius, pipe length, air flow rate and pipe depth under the ground surface. Simulations were performed on five different values of each parameter while the other parameters were maintinaed at the same values. In addition, four different locations were selected which represent four typical climatic conditions in order to investigate the influence of soil temperature and soil condition as well.

Table 2 Soil related parameters

	SOIL CONDITION	**T_M (AVERAGE)**	**A_S (AMPLITUDE)**
Key West	Heavy and moist	24.3 °C	5.0 °C
Peoria	Heavy and moist	10.0 °C	18.8 °C
Phoenix	Heavy and dry	25.0 °C	9.4 °C
Spokane	Heavy and dry	9.9 °C	18.5 °C

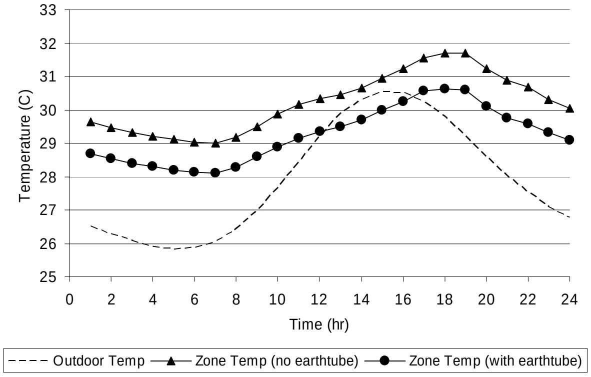

Figure 1 Indoor temperature decrease (Key West)

Aug. 21st is chosen as summer design day for Key West and Spokane, and Jul. 21st is chosen for Peoria and Phoenix. The maximum dry bulb temperature were set at 30.6°C, 30.4°C, 35.7°C and 28.3°C for Key West, Peoria, Phoenix and Spokane, respectively. Table 1 shows the details of parametric studies.

The standard values of each variable were set at: 0.075m for pipe radius, 30m for pipe length, 5m/s for air velocity, and 2.5m for pipe depth. In other words, when changing only one variable at every simulation process for parametric studies, the other variables were kept at those values. Table 2 describes the inputted soil conditions and parameters for each location. The annual average ground surface temperature, T_m, and amplitude of the soil surface temperature variation, A_s, are calculated by a utility program that is provided with EnergyPlus.

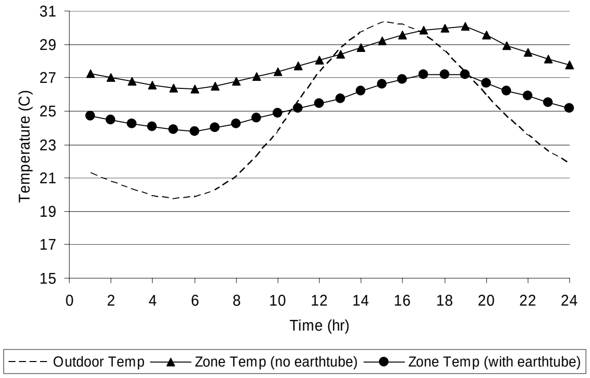

Figure2 Indoor temperature decrease (Peoria)

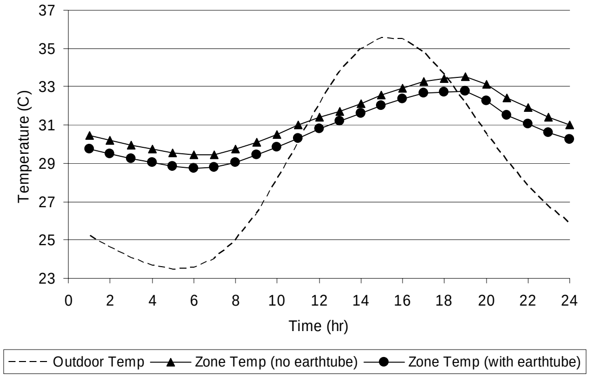

Figure 3 Indoor temperature decrease (Phoenix)

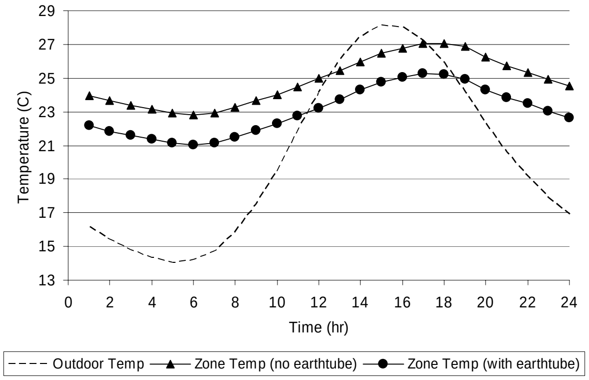

Figure 4 Indoor temperature decrease (Spokane)

A three-zone residential building was chosen for this parametric study. The building consists of a living space, an attached garage and attic above living space and garage having floor areas of approximately 140m^2, 37 m^2, and 176 m^2, respectively. In this study, the living space will be analyzed, which is located on the northern side of the building with the ceiling height of 3.05 m. The internal heat gains for lights and. equipment were set at 5.4W/m^2 and two people were placed in the living space during the simulation Infiltration was set at 0.25 ACH and the earth tube was set to run constantly at the same volumetric flow rate of 285 m^3/h during the whole running period.

DISCUSSION AND RESULT ANALYSIS

Indoor temperature decrease due to earth tube

Fig. 1 through fig. 4 illustrate the indoor temperature

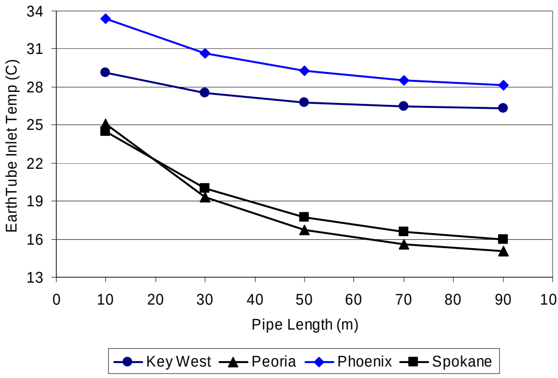

Figure5. Influence of pipe length on inlet temperature.

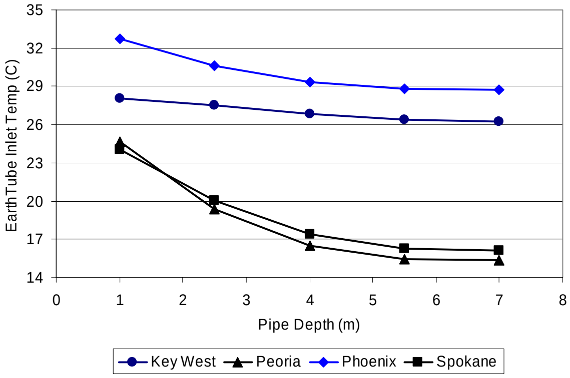

Figure 6. Influence of pipe depth on inlet temperature.

decrease due to the cooling potential of the earth tube in four different locations. The higher zone temperature is the case when the earth tube is shut down, while the lower zone temperature is the case when the earth tube was operated under the same conditions during the whole day. In these cases, the input variables were set at the standard values with 0.075m for pipe radius, 30m for pipe length, 5m/s for air velocity, and 2.5m for pipe depth.

As can be seen in the figures above, the earth tube has the cooling potential to reduce the indoor temperature and therefore reduces the cooling needs in buildings. However, the extents of temperature decrease due to earth tube were different in four locations because of different soil conditions. The temperature decreases were 2.6 °C and 1.8 °C in Peoria and Spokane respectively, while temperature decreases were 1.0 °C and 0.7 °C in case of Key West and Phoenix respectively. This indicates that the hot weather of the latter two locations also had increased soil temperature and, as a result, the cooling potential of earth tube was reduced. Key West and Phoenix have annual average soil surface temperature 10 °C higher than those of Peoria and Spokane (Table 2). Therefore, the earth tube system should be placed more deeply in those hot weather conditions to obtain cooling potential that is similar to the less extreme climates.

Although earth tube can reduce the cooling needs in buildings to a certain degree, it should be noted that it did not appear to be able to replace the conventional air-conditioning system completely, since the indoor temperature does not maintain thermally comfortable air temperatures by only employing the earth tube under hot weather conditions.

Influence of pipe length

Fig. 5 presents the effect of pipe length on the earth tube inlet air temperature at the highest ambient air temperature. As the pipe length increases, the inlet air temperature decreases, regardless of the location. This is due to the fact that the longer pipe provides a longer path over which heat transfer between the pipe and the surrounding soil can take place given the same overall heat transfer coefficient of earth tube. Therefore, a longer pipe should be used if the trenching cost is not prohibitive.

However, the temperature range and range of decrease in terms of pipe length were different among each location. As the pipe length increases from 10 m to 90 m, the inlet air temperature decreases by 2.9°C, 10.1°C, 5.2°C and 8.5°C in Key West, Peoria, Pheonix and Spokane, respectively. This is due to the different soil conditions, ambient air temperature and soil temperature in these locations, indicating that the weather conditions which affect the soil condition and temperature of particular locations should be considered when deciding on whether or not to implement an earth tube. It can be seen from Fig. 5 that at some length the improvements begin to level off.

Influence of pipe depth

Fig. 6 shows the influence of pipe depth under the ground surface on the earth tube inlet air temperature. As the pipe depth increases, the inlet air temperature decreases, regardless of the location, indicating that earth tube should be placed deeply as possible. However, the trenching cost and other factors should be considered when installing earth tubes.

Like the case of pipe length, the temperature range and decrease rate with pipe depth were different at each location due to different soil conditions. As the pipe depth was changed from 1 m to 7 m, the inlet air temperature decreased by 1.8°C, 9.3°C, 4.0°C and 7.9°C in Key West, Peoria, Pheonix and Spokane,

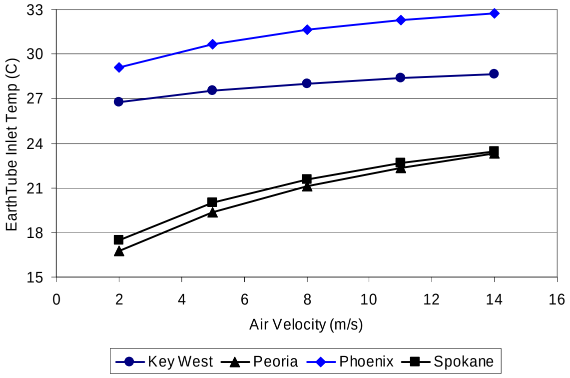

Figure 7. Influence of air velocity on inlet temperature.

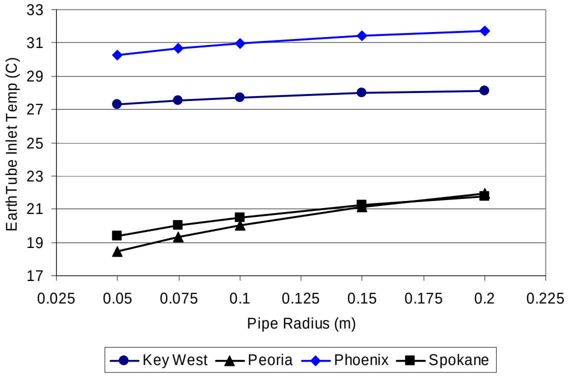

Figure 8. Influence of pipe radius on inlet temperature.

respectively. Based on these results, pipe depth appears to have as large of an influence on earth tube performance as pipe length.

Influence of air velocity inside pipe

Fig. 7 presents the effect of air velocity inside the pipe on the earth tube inlet air temperature. As the air flow rate increases the inlet air temperature increases in all locations, indicating that an earth tube with lower air velocity will perform better since the air spends more time in the tube and thus in contact with the lower soil temperature. This can be seen in the earth tube modeling equations since according to Eq. (30) and Eq. (33) a higher air flow rate causes a higher mass flow rate and higher air temperature.

Likewise, the range and rate of increase of the inlet air temperatures as a function of air velocity inside the pipe were different at each location. As the air velocity increases from 2 m/s to 14 m/s, the inlet air temperature increases by 1.9°C, 6.6°C, 3.6°C and 5.9°C in Key West, Peoria, Pheonix and Spokane, respectively. These different ranges of inlet air temperatures is due to different weather and soil conditions of each location. In comparison to the effect of other parameters described above, the air flow rate turned out to have as large effect on the performance of the earth tube as pipe length and pipe depth.

However, when considering the air flow rate during the design process, simply reducing the flow rate does not necessarily improve the earth tube performance since the cooling heat transfer rate due to earth tubes depends on both air flow rate and temperature difference, not on each factor alone ($q = m_a C_a \Delta T$). Thus both air flow rate and temperature decrease should be considered simultaneously.

Influence of pipe radius

Fig. 8 illustrates the effect of pipe radius on the earth tube inlet air temperature. As the pipe radius increases, the earth tube inlet air temperature also increases, regardless of the location. This is due to the fact that higher pipe radius results in a lower convective heat transfer coefficient on the pipe inner surface and a lower overall heat transfer coefficient of earth tube system. Therefore, a smaller pipe radius should be used for the better performance of the earth tube. It should be noted that only a single pipe is considered in this paper and thus pipes do not have the same cross sectional area.

Similarly, the temperature range and the increase in the inlet temperature as a function pipe radius were different among these locations. As the pipe radius increases from 0.05 m to 0.2m, the inlet air temperature increased by 0.9°C, 3.5°C, 1.5°C and 2.4°C in Key West, Peoria, Phoenix and Spokane, respectively. In terms of comparison with the other three effects described above, pipe radius did not affect the results as much as the other parameters.

However, simply reducing the pipe radius under same air flow rate will increase the air velocity inside the pipe, resulting in an increase in the earth tube inlet air temperature. Thus pipe radius and air flow rate should be considered together and optimized using simulated results.

The trends of the results in terms of the influence of design parameters on the performance discussed above were silimar to those of other studies (Mihalakakou et al. 1989). Due to the limited space, the specific comparison data will not be discussed in this paper.

CONCLUSION

In this paper, the algorithm for the simulation of earth tubes is described, and parametric studies were carried out to investigate the effect of each parameter on earth tube. The following conclusions were drawn.

Although the earth tube alone can not replace conventional air-conditioning system in these case studies, it can significantly reduce the cooling load in the building investigated. A deeply placed and longer earth tube with a lower air velocity and smaller radius should result in better performance. This agrees with common sense and is backed by the model data, yielding similar trends to other referenced studies. However, the trenching cost and other factors should also be considered when installing earth tubes. In addition, pipe length, air velocity inside pipe and pipe depth turned out to have more influence on earth tube performance than pipe radius. However, pipe radius and air flow rate as well as cooling heat transfer rate should be considered simultaneously. Furthermore, weather and soil conditions of particular locations should be specifically considered when using an earth tube since the earth tube will perform differently under different weather and soil conditions. Thus, the availability of an earth tube model in a program such as EnergyPlus is an important step forward when attempting to determine whether or not earth tubes should be used for a particular building and to determine the most optimal combination with regard to depth, length, radius, and air velocity. For example, as seen in Fig. 5 ~ 8, an earth tube could probably not have much impact in Key West or Phoenix, but dependency on the system may be beneficial in Peoria or Spokane.

Based on this study, future work that should be done includes the experimental verification of the newly developed earth tube model and the investigation of the effect of the earth tube during heating season as a potential heat source.

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NOMENCLATURE

A_s : amplitude of the soil surface temperature variation (°C)
C_a : specific heat of air (J/kg°C)
E_{conv} : convective heat transfer between the air and ground (W/ m^2)
E_{solrad} : solar radiation absorption by ground surface (W/ m^2)
$E_{longrad}$: long-wave radiation emitted from ground surface (W/ m^2)
E_{latent} : latent heat loss due to evaporation (W/ m^2)
h_c : convective heat transfer coefficient at the inner pipe surface (W/m^2°C)
h_s : convective heat transfer coefficient at the soil surface (W/m^2°C)
k_{air} : thermal conductivity of the air (W/m°C)
k_p : pipe thermal conductivity (W/m°C)
k_s : soil thermal conductivity (W/m°C)
L : pipe length (m)
m_a : mass flow rate of ambient air through pipe (kg/s)
r_a : relative humidity
R_c : thermal resistance due to convection heat transfer between the air in the pipe and the pipe inner surface (m°C/W)
R_p : thermal resistance due to conduction heat transfer between the pipe inner and outer surface (m°C/W)
R_s : thermal resistance due to conduction heat transfer between the pipe outer surface and undisturbed soil (m°C/W)
R_t : total thermal resistance between pipe air and soil (m°C/W)
ΔR : radiation constant (63W/m^2)
r_1 : inner pipe radius (m)
r_2 : pipe thickness (m)
r_3 : distance between the pipe outer surface and undisturbed soil (m)
S : net horizontal solar radiation (W/m^2)
S_m : average solar radiation (W/m^2)
S_v : amplitude of the solar radiation (W/m^2)
t : time elapsed from beginning of calendar year (days)
T_a : air temperature above the ground surface (°C)
$T_a(y)$: air temperature of the pipe at the distance y from the pipe inlet (°C)
T_{am} : ambient air temperature (°C)
T_m : average soil surface temperature (°C)
T_{ma} : average air temperature (°C)
t_0 : phase constant of the soil surface (sec; days)
t_{0a} : phase constant of the air (sec; days)
T_{sur} : ground surface temperature (°C)
T_{va} : amplitude of the air temperature (°C)
$T_{z,t}$: ground temperature at time t and depth z (°C)
u : wind velocity above the ground surface (m/s)
U_t : overall heat transfer coefficient of the whole earth tube system (W/m°C)
V_a : average pipe air velocity (m/s)
z : depth of the radial center of pipe below soil surface (m)
α_s : soil thermal diffusivity (m^2/s; m^2/days)
β : soil absorption coefficient (= 1 – soil albedo)
ε : hemispherical emittance of the ground surface
φ_I : phase angle between the insolation and the air temperature (rad)

φ_S : phase angle difference between the air and soil surface temperature (rad)
w : annual angular frequency (=1.992 x 10^{-7}rad/s)

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CORRECTIONS

There are some corrections from the original version. In the original paper, pipe length, *L*, is erroneously included in in equations (18), (19) and (20), which leads to significant errors. Therefore, pipe length, *L*, is removed from those equations. The corrections are indicated in the red color to be differentiated from the original paper. This corrected paper is re-uploaded in the SimBuild 2006 webpage.