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ASSESSMENT OF THE COOLING POTENTIAL OF AN EARTH-TUBE HEAT EXCHANGER IN RESIDENTIAL BUILDINGS

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Abstract. At present, we can observe the increase in glazing area of all types of buildings. Large size of south windows to allow for high passive solar heat gains during the heating period and can reduce primary energy demand. But, on the other hand, the big value of glazed openings percentage may cause low quality of thermal comfort inside the living and working spaces in the warm part of the year. The current paper presents results of computer simulations and experimental investigations of thermal performance of earth tube heat exchanger (ETHE). This natural geothermal based system can decrease heating loads and significantly reduce the room air temperature during summer seasons. The authors of this work used energy simulation software - EnergyPlus to estimate the cooling potential of earth–air–pipe systems in residential buildings for different Polish climate conditions. For these simulations three important annual average soil parameters as: surface temperature, the amplitude of surface temperature and the phase constant of this temperature were calculated by computer program CalcSoilSurfTemp. The results of longstanding experimental measurements of double pass earth air heat exchanger made of PCV tubes are presented in this paper, too.

Keywords: earth tube heat exchanger, cooling potential, energy simulation, annual average soil parameters.

1. Introduction

Heating and cooling needs of dwelling houses can be significantly reduced by utilization of the stored energy derived from the ground. So-called earth tubes are becoming more and more popular systems that are applied in the energy saving buildings. Earth to air heat exchangers (EAHE) mostly consists of metal, concrete or plastic buried pipes, inlet tower, registers, condensation management protect device, filter and fan. During heating season the external air that flow through the underground channels is pre-warmed. The direction of heat transfer from the sub-soil environment is reversed in summertime.

There are many mathematical models and experimental investigations concerning this topic.

Kumar and co-authors (Kumar *et al.* 2003) experimentally tested earth tunnel located in Mathura (India). The results of experiments was used to validate a transient implicit numerical model based on finite difference scheme and FTT algorithm implemented in Matlab. The authors predicted the tunnel extracted temperature for various value of air parameter as humidity, flow rate and ambient temperature. It was indicated that average heating potential of 80 m EAHE system is equal to 296 kWh and cooling potential is higher and equal to 456 kWh per day.

Next new model of Kumar (Kumar *et al.* 2006) implemented artificial neural network, based on back propagation algorithm, to estimate heating and cooling potential of ground-air heat exchanger. They developed a computer design tool that can help to obtain thermal performance of EAHE systems for different configurations with a great accuracy rate.

The annual effectiveness of photovoltaic/thermal (PV/T) and earth tube integrated with a energy saving building was studied and reported by (Nayak and Tiwari 2009). The first system operated during daytime hours and the second was used only at night. The results of this project showed that annual thermal energy generated by the developed system was equal to 24728.8 kWh.

Ghosal and co-authors (Ghosal *et al.* 2004) studied the cooling and heating potential of recirculation type EAHE that operated with energy saving building located in Indian Institute of Technology – Delhi (India). As it turned out, internal air temperature in green house, coupled with this system, significantly raised over 6°C in winter and decreased by 3-4°C during the summer compared to the same building without ground-air heat exchanger. It should be noted that the effectiveness of the developed system was higher in winter than in summer.

The main goal of the next project (Ghosal et al. 2005) was to compare ground air collector with typical EAHE

coupled with the same, as in the previous work, greenhouse. Based on experiments and calculation results they concluded that the first system is a more suitable solution for the heating season.
Cooling capacity and thermal performance of EAHE systems were determined experimentally for Southern China climate zone (Wu *et al.* 2007). The model of heat transfer inside an earth tube, based on computational fluid dynamics (CFD) algorithms, was implemented on the PHOENICS platform. Validation tests showed a good agreement between calculations and physical reality. Results of estimations indicated that the cooling capacity of the EAHE systems were 43.2 kWh and 74.6 kWh per day for the pipe radius of 0.2 m and 0.3 m, respectively.
The reduction of heat demand as a result of operating of EAHE system during heating period was analyzed in scientific project that was summarized in (Bansal *et al.* 2009). They developed transient and implicit model inside the ANSYS FLUENT software. Results of numerical simulations were in a good agreement with those of experiment. It was found that energy gain from the 23.42 m long and 0.15 m diameter ground-air heat exchanger was in the range between 423.36 and 846.72 kWh for the air velocity ranging from 2 to 5 m/s.
Interesting project was executed by (Maerefat and Haghighi 2010), that relied on coupled two different systems: solar chimney (SC) together with earth tube. Based on investigation results it was concluded, that this compilation of systems can operate even during low solar intensity periods (diffuse Sun radiation) and the optimal diameter of buried pipe is equal to 0.5 m.
The new transient one-dimensional analytical model to support design of EAHE systems was developed by Cucumo (Cucumo *et al.* 2008). The heat and mass balances for air flow inside the earth tube were calculated based on the principle of superposition of Green's functions. Validation results indicated good agreement between numerical simulations and experimental data available in the literature.
In Kuwait, (Al-Ajmi *et al.* 2006) performed theoretical studies of ground-air heat exchanger performance using mathematical model encoded within TRNSYS-IISiBat environment. The developed system (pipe length – 60 m, diameter – 0.25 m and air flow rate of 100 kg/h) gave the reduction in cooling energy of up to 420 kWh per month.
The cooling and heating capacity of EAHE system in four representative locations in the USA were investigated by (Lee and Strand 2006, 2008). Results of whole-year simulations using EnergyPlus software led to the conclusion that it is possible to save more than 50% of energy for cooling in a typical residential building. This potential greatly depends on pipe length and depth, air flow rate and surrounding soil thermal properties, of course.

2. Results of measurements

Real ground air collector that operates with energy saving building was tested experimentally. Fig 1 shows details of two parallel passes EAHE system. The house under consideration is located in Bialystok (North-East Poland).

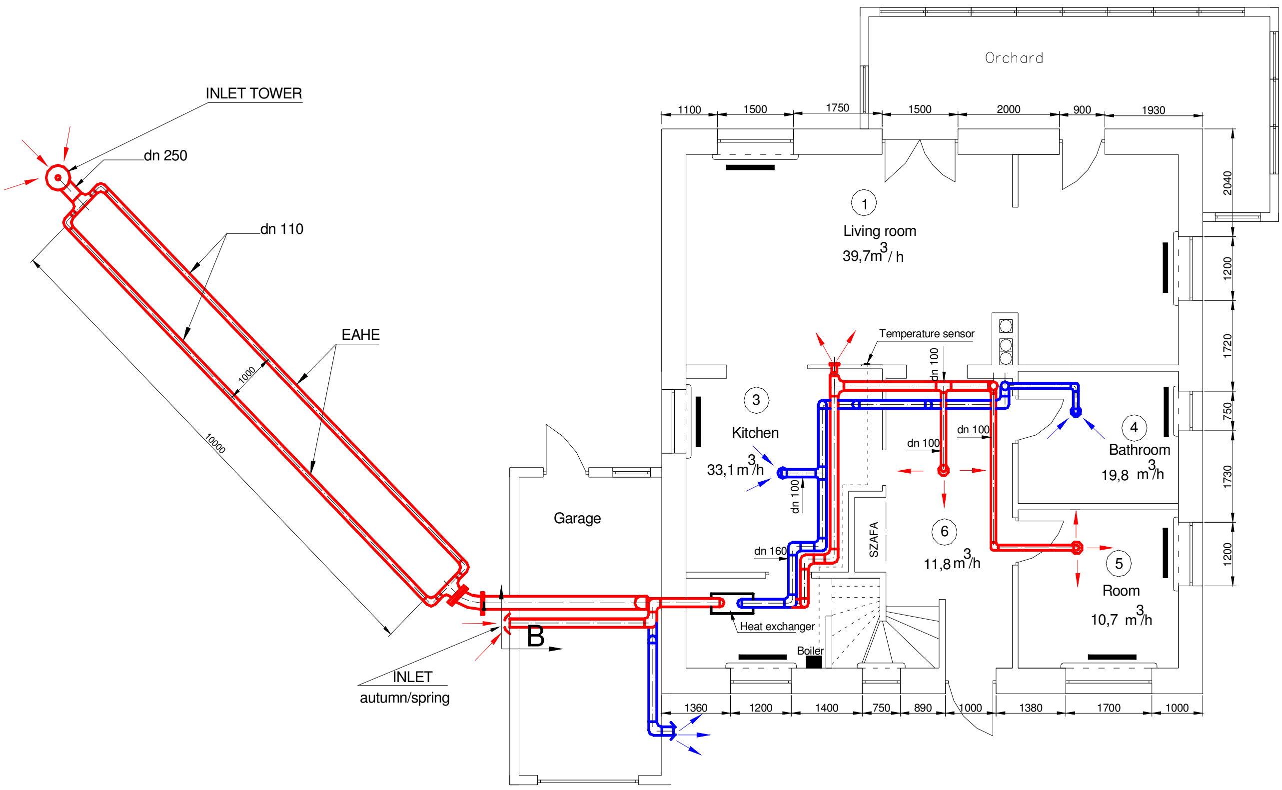

Fig 1. Plan of ground floor and ventilation system (*designed by Pawel Kwasniewski*)

This preliminary work has been carried out to determine the air temperature only in four places: at exit from earth tube, heat exchanger outlet, boiler room and outdoor temperature on the north side of the house. A typical variation of air temperature at the outlet of underground channels is shown in Fig 2.

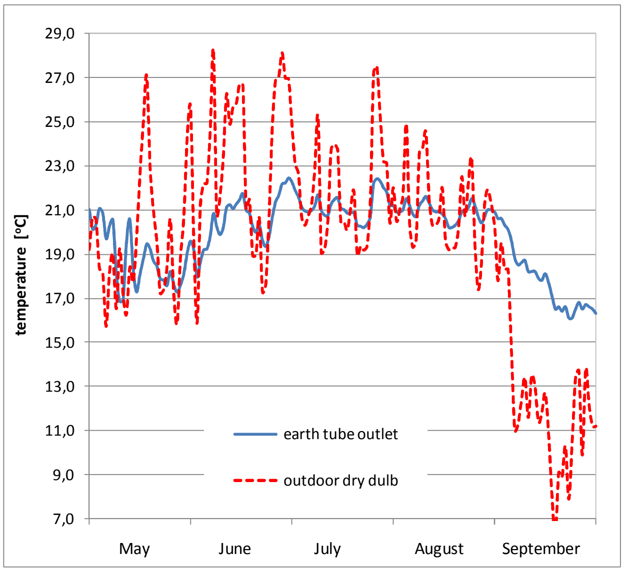

Fig 2. Variation of outdoor dry bulb and earth tube outlet air temperatures

As it turned out, we can use EAHE system to reduce the internal air temperature inside the tested house from June to August. This three-month period is a result of a short hot part of the year in North-East Poland. These measurements have shown that average air temperature at the exit from the earth tube, that was recorded during summer time, is equal about 18.5°C. Detailed information about all the experiment runs has shown in Ph.D. thesis of Sadowska (Sadowska 2011).

The relatively narrow range of measurements cannot allow to determine the cooling potential of the considered earth-tube system and calibrate EnergyPlus simulation model. Thus, as the next stage in this project, we are going to arrange a measurement stand equipped with a 20-chanell data logger, vane-anemometer, relative humidity and velocity sensors, digital PID thermo-regulator and electricity meter. These complex data can help us to obtain thermal performance of the earth tube with a very good accuracy.

3. Model of earth tube and building used in computer simulations

EnergyPlus software is used to simulate operations of EAHE system. Module of this program ZoneEarthtube calculates, from Eq. 1 (Encyclopedic Reference to EnergyPlus 2010), flow rate of outside air $\dot{V}_{a,out}$ passing through the buried duct and entered to the isothermal zone (e.g. room).

$$\dot{V}_{a,out} = \dot{V}_{a,des} F_s \left(A + B\left|T_{a,z} - T_{a,amb}\right| + C \cdot v_w + D \cdot v_w^2 \right), \qquad (1)$$

where:

$\dot{V}_{a,des}$ – maximum amount of air mass flow rate of the earth tube in design conditions (m^3/s),

F_s – schedule coefficient that modifies $\dot{V}_{a,des}$ (-),

A, B – user specified modifying parameters (dimensionless and °C),

$T_{a,z}$ – zone air temperature (°C),

$T_{a,amb}$ – outdoor air dry-bulb temperature (°C),

C, D – velocity term flow coefficients (s/m and s^2/m^2),

v_w – wind velocity (m/s).

Temperature profile of soil $T_{s,h1\text{-}h2}$, that has homogeneous thermal conduction, ranging between depth h_1 and h_2 is calculated by using Eq. 2 (Reference to EnergyPlus Calculations 2010).

$$T_{s,h_1\text{-}h_2(t)} = T_{s,m} + \frac{A_s}{(h_1-h_2)\gamma\sqrt{2}} \cdot \left\{ e^{-\gamma h_1} \cos\left[\frac{2\pi}{365}(t-t_0-h_1 L-45.6)\right] - e^{-\gamma h_2} \cos\left[\frac{2\pi}{365}(t-t_0-h_2 L-45.6)\right]\right\}, \qquad (2)$$

where:

$\gamma = (\pi/365\alpha_s)^{\frac{1}{2}}$,

$L = \frac{1}{2}(365/\pi\alpha_s)^{\frac{1}{2}}$,

$T_{s,m}$ – average soil surface temperature (°C),

A_s – amplitude of the soil surface temperature variation (°C),

α_s – soil thermal diffusivity (m^2/s),

t – time elapsed from beginning of year (days),

t_0 – phase constant of the soil surface (s).

The value of $T_{s,m}$, A_s, h_0 are inputs to EnergyPlus. A separate stand-alone program CalcSoilSurfTemp can be used to calculate these three parameters that depend on weather data, soil condition and ground surface condition.

Heat balance between surrounding soil and air stream passed through the tube is described by Eq. 3 and is used to determine outlet air temperature $T_{a,out}$ (Auxiliary EnergyPlus Programs 2010)

$$U[T_a(y) - T_{s,h(t)}]dy = -\dot{m}_a c_a [dT_a(y)], \qquad (3)$$

where:

$U = \frac{1}{R_C + R_P + R_S}$,

U – heat transfer coefficient of the EAHE (W/m°C),

R_C – thermal resistance due to heat transfer by forced convection between the air and inner surface of the tube (m°C/W),

R_P – thermal resistance due to heat transfer by conduction between inner surface of the tube and outer surface (m°C/W),

R_S – thermal resistance due to heat transfer by conduction between outer surface of the tube and surrounding soil (m°C /W),

y – distance from the tube inlet (m),

$\dot{m}_a$ – air mass flow rate (kg/s),

c_a – air specific heat (J/kg°C).
In EnergyPlus we can model three types of EAHE as follows:
Exhaust – fun is mounted on the outlet duct (used in our simulations),
Intake – fun is mounted inside the inlet tower (heat generated from fan motor is added to the air passing along the tube),
Natural – natural air passing through the tube.
Model of the building was created in a three-dimensional Cartesian coordinate system, as shown in Fig 3. It was split into four adjacent volumes (zones) at a uniform temperature: ground floor, second floor, garage and attic.

Fig 3. 3D model of the house coupled with the earth tube prepared in the EnergyPlus environment

The thermal performance of this energy-saving building components we can describe using *U*-value (coefficient of heat transmission):

- External walls – $U_{E\text{-}W} = 0.206$ W/m^2°C,
- Roof – $U_R = 0.193$ W/m^2°C,
- Slab floor – $U_S = 0.315$ W/m^2°C,
- Windows – $U_W = 1.863$ W/m^2°C.

4. Assessment of the cooling potential of the earth-tube

Calculations were performed from 1st of May to 30th of September for five following locations in Poland: Kolobrzeg, Poznan, Warszawa, Bialystok, Suwalki. Weather data for these towns came from the ASHRAE Handbook (ASHRAE 2005) and correlate with five different climate zones. First region that is represented by Kolobrzeg characterizes by most warm weather conditions. Suwalki represents the fifth zone with severe weather in Poland.

Zone sensible cooling energy E_c that is reported in the current work we can defined as energy actually supplied by the system to isothermal zones for the specified time step size Δt.

$$E_c = V_{a,des} c_a \rho_a \left(T_{a,z} - T_{a,amb}\right) \Delta t \,. \tag{4}$$

The results of calculations of earth tube cooling potential is presented in Fig 4. Average value of E_c is equal about 595 kWh for five months of warm period of the year.

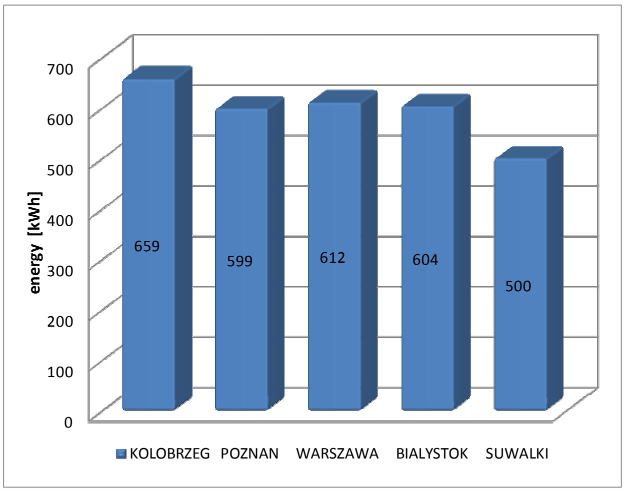

Fig 4. Cooling energy generated by EAHE system in five Polish locations

In order to show the influence of EAHE system on internal air temperature more clearly, it is compared operative temperature T_O (Eq. 5) of the zones for two cases: building coupled with earth tube and building without this system.

$$T_O = A \cdot T_{a,z} + (1 - A_O) T_{r,z} \,, \tag{5}$$

where:
A_O – radiative fraction defined as $A_O = \dfrac{h_r}{h_r + h_c}$ (-),
$T_{r,z}$ – mean radiant temperature for the zone (°C),
h_r – radiation heat transfer coefficient (W/m^2°C),
h_c – convection heat transfer coefficient (W/m^2°C).

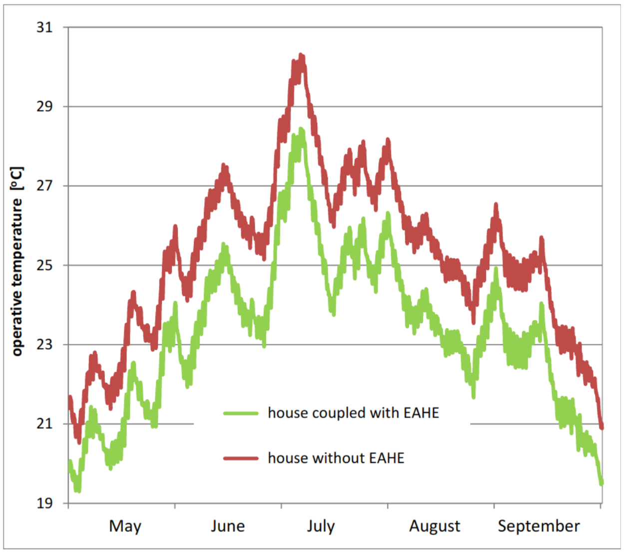

Fig 5. Comparison of operative temperatures inside the building

As seen in Fig 5, the difference between the operative temperatures is significant and stayed at approximately the same level equal to about 1.9°C during almost the whole warm season. Maximum and minimum values of this difference are 2.3°C and 1.2°C, respectively.

The positive influence of earth tubes on indoor thermal conditions we can observe in Fig 6, too. Between dashed lines there is a range of recommended value of Predicted Mean Vote (*PMV*).

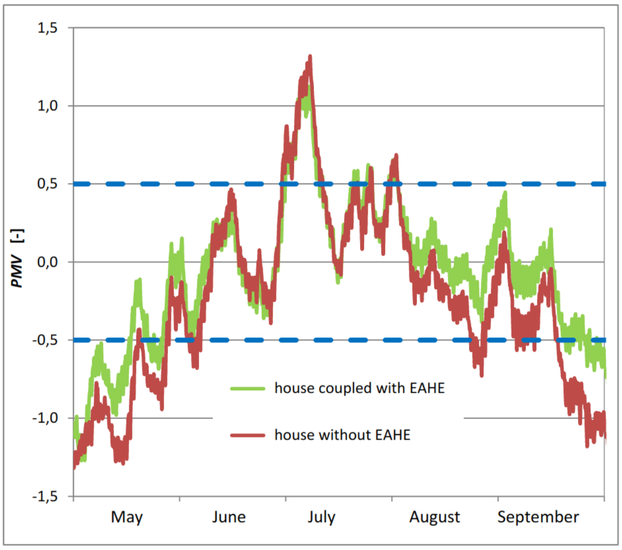

Fig 6. Comparison of *PMV* index inside the building

Thermal comfort is more accurate in building with ventilation system cooperating with earth tube, as we see in Fig 6. Unfortunately, even in this case we can observe overheating effect in July.

5. Summary and concluding remarks

The main goal of this work was estimation of the cooling potential of EAHE system for Polish climate conditions. The experimental data and calculations results indicate that earth tube is an energy saving solution. We can reduce cooling energy load by about 595 kWh due to this system. As mentioned before, the underground channels reduce the operative temperature inside the tested building by average 1.9°C. This effect has positive influences on improving occupant thermal comfort.
The future work in this research project will be directed to continuation of experimental investigations in more wide range and better calibration of numerical models.

Acknowledgements

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References

Al-Ajmi, F. *et al.* 2006. The cooling potential of earth–air heat exchangers for domestic buildings in a desert climate. *Building and Environment*, 41: 235–244.

ASHRAE Handbook - Fundamentals. Atlanta 2005: American Society of Heating, Refrigerating and Air Conditioning Engeneers Inc., ASHRAE 2005.

Auxiliary EnergyPlus Programs. 2010. University of California, Orlando Lawrence Berkeley National Laboratory, October 12.

Bansal, V. *et al.* 2009. Performance analysis of earth–pipe–air heat exchanger for winter heating. *Energy and Buildings*, 41: 1151–1154.

Cucumo, M. *et al*. 2008. A one-dimensional transient analytical model for earth-to-air heat exchangers, taking into account condensation phenomena and thermal perturbation from the upper free surface as well as around the buried pipes. *International Journal of Heat and Mass Transfer*, 51: 506–516

Ghosal, M. K. *et al*. 2004. Thermal modeling of a greenhouse with an integrated earth to air heat exchanger: an experimental validation. *Energy and Buildings*, 36: 219–227

Ghosal, M. K. *et al*. 2005. Modeling and comparative thermal performance of ground air collector and earth air heat exchanger for heating of greenhouse. *Energy and Buildings*, 37: 613–621.

Kumar, R. *et al*. 2003. Performance evaluation and energy conservation potential of earth–air–tunnel system coupled with non-air-conditioned building. *Building and Environment*, 38: 807–813.

Kumar, R. *et al.* 2006. Heating and cooling potential of an earth-to-air heat exchanger using artificial neural network. *Renewable Energy*, 31: 1139–1155.

Lee, K. H. and Strand, R. K. 2006. Implementation of an earth tube system into EnergyPlus program. In *Proceedings of SimBuild 2006*, held at MIT in Cambridge, Mass., August 2-4.

Lee, K. H. and Strand, R. K. 2008. The cooling and heating potential of an earth tube system in buildings. *Energy and Buildings*, 40: 486–494.

Maerefat, M. and Haghighi, A. P. 2010. Passive cooling of buildings by using integrated earth to air heat exchanger and solar chimney. *Renewable Energy*, 35: 2316–2324.

Nayak, S. and Tiwari G. N. 2009. Theoretical performance assessment of an integrated photovoltaic and earth air heat exchanger greenhouse using energy and exergy analysis methods. *Energy and Buildings*, 41: 888–896.

Sadowska, B. 2011. *Operational model of design of energy-saving residential buildings*. Bialystok Technical University, January 17.

The Encyclopedic Reference to EnergyPlus Input and Output. 2010. University of California, Orlando Lawrence Berkeley National Laboratory, October 11.

The Reference to EnergyPlus Calculations. 2010. University of California, Orlando Lawrence Berkeley National Laboratory, October 11.

Wu, H. *et al*. 2007. Modelling and evaluation of cooling capacity of earth–air–pipe systems. *Energy Conversion and Management*, 48: 1462–1471.