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Earth-Air Heat Exchangers for Passive Air Conditioning: Case Study Burkina Faso

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Abstract: An earth-air heat exchanger (EAHX), also known as an earth tube heat exchanger or Canadian well, is a system for cooling and heating buildings using the ground as a heat sink/source. This study examines the ground temperature gradient and the performance of an EAHX performance in Burkina Faso. Ground temperature measurements were made at depths of 0.5 m, 1.0 m and 1.5 m. At the hottest time of the day, 15:00, the average outside temperature was 39.0°C, but the average temperature 1.5 m underground was 30.4°C. A clear phase shift was observed between the maximum outside temperature and the maximum ground temperature: the time of the day when the outside temperature is highest corresponds to the time when the underground temperature was lowest. The EAHX was 25 m long, 1.5 m underground and used a 95 m^3/hr ventilator. It was able to cool the air drawn in from the outside by 7.6°C.

Keywords: Earth-air heat exchanger (EAHX), Canadian well, Passive solar cooling, Burkina Faso, Thermal ground gradient, Sub-Saharan Africa

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) (Pachauri and Reisinger, 2007) estimates that the Earth's surface temperature has increased by 0.6°C and that human activities, such as burning fossil fuels for energy, have played a major role in climate change. Unfortunately, the world's insatiable thirst for energy will only increase as poorer countries become more industrialised.

Future energy demand will be particularly strong in the home heating and cooling sector in the developing world. As people gain affluence, one of the first luxuries they seek are heating and cooling systems for their homes and offices. For example, in the United States (USA), 87% of homes have air conditioning, while in India, only 2% of homes have air conditioning (Sivak, 2009). By 2030, India will catch up with the USA in the number of air conditioning units used within the country (Issac and van Vuuen, 2009). Once a home has air conditioning, the system can account for more than half of the home's energy consumption (Environmental Protection Agency, 2009).

A study conducted by Michael Sivak (2009) estimates that 24 of the top 50 metropolitan cities are in the developing world and are in warm climates. One city alone, Mumbai, has a cooling need equal to one quarter of the USA. It is predicted that by the end of the 21st century, the energy used for indoor cooling will be 40 times greater than it is today. This will cause the total CO_2 emissions to rise from 0.8 Gt C in 2000 to 2.2 Gt C in 2100 (Issac and van Vuuen, 2009).

Burkina Faso, a landlocked country in western Africa, is an example of a developing country with a major cooling demand. In the northern part of the country, temperatures can reach 50°C, and in the south, temperatures can reach

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45°C (Ogou et al., 2008). Even indoor temperatures can be dangerously high; it is not uncommon for it to be 40°C in a bedroom and 50°C in the kitchen.

Unfortunately, Burkina Faso is very poor, and its citizens have few options to cool their homes. Approximately 46.4% of the population lives below the poverty line (International Monetary Fund, 2005), and in 2003, Burkina Faso was ranked 6th among the least developed countries (United Nations, 2003). Hence, fans and air conditioners are luxuries for the very rich. To stay cool, most Burkinabe work and sleep outside. However, this puts people at a greater risk for contracting malaria or being attacked.

Even if a family can afford an air conditioner, only a small proportion of the country has electricity. It is estimated that 45.7% of the population has electricity in the cities and that only 1.1% of the population has electricity in rural areas (International Monetary Fund, 2005). In 2006, the country's energy consumption was 0.019 quadrillion BTU, but its energy production was 0.001 quadrillion BTU (US Energy Information Administration, 2006). Clearly, there is a major energy need in the country.

To ameliorate indoor temperatures, Burkinabe architects and engineers can design homes to take advantage of passive solar cooling techniques, such as thermal walls, cross ventilation and earth-air heat exchangers (EAHX). An EAHX is a passive climate control technology that relies on the ground mean temperature to heat and cool buildings (Florides and Kalogirou, 2007). A simple EAHX consists of underground tubes with both an inlet for outside air to enter and an outlet for air to exit a room. In warm weather, hot air from the outside enters the tube and cools as it travels through the tubes. The cooled air is then drawn or pumped into a room. In colder climates, cool air is drawn into the tubes and warmed as it travels through the tubes. The warm air is then used to heat a home.

Historically, EAHX research and implementation have been confined to Europe and America, although in recent years, researchers in emerging economies have investigated EAHXs. In India, Shukla, Tiwari and Sodha (2008) tested a closed-loop EAHX for an adobe house in New Delhi. In the summer, the EAHX cooled the room by 3°C, and in the winter, the EAHX heated the room by 6.5°C. Another researcher in India, Girja Sharan (2004), built several EAHXs, including an exchanger for a zoo and a greenhouse. In one of Sharan's studies, researchers used 50 m of pipe to cool the inside air from 40.8°C to 27.2°C.

Al-Ajmia, Lovedayb and Hanbyc (2006) conducted a theoretical study on EAHXs for desert environments in Kuwait. Kuwait has a hot and dry desert environment like that of Burkina Faso. In July and August, the average afternoon temperature in Kuwait is 45°C, and in the summer months, the average humidity is between 14% and 42%. Al-Ajmia et al. modelled several EAHXs and concluded that the optimal EAHX configuration used 60 m of pipe with a diameter of 0.25 m, buried 4 m deep, with a 100 kg/hr air flow rate. They conclude that an EAHX at the peak midday temperature in the summer (45°C) can cool a 300 m^3 building by 2.8°C. If the system is combined with traditional air conditioning, it can reduce the monthly energy demand by 420 kW hr and reduce the seasonal cooling demand by 30%.

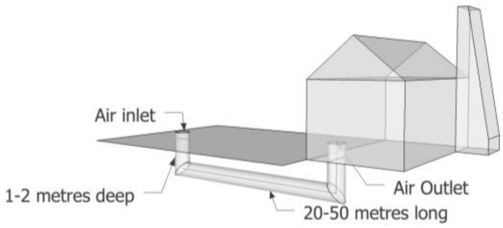

Figure 1. Diagram of A Simple EAHX

At the International Institute for Water and Environmental Engineering, two studies investigated EAHXs in Burkina Faso. In the first study (Ogou et al., 2008), a team tested the underground thermal gradient in Ouagadougou, Burkina Faso and modelled the cooling affects of a 30 m long EAHX buried 2 m underground. Over a two-day period, the team measured the soil temperature at 5 depths (0.4 m, 0.8 m, 1.2 m, 1.6 m and 2.0 m) and found that the soil temperature fluctuated between 30.6°C and 32.5°C at 2.0 m. In comparison, the outdoor temperature varied from 24°C to 40°C. They suggested that the best EAHX design for Burkina Faso would use 30 m of pipe (200 mm in diameter) and a volume flow rate of 245 m^3/hr. They predicted that the EAHX would cool the inside air by 5°C.

The other EAHX study conducted in Burkina Faso by Kintonou et al. (2008) examined the relationship between the tube length, tube diameter and the flow rate. The team concluded that a long, thin pipe and slower airflow in the tube allow better heat transfer between the soil and the air. De Paepe and Janssens (2003) reached a similar conclusion in 2003 when they studied EAHXs. However, De Paepe and Janssens also determined that arranging the tubes in a parallel sequence increases thermal performance by decreasing the pressure drop in the tube. Kintonou et al. (2008) concluded that the best EAHX for Burkina Faso would consist of two 17 m long tubes in parallel, buried 2.2 m underground, with a 90 m^3/hr ventilator. Overall, the EAHX would cool the air in the tube by 10°C.

Thermal Gradient of the Soil

The performance of an EAHX is governed by two factors: the underground temperature and the heat transfer between the pipes and the ground. The underground soil temperature depends upon the heat conduction through the soil and two boundary conditions: the initial surface temperature and the soil temperature as the depth approaches infinity (Elias et al., 2004; Mihalakakou et al., 1997). The one-dimensional solution proposed (Eq. 1) by Van Wijk and de Vries in 1963 (Elias et al., 2004) is a common method to describe the ground temperature profile, T(z,t) with respect to depth (z) and time (t). The variable "*a*" is the thermal diffusivity of the soil calculated by Eq. 2. For a list of the variables, refer to Table 1.

$$\frac{\partial^2 T(z,t)}{\partial z^2} = \frac{1}{a} \cdot \frac{\partial T(z,t)}{\partial t} \qquad (1)$$

$$a = \frac{\lambda_s}{\rho_s \times c_s} \quad (2)$$

The initial surface temperature can be described by a complex sinusoidal wave that combines the temperature variation over a day and the temperature variation over a year (Eq. 3).

$$T(0,t) = T_{sur} + A_a \sin(\omega_a t + \varphi_a) + A_j \sin(\omega_j t + \varphi_j) \quad (3)$$

The other boundary condition, the final temperature as the depth approaches infinity, equals the average annual temperature at the surface (T_{sur}) (Eq. 4).

$$\lim_{z \to \infty} T(z,t) = T_{sur} \quad (4)$$

The solution to Eqs. 1, 3 and 4 is given by Eq. 5.

$$T\ z,t\ = T_{sur} + A_a e^{-\frac{z}{Da}} \sin\left(\omega_a t - \frac{z}{B_a} + \varphi_a\right) + A_j e^{-\frac{z}{Dj}} \sin\left(\omega_j t - \frac{z}{B_j} + \varphi_j\right) \quad (5)$$

B is the dampening depth found using Eq. 6.

$$B = \sqrt{\frac{2a}{\omega}} \quad (6)$$

In Eq. 5, A_a = annual amplitude, ω_a = annual radial frequency, φ_a = annual phase constant, A_j = average daily amplitude, ω_j = daily radial frequency, and φ_j = daily phase constant.

Although the Van Wijk and de Vries method has been improved, for example, by re-examining the initial surface temperature (Elias et al., 2004) and the daily amplitude (Mihalakakou et al., 1997), researchers still consider the Van Wijk and de Vries solution to be an accurate simplification (Mihalakakou et al., 1997).

Table 1. Characteristics and Constants for Soil in Ouagadougou, Burkina Faso

Characteristics of Climate and Soil in Ouagadougou, Burkina Faso			
Thermal conductivity (soil)	λ_s	1.23	W/m.k
Mass volume (soil)	ρ_s	1520	kg/m^3
Specific heat (soil)	c_s	1650	j/kg.k
Thermal diffusivity	a	4.90E–07	m^2/s
Depth in the soil	z		metres

(continued on next page)

Table 1. (*continued*)

Characteristics of Climate and Soil in Ouagadougou, Burkina Faso			
Average annual surface temperature	Tsur	28.9	°C
Average annual temperature amplitude	A_a	6.17	°C
Daily temperature amplitude	A_j	5.5	°C
Dampening depth (annual)	B_a	0.037	metres
Dampening depth (daily)	B_j	1.93E–3	metres
Annual temperature radial frequency	ω_a	7.17E–4	rad/h
Daily temperature radial frequency	ω_j	0.262	rad/h
Annual temperature phase constant	φ_a	–4.00	rad
Daily temperature phase constant	φ_j	–1.57	rad

Source: Onou, 2008

Earth and Air Heat Transfer

The heat transfer between the soil and pipe is complex, but it can be simplified using several assumptions. First, we assume that the Earth is a semi-infinite body with an infinite heat capacity and that the temperature gradient across the tube wall is negligible. Moreover, if the Biot number is less than 0.1, we can assume that the heat conduction rate in the soil is higher than the heat convection from the tube wall to the air in the tube and therefore, that the tube will not affect the soil temperature. The Biot number can be calculated from the pipe diameter, D, the thermal conductivity of the soil, λ, and the global convection coefficient between the wall and air, h. These values are found in Tables 1 and 2.

$$\text{Biot number} = \frac{h * D}{\lambda} = 10.28 * 0.00125 / 1.23 = 0.0104. \quad (7)$$

(For a list of the variables refer to Table 2)

In a small section of tube, ds, the heat loss of the air in the tube is equal to the heat gain of the tube wall (Eq. 8).

$$\dot{m}C_p \; dT = h \, ds(T_p - T_x) \text{ where } ds = \pi D \, dx \quad (8)$$

Eq. 8 can be simplified to Eq. 9.

$$\dot{m}C_p dT = h\pi D(T_p - T(x))dx \quad (9)$$

This equation is solved for T(x) (Eq. 10). Note that the variable G is merely a constant that appears from taking the integral. It is replaced in Eq. 11.

$$T(x) = T_p - G\exp\left(-\frac{\pi hD}{\dot{m}C_p}\cdot x\right) \tag{10}$$

The initial conditions are the following (Eq. 11):

$$T(0) = T_i = T_p - G \Rightarrow G = T_p - T_i \tag{11}$$

Once the equation is solved with the initial conditions, the final solution is given by Eq. 12.

$$T(x) = T_p - (T_p - T_i)\exp\left(-\frac{\pi hD}{\dot{m}C_p}x\right) \tag{12}$$

To find the global convection coefficient, h, the Reynolds number (Eq. 13), Prandtl number (Eq. 14) and Nusselt number (Eq. 15) are calculated.

$$\mathrm{Re} = \frac{\rho \times V \times D}{\mu} \tag{13}$$

$$\mathrm{Pr} = \frac{\mu \times C_p}{k_a} \tag{14}$$

Because the Reynolds number is greater than 2300, the flow is in the turbulent region. The Nusselt number can be determined using the Dittus-Boelter equation (Al-Ajmia, Lovedayb and Hanbyc, 2006) because there is fully developed turbulent flow in a smooth tube. The global convection coefficient is found using Eq. 16.

$$Nu = .023 \times \mathrm{Re}^{0.8} \times \mathrm{Pr}^{0.4} \tag{15}$$

$$Nu = h \times \frac{D}{k_a} \tag{16}$$

The global convection coefficient is calculated to be 10.28 W/(m^2.°C).

Table 2. Characteristics and Constants of EAHX

Constants and Calculated Values			
Specific heat (air)	C_p	1.005	$J.kg^{-1}.°C^{-1}$
Thermal conductivity air	k_a	0.0257	$W.m^{-1}.°C^{-1}$
Length of pipe	x		m
Diameter of tube	D	0.00125	m
Length of tube	L	25	m
Flow volume of air	$\dot{q}$	95	m^3/hr
Velocity of air	V	2.15	m/s
Mass flow of air	$\dot{m}$	114.48	kg/s
Mass volume of air	ρ	1.205	kg/m^3
Dynamic viscosity	M	$1.86X10^{-5}$	Pa.s
Temperature of air entering tube	T_i		°C
Temperature of air leaving the tube	T_o		°C
Temperature of the experiment room	T_r		°C
Temperature of the control room	T_{con}		°C
Temperature of the air at point X	T_x		°C
Temperature of tube wall	T_p		°C
Global convection coefficient between wall/air	h	10.28	$W.m^{-2}.°C^{-1}$
Reynolds number	Re	17410	dimensionless
Prandtl number	Pr	7.27E–01	dimensionless
Nusselt number	Nu	50.01	dimensionless

Source: Onou, 2008

Experimental setup

The EAHX constructed at the International Institute for Water and Environmental Engineering in Ouagadougou, Burkina Faso is a horizontal, open-loop system, 25 m long and 1.5 m deep (the pipe is slightly declined so that condensation can drain from it through a hole drilled in the bottom). The pipe is a 125 mm diameter, schedule 80, PVC pipe. The EAHX has two air inlets, located 15 m and 25 m away from the air outlet in the building. The two air inlets allow the system to be tested with two different pipe lengths. In this study, an EAHX using 25 m of pipe was tested.

There are five temperature sensors located inside the pipe: 5 m, 10 m, 15 m, 20 m and 25 m away from the air inlet. In addition, there are temperature sensors buried 0.5 m, 1.0 m and 1.5 m in the ground to measure the soil temperature gradient. To clean the EAHX, a nylon cord was placed inside the tubes, which allows a cloth to be pulled through the system, removing all of the dust and debris.

The experiment room and the control room are each 3.50 m × 2.75 m × 5.35 m. The experiment and control rooms share a wall, and both of the rooms are connected to a larger laboratory. The walls are 18 cm thick and made from locally produced brick covered in concrete. The ceiling is made from wood slates, and the roof of the structure is corrugated steel. This is a typical construction for homes and offices in Burkina Faso. The ventilator used to draw the air through the pipes is 14 W and has a volume flow rate of 95 m^3/hr.

Figure 2 is a diagram of the EAHX and laboratory. The experiment room is on the right, and the control room is connected on the left. The large laboratory (not shown) extends from the rear of these rooms. The 25 m long EAHX (serpentine pattern) is connected to the experiment room.

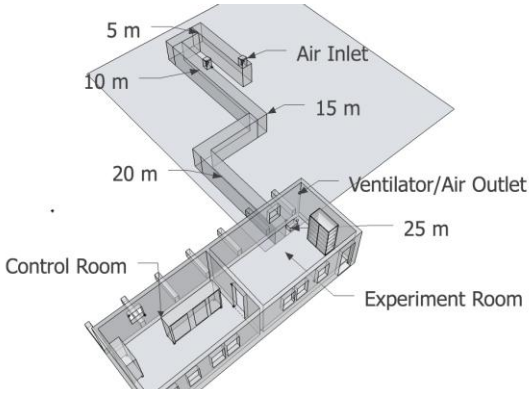

Figure 2. Schematic of EAHX and Laboratory in Ouagadougou, Burkina Faso

Baseline measurements were taken from 11 February 2009 to 14 April 2009, and the EAHX was tested from 14 April 2009 to 14 May 2009. Temperature measurements were taken at 09:30, 11:45, 15:00 and 16:30, and the EAHX ventilator was operational from 10:00 until 16:30. From 12 May 2009 to 14 May 2009, the system was monitored continuously for 52 hours to observe the overnight temperature trends. Temperatures at twelve different points were measured: in the experiment room, in the control room, in the main laboratory, outside the building, inside the pipe (at 5 m, 10 m, 15 m, 20 m and 25 m away from the inlet) and in the soil (at depths of 0.5 m, 1.0 m and 1.5 m).

Sensors

We used an Almemo 2290-8 V5 with NiCr-Ni probes to measure the temperature of the rooms and the outside air, and we used a TPI-343 digital thermometer with standard K-type thermocouples to measure the ground temperatures and the air temperatures inside the pipe. The K-type thermocouples were permanently placed inside the tube. Hollow steel pipes protected the thermocouple cord as they ran from the pipe to the surface.

Statistical Modelling

Two different statistical parameters, Pearson's correlation coefficient (r') and the root mean square error (RMSE), (*e*), are used to describe the relationship between the theoretical and measured values (Shukla, Tiwari and Sodha, 2006).

$$r' = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2}\sqrt{n\sum y_i^2 - \left(\sum y_i\right)^2}} \tag{17}$$

$$e = \frac{\sqrt{\sum (e_i)^2}}{n}, \quad e_i = \frac{x_i - y_i}{x_i} \tag{18}$$

Table 3. Variables for Pearson Correlation Coefficient and Root Mean Square Error

Variables for Statistical Analysis	
Number of elements	n
Theoretical value	x
Experimental value	y

RESULTS

The ground temperature gradient shows a clear thermal dampening and thermal shift. At a depth of 0.5 m, the ground temperature ranged from 28.6°C to 36.2°C, and the average temperature was 32.1°C. At a depth of 1.5 m, however, the temperature ranged from 26.6°C to 33.1°C, and the average temperature was 30.4°C. Figure 3 shows a comparison of the theoretical values of the ground temperature gradient with the measured ground temperatures. The measurements were taken between 31 March 2009 and 14 May 2009. On the x-axis, 0 = 0:00 hours (midnight) and 12 = 12:00 (noon). The measured values were, on average, 1.2°C, 2.0°C and 1.7°C higher than the theoretical values for the temperature gradient at depths of 0.5 m, 1.0 m and 1.5 m, respectively. Although the measured values of the temperature were on average higher than the theoretical temperature values, the root mean square errors between the theoretical and experimental values are small.

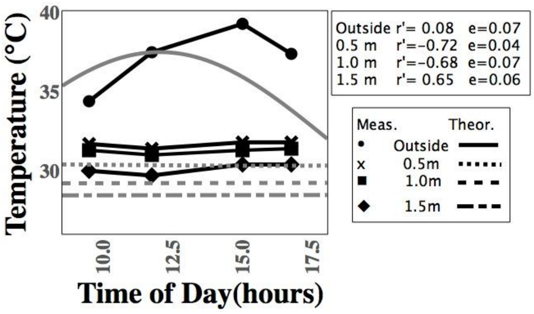

Figure 3. Temperature vs. Time of Day (Hours)

In addition, the ground temperature gradient model accurately predicts the soil temperature over a 52-hour period between 12 May and 14 May (see Figure 4).

During this time period, the outside temperature and the ground temperature were recorded approximately every three hours, and the RMSE between the theoretical and measure values ranged from 0.02°C to 0.10°C. Figure 4 is a plot of the theoretical and measured temperatures during the 52-hour period. In the figure, the origin on the x-axis represents midnight on 12 May. The data clearly show the soil temperature decreasing with depth and the phase shift of the ground temperature with respect to the outside air temperature. At the hottest time of the day (11:45 to 15:00), the ground temperature was the coolest, and at the coldest time of the day (06:00 to 07:30), the ground temperature was the hottest.

Overall, the EAHX is effective in lowering the temperature of air drawn in from the outside. At 15:00, the air was cooled by an average of 6.18°C, 6.93°C, 7.42°C and 7.62°C after the air travelled 5 m, 10 m, 15 m and 20 m, respectively. At 09:30, the air was cooled by an average of 2.07°C, 1.90°C, 1.82°C and 2.53°C after the air had travelled 5 m, 10 m, 15 m and 20 m, respectively. The cooling affects are less pronounced early in the morning because the outside air is already cool. One notable observation is that the air leaving the tube (T_o) is warmer than the air measured inside the tube at 20 m (T_{20}). At 15:00, the average T_S was 32.4°C, while the T_{20} is 31.4°C. It is likely that the air warms as it travels in the vertical tube that connects the underground portion of the EAHX to the experiment room. The average temperature differences (ΔT) between the temperature entering the tube (T_i) and the temperature exiting the tube (T_O) at 09:30, 11:45, 15:00 and 16:45 are 0.93°C, 4.15°C, 6.65°C and 3.80°C, respectively. Figure 5 shows a graph of the outside temperature minus the tube temperature at length ($T_i – T_x$) vs. tube length. The graph shows a comparison of the measured temperature difference with the theoretical temperature difference. The temperature was measured at four times each day: 09:30, 11:45, 15:00 and 16:45.

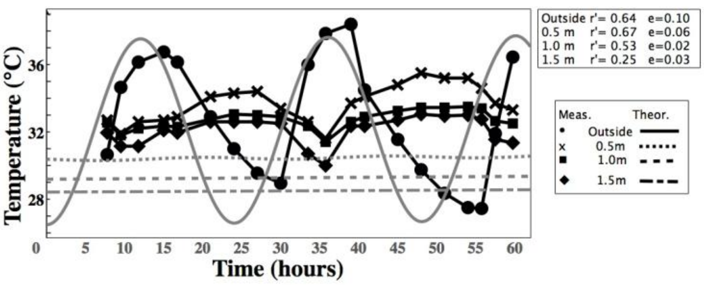

Figure 4. Temperature vs. Time

Unlike the results from the previous experiments, these results exhibit a large error between the theoretical and measured values of the cooling potential of the EAHX. Overall, the cooling ability of the EAHX was greater than predicted. The differences between the theoretical and measured values could be caused by a variety of factors, such as an inaccurate model, varying weather conditions, or measurement error.

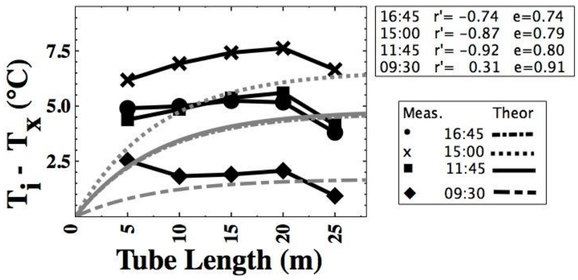

Figure 5. Outside (T_E)-Tube Temperature vs. Tube Length

CONCLUSIONS AND FUTURE WORK

It was shown that a 25 m long EAHX buried 1.5 m in the ground can cool air drawn in from outside by more than 7.5°C. In addition, despite the extreme outdoor temperatures, which varied from 25°C to 43°C, the soil temperature at a depth of 1.5 m remained at approximately 30.4°C. The models accurately predicted the underground soil temperature, but they did not accurately predict the difference between the temperature in the tube and the outside air.

In the future, we will improve our EAHX model, compare our results with other EAHX models and study the cooling potential of an EAHX to lower the cooling load of air conditioning systems. We will also investigate different configurations that may make the EAHX more effective in Burkina Faso and other desert-like environments. The biggest hindrances to implementing EAHX technology in Burkina Faso are social and architectural norms unrelated to EAHX. For example, many homes in Burkina Faso have corrugated steel roofs. Although steel is sturdy, it becomes very hot in the sun and raises the temperature inside the home. Before an EAHX can be successful, architects and engineers must design homes to take advantage passive cooling techniques.

EAHXs are a good technology to improve the quality of life in developing countries and to reduce the electricity demand in those countries. If the developing world can reduce its energy demand for cooling, then perhaps the IPCC's dire outlook for world emissions and climate change can be altered.

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