The use of Earth-air heat exchanger for improving building comfort conditions in the Tropical Climate

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Abstract:

Tropical climate is characterised by high ambient temperatures and solar radiation, a combination of these factors causes thermal discomfort in buildings. The common approach to maintaining comfortable thermal environment in buildings in such climates is using mechanical air-conditioning systems. High energy demand is needed to operate and maintain these systems continuously over long periods of time. With the rapid increase in population and economic growth of countries in the tropical regions, it is becoming inevitable that passive and low energy strategies must be used as suitable alternatives. Earth-air heat exchanger (EAHX) is a subterranean ventilation system that explores soil temperature below the surface to pre-cool or pre-heat ventilation air. Performance of EAHX varies with climatic and soil condition of the area. Climatic and soil parameters affecting the thermal performance of EAHX has been determined for Tropical climate of Nigeria. Thermal simulations have been carried out using Transient System Simulation Environment (TRNSYS) to evaluate the cooling energy gain and the reduction of ambient temperature extremes. The results show that the system can be used to improve comfort conditions and reduce building cooling loads.

Keywords: Earth-air heat exchanger, Sustainability, Tropical climate, TRNSYS, indoor condition, passive and low-energy cooling, soil temperature.

Introduction

Earth-air heat exchanger is a subterranean cooling system that utilises ground temperature for pre-cooling or pre-heating ventilation air in summer and winter respectively. Research has established that subsurface soil temperature is lower than ambient air temperature in summer and higher than ambient air temperature in winter, this is as a result of high soil thermal mass that store high percentage of the heat gain on daily basis to less than 30cm below the surface (Labs, 1989). Temperature difference between air and soil can be utilised to pre-cool or pre-heat ventilation air supply using earth-air heat exchanger, which consists of pipes buried below ground surface through which ventilation air is circulated. Potential of earth-air heat exchanger has been established in moderate climates of Europe, however not much research has been carried out in hot climates because of the claim that the potential is low due to higher soil temperature in summer. Potential of the system in hot climates may however be improved using various soil cooling strategies to lower the natural subsurface soil temperature such as shading, irrigation and so on. (Givoni, 2007, Kasuda, 1975).

Tropical climate is characterised by high ambient temperatures and solar radiation, a combination of these and other factors causes thermal discomfort in buildings. The common approach to maintaining comfortable thermal environment in buildings in tropical climates is using mechanical air-conditioning systems. In buildings where mechanical cooling cannot be afforded, buildings are occupied in harsh conditions which affect performance especially in offices. High energy demand is needed to operate and maintain mechanical systems continuously over long periods of time. With the rapid increase in population and economic growth of countries in the tropical regions, it is becoming inevitable that passive and low energy strategies must be used as suitable alternatives. Passive system have the potential to reduce operational energy consumption for cooling buildings in the tropical climate, help reduce rising energy demands and the associated greenhouse gas emissions that is detrimental to the planet.

To explore this potential, the soil temperature for different surfaces has been established for three climatic regions of Nigeria and the potential of earth-air heat exchanger have been evaluated for the three climatic regions. Thermal simulations have been carried out using Transient System Simulation Environment (TRNSYS) to evaluate the thermal energy gain and the reduction of ambient temperature extremes. The results show that the system can be used to improve comfort conditions and reduce building cooling loads. Figure 1 shows a typical configuration of EAHX (Ahmed et al., 2007).

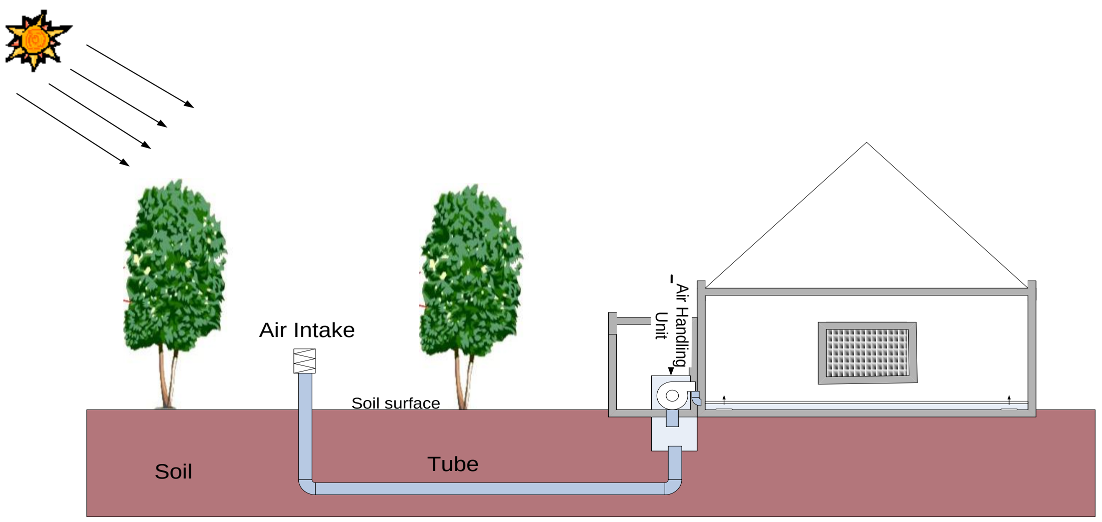

Figure 1 Configuration of Earth-air heat exchanger

Methodology and Simulation

The research was carried out using thermal modelling of the EAHX evaluated within the Transient System Simulation Software Program (TRNSYS) environment. TRNSYS is a complete and modular simulation environment for the study of dynamic systems (TRNSYS16.0, 2005). The open modular structure within TRNSYS allows for the use of inter-connection of existing components and user written components to develop a simulation project. Thermal models and tools for evaluating the thermal performance of EAHX have been developed with varying degree of detail and flexibility. for the After rigorous review of existing models/tools, the air-soil heat exchanger model (Type 460) developed by Hollmuller and Lachal (Hollmuller and Lachal, 2001) has been selected and adopted for this study. Earth-air heat exchanger model has been coupled with building interface TRNBLD to study the impact of the earth tube on indoor temperature. Monthly average climate data for three Climatic regions of Nigeria has been established from NASA Solar energy and surface meteorology database (NASA, 2006). For the purpose of TRNSYS simulation, typical metrological year (TMY) for these locations has been established using meteonorn programme which generates hourly data based on long term monthly averages for locations around the world. Soil parameters have been established from Nigerian soil reconnaissance survey (Okeye et al., 1990)

Soil temperature

Temperature gradient between ambient air and soil is the main driving force for the design of EAHX. Therefore the most important parameter in the evaluation of ground cooling systems is the ground temperature over the year, unfortunately this is not measured by most weather stations around the world, and in particular there is no evidence of any records of soil temperature in Nigeria. Thermal model for predicting the performance of ground cooling system require soil temperature or soil surface temperature, therefore these should be achieved using readily available climatic parameters. Empirical correlations have been developed over the years for predicting soil temperature at various depths, (Kasuda, 1967, Mihalakakou et al., 1997, Labs, 1989). These mathematical models are Fourier's series based on one-dimensional heat transfer solution in semi-infinite soil medium.

Soil temperature mathematical correlations require information on ground physical and thermal properties, ground surface temperature, as inputs. Equation 1 shows the fourier series developed by Labs (1989) and used to generate soil temperature and soil surface temperature for three locations in the three climatic regions of Nigeria. How ver the models have been validated for temperate climates and desert climate (Al-Ajmi, 2002). The models are based on the fact that annual variation in soil surface temperature follows similar pattern of air temperature and intensity of solar radiation on ground surface, which can be approximated to a sine wave if variations as a result of cloud cover and other atmospheric effects such as as haze and fog are ignored.

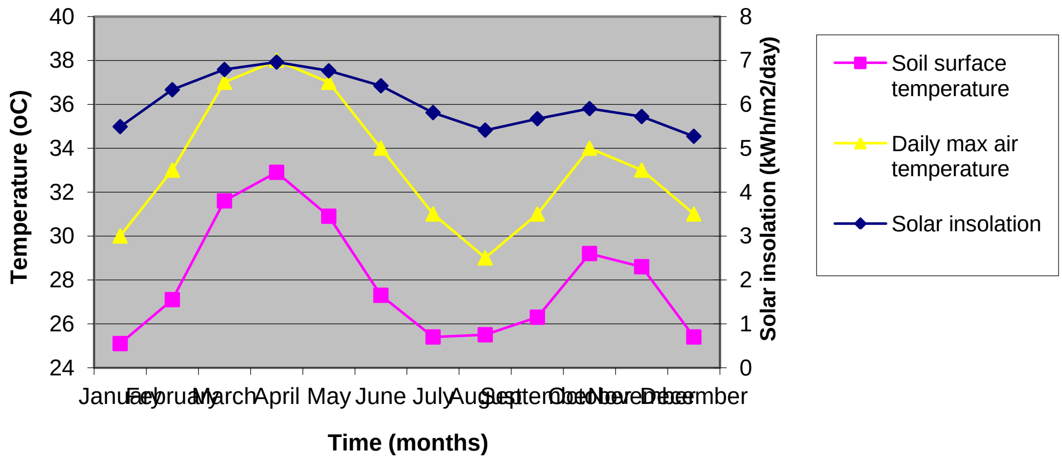

Figure 2 Climate variables for composite climate of Kano Northern Nigeria

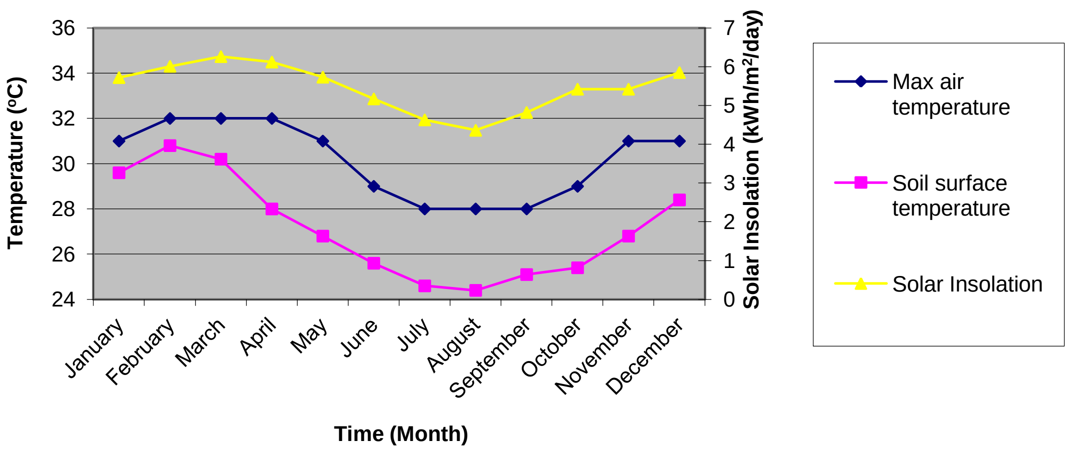

Figure 3 Climate variables for hot humid climate of Lagos, Southern Nigeria

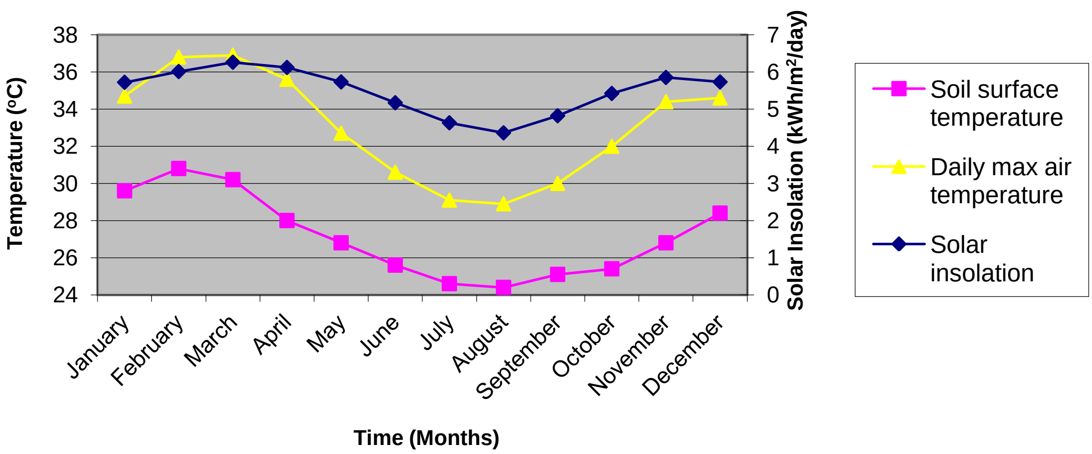

Figure 4 Climate variables for composite climate of Minna central Nigeria

Figures 1,2,3 shows the variation of solar radiation, ambient air and soil surface temperature for three climatic regions of Nigeria, composite climate of Kano, hot humid climate of Lagos and composite climate of Minna in central Nigeria, each exibiting different characteristics. From figure 1,2,3 It is reasonable to say that the annual variation of ambient temperature, solar radiation and soil surface temperature cannot be approximated into a single sine wave that is the basis of calculating soil temperature. Equation 1 show the Labs (1989) correlation used in temperate and desert climates to successfully predict soil temperature with reasonable accuaracy.

$$\frac{2\pi}{365}\,T_{z,t} = T_m - A_s \times \exp\left[-z\left(\frac{\Pi}{365\alpha}\right)^{1/2}\right] * Cos\left\{\frac{2\Pi}{365}\left[t - to - \frac{z}{2}\left(\frac{365}{\Pi\alpha}\right)^{1/2}\right]\right\}$$ ....**Equation 1**

$T_{z,t}$ = Soil temperature at time t and depth z (ºc)

A_s = Mean annual ground surface temperature (ºc)

α = Thermal diffusivity of soils (m²/h)

Z = Depth below surface (m)

t = Time elapsed from the beginning of calendar year.

t_o= Phase constant (day of year of minimum surface temperature) (days/hours)

For calculating the soil surface temperature for locations in Nigeria equation 1, is adjusted to generate soil surface temperature over an annual cycle by approximating the sinusoidal wave to two sine waves by changing $\frac{2\pi}{365}$ in equation 1 into $\frac{4\pi}{365}$. Equation 2 shows the new equation which has been validated using the records of soil surface temperature for two locations in Nigeria, Composite savannah climate of Kano bordering the Sahara desert and hot humid climate of Lagos on the Atlatic ocean.

$$T_{z,t} = T_m - A_s \times \exp\left[-z\left(\frac{\Pi}{365\alpha}\right)^{1/2}\right] * Cos\left\{\frac{4\Pi}{365}\left[t - to - \frac{z}{2}\left(\frac{365}{\Pi\alpha}\right)^{1/2}\right]\right\}$$ .....**Equation 2**

The altered models have been used to predict the surface temperature for Kano, the result of prediction and NASA surface temperature data shows very good agreement within the range of 1.4K and -0.1K Shown in figure 5. Figure 6 show the predicted and NASA soil surface temperature for Lagos, this models show similar pattern with records over time

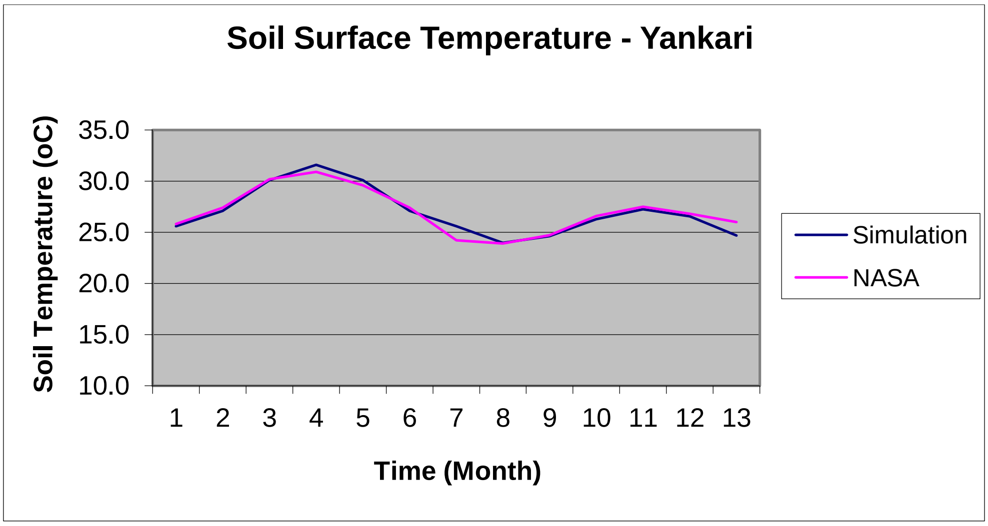

Figure 5 Soil surface temperature for Kano Nigeria

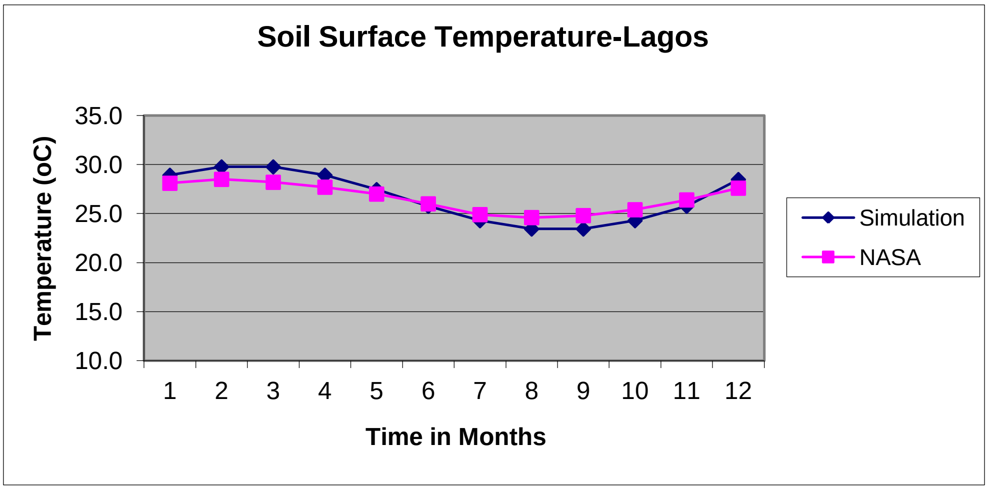

Figure 6 Soil surface temperature Lagos-Nigeria

Simulation studies

Earth-air heat exchanger simulation projects have been developed and simulations run for the two loactions.

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