THERMAL PERFORMANCE OF EARTH-AIR HEAT EXCHANGER FOR REDUCING COOLING ENERGY DEMAND OF OFFICE BUILDINGS IN THE UNITED KINGDOM

Abdullahi Ahmed, Kenneth Ip, Andrew Miller and Kassim Gidado
School of Environment and Technology, University of Brighton, Cockcroft Building, Lewes Road, Brighton, East Sussex, BN2 4GJ, United Kingdom

ABSTRACT

There is a rising demand for conventional mechanical cooling systems in UK buildings over the last 10 years, which is due to increase in building internal and solar heat gains. Use of passive and low energy strategies for cooling and heating of buildings is an attractive alternative for providing comfortable indoor environments with low energy use. Earth-air heat exchanger (EAHX) is a low-energy system that utilises the stable subsurface soil temperature to reduce ventilation air temperature. There appears to be very limited research and published data on their thermal performance in the UK. This paper evaluates the thermal performance of the earth-air heat exchanger under different configurations and operating conditions in the UK. Transient Systems Simulation Software (TRNSYS) has been used to model EAHX using UK climatic and soil parameters. The result reveals significant improvement in indoor thermal conditions and the potential to reduce use of energy intensive conventional cooling systems.

INTRODUCTION

Cooing demand in buildings in UK has been increasing over the last decade and projected to increase over the next 10 years (Hitchin, 2000). The rise in use of mechanical cooling is because of increase in building cooling load due to a combination of factors. These factors include urban heat island effect, increase in building internal load due to density of people and other heat emitting equipments in buildings and high ambient temperatures in urban centre (Santamouris, 2007). CIBSE (2005) found that rise in global temperatures due to climate change have the potential to result in buildings overheating unless some adaptive measures are taking over the next 50 years. One of the greatest challenges of current generation is dealing with threat of global climate change. Global climate change is scientifically proven to result from human activity such as emission of greenhouse gases through burning of fossil fuel. Conventional mechanical cooling systems are highly energy intensive and still utilise some Hydro Chloro-Flouro Carbons (HCFCs) as refrigerants, which releases some greenhouse gases to the atmosphere. The desire to reduce emission of greenhouse gases is bringing about increased pressure by both UK and European regulations to improve building energy efficiency and the use of on-site low and renewable energy technologies. Passive and low energy strategies for cooling such as earth-air heat exchangers are gaining popularity in Europe. Although the use earth-air heat exchangers for low-energy cooling and heating of building is gaining recognition as a low or zero carbon emission technology, there is very limited research and published data on their thermal performance in the UK. Breesch et al. (2005) argued that lack of adequate design information might prevent some designers from application of passive and low energy systems in their design. The thermal performance of earth-air heat exchanger is dependent on climatic and soil parameters, which makes the simplified rules of thumb inadequate for the evaluation of system performance for all locations. Eventhough EAHX may be applied for both pre-cooling and pre-heating this work focusses on the thermal performance for cooling.

THERMAL MODELLING

The analysis of the thermal performance of earth-air heat exchanger require heat transfer analysis of the convective heat transfer between air and soil and heat diffusion in pipes and surrounding soil. There are a number of attempts by researchers to develop analytical and numerical thermal models for predicting the outlet air condition and heat transfer in earth-air heat exchanger. These models have been developed with different levels of accuracy, complexity and assumptions. A review of existing thermal models and their underlying assumptions have been carried out to establish current state of the art. Sodha et al., (1985) used steady state heat transfer analysis to develop a one-dimensional model by solving only the convective heat transfer between pipe and air. This solution is inappropriate for a transient system like EAHX, because heat exchange from air to soil gradually changes soil temperature around the pipe. Kumar et al. (2003) developed three-dimensional heat and mass transfer model for single pipe EAHX. The model solves convective heat transfer and three dimensional heat and mass transfer in EAHX. These categories of models are limited to modelling single pipe configurations, which does not account for the thermal interference by neighbouring pipes or buildings. DePaepe (2002) developed multiple pipe transient model using numerical method. The model solves both sensible and latent heat exchange between pipe and air and the three-dimensional heat and mass transfer in soil. The model also allow for the dimensioning of multiple pipe configurations. Mihalakakou et al. (1994) uses principle of superposition of the solution of single pipe models to account for thermal interference of neighbouring pipes. These solutions assume homogenous soil conditions and uniform soil surface condition, which limits their application to simple geometries. Detailed numerical solutions developed by Hollmuller and Lachal (2001) has been found to be the most comprehensive for the thermal analysis of EAHX. The model solves both sensible and latent heat exchange and three-dimensional heat and mass transfer in soil. The model also allow for dimensioning multiple layers of pipes with non-homogenous soil profile, multiple soil surfaces and variation in direction of airflow. The model has been validated against analytical solution and long term monitored data from real scale installation by Holmuller and Lachal, (2005).

SYSTEM SIMULATION

The thermal simulation of the system has been developed within Transient System Simulation Environment (TRNSYS). TRNSYS is a modular simulation environment for the study transient low and renewable energy system. TRNSYS also have a building interface (TRNBuild) for integrated building and system simulation. The adopted thermal model require large set of input parameters defined in the form of a parameter files, which consist of the system geometry, thermal properties of air, soil and pipes and heat exchange coefficients. The development of these files is a tedious process and often a source of error for the simulation. C++ executable have been developed as a TRNSYS plug-in, plug-in technology allows for external applications to be called first to generate the parameter files before the simulation is run. The simulation of earth-air heat exchanger also requires climatic data such ambient air temperature and relative humidity. Weather data for UK locations have been generated using Meteonorm files provided within TRNSYS. Metenorm uses monthly average weather data for any location to generate Typical Metrological Year at small time steps. This feature allows system simulations even in locations where hourly climate data is not available. TYPE 109 TRNSYS weather data reader has been used to read weather data and process solar radiation at different time intervals for both system and building simulations. Soil surface temperature and thermal properties determine the heat balance at the soil surface, which affects the subsurface soil temperature (Labs, 1989). Soil thermal properties have been determined from British Geological Survey (BGS) borehole records (BGS, 2006). The soil surface temperature is not measured by most weather stations around the UK. The soil surface temperature has been generated using TRNSYS Type54 weather data generator, which uses long-term monthly average climate data to generate hourly data. Long-term monthly soil surface temperature from NASA database of Surface Meteorology and Solar Energy has been used. The data has been developed based long-term estimates of meteorological quantities and surface solar energy fluxes (NASA, 2006).

Simulation tool

Because of the complex set of input parameters and the need for climate data for the simulation of the system, a Windows based simulation tool has been developed using TRNSYS interface TRNedit, which allows for the creation of Windows based application that allow for system parametric analysis. The parametric simulation runs has been achieved by setting parametric tables of simulation parameters. All relevant simulation files and weather data files were provided and can be selected for about 32 UK locations using drop down menu. The TRNSED application shown in Figure 1 makes the simulation of earth-air heat exchanger less complicated especially for users that have no experience of thermal modelling and the TRNSYS environment and can serve as standalone EAHX simulation tool for people with no TRNSYS licence or experience with TRNSYS software.

Office building models have been developed using the TRNSYS building interface (TRNBuild). The office building description has been generated using values of building internal gain recommended by CIBSE environmental design guide (CIBSE, 2006). The climate data of London and Aberdeen has been used for the integrated EAHX and building simulation. The building model has been integrated with the earth-air heat exchanger simulation, the outlet air condition from the earth-air heat exchanger provides the supply air condition for the building ventilation system.

RESULTS AND DISCUSSION

Thermal simulations have been carried out using the TRNSED application developed, to establish the outlet air condition and the cooling energy gain due to the operation of earth-air heat exchanger. The results have been presented for two UK locations of Aberdeen and London, which represents climatic regions with the coldest and warmest conditions respectively. The results have been presented in terms of outlet air condition and annual thermal energy gain for the selected locations.

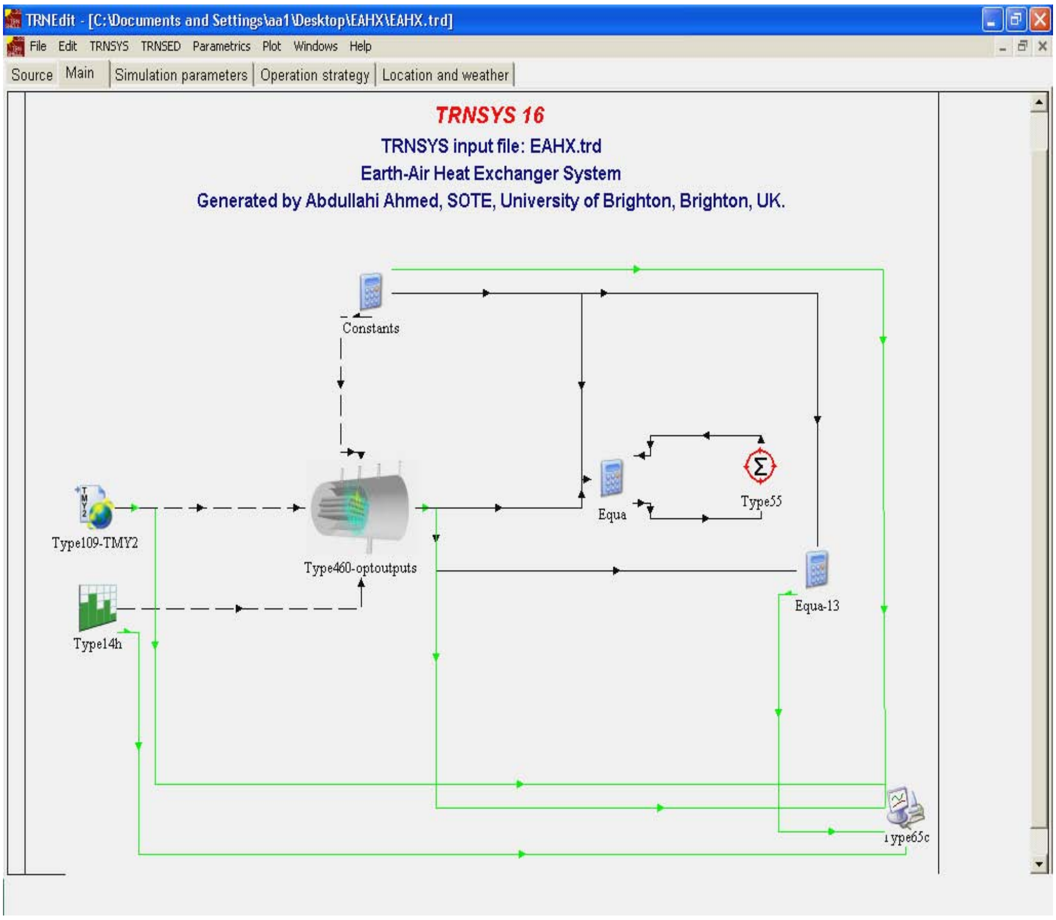

Figure 1 TRNSED earth-air heat exchanger simulation tool

Outlet air temperature profile

The heat exchange between air and soil results in the reduction or increase in supply air temperature during summer and winter respectively. Figure 2 shows the annual profile of outlet air temperature for 20cm diameter EAHX, 2m depth and 30m to 80m long. The outlet air temperature is plotted against ambient air temperature for London in South East England, to show the thermal potential of the system for reducing ventilation air temperature. The results reveal a reduction of ambient inlet air temperature of about 8K to 13 K, which shows that small diameter pipes provide peak outlet air temperature of about 16°C and 20°C for 80m to 30m length respectively. The thermal performance of earth-air heat exchanger can be improved by increasing the length or by reducing the air velocity to the very minimum. The increase in length increases heat exchange area which compensates for the low convective heat transfer rate. In Aberdeen, the summer condition is mild with very cold winter as is the case Northern United Kingdom. The soil temperature is affected by the immediate ambient climatic conditions, therefore the soil temperature in summer is very low in Scotland and Northeast United Kingdom. The combination of low soil temperature and mild ambient summer temperatures increases the potential of the system for avoiding the need for conventional mechanical cooling even in buildings with very high internal heat load. Figure 3 shows the outlet air temperature for a 20cm diameter EAHX buried at 2m depth, 2 m/s air flow rate and 30m to 80m length, for Aberdeen, North Eastern Scotland, which reveals a peak outlet air temperature of about 16°C and 14°C. The temperature drop between inlet and outlet air is about 8K to 10K for 30m and 80m systems respectively. In this part of the UK, there appears to be no significant reduction in ambient temperature with increase in length, which is about 2K for increase in length from 30m to 80m. This reflects a similar temperature drop for similar system configuration in London, even though the soil temperature is lower in Aberdeen. The reason for the similarity in air temperature drop may be the high temperature difference between air and soil in London, which is as a result of high ambient air temperatures in summer. Despite the low soil temperature the temperature difference between air and soil in Aberdeen is small due to mild ambient temperatures. This reveals that with small diameter pipe and low air velocity provides the best option in Aberdeen.

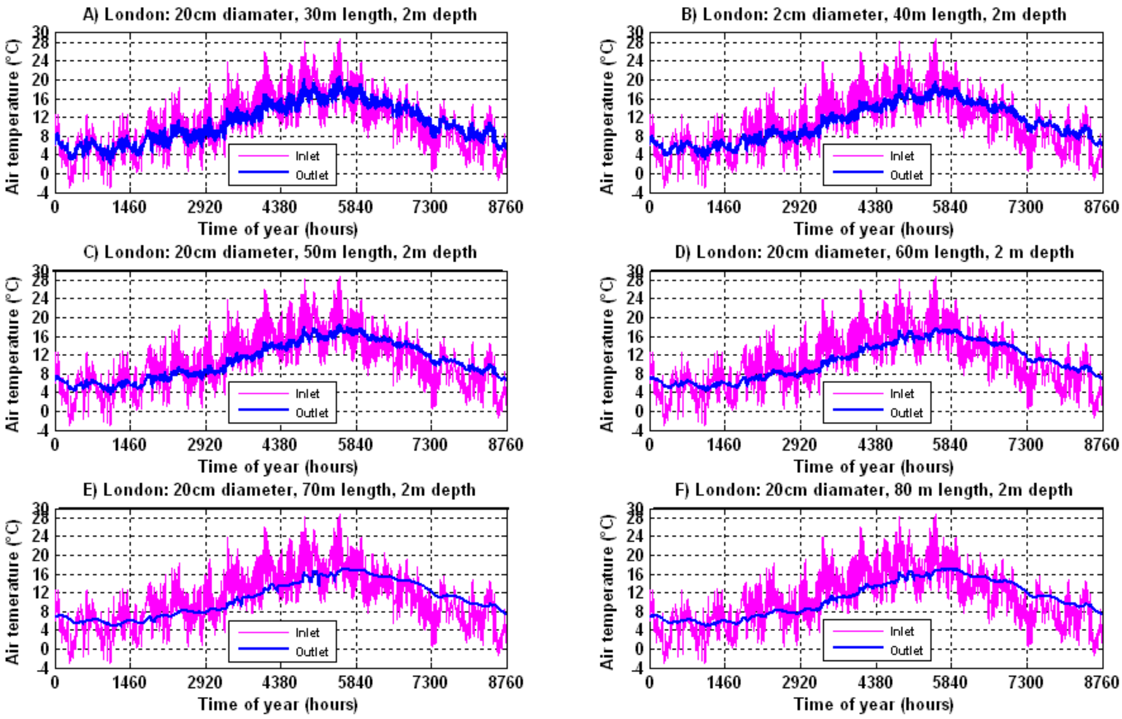

Figure 2 Inlet and Outlet air temperature profile for 20 cm diameter EAHX, London

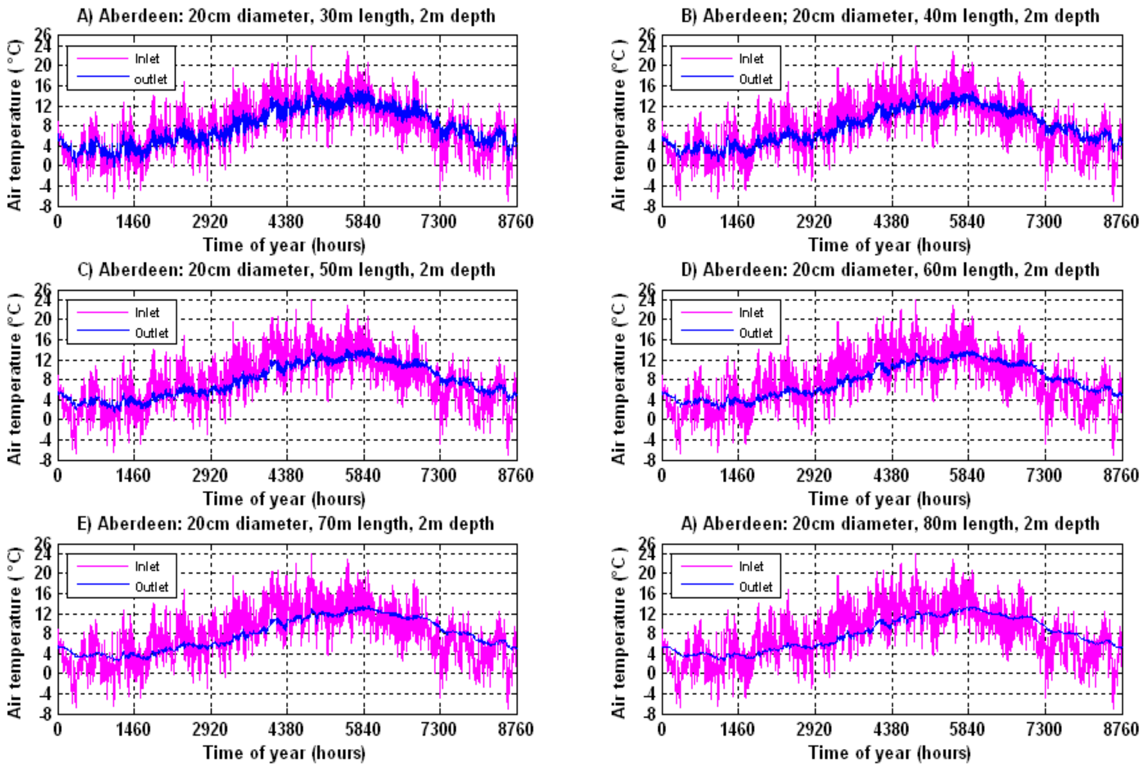

Figure 3 Inlet and outlet air temperature for 20cm diameter EAHX in Aberdeen

Cooling energy gain

Thermal simulation for a range of EAHX dimensions and airflow rate has been carried out to generate the cooling energy gain from EAHX. The total thermal energy for cooling derived by air flowing through EAHX is determined using Equation 1 (Holmuller, 2001). The heat transfer rate is dependent on the temperature gradient between air and soil. Annual thermal simulation runs have been carried out for the range of earth-air heat exchanger dimensions and climatic parameters of Aberdeen and London. Thermal energy exchange between air to soil is a good measure to directly compare the thermal potential of different configurations of EAHX system.

$$P_{sbl} = S_{pipe} h(T_{air} - T_{pipe}) \quad (1)$$

Where:

P_{sbl} sensible heat transfer rate (W)
S_{pipe} pipe surface area (m^2)
h heat exchange coefficient ($W/m^2.K$)
T_{air} air temperature (°C)
T_{pipe} pipe surface temperature (°C)

Figure 4 shows the cooling energy gain (kWh) for a range of EAHX dimensions and air flow rate corresponding to 3 m/s air velocity for London in South East, UK. Cooling energy gain increases with increase in length for all pipe diameters, and increases with increasing diameter for all lengths of EAHX. The increase in cooling energy with length is most sensitive with large pipe diameters, and least sensitive with small pipe diameters.

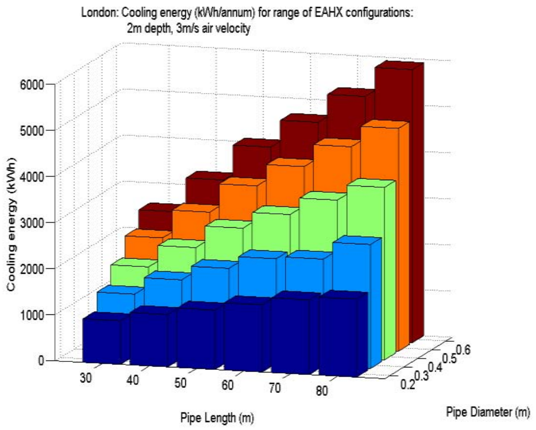

Figure 4 Cooling energy (kWh/annum), London

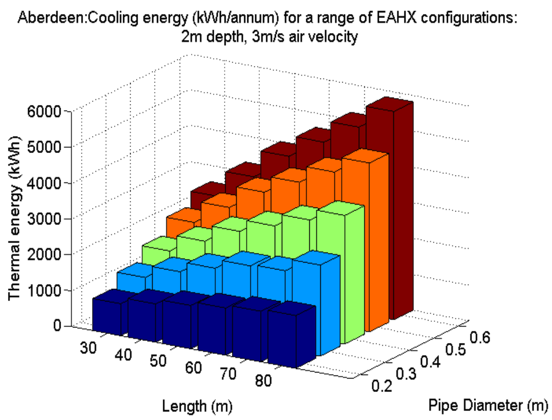

Figure 5 Cooling energy (kWh/annum), Aberdeen

The cooling energy in London for 0.6m diameter increases by about 130% when the length is increased from 30m to 80m, while similar increase in length for a 0.2m diameter pipe results in about 68% increase in cooling energy. The difference in sensitivity of pipe length on thermal energy capacity for different pipe diameters appears to be because small diameter pipes have high convective heat transfer coefficient which reduces with increase in EAHX diameter, therefore the long lengths of EAHX should only be considered for large diamater pipes, while smaller lengths for small diameter pipes.

Coefficient of Performance (COP)

The cooling energy provides the energy gain from the operation of earth-air heat exchanger, but did not take into account the effect of system configuration and air flow rate on the system pressure drop and fan dissipation energy. The system pressure drop affects the fan energy input required to drive airflow through EAHX system. Even though there is significant variation in the thermal capacity of different configurations of EAHX, there is also similar effect on the pressure drop along the pipe. The system pressure drop affects the fan dissipation energy required to drive the required airflow through the pipe or network of pipes. The thermal efficiency of EAHX has to be studied within the context of both thermal energy gain and the fan energy input to the system. Coefficient of performance (COP) is used to provide the efficiency indicator of EAHX. COP is determined as a ratio of total thermal energy gain from the EAHX and the mechanical dissipation energy (Pfafferott et al 2007). Equation 2 has been used to calculate system COP, which shows the relationship of thermal energy, pressure drop, volumetric flow rate and fan efficiency.

$$COP = \frac{\sum_t (Q_{cooling})}{\sum_t (\Delta p . \dot{V})} \quad (2)$$

Where:

COP coefficient of performance
$Q_{cooling}$ energy gain for heating or cooling (kWh)
Δp pressure drop (pa)
V air flow rate (m^3/hr)
E Fan efficieny(A fan efficiency of 75% assumed)

Pressure drop

The main parameter in Equation 2, that is unknown and important for calculating the fan dissipation energy is the pressure drop, which has been calculated using Equation 3 (Butcher, 2007). The properties of air at different temperatures used in determining the system pressure drop.

$$\frac{\Delta p}{l} = \lambda \frac{1}{d_i} \frac{1}{2} \rho c^2 \qquad (3)$$

Where:

λ Friction coefficient
Δp Pressure drop (pa)
di Pipe internal diameter (m)
c Air velocity (m/s)
l Pipe length (m)

Friction coefficient (λ) for turbulent flow Reynolds number (Re >3000) has been determined using Equation 4.

$$\frac{1}{\sqrt{\lambda}} = -1.8 \log \left[\frac{6.9}{\mathrm{Re}} + \left(\frac{k/d}{3.71} \right)^{1.11} \right] \qquad (4)$$

Where;

k/d = relative roughness

$$\mathrm{Re} = \frac{c d_i}{\nu}$$

k = pipe roughness
d = pipe internal diameter (m)
c = air velocity (m/s)
ν = fluid viscosity (pa s)

Pressure drop for concrete pipe have been calculated for 0.2 to 0.6m concrete pipes and 1 to 5m/s air velocity. These values of pressure drop have been used to determine the COP for various configurations of EAHX. Figure 6 and 7 show the COP of different dimensions of earth-air heat exchanger for London and Aberdeen respectively. The result indicates that COP increases with increasing pipe diameter and decreases with increase in pipe length. The main reason for the low COP at small pipe diameters is that the pressure drop is highest with small diameter pipes. The pressure drop also increases with increase in air velocity from 1 m/s to 5 m/s. The reduction in COP with increasing length is due to increasing pressure drop with length. Even though increasing length of EAHX increases the cooling energy gain, the related increases in fan dissipation energy means that the increase in length may not always result in the most efficient EAHX, especially with small diamater pipes. For two locations studied, the maximum and minimum COP corresponds to 0.2m diameter, 80m long and 0.6m diameter, 30m long EAHX respectively. Aberdeen and Scotland areas have the lowest COP mostly because of mild ambient temperatures in summer, and therefore lower heat transfer rate.

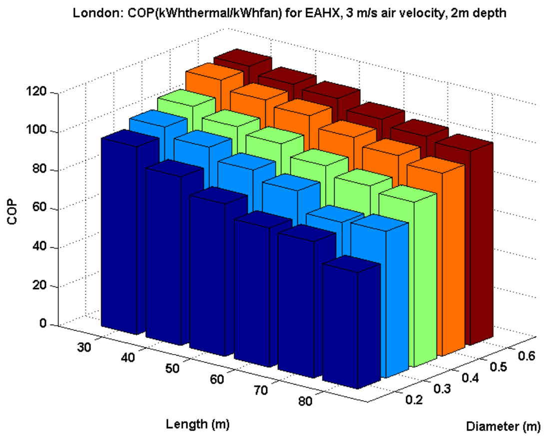

Figure 6 Coefficient of performance, London

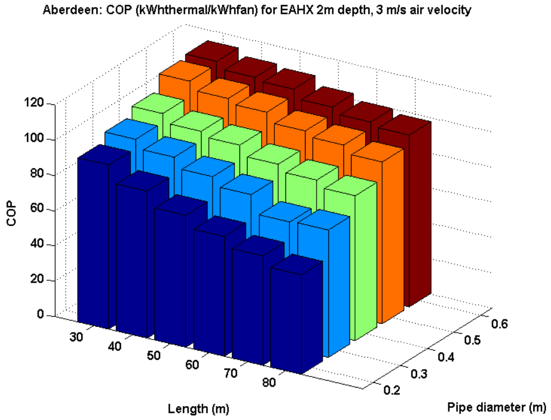

Figure 7 Coefficient of performance, Aberdeen

Building simulation

To simulate the impact of earth-air heat exchanger on building indoor environment An integrated EAHX and building simulation of low-rise office building of dimension (10m X 10m X 3m) has been developed to simulate the building cooling system with and without earth-air heat exchanger. First, the air supply to the building ventilation system is supplied from outside ambient air. The simulation is achieved with airflow rate of four and five volumetric air-changes per hour. Volume of the office building is 300m^3, therefore one air change per hour (ACH) corresponds to a flow rate of 300 m^3/hr. The building is free floating in terms of temperature control, with no additional cooling. Figure 8 shows scatter plots of indoor air temperature and relative humidity for ventilation rate of 4 to 5 air changes per hour (ACH) in London. The result reveals indoor condition is above 25ºC for significant percentage of occupied hours, with peak indoor condition of about 32ºC. Figure 9 shows similar plot when EAHX ventilation is used, which reveals that peak indoor condition remained below 28°C and 27°C for 4 and 5 air changes respectively. Even though the indoor condition still does not meet the indoor condition recommended by CIBSE (Butcher,2006) it is still a significant improvement over the case without

EAHX. In Aberdeen, a combination of mild summer temperature and low soil temperature shows that it is possible to keep the building below 25°C as recommended by CIBSE (2006). The peak indoor temperature is about 28ºC, when ventilation ambient air is used as shown in Figure 10 while the indoor temperature when EAHX ventilation is used remained below 24ºC for 4 and 5 air changes per hour as shown in Figure 11. The indoor relative humidity sometimes exceed the recommended 70% limit and even goes up to 100%, for both London and Aberdeen.

The high relative humidity corresponds to periods of low indoor temperature, when additional heating is required maintain indoor comfort temperatures, the additional heating will result in some dehumidification of the indoor air. The results reveal periods when the indoor temperature is too cold, it is important that EAHX be applied with simple but effective control. The ventilation rate need to be minimised during the period when indoor temperature is below comfort levels even though some auxilliary heating will be required to maintain indoor comfort condition.

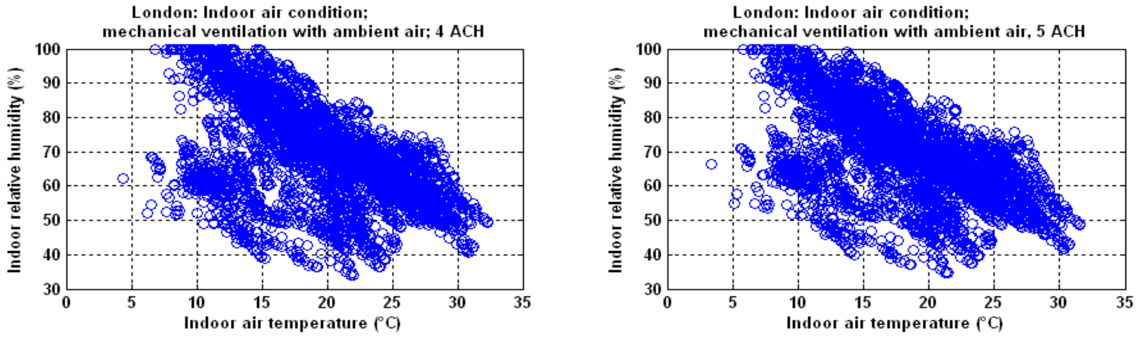

Figure 8 London: Indoor condition for ventilation with ambient air, 4 & 5 room air changes per hour (ACH)

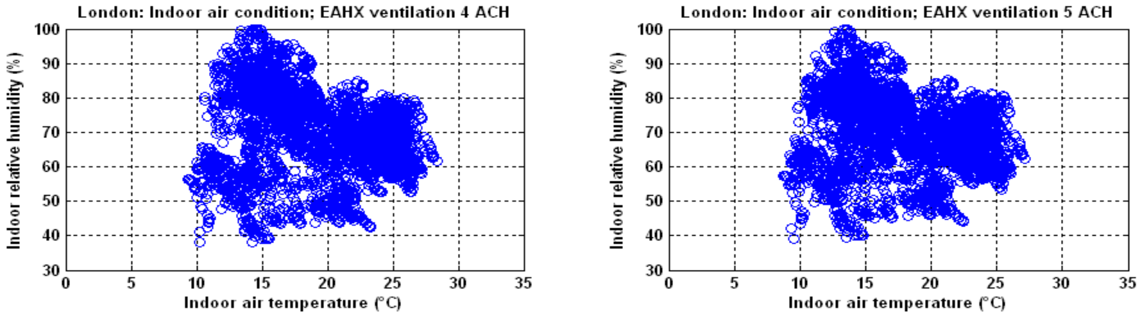

Figure 9 London: Indoor condition; EAHX ventilation 0.3m diameter, 60m length and 4 & 5 room air changes

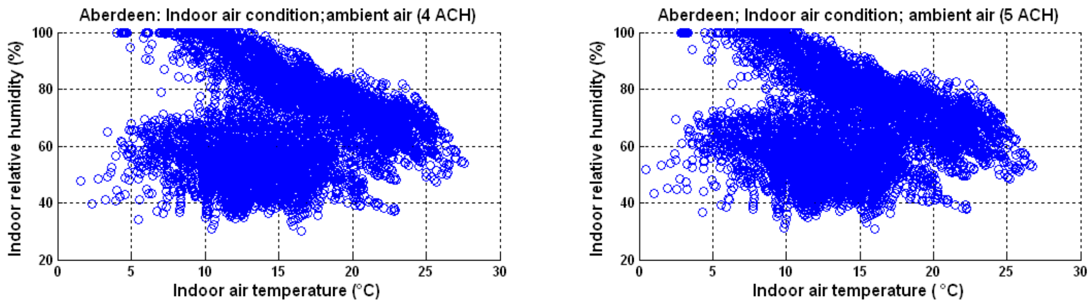

Figure 10 Aberdeen: Indoor air condition for ventilation with ambiant air, 4-5 Air changes (ACH)

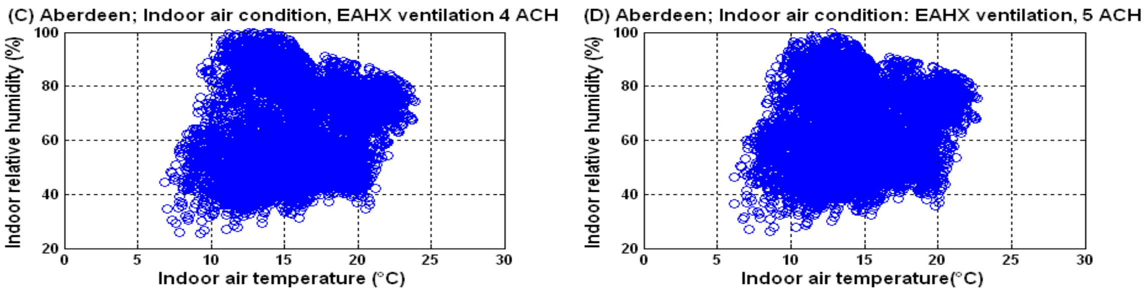

Figure 11 Aberdeen; Indoor condition, EAHX ventilation 30cm diameter, 60m length and 4-5 air changes (ACH)

CONCLUSION

The energy use for heating and cooling of buildings accounts for a significant percentage of energy consumption in UK and Europe. The reductions in building energy consumption using passive and low energy systems for indoor environmental control have significant potential for reducing building energy consumption and the related co_2 emissions. Earth-air heat exchanger utilise soil temperature below the surface, which is lower than ambient temperature in summer and higher than ambient temperature in winter. A Windows based simulation tool has been developed within TRNSYS environment, to simplify the complex EAHX simulation process. The tool is provided with the required simulation data in the form of pre-compiled simulation input files.

Thermal performance of EAHX has been established using the thermal simulation tool, to evaluate the potential of the system under UK climatic condition. The result of thermal analysis reveals significant improvement in the temperature of ventilation air supply in both summer and winter. The performance of EAHX varies with the dimension and climatic condition of the area under study. In London, South East England, there is significant improvement in indoor condition compared with the ventilation with ambient air. In Aberdeen and the Scotland area, EAHX can meet CIBSE recommended indoor condition in office buildings in the summer. Different dimensions of earth-air heat exchanger have been evaluated with respects to outlet air temperatures, cooling energy gains and coefficients of performance (COP). Earth-air heat exchangers have the potential to reduce the rising trend of conventional mechanical cooling system use in buildings and the energy consumption of such systems. It is important however, to look at the application of the system with simple but effective control.

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