Optimization of an Earth Tube System by Means of Factorial Analysis

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Abstract

An Earth Tube system is a hybrid ventilation system using an air-to-soil heat recovery approach. Energy saving of an Earth Tue system depends on several factors such as soil type and depth, tube length and radius, fan volume flow rate, climatic conditions, etc.

While several papers have studied some of these elements, there is a lack of a holistic approach to study the factors in relation to each other. A factorial analysis uses a previously developed parametric model to find the significant factors on the system performance. The main takeaway of this paper is the process of optimization and the features to consider while designing an Earth Tube system.

Introduction

An air-to-soil ventilation system reduces both heating and cooling loads due to the relatively constant temperature of the undisturbed soil. In this system, ground works as a heat sink in summer and heat source in winter. Basically, the temperature of the undisturbed soil deep in the ground is lower than the outside air temperature in summer and higher in winter (Peretti, Zarrella, De Carli, & Zecchin, 2013). Passing through the pipes, air is cooled in summer and heated in winter (Bradley & Utzinger, 2009).

Different papers have used a range of terms to refer to an Earth Tube system including but not limited to *earth-air tube ventilation system* (Yang & Zhang, 2015), *earth-to-air heat exchangers*, *EAHE, EAHX, ETAHE, ATEHE* (Yang & Zhang, 2015) (Santanouris et al., 1995), (Peretti et al., 2013), *ground-coupled heat exchangers* (Yang & Zhang, 2015), *earth channels* (Yang & Zhang, 2015), *ground source heat pump, GSHP* (Peretti et al., 2013), *buried pipes* (Santanouris et al., 1995), HETS (Horizontal Earth Tube System) (Mongkon, Thepa, Namprakai, & Pratinthong, 2013) (Mongkon, Thepa, Namprakai, & Pratinthong, 2014).

Interestingly, the Earth Tube system has been employed in very different climates and for various building types with totally different dimensions. It has been used for pre-cooling the air, pre-heating the air, or both.

Buried pipes have been used for the purpose of cooling the air of a greenhouse in a Mediterranean climate such as Greece (Santanouris et al., 1995).

In 2004, Earth Rangers Centre (ERC), a Canadian kids' conservation organization, in Ontario, Canada, applies an Earth Tube system to reduce both heating and cooling energy loads in order to be environmentally friendly. There are 9 prefabricated concrete tubes, buried 3 meters below the ground level, with the length and diameter of 20 and 0.9 meters respectively, at the East wing of the building.[1]

In 2008, inspired by traditional windcatchers, the Earth Tube system was used differently in the design of a school in Damascus, Syria. The outdoor intake air is pre-cooled using miniature earth ducts made up of pipes embedded in the ground floor slab. The exhaust happens through the stack effect of some chimneys mimicking windcatchers.[2]

In 2007, Aldo Leopold Foundation (ALF), a LEED[3] Platinum nature centre in Wisconsin, USA, applies an Earth Tube system for both precooling and preheating in a cold climate (Utzinger & Bradley, 2009). There are 5 tubes buried close to 2.4 meters below the ground surface, with a diameter of 0.6 meters and a length of about 32 meters.

In 2015, an Earth Tube system was integrated into the ventilation system of the Environmental Science and Chemistry Building, University of Toronto's Scarborough Campus (UTSC), a LEED gold project in a cold climate.[4]

The same year, the Bellevue Youth Theatre, a LEED gold certified building in Washington, USA, used an underground pre-insulated duct system. BlueDuct® system was installed around the inside perimeter of the Theatre.[5]

In 2016, Avasara Academy used a set of Earth ducts as part of the ventilation system, in Lavale, India. This case combines an Earth Tube system to precool the fresh air, with a few stacks to exhaust the air.[6]

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[1] http://www.ercshowcase.com/

[2] https://www.german-architects.com/en/transsolar-klimaengineering-stuttgart/project/lycee-charles-de-gaulle

[3] Leadership in Energy and Environmental Design

[4] https://smithandandersen.com/smith-andersen-receives-2017-ontario-consulting-engineering-award-merit

[5] https://www.aqcind.com/cubeportfolio/bellevue-youth-theater-washington/

[6] https://transsolar.com/projects/avasara-academy

There are numerous other examples. Different studies have considered a few factors affecting the performance of the Earth Tube systems. However, the relationships between the factors need to be studied further. Knowing the significant factors and their interactions helps us optimize the future Earth Tube systems.

Methods

The Earth Tube system is considered as a hybrid ventilation. In hybrid systems, there are two modes of ventilation, natural and mechanical. Natural mode is on only and only when two conditions are satisfied. First, the minimum airflow rate is satisfied. Second, the outdoor weather temperature and relative humidity is within the comfort range. When at least one of the conditions is not satisfied, the control system switches to the mechanical mode. It is only in the mechanical mode when the fresh air is passing through the tubes and energy saving due to the preheating and precooling will happen.

The natural ventilation mode is simulated using off-the-shelf components for TMY climate data and natural ventilation tools from Ladybug and Honeybee tools in Grasshopper in Rhinoceros. (Sadeghipour Roudsari and Park, 2013), (Roudsari, Mackey, Yezioro, Harriman, Chopson, Ahuja, 2014).

The mechanical ventilation mode as well as the thermal performance of the tubes are simulated based on a numerical model previously developed in Python in Grasshopper in Rhinoceros. The model is partially validated by the data measurement from an existing Earth Tube system in the Aldo Leopold Foundation in Wisconsin (Ganji, Utzinger, Bradley, 2019), (Ganji, Utzinger, Renken, 2018).

A factorial analysis uses this parametric model to find the significant factors on the sensible energy saving of the system using Minitab 17. As the latent heat transfer part of the model is not yet validated, this paper only considers sensible energy, both heating and cooling. Figure 15 provides a workflow diagram (at the end of the paper).

Assumptions

This paper focuses only on the optimization of the Earth Tubes, not the building. As the natural ventilation depends on the geometry of the building, arrangement of windows, and so on, we are considering an auditorium with six operable windows, three at the east, and three at the west side, as shown in Figure 1.

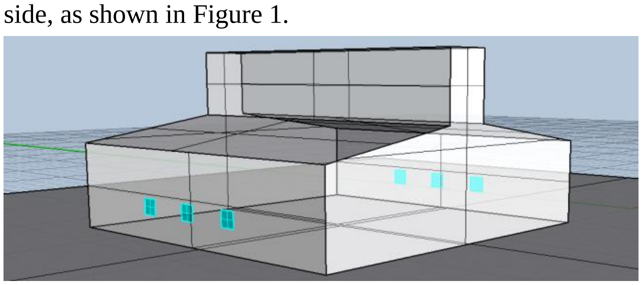

Figure 1. Hypothetical Building Geometry

Location

The hypothetical model is in Milwaukee, Wisconsin, USA.

Program, Occupancy and Schedule

The auditorium is a multi-use space. Occupancy schedule follows seven days per week, 9 am to 5 pm Sunday through Thursday and 9 am to 10 pm Friday and Saturday. There are typically 15 people in the room from 9 am to 5 pm every day and 80 people from 5 pm to 10 pm Friday and Saturday.

Ventilation Rate

Minimum ventilation rates in breathing zones are listed in the ASHRAE Standard 62.1-2013 for various occupancy categories (ASHRAE 62.1, 2013). Equation 1 determines the minimum airflow value as a function of number of occupants and the floor area.

$$V_{bz} = R_p \times P_z + R_a \times A_z \qquad (1)$$

V_{bz} = Outdoor airflow of the breathing zone, L/s

R_p = Outdoor airflow rate per person, L/s-person

P_z = Zone population

R_a = Outdoor airflow rate per unit area, L/s-m^2

A_z = Zone floor area, m^2

the minimum airflow, V_{bz}, for the auditorium is 107 L/s when 15 people are in the room and 354 L/s when there are 80 people in the room. The rates have been considered in the schedule. The fan follows these numbers to provide sufficient airflow when it is on. The schedule also forces the fan to turn off whenever the outdoor conditions are suitable to leave the windows open.

Earth Tube System Simulation

The Earth Tube model considers both the convection and the conduction of the soil (Equation 2).

$$f(\dot{q}_{Conv} + \dot{q}_{Cond}) = m_a C_P (T_o - T_i) \qquad (2)$$

$\dot{q}_{Conv}$ = Convective heat transfer rate, kW

$\dot{q}_{Cond}$ = Conductive heat transfer rate, kW

Convective heat transfer rate is calculated by applying Equation 3.

$$\dot{q}_{Conv} = h_f A_s \Delta t_{lm} \qquad (3)$$

Conduction of the soil is solved through an existing solution in terms of a Shape Factor (Bergman, Incropera, DeWitt, 2011).

$$\dot{q}_{Cond} = S k_s \Delta t_{s-i} \qquad (4)$$

Assuming that we have a horizontal isothermal cylinder buried in a semi-infinite medium, Equation 5 is used to calculate the shape factor.

$$S = \frac{2\pi L}{ln(4d/D)} \qquad (5)$$

Soil temperature at a depth below the surface ground is calculated by means of Equation 6 (Kusuda and Achenbach, 1965).

$$T = T_{mean} - T_{amp} * exp\left[-d * \left(\frac{\pi}{365\alpha}\right)^{0.5}\right] * cos\{\frac{2\pi}{365} * [t_{now} - t_{shift} - \frac{d}{2} * (\frac{365}{\pi\alpha})^{0.5}]\} \quad (6)$$

Equation 7 is developed based on Equation 2.

$$h_f A_s \frac{(T_o - T_i)}{ln\frac{(T_s - T_i)}{(T_s - T_o)}} + Sk_s(T_s - T_i) = \dot{m}_a C_P (T_o - T_i) \quad (7)$$

A numerical method is required to solve Equation 7 for the outlet temperature.

In summertime, the soil temperature should be less than the temperature of both the inlet and outlet of the tubes. On the other hand, outlet temperature should be less than the inlet temperature because the air is being cooled. A range of numbers between the soil temperature and the inlet temperature are calculated to find the outlet temperature in which the two sides of the Equation 7 has the least difference.

$$T_s \leq T_o \leq T_i \quad (8)$$

In wintertime, the outdoor air should be colder than the outlet air, and they are both colder than the soil temperature. The same difference minimization procedure was applied to find the outlet temperature in winter.

$$T_i \leq T_o \leq T_s \quad (9)$$

The numerical model is developed using Python and it has visual representation in Grasshopper, Rhinoceros.

Earth Tube Model (ET) Validation

The theoretical model was validated by the results of the experiment performed on the Aldo Leopold Foundation Building (ALF), located close to Baraboo, Wisconsin, USA.

Data collection started at May 2017 and continued for about 15 months. A Hobo® U20-001-01 datalogger was used to measure and log the outdoor air pressure and temperature. Hobo® U12-012 dataloggers were installed outside and inside the tubes to measure and log the air temperature and relative humidity.

Soil moisture and temperature sensors were attached to a Hobo® micro station datalogger. The micro station was screwed to the manhole wall. The soil temperature sensors were located at a depth of 2.4 m below the ground surface.

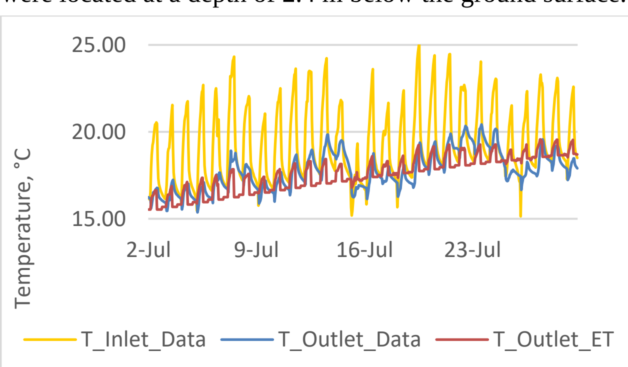

Figure 2. Model validation, Earth Tube outlet temperature, July

Figure 2 indicates that the Earth Tube system reduced the air temperature by 3.6 °C on average during the scheduled work hours. The difference between inlet and outlet air temperatures was as high as 5.9 °C on July 7th and 19th. The Mean Bias Error (MBE) and the Root Mean Square Error (RMSE) of the model were -0.20 °C and 0.92 °C for the outlet air temperature respectively.

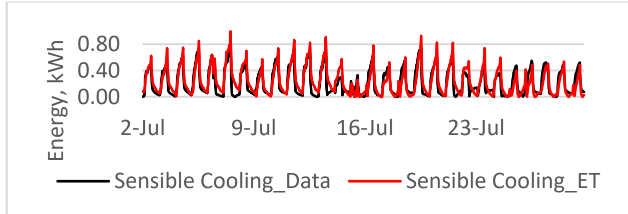

Figure 3. Model validation, Earth Tube sensible cooling energy saving, July

Figure 3 indicates the amount of saved sensible cooling energy resulted from reducing the outdoor air temperature. The black line shows the real data, while the red line represents the saved energy calculated by our model. MBE and RMSE were 0.02 kWh and 0.10 kWh respectively.

We used a month of measured heating data, from October 13th to November 9th, 2017, to validate the winter seasonal performance of the model. (Figure 4). The MBE and RMSE of the ET model were 0.13 °C and 0.63 °C for the outlet air temperature during the four weeks of the heating season.

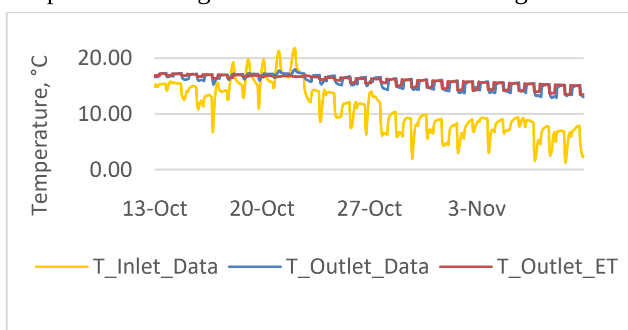

Figure 4. Model validation, Earth Tube outlet temperature, heating season

Figure 5 demonstrates the heating energy savings. The black line shows the actual amount of heating energy saving, while the red line represents the ET model value. The MBE and RMSE of the ET model were 0.03 kWh and 0.08 kWh for the heating energy saving.

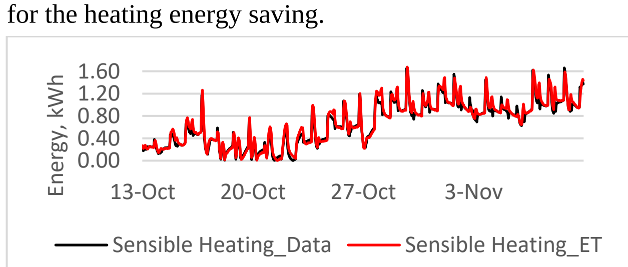

Figure 5. Model validation, Earth Tube sensible heating energy saving, heating season

Factorial Design

Several factors affect the thermal performance of an Earth Tube system including but not limited to the climate and weather data, soil type, conductivity and moisture content, the depth the tubes are buried at, radius and length of the tubes, number of tubes, fan volume flow rate. Realistically, we have control over some, but not on all factors.

In this paper, we focus on four affecting factors which are mentioned as the influential aspects in literature reviews (Florides & Kalogirou, 2007), (Peretti et al., 2013). The factors are soil conductivity, the depth at which the pipes are buried, the length of the tubes and their radius. The response factor is the total annual saved sensible energy in kWh.

Two level of values is considered for each factor (Table 1).

- Conductivity of soil: 0.3 and 0.5 (W/m-k)
- Depth of soil: 1.8 and 2.4 (m)
- Radius of the tubes: 0.3 and 0.9 (m)
- Length of Tubes: 50 and 75 (m)

Table 1. Factorial Analysis, Two-Level Factors

A	Conductivity_Soil (W/m-K)	0.5	1
		0.3	-1
B	Depth_Soil (m)	2.4	1
		1.8	-1
C	Radius_Tubes (m)	0.9	1
		0.3	-1
D	Length_Tubes (m)	75	1
		50	-1

Results and Discussion

Study of One Variable at a Time

Before heading to the factorial analysis, we studied the effect of only one factor when all the other ones are constant. This resulted in a better understanding of the model and selecting reasonable levels for each value.

Conductivity of Soil

Conductivity of soil is one of the factors that we have no control on unless we fill the land with a different soil type after excavations. Nonetheless, soil conductivity is an important factor to think about in an Earth Tube system.

Let us assume a common soil type such as Sandy Loam soil. Sandy Loam soil has a porosity of about 40%, a density of 1.25 to 1.45 kg/m^3 and a moisture content of 7 to 17% (Trząski and Zawada, 2011). Thermal conductivity of a hypothetical average Sandy Loam soil with a density of 1.35 kg/m^3 and a moisture content of 10% is 0.5 W/m-K. This number would be 0.3 should we consider a lighter drier soil with a density of 1.25 kg/m^3 and moisture content of 7 to 8%. On the other hand, thermal conductivity of a heavier wetter Sandy Loam soil could increase to 0.7 W/m-K (Abu-Hamdeh, 2001), (Alnefaie & Abu-Hamdeh, 2013).

In the first scenario, the effect of the soil thermal conductivity on total annual saved sensible energy is studied while the other three factors are constant. The total tube length is 75 meters, the radius of the tubes is 0.3 meters, and the depth of the soil is 3 meters (Figure 6).

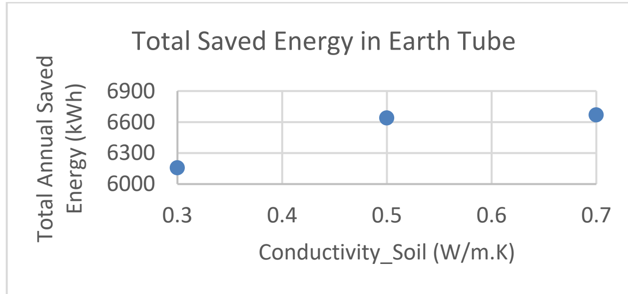

Figure 6. Effect of Soil Conductivity on Saved Energy

While there is a huge difference in the total saved sensible energy between the thermal conductivities of 0.3 and 0.5 W/m-K, this difference becomes lower when we compare soils with conductivities of 0.5 and 0.7 W/m-K.

Depth of Soil

The second scenario studies the effect of soil depth on the total annual saved sensible energy. In this case, the total tube length is 75 meters, the radius of the tubes is 0.3 meters, and the soil thermal conductivity is 0.5 W/m-K (Figure 7).

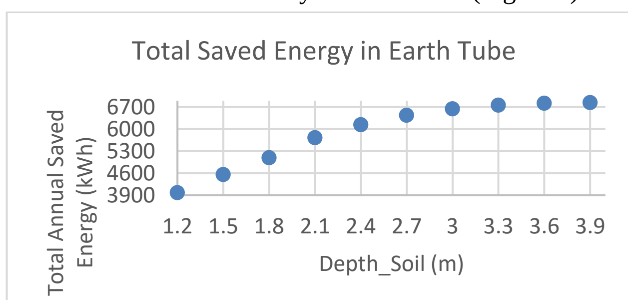

Figure 7. Effect of Soil Depth on Saved Energy

The effect of soil depth becomes lower as we go deeper into the ground. Considering the cost of excavations and the possibility of digging the ground, considering an optimum soil depth is a good idea depending on the project.

Radius of the Tubes

Radius of the tubes is one of the factors that we can control, and different options would not tremendously increase the costs in comparison to soil depth and excavation.

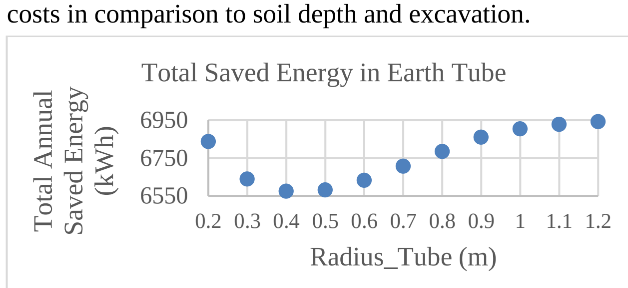

Figure 8. Effect of Tube Radius on Saved Energy

Figure 8 demonstrates the relationship between the radius of the tubes and the total annual sensible saved energy. In this scenario, the total tube length is 75 meters, the soil depth is 3 meters, and the soil thermal conductivity is 0.5 W/m-K. Within a radius of 0.5 and 1, the effect is almost linear. In radius of 1 meter and above that, the effect of increasing the tube radius tends to be minimal.

Length of the Tubes

In this scenario, the effect of the tube length on the total annual saved sensible energy is studied whilst the other three factors are constant. Different total tube length is a result of different length of one tube in 3, 4, and 5 branches. The total radius is 0.3 meters, the soil depth is 3 meters, and the soil thermal conductivity is 0.5 W/m-K (Figure 9).

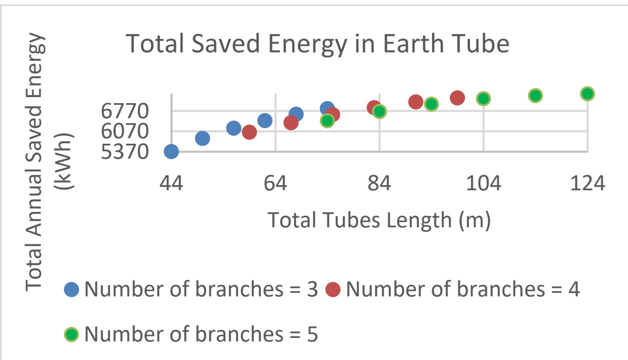

Figure 9. Effect of Total Tube Length on Saved Energy

In general, the longer the tubes are, the higher the amount of sensible saved energy would be. However, considering that the soil capacity to exchange heat with the air in the tubes is limited, there is no point in further increasing the total tube length when we have used all the soil capacity. Finding the optimum tube length should be considered.

Factorial Analysis

A 2^4 factorial analysis is developed in Minitab 17 (Table 1). Due to the initial Normal Plot (Figure 16), while all the main factors are significant, it seems that a couple of interactions are not significant. After reductions, the Normal Plot looks like Figure 17 (at the end of the paper).

Table 2. Analysis of Variance (ANOVA)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	4455489	636498	75.59	0.000
Linear	4	4095616	1023904	121.60	0.000
Conductivity	1	93330	93330	11.08	0.010
Depth	1	1565001	1565001	185.86	0.000
Radius	1	76452	76452	9.08	0.017
Length	1	2360832	2360832	280.37	0.000
2-Way Interactions	3	359873	119958	14.25	0.001
Conductivity*Depth	1	196249	196249	23.31	0.001
Conductivity*Length	1	118680	118680	14.09	0.006
Depth*Length	1	44944	44944	5.34	0.050
Error	8	67363	8420		
Total	15	4522852			

Table 2 displays the Analysis of Variance (ANOVA) table for the reduced model. Based on the ANOVA table, all the four main factors are highly significant and have a P-value of at most 0.017. Soil depth and tubes length are more significant than soil conductivity and tubes radius. The radius of the tubes is the least significant of the four factors. Within the 2-way interactions, conductivity*depth, conductivity*length and depth*length are important. The other 2-way interactions and the 3-way interaction are not significant. Table 3 describes the model summary. The Equation of the model will be:

Energy_Saved = 4054 - 2683 Conductivity - 1317 Depth + 230.4 Radius + 28.6 Length + 3692 Conductivity*Depth - 68.9 Conductivity*Length + 14.13 Depth*Length (4)

Table 3. Factorial Analysis, Model Summary

S	R-sq	R-sq (adj)	R-sq (pred)
91.7624	98.51%	97.21%	94.04%

Main Effects Plot corroborates the Table 3 data (Figure 10). Tubes length and soil depth are more significant than soil conductivity and tubes radius. Hence, if we are trying to have the most effective Earth Tube system, it would be reasonable to dig the soil deeper and increase the tubes length, rather than increasing the radius of the tubes.

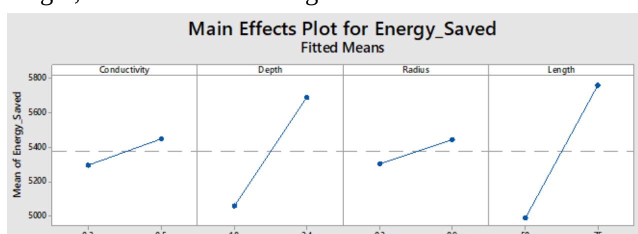

Figure 10. Factorial Analysis, Main Effects Plot

Soil Conductivity and Depth Interaction

When soil depth is only 1.8 meters, conductivity of soil does not make a tremendous change. However, as we go deeper into the ground (2.4 meters), a soil with a higher thermal conductivity would increase the energy saving (Figure 11).

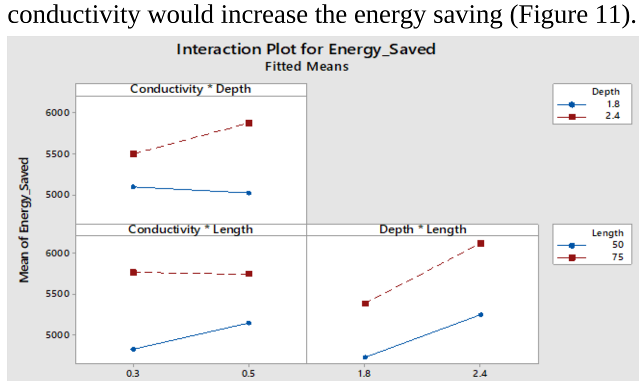

Figure 11. Factorial Analysis, Interaction Plot

We probably do not have much control over the soil type and soil conductivity. However, if we already know that the field soil has a high conductivity such as 0.5 W/m-K, it is a good idea to dig the soil deeper.

Soil Conductivity and Tubes Length Interaction

Based on Figure 11, when the total length of the tubes is 75 meters, the soil conductivity does not play a huge role. Maybe that is because we have already used the whole capacity of the soil by having longer tubes. When the total length of the tubes is lower, around 50 meters, the conductivity would be more important.

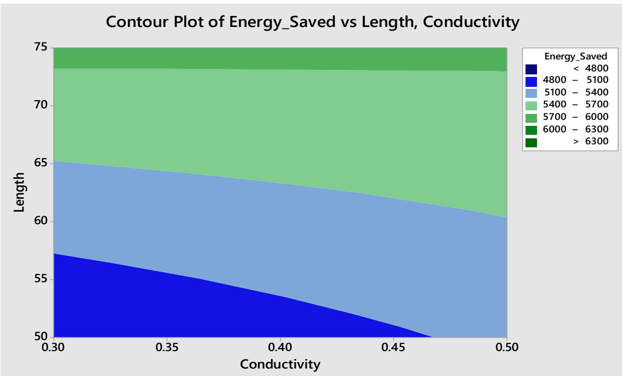

Figure 12. Contour Plot of Energy Vs Conductivity, Length

If we know that the soil conductivity is low such as 0.3 W/m-K, it would be a good idea to consider either longer tubes or a higher number of branches, or both, to increase the total tubes length (Figure 12).

Soil Depth and Tubes Length Interaction

Based on Figure 11, the deeper the tubes are buried and the longer they are, the higher the amount of saved energy would be. Increasing the tubes length is even more influential when the soil depth is also increased (Figure 13).

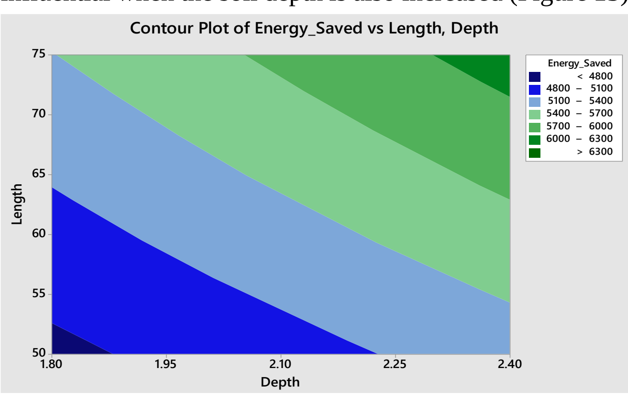

Figure 13. Contour Plot of Energy Vs Depth, Length

Total Annual Saved Energy

In all 16 scenarios, there is more reduction in sensible heating energy than sensible cooling energy (Figure 14).

The ratio of saved heating energy to total saved energy varies between 56% to 62%. Higher amount of saved heating energy could be because of the climate conditions and the energy requirements. In the cold weather of Wisconsin, heating loads are higher than cooling loads. This could also suggest that the heating performance of an Earth Tube system is better than its cooling performance.

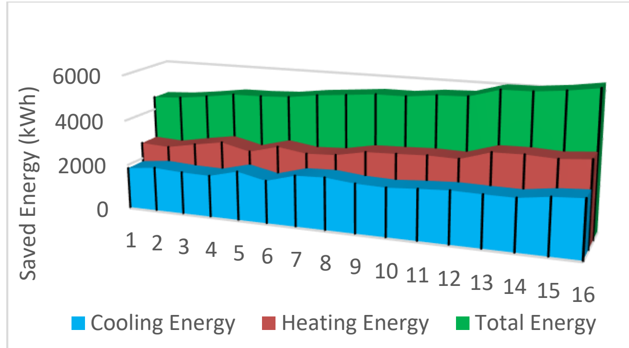

Figure 14. Total Annual Saved Energy

Conclusion

The prevalence of using the Earth Tubes in very different conditions from hot and humid to dry and cold climates indicates the necessity to understand what factors contribute to the system thermal performance and how they interact.

This paper establishes a factorial design to analyse the significance as well as the interactions between several factors contributing to Earth Tube performance including soil thermal conductivity, the depth the tubes are buried at, the radius of the tubes and total tubes length.

The factorial analysis is based on a theoretical model (ET) created to evaluate the thermal performance of an Earth Tube system. The model is validated using the data from the ALF building located close to Baraboo, WI.

While all the four factors are significant, soil depth and tubes length seem to be more influential than soil conductivity and tubes radius. The deeper the soil is, the steadier the soil temperature will be. Moreover, as the soil depth increases, there is a higher temperature difference between the fresh air temperature and the soil temperature. Hence, increasing the soil depth elevates the system potential heating and cooling capacity. Nonetheless, should we dig the soil deep enough, the annual soil temperature will be a constant number and there is no use going any deeper.

Regarding the interactions between the main factors, only three of the two-way interactions are significant: the soil conductivity and depth, the soil conductivity and tubes length, and the soil depth and tubes length. Interactions suggest that in a soil with a higher conductivity, it is a good idea to increase the soil depth. In a soil with lower levels of conductivity, it is a good idea to increase the tubes length to improve the system thermal performance.

In the future works, we will work on changes in the thermal performance of the system along the direction of the airflow. A Finite Element Model is being developed to study the thermal performance of the Earth Tubes in more details.

Acknowledgement

The authors would like to thank Kyle Talbott and Dr Kevin Renken, Associate Professors at University of Wisconsin Milwaukee for their help and support regarding the Earth Tube script and simulation.

Nomenclature

A_s	Tube surface area (m^2)
A_z	Zone floor area, m^2
Adj MS	Adjusted Mean Squares
Adj SS	Adjusted Sum of Squares
C_P	Specific heat of air, kJ/kg-K
d	Soil depth, m
D	Tube Diameter (m)
DF	Degree of Freedom
ET	Earth Tube model
h_f	Convective heat transfer coefficient of air inside tubes (W/m^2-K)
k_s	Thermal conductivity of soil (W/m-K)
L	Tube Length (m)
m_a	Mass flow rate of the air inside the tubes, kg/s
P_z	Zone population
$\dot{q}_{Cond}$	Conductive heat transfer rate, kW
$\dot{q}_{Conv}$	Convective heat transfer rate, kW
R_a	Outdoor airflow rate per unit area, L/s-m^2
R_p	Outdoor airflow rate per person, L/s-person
R-sq	R-squared
R-sq (adj)	Adjusted R-Squared
R-sq (pred)	Predicted R-squared
S	Soil Conduction Shape Factor (m)
T	Temperature, °C
T_{amp}	Amplitude of surface temperature, °C
T_i	Inlet temperature of the air inside the tubes, K
T_{mean}	Average air temperature, °C
t_{now}	Current day of the year, day
T_o	Outlet temperature of the air inside the tubes, K
t_{shift}	Day of the year corresponding to the minimum surface temperature, day
T_{soil}	Soil Temperature, °C or K
Δt_{lm}	Log mean temperature difference (°C or K)
α	Soil thermal diffusivity, m^2/day
V_{bz}	Outdoor airflow of the breathing zone, L/s

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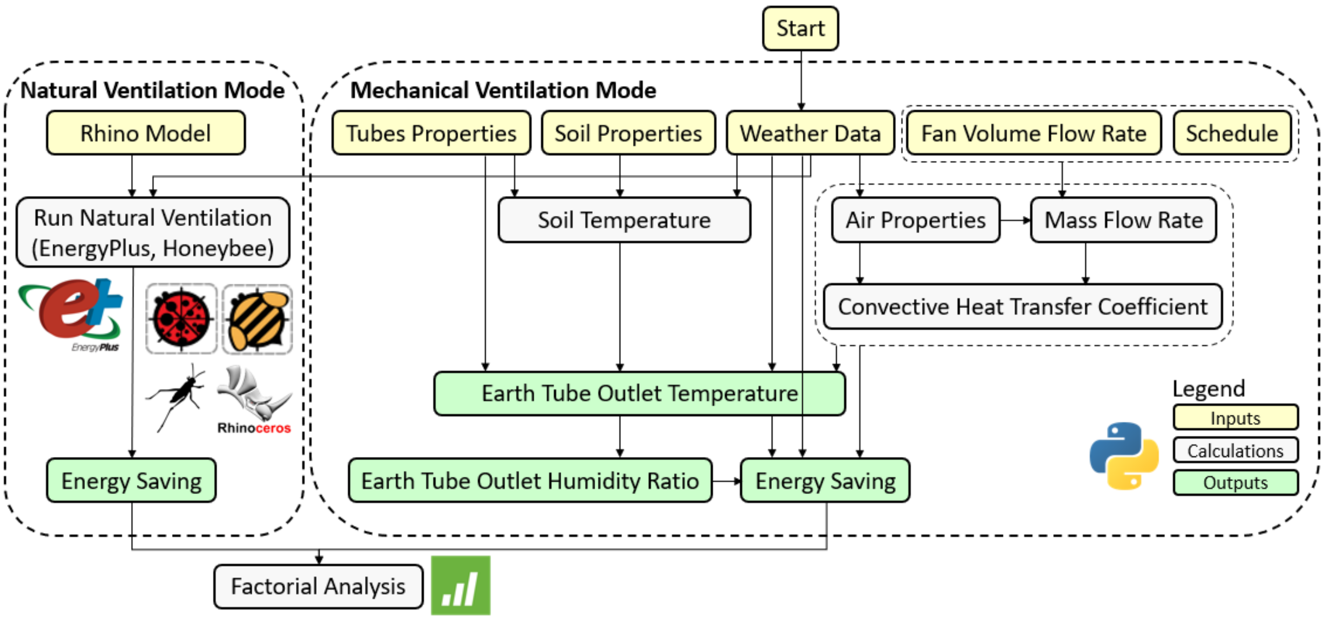

Figure 15. Workflow Diagram

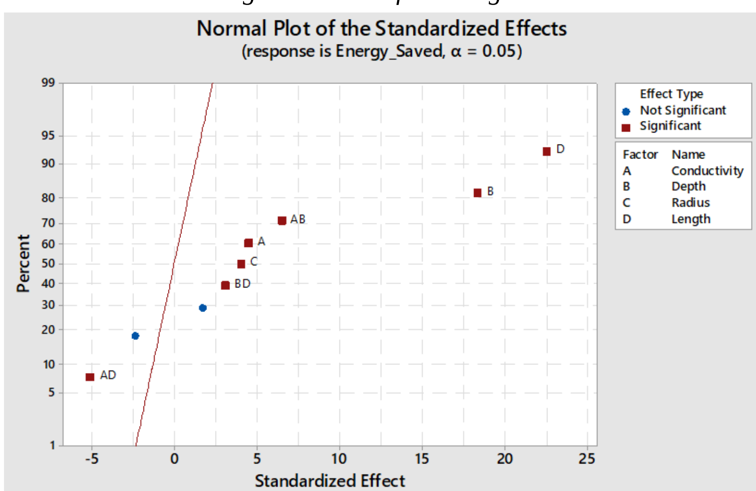

Figure 16. Factorial Analysis, Normal Plot

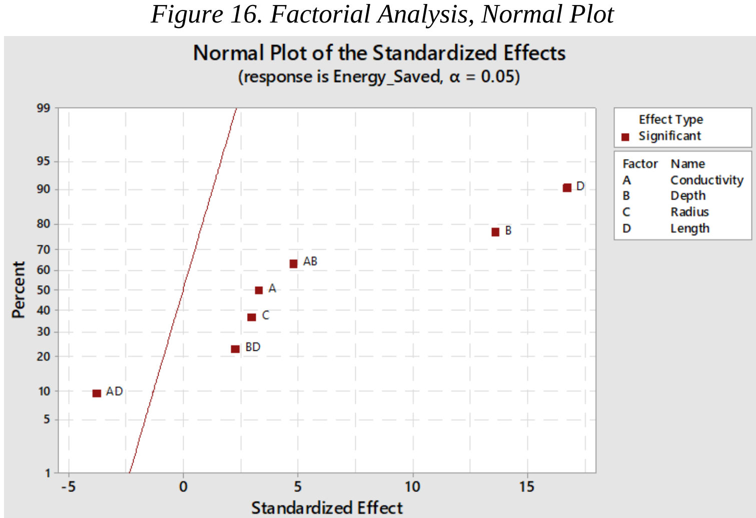

Figure 17. Factorial Analysis, Normal Plot after Reduction