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AN ANALYSIS ON THE THERMAL PERFORMANCE OF A HORIZONTAL EARTH TUBE SYSTEM

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ABSTRACT

The Aldo Leopold Foundation (ALF) located near Baraboo, WI, employs several passive approaches including using a Horizontal Earth Tube System (HETS). The simulation during the design level indicated that HETS would perform better than an enthalpy-heat-recovery system precooling and dehumidifying the air, but not quite as well preheating the air in winter. The earth tube model which was used in the design simulation had not been validated. This paper focuses on setting up a data collection system to measure the amount of precooling. A bulk flow model and a CFD[1] model are further developed based on the collected data.

INTRODUCTION

In 2008 AIA COTE top ten, the Aldo Leopold Foundation (ALF) in Wisconsin, designed by Kubala-Washatko Architects, was in the spotlight as the first LEED Platinum, carbon neutral building and was also recognized with an accolade from the Forest Stewardship Council for using sustainably-harvested timber throughout the structure.[2]

In addition, ALF applies some passive approaches to become close to a net-zero building and decrease energy consumption as much as possible. One of these passive methods is using a Horizontal Earth Tube System (HETS). Hypothetically, it reduces both heating and cooling loads of the building due to the relatively constant temperature of the undisturbed soil (Bradley & Utzinger, 2009). 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. Passing through the pipes, air is cooled in summer and heated in winter before any other active conditioning (Peretti, Zarrella, De Carli, & Zecchin, 2013).

A subtle point is that the HETS should perform differently in summer and winter. In winter, HETS affects the dry bulb temperature; therefore, the sensible heating. In summer, not only it affects the dry bulb temperature, but also the moisture content as well; therefore, the latent cooling. Cooling down the air in summer may cause the air to reach the dew point. As soon as it hits the dew point, both temperature and the amount of moisture in the air decrease, so both sensible and latent cooling are subjects of study during summer.

Other researchers have used distinct terms to refer to this system such as earth-air tube ventilation system (Yang & Zhang, 2015), earth-to-air heat exchangers, EAHE (Santanouris et al., 1995), earth-to-air heat exchanger (EAHE, EAHX, ETAHE, ATEHE) (Peretti et al., 2013) (Ascione, Bellia, & Minichiello, 2011), ground-coupled heat exchangers (Yang & Zhang, 2015), earth channels (Yang & Zhang, 2015), ground source heat pump, GSHP (Peretti et al., 2013), or simply buried pipes (Santanouris et al., 1995). Mongkon et al. use the term HETS (Horizontal Earth Tube System) which we also apply in this paper (Mongkon, Thepa, Namprakai, & Pratinthong, 2013) (Mongkon, Thepa, Namprakai, & Pratinthong, 2014).

EXPERIMENT

Earth Tubes arrangement

The geometry and arrangement of the tubes affect the air flow pattern and thermal performance of the tubes. In this project, there are 5 earth tubes with an Inner Diameter (ID) of 2 feet (0.6 m). According to Figure 1, there are 12 straight sections of concrete pipes in each

[1] Computational Fluid Dynamics

[2] https://inhabitat.com/aiacote-top-ten-green-building-projects-of-2008/

line in addition to two 2 feet stubs at the two ends of Tee pipes. The length of each piece is about 8 feet (2.44 meters) which makes the total length 104 feet which is about 32 meters (Figure 2). Total length of the pipes is about 598 feet (182 meters). The pipes are sloped by 4°.

Figure 1 Horizontal Earth Tube System (HETS)

There is a manhole at the entrance of the earth tubes which makes it accessible. The manhole has an Inlet Diameter (ID) of 4 feet (1.2 m). It has a metal cap to prevent the entrance of animals, water and.

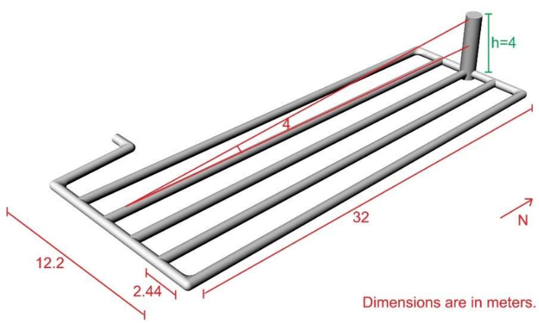

Figure 2 Earth Tubes Rhino model

Modes of heat and mass transfer

To investigate the thermal performance of the earth tubes, first we need to figure out what types of heat and mass transfer is happening throughout the system. Let us assume the system includes the tubes, the manhole, the soil, and the air entering the manhole, moving through the pipes, ending in the Air Handling Unit. Figure 3 illustrates the heat and mass transfer in a schematic diagram. Basically, cooling loads are divided into two parts: sensible and latent cooling. Table 1 demonstrates the relationship between the heat and mass transfer and the types of cooling.

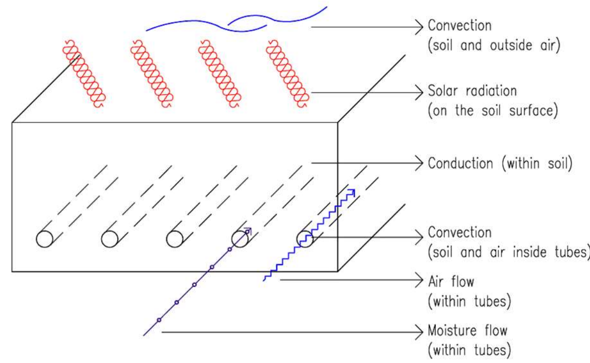

Figure 3 Heat and mass transfer schematic diagram

Table 1 heat and mass transfer, and types of cooling

	MODE	MATERIAL	COOLING
1	Conduction	Within soil	Sensible cooling
2	Convection	Soil and outside air	Sensible cooling
3	Convection	Soil and air inside tubes	Sensible cooling
4	Radiation	On the soil surface	Sensible cooling
5	Air flow	Within tubes	Sensible cooling & latent cooling
6	Moisture flow	Within tubes	Latent cooling

Some of the heat exchanges above relate to soil as a medium, while the others refer to air within the tubes. In what follows, the heat and mass transfer of the air within the tubes (rows #3, #5, and #6 of Table 1) will be studied through a CFD model and a mathematical bulk flow model.

The CFD model is based on fan speed, geometry of the tubes and the manhole. It compensates the fact that we could not put any air-flow sensors in the field due to technical and financial problems. Based on the collected data and CFD results, a mathematical model (employing EES®[3] software) is defined to predict future HETS thermal performance.

Data collection

First set of sensors were installed on 22nd of May 2017 including the following types:

- Hobo U20-001-01[4] (Pressure and Temperature),
- MX1102[5] (CO_2 level, Temperature and Relative Humidity) – Bluetooth smart,
- MX1101[6] (Temperature and Relative Humidity) – Bluetooth smart (Figure 4).

[3] Engineering Equation Solver
[4] http://www.onsetcomp.com/products/data-loggers/u20-001-01
[5] http://www.onsetcomp.com/products/data-loggers/mx1102
[6] http://www.onsetcomp.com/products/data-loggers/mx1101

U20-001-01, MX1102, MX1101

Figure 4 Sensors (Photos from: ONSET website[7])

Figure 5 and Table 2 demonstrate the location of the sensors, what they measure and if they are Bluetooth smart or not.

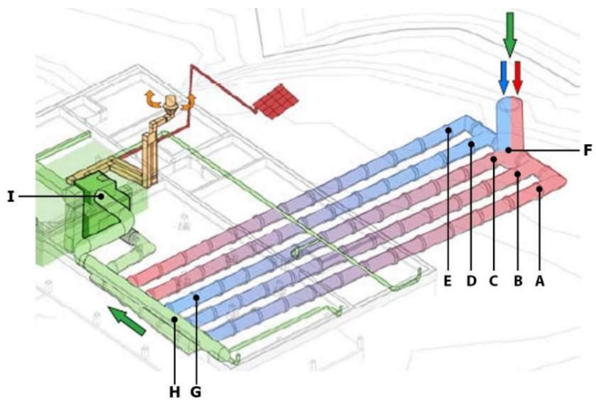

Figure 5 Location of the sensors

Table 2 Name, type and location of the sensors

NAME	PLACE	TYPE	T	RH	P	BT
10743983	C	MX1101				
10151230	F	U20-001-01				
10151231	I	U20-001-01				
20045799	I	MX1102				

Second round of sensor installation was carried out on 4th of August 2017. A micro station data logger (H21-002[8]) was set to measure the soil temperature and water content, 1.2 meters (4 feet) below the ground surface.

CFD MODEL

Due to some technical and financial problems, we did not put any sensors in the field to measure the air velocity or volume flow rate. Therefore, some CFD simulations have been carried out to address this issue in Autodesk CFD 2018.

Basically, there is a forced flow along the tubes since there is a fan in the outlet of the tubes in the Air Handling Unit. As the design team state, the amount of volume flow rate provided by the fan is about 300 L/s (0.3 $\frac{m^3}{s}$) or higher. This is the main input for the CFD analysis. The boundaries conditions and other specifications of the simulation is as follows:

- ✓ Inlet pressure: 97.5 kPa
- ✓ Outlet (AHU) pressure: 98.5 kPa
- ✓ Outlet volume flow rate: 300 L/s
- ✓ Pipes surface material: Concrete

Figure 6 demonstrates a general section of the tubes and the air velocity in them. Although the design team expected the 5 tubes to have an evenly distributed flow, the CFD results seem to reveal different results.

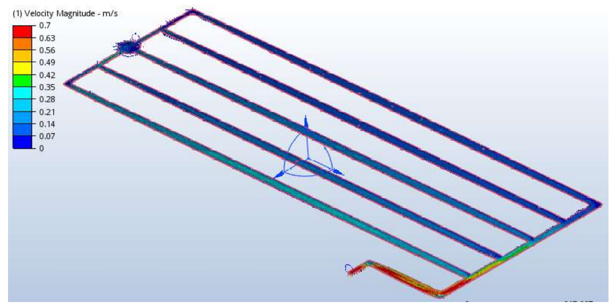

Figure 6 Velocity profile in the Earth Tubes

Based on the Equation (1), the relationship between volume flow rate and velocity is this:

$$Q = VA \quad (1)$$

The velocity of the air at the outlet surface is:

$$V = Q/A = 1.028$$

Also, Equation (2) shows how the volume flow rate of tubes connecting to each other combine:

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \quad (2)$$

As the area of all branches is the same, we can develop Equation (3):

$$V = V_1 + V_2 + V_3 + V_4 + V_5 \quad (3)$$

Therefore, one should expect the sum of the velocity of the 5 main branches should equal 1.028 $\frac{m}{s}$ (velocity at the outlet). However, simulation verifies a velocity drop due to the 90-degree elbows, the concrete surface, and so on.

To study the velocities more carefully, 10 cross sections have been made align the 5 branches (Figures 7-12). All velocity magnitudes are in $\frac{m}{s}$.

As the diagrams reveal, there is about 20% velocity drop right after the first 90-degree elbow. Probably, the first elbow is too close to the outlet. Had the designers considered a larger distance between the outlet and the elbow, less velocity drop would have happened. These numbers will be employed in the mathematical bulk flow model.

[7] http://www.onsetcomp.com/products/data-loggers

[8] http://www.onsetcomp.com/products/data-loggers/h21-002

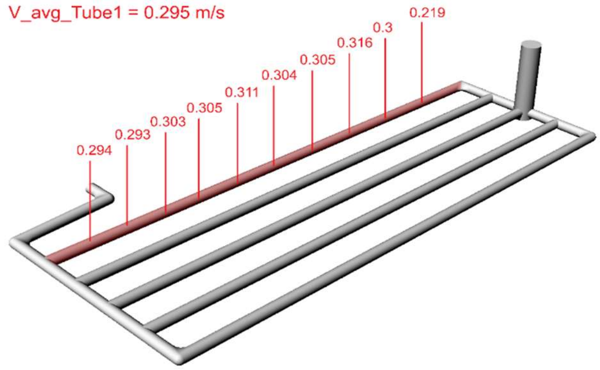

Figure 7 Average air velocities in main tube branch 1

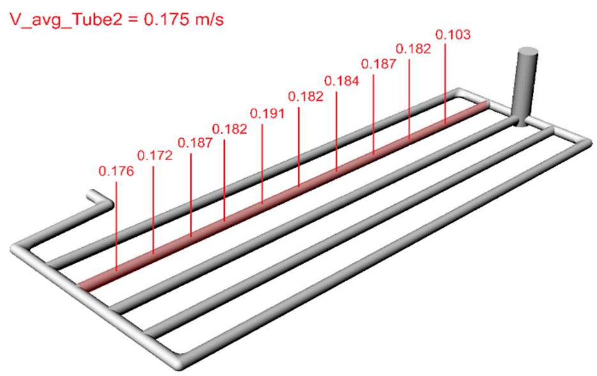

Figure 8 Average air velocities in main tube branch 2

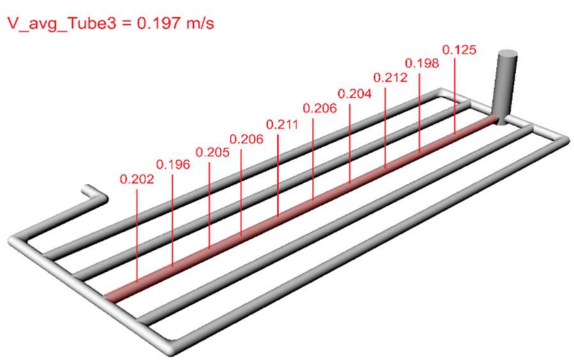

Figure 9 Average air velocities in main tube branch 3

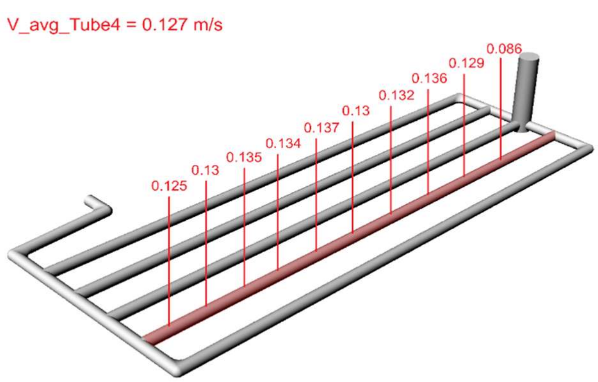

Figure 10 Average air velocities in main tube branch 4

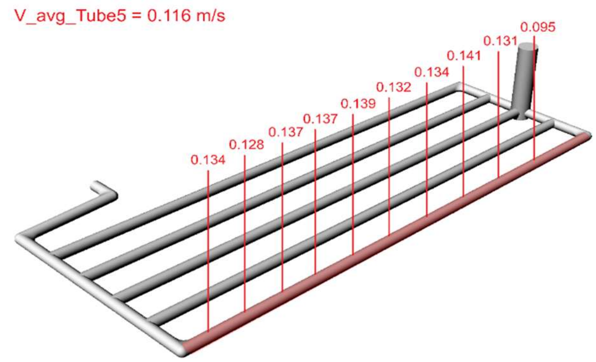

Figure 11 Average air velocities in main tube branch 5

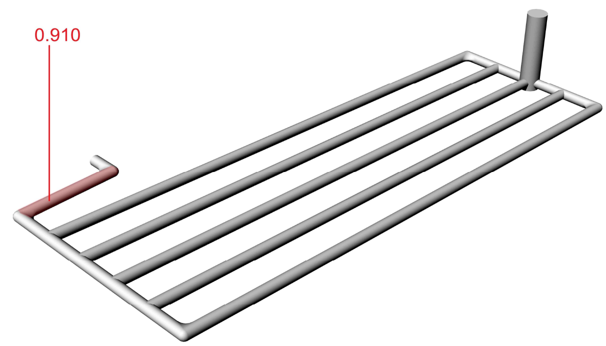

Figure 12 Average air velocities in main outlet tube

BULK FLOW MODEL

To make this model simple, there are a couple of assumptions:

i. This model accounts for convection between the Soil and air inside tubes, and the air and moisture flow (rows #3, #5 and #6 of Table 1).

ii. This model is only based on inlet and outlet data and does not study each branch separately.

iii. Based on the geometry of the tubes, this is a case of fully developed flow since: $L_{tube}/D_{tube} \geq 10$

Considering that the soil sensors were installed no sooner than August 4th, the data from the second week of August 2017 was selected as a sample to create the mathematical model. Basically, the work hours of the building are 10 AM to 4 PM for the visitors, and 8 AM to 4 PM for the staff. Therefore, the mathematical model is based on the data from August 7th to 11th, Monday through Friday, 8 AM to 4 PM.

We used the pressure data from U20 sensors #10151230 (located in the Manhole), and #10151231 (located in the Air Handling Unit); Temperature and Relative Humidity from MX1101, #10743983 and MX1102, #20045799 sensors located in the Manhole and in the AHU respectively (see Figure 5 and Table 2).

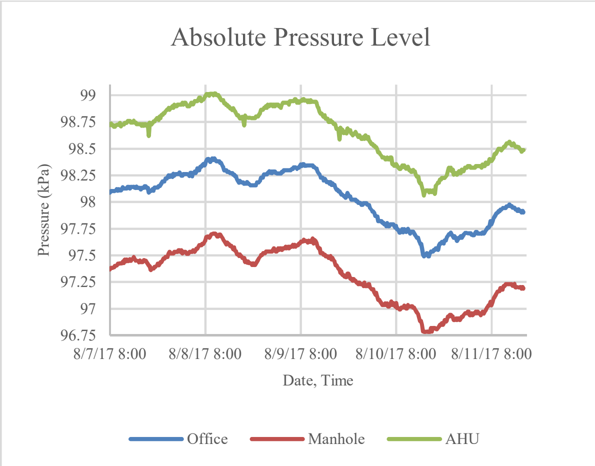

Figure 13 Absolute Pressure Level, 24-hour diagram

Figure 13 shows the profiles of the absolute pressure level (kPa) from 8 AM August 7th to 4 PM August 11th, all 24 hours. Based on this plot, there is a constant slight pressure difference between the inlet and the outlet. Apparently, this is due to the fan in the AHU being on all 24 hours with a constant rate, which is supposed to be 300 L/s (0.3 m^3/s) based on the design documents. They do not turn the fan on and off, at the start and the end of the office hours, nor there is any smart program to do that. Moreover, it seems that the pressure drop in the pipes is negligible.

Figure 14 depicts the temperature and relative humidity profiles for the same period. The grey parts show the work hours of the building.

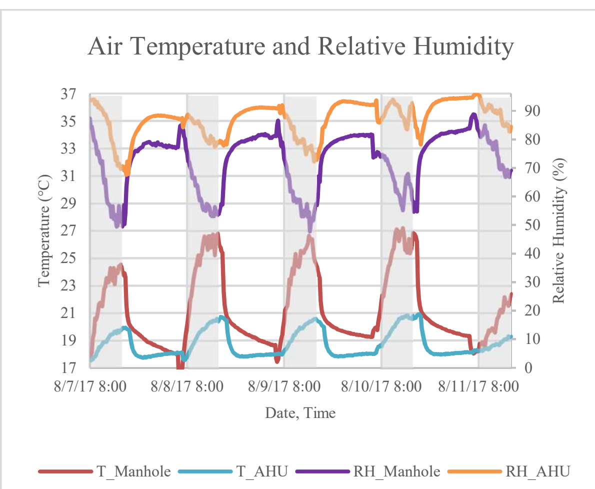

Figure 14 Temperature (°C) and Relative Humidity(%), 24-hour diagram

This diagram bolds a couple of points:

- ✓ First, it shows that the temperature and relative humidity changes, therefore the heat and moist exchange, are greater in the daytime rather than nighttime in this time of the year.
- ✓ Second, interestingly, the temperature has dropped by an average of 4 °C during the office hours. This indicates a huge amount of sensible precooling.
- ✓ Third, despite what one might suppose, the relative humidity has been increased by an average of 20%. This could be partly due to the fact that the lower the temperature, the less amount of moisture the air can hold. That is, since the temperature has dropped, the air can hold less amount of moisture; therefore, the relative humidity has increased.
  However, this diagram raises the question whether the tubes has increased the moisture or not. We will answer this question by studying humidity ratio and latent cooling as we go on.

Sensible Cooling

To evaluate the convection between the soil and the air inside the tubes, the type of flow should be found out. Therefore, Reynolds number is calculated.

$$R_{e_D} = \frac{4m_a}{\pi\mu D} \tag{4}$$

We need to know the viscosity and the mass flow rate inside the tubes. Therefore, the air density and volume flow rate should also be calculated. Both of them are functions of pressure, temperature and relative humidity. These values are obtained in EES® program based on both inlet and outlet data.

$$\rho = \rho\ (\text{AirH2O}, T = T, R = rh, P = P) \tag{5}$$

$$\mu = \mu\ (\text{AirH2O}, T = T, R = rh, P = P) \tag{6}$$

Due to the CFD analysis, the average volume flow rate is 0.0607 $\frac{m^3}{s}$. Reynolds number is close to the turbulent flow (Table 3).

Table 3 Reynolds number

ρ	v_dot	m_a	D	μ	R_{e_D}
[kg/m^3]	[m^3/s]	[kg/s]	m	kg/m-s	-
1.166	0.0607	0.0708	0.6096	0.0000182	8127

Now, if we considesr the tube surface temperature is equal to the soil temperature, we can use the Equation (7) for sensible cooling load:

$$Q_t = h_f A_s \Delta t_{lm} \tag{7}$$

$$h_f = \frac{Nu_D k}{D} \tag{8}$$

The thermal conductivity of air inside the tubesis a function of pressure, temperature, and relative humidity. This is calculated in EES® as well:

$$k = k\ (\text{AirH2O}, T = T, R = rh, P = P) \tag{9}$$

The Nusselt number can be calculated based on the DittusBoelter Equation (10) (Bergman, 2011).

$$N_{u_D} = 0.023\, (R_{e_D})^{4/5}\, P_r^{0.3} \quad (10)$$

$$P_r = P_r\ (AirH2O, T = T, R = rh, P = P) \quad (11)$$

Table 4 shows the convective heat transfer coefficient.

Table 4 Convective heat transfer coefficient

K	D	P_r	R_{e_D}	N_{u_D}	h_f
[W/m-K]	m	-	-	-	W/m^2-K
0.02515	0.6096	0.743	8127	28.25	1.165

$$A_s = \pi DL \quad (12)$$

$$\Delta t_{lm} = \frac{(T_{soil}-T_{in}) - (T_{soil}-T_{out})}{\ln\frac{(T_{soil}-T_{in})}{(T_{soil}-T_{out})}} \quad (13)$$

Table 5 displays the A_s and Δt_{lm} mean calculated values.

Table 5 A_s and Δt_{lm}

D	L	A_s	T_{in}_Man hole	T_{out}_ AHU	T_{soil}	Δt_{lm}
m	m	m^2	°C	°C	°C	°C
0.6096	166	318	23.49	19.41	17.55	-3.514

Total saved cooling load is 216 kW. As the time step was a quarter of an hour, we can multiply this number by 0.25 to come up with the equivalent kWh amount which is 54 kWh. As mentioned, these values are for 5 work days on the second week of August.

Sensible Cooling – Enthalpy difference

So far, we calculated the total sensible cooling through Equation (7). However, heat removal could also be explained by the temperature and enthalpy difference between the inlet and outlet by Equation (14):

$$Q_t = m_a \Delta H \quad (14)$$

$$Q_t = m_a C_p (T_{out} - T_{in}) \quad (15)$$

$$C_p = C_p\ (AirH2O, T = T, R = rh, P = P) \quad (16)$$

Based on Equation (14), the cooling load is 244 kW or 61 kWh. The numbers obtained from Equation (7) and (14) are quite close which corroborates the calculations.

Latent Cooling

The next step is to calculate the latent heat exchange which is calculated by the following equations. Δh_{vap} and ω can be calculated by EES®. Table 6 summarizes the latent cooling calculations.

$$LE = m_w \Delta h_{vap} \quad (17)$$

$$\Delta h_{vap} = (Water, T = T) \quad (18)$$

$$m_w = m_a\, (\omega_{in} - \omega_{out}) \quad (19)$$

$$\omega = \omega\ (AirH2O, T = T, R = rh, P = P) \quad (20)$$

In the second week of August, the amount of latent load has been -32 kW or -8 kWh.

Table 6 Latent cooling

m_a	ω_{in} (total)	ω_{out} (total)	m_w	Δh_{vap}
[kg/s]	kg_vapor/ kg_air	kg_vapor/ kg_air	kg_vapor/s	kJ/kg_vapor
0.349	1.999	2.037	-0.013	2445

As we had considered ω_{in}-ω_{out}, the negative values show that the ω_{out} has been greater than ω_{in}. This means that the tubes have added a negligible amount of moisture to the air. This is somehow far from expected. When the air inside the tubes is cooled down to the dew point, dehumidification happens which should result in reducing latent cooling loads. Traces of dehumidification can distinctly be seen in the photos from August 4th below (Figure 15). According to the ONSET website, MX1101 and MX1102 are suitable in places up to only 90% humid. The discrepancy between latent cooling results and the observations could be due to the lack of approriate accuracy of the sensors in places with 90% Relative Humidity or higher.

Figure 15 Condensed water, August 4th, 2017

Uncertainty analysis

Considering the accuracy of devices, there is some uncertainty in the calculated amount. The accuracy of the devices is as follows:

- Pressure: ±0.21 kPa (0.2%)[9]
- Temperature: ± 0.21 °C (1%)
- Relative Humidity, above 80%: ±6% (8%)[10]
- Velocity (simulation): ±0.01 m/s (5%)

Using "Uncertainty Propogation" option in EES®, Uncertainty analysis has been done which is illustrated in Figure 16. The amount of sensible cooling calculated by two methods are 54±5 and 61±4 kWh, respectively.

[9] Pressure uncertainty is negligible.

[10] http://www.onsetcomp.com/products/data-loggers

The results reveal that the temperature accurancy has the most influence on sensible cooling uncertainty.

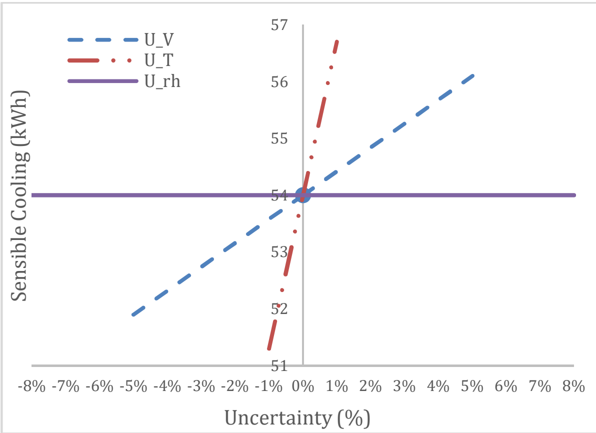

Figure 16 Uncertainty Analysis

Proposed model for future HETS

In a pre-design Earth Tube performance prediction, the main unknown value would be the temperature of the outlet of the tubes. In order to use this model to predict the performance of an Earth Tube in the pre-design phase, we need to define an algorithm.

Figure 17 displays the algorithm of the sensible cooling calculations. As Equations (7) and (14) evaluate the same value, we can estimate the outlet temperature, and the amount of sensible cooling, for a non-existing Earth Tube model.

To use this model, we only need to have the weather data, the geometry of the tubes, the fan specifications, and the soil temperature.

Based on TRNSYS mathematical references, we can use the Kasuda Equation (21) to figure out the soil temperature profile as a function of depth and the day of the year (Solar Energy Laboratory, 2007).

$$T = T_{mean} - T_{amp} * \exp\left[-d * \left(\frac{\pi}{365\alpha}\right)^{0.5}\right] * \cos\left\{\frac{2\pi}{365} * \left[t_{now} - t_{shift} - \frac{d}{2} * \left(\frac{365}{\pi\alpha}\right)^{0.5}\right]\right\} \quad (21)$$

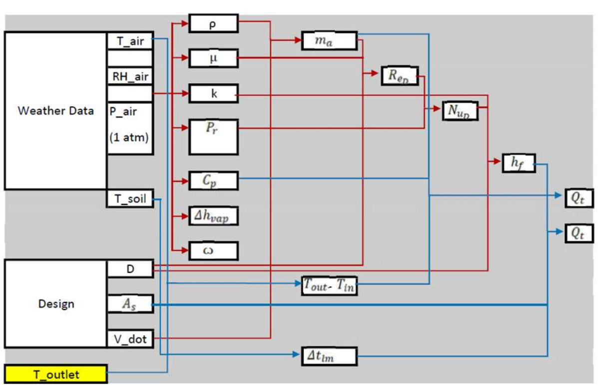

Figure 17 Sensible Cooling Algorithm

DISCUSSION AND RESULT ANALYSIS

CFD model

Despite what the designers of the system presumed, the flow is not distributed equally between the 5 parallel tubes. That is, instead of having one fifth of the air volume in each tube, the distribution is 13%, 14%, 22%, 19%, 32% from East to West. The furthest tubes from AHU and from the Manhole are the ones with 13% and 14% of the air flow. Accordingly, the thermal performance should be a bit different in each branch.

If we would rather a more evenly distributed kind of flow, an alternate arrangement of tubes could be considered. Changing the location of the manhole is probably one way to do that.

It seems that the very first 90-degree elbow after the Air Handling Unit is causing a huge amount of pressure drop, simply because it is too close to the fan.

Bulk flow model

According to the bulk flow model, in a period of 5 work days (8 am to 4 pm), on the second week of August, about 60 kWh (240 kW) has been saved due to sensible cooling loads. The results for latent cooling are not reliable due to sensors inaccuracy. The experiment will be reiterated next summer with appropriate equipment.

The mathematical bulk flow model enables us to predict the thermal cooling load of a HETS. Based on Figure 17, if we have the weather data, the soil temperature (Equation (21)), the diameter and the length of the tubes, and the fan volume flow rate, the only unknown would be the temperature of the outlet based on which we can calculate the sensible cooling load.

Future Works

Experiment: The experiment will be reiterated in cooling season 2018, with modifications including:

- Apply a more reliable RH sensor which works precisely even in ambient with RH close to 100%.
- Put the soil sensors deeper into the ground (we should find ways/devices to dig a deeper hole).
- Monitor and modify the hours the fan is working.

Model:

- Extend the data to evaluate the whole cooling season, not only a single week.
- Extend the model to heating season in addition to cooling season.
- So far, we only studied the behavior of air inside the tubes. A Finite Element model is being developed to study the behavior of soil besides air. Other papers have had similar approach (Trząski & Zawada, 2011).

CONCLUSION

A Horizontal Earth Tube System (HETS) is a passive system which helps with the pre-cooling and pre-heating fresh air before entering the building. Based on the data from a recent experiment, the system causes about 54±5 to 61±4.5 kWh sensible cooling energy saving during the work hours of one week in August in Wisconsin.

This paper has introduced an algorithm to predict thermal performance of a Horizontal Earth Tube System (HETS) during the cooling season. The model is based on the data from an existing sample located in the Aldo Leopold Foundation building, near Baraboo, WI. The experiment needs to be repeated using more accurate sensors. The project is still in progress and will include the heating season calculations as well.

ACKNOWLEDGMENT

We appreciate the staff of Aldo Leopold Foundation who helped us set up the experiment.

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NOMENCLATURE

A	Cross sectional area (m^2)	T	Temperature (°C)
A_s	Tube surface area (m^2)	T_{amp}	Amplitude of surface temperature (°C)
CO_2	Carbon dioxide	T_{in}	Air inlet temperature (°C or K)
C_p	Specific heat of air (kJ/kg-K)	T_{mean}	Average air temperature (°C)
d	Soil depth (m)	t_{now}	Current day of the year (day)
D	Tube Diameter (m)	T_{out}	Air outlet temperature (°C or K)
HETS	Horizontal Earth Tube System	t_{shift}	Day of the year corresponding to the minimum surface temperature (day)
h_f	Convective heat transfer coefficient of air inside tubes (W/m²-K)	T_{soil}	Soil Temperature (°C or K)
k	Thermal conductivity of air inside tubes (W/m-K)	U_rh	Relative Humidity Uncertainty (%)
L	Length of tubes (m)	U_T	Temperature Uncertainty (°C)
LE	Latent Cooling Energy (kW)	U_V	Velocity Uncertainty (m/s)
m_a	Mass flow rate of air inside tubes (kg/s)	Δh_{vap}	Latent heat of vaporization (kJ/kg)
m_w	Water condensation rate inside tubes (kg/s)	Δt_{lm}	Log mean temperature difference (°C or K)
N_{u_D}	Nusselt number	V	Air velocity (m/s)
P_r	Prandtl number	v_dot	Volume flow rate (m^3/s)
P	Pressure (kPa)	ω_{in}	Inlet air humidity ratio (kg_vapor/kg_air)
Q	Volume flow rate (m^3/s)	ω_{out}	Outlet air humidity ratio (kg_vapor/kg_air)
Q_t	Sensible Cooling Energy (kW)	α	Soil thermal diffusivity (m^2/day)
R_{e_D}	Reynolds number	μ	Air viscosity (kg/m-s)
RH	Relative Humidity	ρ	Air density (kg/m³)