MEASUREMENTS AND MODELLING OF AN EARTH-TO-AIR HEAT EXCHANGER FOR RETAIL BUILDING VENTILATION

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ABSTRACT

An earth-to-air pipe type heat exchanger (EAHE) is a simple and effective ventilation system component, used for preconditioning of the fresh air supplied to a building. This paper presents two sets of results of operational parameters long-term measurements and energy analysis of EAHEs, located under two different retail buildings of floor area over 1000 square meters each.

In the second part of this paper there is described the mathematical model of the EAHE operating in a mechanical ventilation system of a retail building implementation into computer code, written in MS Excel and used for simulation of EAHE long-term operation (i.e. at least one year). The thermo-hydraulic phenomena inside the EAHE are simulated, as well as the calculation of transient three-dimensional (3-D) ground temperature field is performed with use of the method of elementary balances, in an open schema.

The elaborated model allows to analyse the impact of control strategy of ventilation system on the energy efficiency of this exchanger. As a result of this investigation, the control algorithms in described real facilities were found to be not optimal. Changes in the control strategy, leading to improvement of energy efficiency of EAHE and ventilation system in the same way, were proposed.

KEYWORDS

earth-to-air heat exchanger (EAHE), renewable energy, long-term measurements, numerical modelling, control strategy

1 INTRODUCTION

One of the most energy-intensive fields of the economy is the residential and public buildings sector. Reduction of energy demand in buildings can be obtained by improving their thermal insulation, increasing airtightness of envelopes and improving efficiency of ventilation systems. The practical result of these efforts is the idea of low-energy, passive and zero-energy buildings. In these buildings, the share of ventilation losses in total energy balance could be dominant. This situation leads in the first step to the use of heat recovery systems, which implies the application of supply-exhaust mechanical ventilation. In order to obtain further net energy demand reduction, to improve protection against freezing of heat recovery exchanger, as well as to increase the quality of climatic comfort, earth-to air heat exchangers (EAHE) are applied, as a source of renewable energy.

The EAHE is the ventilation system component – pipe buried underneath ground surface, which allows heating of fresh air in the winter period and cooling during summer time, using energy from the ground adjacent to the exchanger.

The open literature offers numerous publications on the pipe-type ground heat exchangers. The review indicates that EAHE are investigated and applied almost all over the world (from the cold climates of Scandinavia to the hot climates of Africa, Kuwait and Brazil) as well as for various types of buildings (residential, public, industrial, agricultural, etc.). All these papers can be divided into the following groups:

- describing experimental investigations of EAHEs (e.g. Eicker, 2010; Santamouris, 2007; Sawhney et al., 1999; Thanu et al., 2001),
- presenting computational models and the results of theoretical analyses (e.g. Badescu, 2007; Bojic et al., 1997; Kabashnikov et al., 2002; Tittelein et al., 2009; Wu et al., 2007),
- engineering type publications like handbooks, design guidelines, selection software descriptions / manuals, etc.

It often happens, that one item can be located in several of the above mentioned groups simultaneously – for example numerical simulations validated by measurements results (e.g. Szymanski and Wojtkowiak, 2013; Tiwari et al., 2006; Trzaski and Zawada, 2011). In each group, the authors approaches of different complexity and levels of sophistication could be found. The biggest discrepancies reveal in the description temperature changes of soil and the EAHE cooperation with other ventilation system components and the building. Another important conclusion, emerging from the analysis of the cited works, is the opinion difference on the EAHE application effectiveness.

There are more publications concerning small one-pipe installations than large multi-pipe systems. Very low number of researchers investigated EAHE and ventilation control algorithms as well as the system optimization.

In this paper two sets of results of long-term experimental investigations of earth-to-air pipe-type heat exchangers (EAHE) in mechanical ventilation systems of retail buildings are presented. There are also included results of EAHE numerical calculations. In the numerical model it is possible to apply different control strategies of the exchanger, what often influences very significantly EAHE energy efficiency. It is most important issue in moderate periods (like spring and autumn), when unwanted fresh air heating or cooling can occur. To avoid such a situation automated control dampers should by-pass the exchanger and take the fresh air directly from outside (e.g. direct wall or roof inlet to the AHU). Another possibility of these dampers use is for air mixing purpose (ambient and EAHE outlet air mixing) – to exactly meet the set point of fresh air temperature for space conditioning (especially in early summer time). The control algorithm (set points boundaries) also strongly depends on building type and climate.

2 CASE STUDIES

2.1 Investigated facilities

This study is focused on the effectiveness of two earth-to-air heat exchangers located underneath two similar one-storey retail stores in southern Poland. The floor area of the store "A" is about 1300 m^2. EAHE was installed as a system of 20 parallel pipes, Ø200 mm diameter, each 35 m long, connected in Tichelmann scheme, with manifold pipes of Ø500 mm diameter. Installation layout is presented in Figure 1. Air inlet to the exchanger is placed on the roof of the building and in opposite corner air goes out from EAHE to air handling unit (AHU). The nominal air flow rate for this EAHE is 2700 m^3/h, what corresponds to 135 m^3/h for each pipe and average air speed of 1,4 m/s inside exchanger pipes.

The second retail store "B" is quite similar to the store "A". The most important parameters of the building "B" and its EAHE are as follows:

- floor area: 1100 m^2

- air flow rate: 2400 m^3/h
- pipes: 18 parallel pipes, Ø200 mm, 38 m length, air speed: 1,4 m/s.

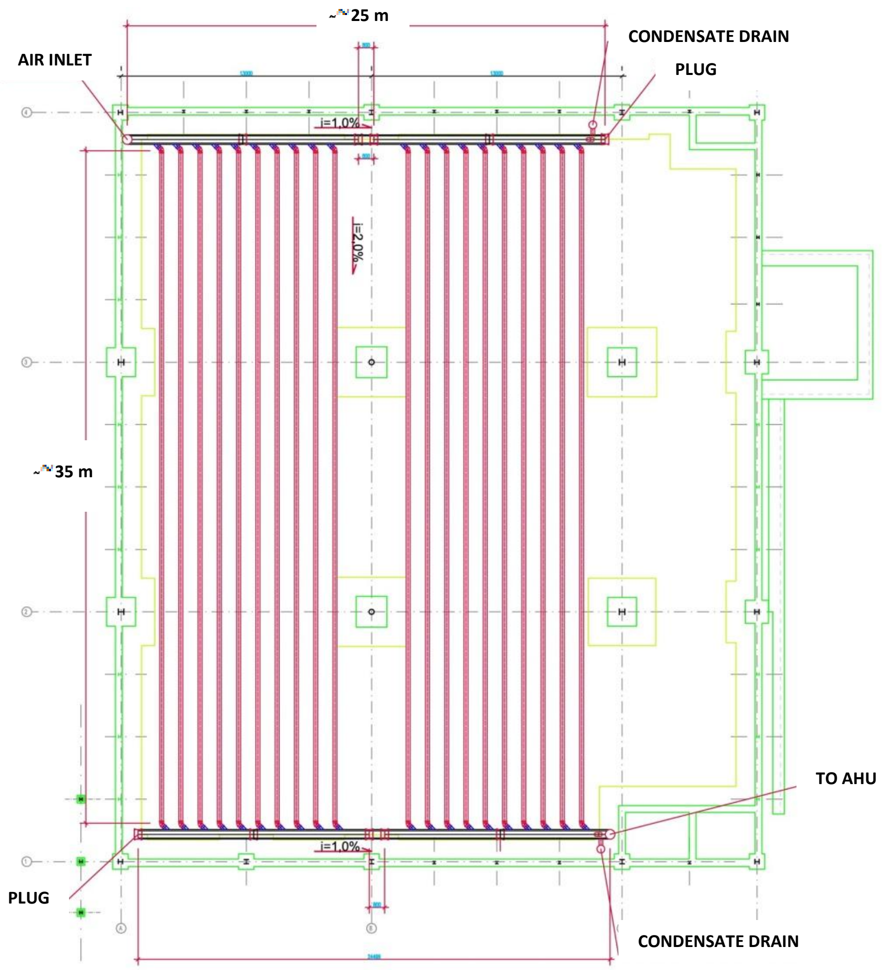

Figure 1. Layout of EAHE installation underneath the floor of commercial facility "A"

2.2 Objectives and scope of measurements

The first objective of the measurements was to precisely define the quantity of energy supplied to ventilation air in winter and recovered from ventilation air in summer, to assess the energy efficiency of EAHE in Polish climate. The second purpose of the measurements was a detailed recording of short-term and long-term variability of the operational parameters of EAHE. Collected data served later to improve of the operation of the EAHE in subsequent years.

To achieve accurate results, the following rules were adopted:

- measurements lasted for a period of one year,
- parameters were measured at short intervals of 5 minutes,
- recorded data included basic parameters allowing to define enthalpy of inlet and outlet air and to define the ventilation air flow: EAHE inlet and outlet air temperature and relative air humidity and air velocity in the duct.

2.3 Measurements results

Changes of temperature and relative humidity measured in February for case A is shown in the Figure 2 and outlet temperature as function of inlet temperature for the whole year – in Figure 3. Based on the collected data and common energy equations, the energy output of EAHE was calculated. This is shown in Figure 4.

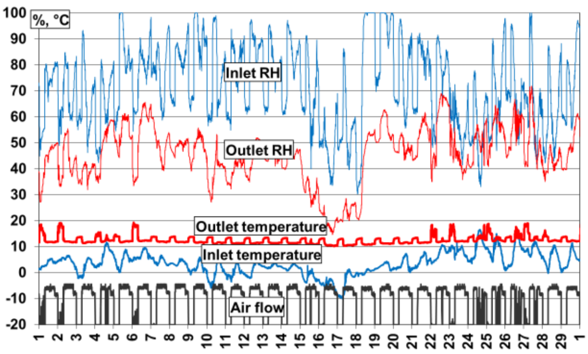

Figure 2. Measurement results for February – case A

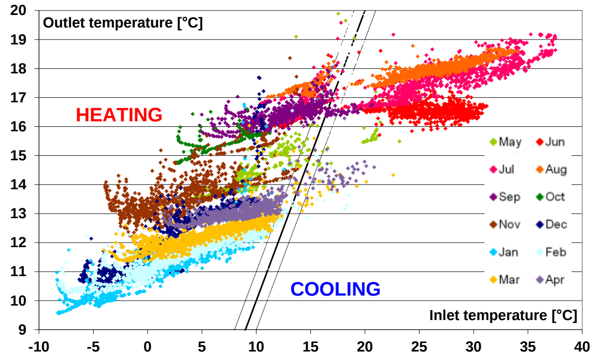

Figure 3. Distribution of outlet air temperature as a function of inlet air temperature for EAHE – case A

The control system of the air handling unit (AHU) in case A was programmed to turn on the ventilation system daily from 6:00 to 23:00 and to bypass the EAHE if the temperature difference between inlet and outlet is less than 1°C.

The winter 2007/2008 was exceptionally mild in the South of Poland – all ambient temperatures were higher than -10°C – so the maximum expected heat output of the EAHE couldn't be observed. It was however possible to investigate the influence of thermal capacity of the ground on the output air temperature: at +30°C air inlet temperature, outlet air temperatures were respectively: +16,5°C in June, +17,5°C in July and about +18,5°C in August. Basing on the data presented in Figure 3, the following remarks regarding control system can be formulated:

- the algorithm general rule, preventing use of EAHE with the temperature difference between inlet air and outlet air of less than 1°C, didn't work properly – especially in October,
- the EAHE was used sometimes in July and August to unnecessary preheat the fresh air, what prevented the use of natural cooling of the building.

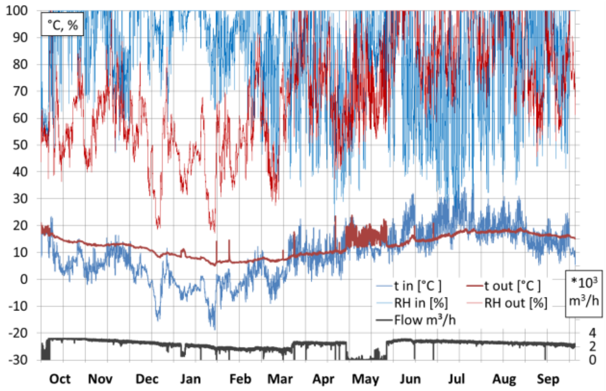

Figure 4. Annual measurement results – case B

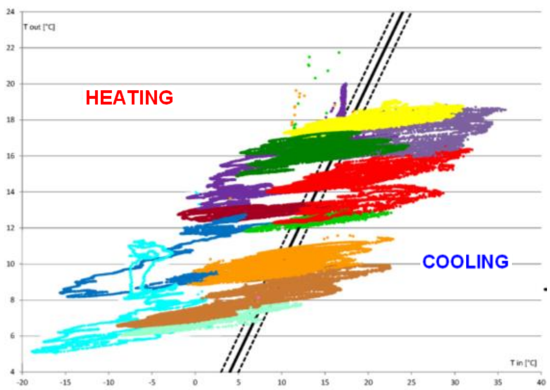

Figure 5. Distribution of outlet air temperature as a function of inlet air temperature for EAHE – case B

The EAHE investigated in case B operated nonstop all year round, because of no automated control system installed in the ventilation system. The worst consequence of the total absence of controls system was wasting energy for ventilation of an unoccupied building during nights. Other disadvantage related to EAHE was passing of the air thru the EAHE with no effect in temperature change and the last consequence was preheating the air in summer or precooling in spring – exemplary at 26.03 the ambient air was unnecessary cooled from +22°C to +10°C. The above mentioned negative effects occurred in case B to much greater extent, than observed in case A. Essential data regarding operation of the investigated installations are presented in the Table 1 and in Figures 6 and 7.

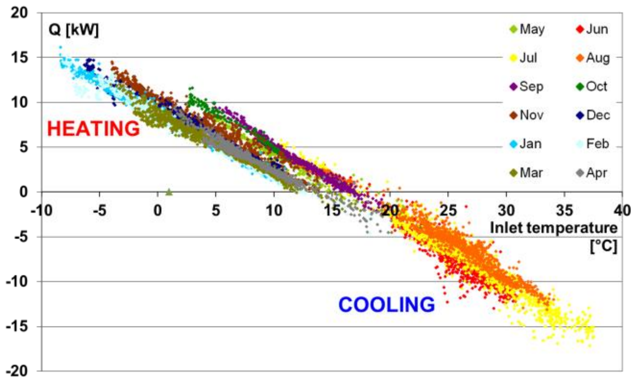

Figure 6. Heating and cooling capacity of EAHE case A as a function of outdoor air temperature

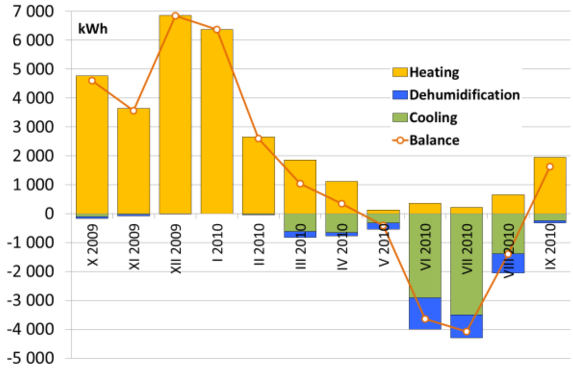

Figure 7. Monthly energy balances of EAHE – case B

As a result of EAHE application, variations of air temperature at the inlet of AHU were reduced almost 5 times in case A – from range (-8 ÷ +37°C) to range (+9,5 ÷ +19°C) and 4 times in case B. This allowed to reduce of the nominal output of heating and cooling systems required for AHU operation.

Table 1. Summary of key operating parameters of investigated installations

	Case A	Case B
Measurement period	V.2007 - IV.2008	X.2009 - IX.2010
Maximum heating output	15 kW	19 kW
Maximum cooling output	17 kW	22 kW
Energy delivered for heating	22 400 kWh	30 600 kWh
Energy delivered for cooling	9 200 kWh	13 100 kWh
Reduction of the air temperature fluctuations at the inlet to AHU	5 times	4 times

In both cases, the installations operated at air flows reduced by 10% - 50% from the design air flow. At higher, nominal air flows the heating and cooling outputs and delivered energy would be higher, however EAHE outlet temperature fluctuations would be higher too.

Despite the slightly longer pipes and air change rate in case A, output power and delivered energy are greater in case B. The reasons were mild winter occurred in case A and longer operating time in case B. Other important cause of the big difference in delivered energy is the control system. In case B there was no automated control system at all, so cooling and heating energy was delivered regardless of the real needs. It was delivered just when it was available. On the other hand, the control algorithm in case A was too complex in the first few months of measurements and EAHE was bypassed even its operation was needed.

The overall EAHE energy efficiency was very high in both cases. Amount of energy obtained from the EAHE in relation to the energy supplied to the fan was higher than 20, both in summer and in winter.

3 NUMERICAL MODELLING

3.1 Method of modelling

The numerical model is based on the method of elementary balances, in an open schema. The model is designed to simulate transient heat flow and is built of 45 sections, located perpendicular to the tubes. Each of the sections represents 1 m thick layer (Fig. 8) and was calculated in Microsoft Excel sheet (Fig. 9). There was adopted a rectangular grid in the cross-section; the pipes were approximated by squares with constant temperature equal to the average air temperature in the section (Fig. 9). The model is based on energy balances of the elements in time – equations (1) and (2). In the simplest case, temperature of the element at the end of the time step can be described by equation (3).

$$\dot{Q}\cdot\Delta\tau = m.c.\left(t'_{x,y,z} - t_{x,y,z}\right) \quad (1)$$

$$\dot{Q} = \sum_{i=1}^{6}\left(\frac{1}{R_i}\cdot A_i\cdot\Delta t_i\right) \quad (2)$$

$$t'_{x,y,z} = t_{x,y,z} + a\cdot\frac{\Delta\tau}{l\cdot d^2}\cdot\left[\cdot\left(t_{x+1,y,z}+t_{x-1,y,z}+t_{x,y+1,z}+t_{x,y-1,z}-4\,t_{x,y,z}\right)+d\cdot\left(t_{x,y,z+1}+t_{x,y,z-1}-2\,t_{x,y,z}\right)\right] \quad (3)$$

where $t_{i,j,k}$ [K] are temperatures of the "*i,j,k*" element at the beginning of current time step, $t'_{x,y,z}$ [K] is the temperature of the "x,y,z" element at the end of current time step, $\Delta\tau$ [s] is the length of current time step, *d* [m] is the distance between calculation grid nodes in x and y direction, *l* [m] is the distance between calculation grid nodes in z direction, *a* [m^2s^{-1}] is the thermal diffusivity, *c* [$J\cdot kg^{-1}K^{-1}$] is the specific heat capacity, *m* [kg] is the mass of the element, R_i [$m^2K\cdot W^{-1}$] is the heat resistance between elements and $\dot{Q}$ [W] is the heat flux.

The convective heat transfer coefficient inside the EAHE pipes was assumed as variable, air velocity dependent.

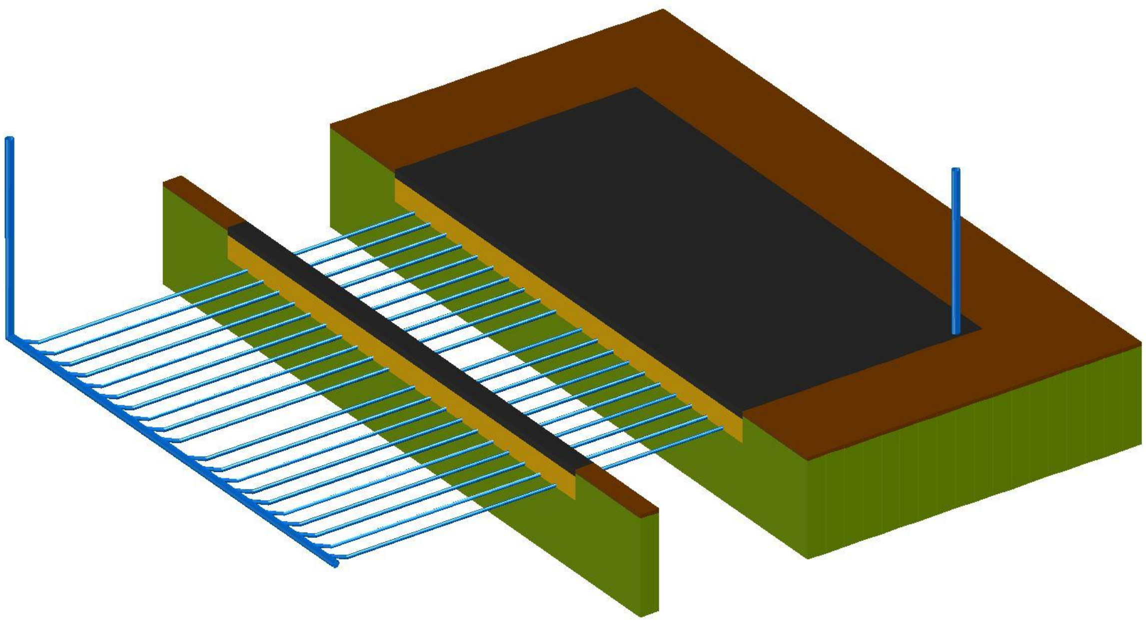

Figure 8. Division of the 3D model into layers

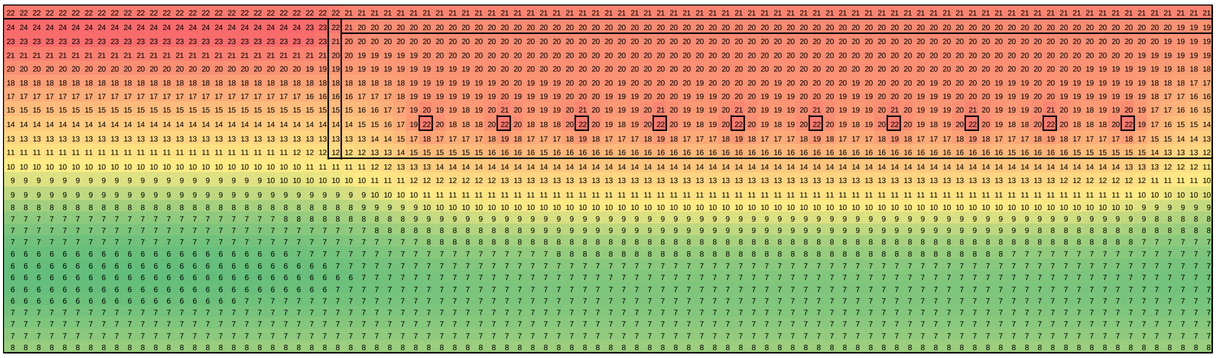

Figure 9. Exemplary, transient temperature distribution in one of the layers – air cooling mode

3.2 Control algorithms tested

Two control algorithms were tested for the same building and EAHE installation. The rules taken into account in control strategy are summarized in Table 2. It is assumed, that the EAHE is in use, when all conditions are ***TRUE***.

Table 2. Rules applied in control algorithms

	CS1	CS2
Condition 1	Control timer 6:00-23:00	Control timer 6:00-23:00
Condition 2	Ambient air temperature lower than +10°C or higher than +22°C	Ambient air temperature higher than +20°C in cooling mode (outlet EAHE temperature lower than inlet temperature)
Condition 3	-	Outlet EAHE temperature lower or higher than inlet temperature by at least 1°C

3.3 Modelling results

The calculations were performed for a period of one year, for ambient conditions of Poznan. The results of modelling, as plots of outlet temperature in function of inlet temperature for subsequent months are presented in Figures 10 and 11.

The control strategy in **CS1** is simple and requires only measurement of ambient air temperature. The condition 2 in **CS1** was introduced to avoid unnecessary precooling of air in spring and unnecessary preheating in summer months. This control algorithm unfortunately bypasses the EAHE also in periods, when the EAHE could preheat the air – for example from +11°C to +16°C. The heat exchanger operates also sometimes with no (or very small) temperature difference between inlet and outlet air – this is wasting of electrical energy used for powering fans.

In **CS2**, the condition 3 prevents wasting of energy for passing air thru EAHE without significant temperature change. In combination with condition 3, the temperature threshold of cooling mode (condition 2) could be safely reduced to +20°C and the temperature threshold of heating mode (+10°C) is unnecessary.

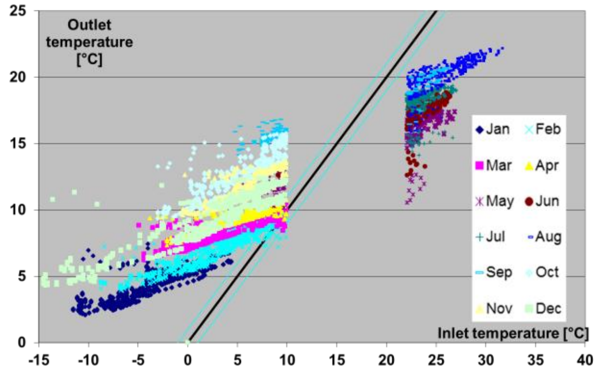

Fig. 10 Distribution of outlet air temperature as a function of inlet air temperature for EAHE – CS1

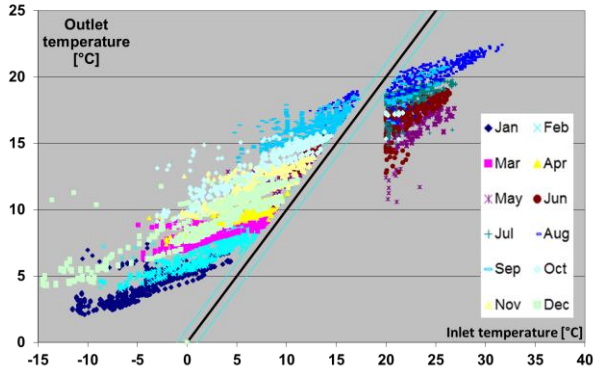

Fig. 11 Distribution of outlet air temperature as a function of inlet air temperature for EAHE – CS2

Results of the modelling are detailed annual variability of all operational parameters of the EAHE. This allows to compare and evaluate control strategies for EAHE. The developed model, after minor modifications, allows for calculation and comparison of any control strategy for the EAHE.

4 CONCLUSIONS

Earth to Air Heat Exchangers (EAHE) are energy efficient, delivering over 20 times more heating or cooling energy than they need for powering of fans. The fluctuations of temperature of inlet air in the AHU decreases 4 – 5 times as the result of EAHE application. This allows to decrease the size of heating and cooling equipment and to reduce investment costs. Applying of EAHE in investigated cases reduced the heating demand by about 17-28 kWh/(m^2·a) and cooling demand by about 7-12 kWh/(m^2·a). In similar installations even greater savings are expected, because the investigated cases didn't reach designed air flow rates. The energy saving may differ from analyzed cases, depending on operational parameters and control strategy of EAHE.

Energy efficiency of a ventilation system equipped with EAHE depends largely on the control strategy. In the second part of the paper two control algorithms of EAHE were evaluated, using numerical modeling. Algorithm **CS2**, gave 8% more heating energy and 22% more cooling energy than the algorithm **CS1**, which took into account only control timer and ambient air temperature. It is recommended to apply the algorithms similar to **CS2** in control systems of EAHE.

More energy savings are possible by application of control strategy based on control error and by use of more sophisticated control algorithms, including fuzzy logic and predictive control. The above mentioned methods of control are subjects of future research.

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