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Article

On Preheating of the Outdoor Ventilation Air

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Abstract: Growing popularity of buildings with integrated sub-systems, requires a review of methods to optimize the preheat of ventilation air. An integrated system permits using geothermal heat storage parallel to the direct outdoor air intake with additional treatment in the mechanical room as a part of building automatic control system. Earth Air Heat Exchanger (EAHX) has many advantages but also has many unanswered questions. Some of the drawbacks are: a possible entry of radon gas, high humidity in the shoulder seasons as well as the need for two different air intake sources with a choice that depends on the actual weather conditions. While in winter, the EAHX may be used continuously to ensure thermal comfort, in other seasons, its operation must be automatically controlled. To generate the missing information about the EAHX technology we have examined two nearly identical EAHX systems, one placed in ground next to the building and the other under the basement slab. In another project, we have reinforced the ground storage action by heat exchanger placed on the return pipes of the hydronic heating system. Effectively, the information provided in this paper, shows advantages of merging both these approaches while the EAHX could be placed under the house or near the basement foundation that is using an exterior basement insulation.

Keywords: earth-air heat exchanger; energy efficiency; using thermal mass; smart and integrated control systems, thermal comfort

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1. Introduction

As the fraction of buildings with integrated heating/ cooling, solar and geothermal sub-systems in the market steadily grows, the sub-system integration changes the economics of the traditional solutions. In this paper, we are focused on pre-heating of the outdoor ventilation air and specifically on the design and performance of the Earth-Air Heat Exchanger (EAHX). Recent information on the optimal design with two different air intake sources [1] and automatic control systems [2], warrants a broader review of EAHX technology.

Nevertheless, when a risk of radon gas exists, one may use a hydronic heating system and preheat ventilation air in the heat exchanger on the return of heating water [3, 4]. Despite of several papers on EAHX technology, not much is known about optimization of their field performance for both summer and winter in cold climates. To fill the knowledge gap, this paper reviews a demonstration project in Cracow, Poland, where two nearly identical EAHX systems were examined and in Syracuse, NY, USA where an integrated hydronic and mechanical ventilation system was built. In both cases the evaluation lasted for one year of occupancy.

2. Literature review

It is now a standard practice to heat or cool the fresh air between the point of intake and the entry to the room with mechanical services [5]. This can be done with earth-air heat exchanger (EAHX) [6, 7]. The use of earth for cooling air was already known in historic Greece and Persia [8, 9], yet, recently it became popular for a different reason, namely for the energy conservation.

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A number of publications on this topic exist; some researchers [6, 10] looked at the average yearly EAHX performance, others analyzed design of the EAHX to maximize their yearly performance including the dynamic interactions between EAHX and the environment [11]. These works were based on the laboratory work [12] or computer-fluid-dynamic calculations [13]. The literature includes a review [14] of various designs and life-cycle analysis of EAHX [15].

While different papers are dealing with the interaction of EAHX with surrounding soil and benefits or risks in design, only a handful papers deal with the annual cycles of field performance [16, 17, 18]. As we do not have any concise guidance for integration of EAHX with other subsystems in the building, an objective of the Cracow University project and of the following paper was to develop a basis for such a guidance. As discussed below, the design of EHAX included two cases deemed to be identical and representative of typical European systems designed for cold climate.

3. Experimental set-up

The experimental set-up used in Cracow's project, includes a direct intake of outdoor air though a wall and two remote intakes, both placed next to each other. One EAHX system was placed under the building and had the pipe slope ascending with drainage down pipe in ¾ distance to the mechanical room, while the other was placed outside the building and had the slope descending with the drainage down pipe in the middle of the length.

Each EAHX is provided with temperature and humidity sensors connected to the data-logger. Measurements of earth temperatures are performed in two ranges (a) -25°C to 0°C with precision of ±0.3°C and (b) from 0°C to 40°C with precision of ±0.1°C. Relative humidity is measured in the range 10%-90% with precision of ±3%. Measurements are recorded every 5 minutes. One of these ground heat exchangers is located under the building (EAHX 1) and the other outside the building (EAHX 2, see the schematic shown in Figure 1).

The symbols used in this Figure: V_1, V_2, V_3 – are the air valves with actuators, T_{1in}, T_{2in} – are the air temperature sensors on inlets, T_{1out}, T_{2out} – the same on outlets, AF_1, AF_2 – air flow meters; air handling unit's elements: Fin – supply fan, Fout – exhaust fan, R – recuperator, H – water heater, C – water cooler.

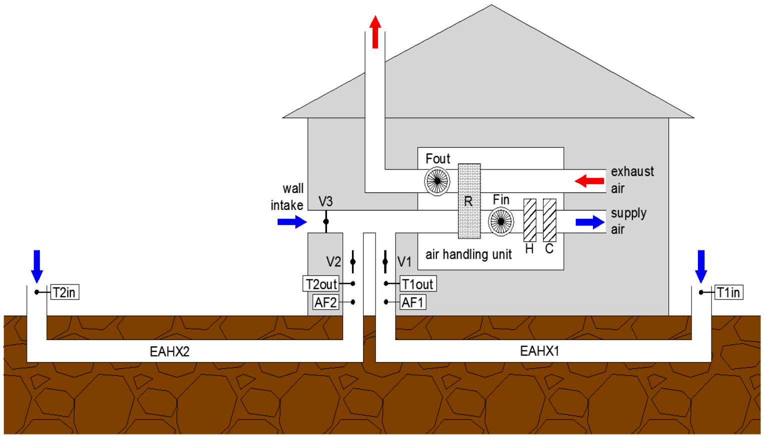

Figure 1. *An experimental set-up with two ground air heat exchangers (EAHX) connected with the air handling unit. EAHX 1 is placed under the building, EAHX 2 the same system but placed outside the building. (From Romanska-Zapala [1]).*

The mechanical room has rotational heat exchanger with 1850 m³/h flow and 80 percent efficiency, heating coil 3.25 kW and water cooling with 4.22 kW power. The experiments were performed with air flow measured to be 400 m³/h on average and air speed in EHAX pipe with internal diameter of 185 mm, about 4.1 m/s. Temperature was measured with 25 sensors within the system and 72 in the soil adjacent to the EAHX. The automatic steering and control system (BACS), was designed and built at the University, based on the study "Assumptions and requirements for the measurement system; the architectural and construction design of the Malopolska Energy Efficient

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Building Laboratory. The heat exchangers were 60 and 59 m long of 200 mm diameter PVC pipe was either starting at a depth of 1.6 m with a downward 2% slope to a depth of 2.5 m or the opposite, starting at the depth of 2.5 m and ascending to 1.6 m. Water drainage wells were installed in some distance from the end.

Both air inlets are on the North side of the building. An exhaust for air is located on the roof. As the selected technical characteristics of EAHX represent a typical case allowing one to focus the analysis on efficiency of the EAHX solution and means of control and steering. The automatic control is necessary for the EQM (Environmental Quality Management) technology as the exterior temperature changes combined with thermal mass of the building may cause more frequent switches between heating and cooling modes [19].

Figure 2 shows the lay-out of the pipes in both EAHX with temperature and humidity measurements made in one moment to highlight how instantaneous measurements may vary and where the vertical measurements of soil temperature were made. One may observe that both inlets and outlets of these two EAHX are placed next to each other and that measurements of soil temperatures will permit to see the effect of heat exchangers on the soil temperatures.

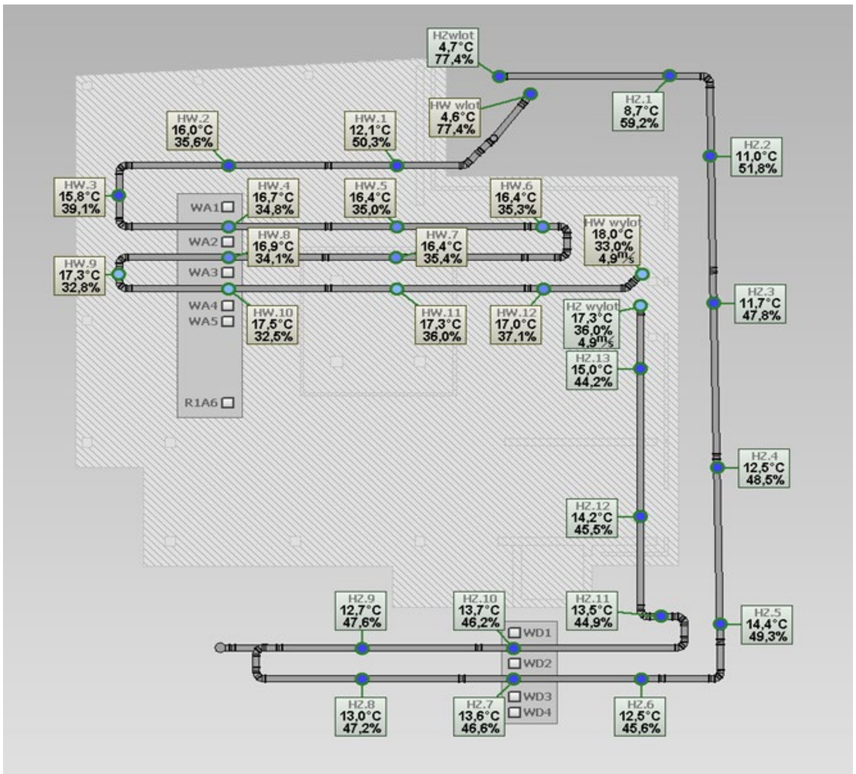

***Figure 2**. Schematic lay-out of both EAHX shown against the plan of the building. The temperature and relative humidity measurements in the EAHX pipes and their codes (HZ) are shown as well as vertical distribution of soil temperatures under the building (WA) and outside the building (WD). Temperature profile R1A6 is measured far from the heat exchangers and represent undisturbed soil temperature under the building.*

4. Reference temperature curves under insulated slab

Figure 3a shows a vertical cross-section through an insulated slab and Figure 3b locations of vertical temperature measuring points vs the EAHX pipe as well as positions of the measurement points on the reference soil temperature line.

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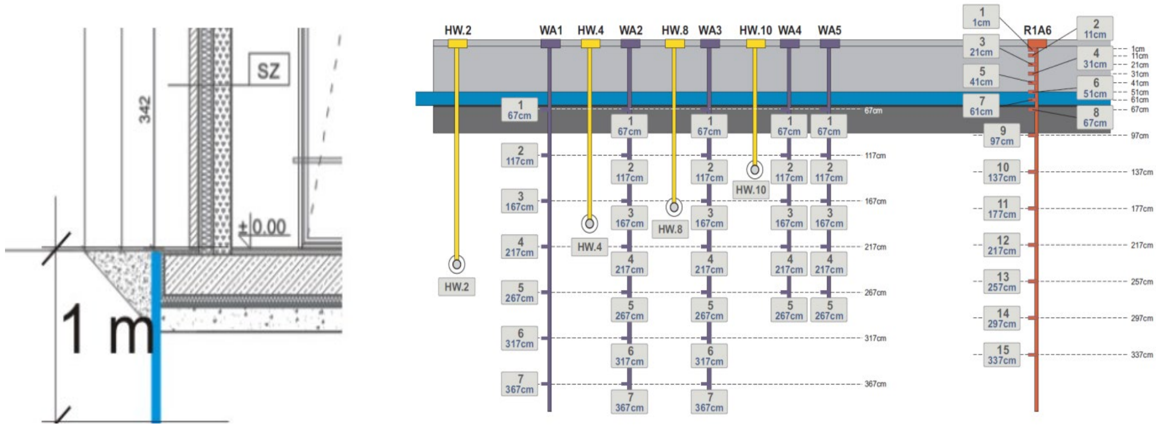


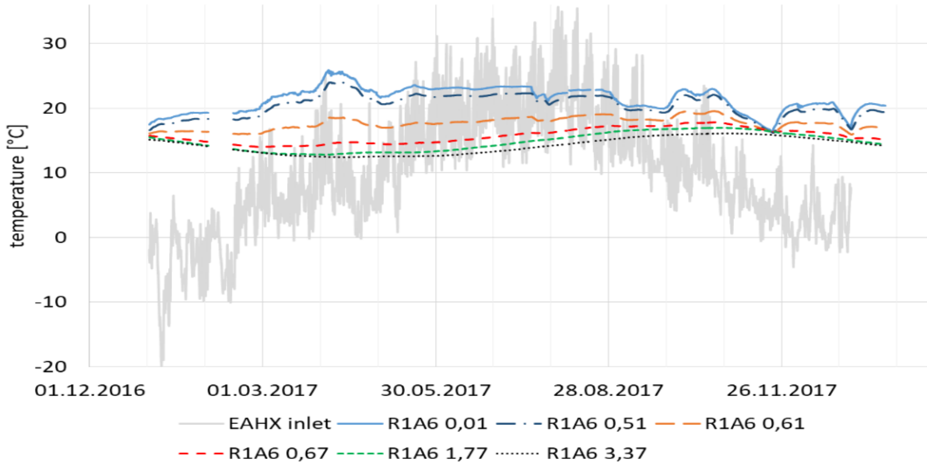
Figure 3a. ***(Left)*** *Vertical cross-section through an insulated slab;* ***Figure 3b*** *(Right) locations of vertical temperature measuring points vs the EAHX 1 pipes as well as positions of the measurement points on the reference soil temperature line.*

The slab on ground has a total thickness 1020 mm and comprises of the following layers:

- Ceramic plates 30 mm
- Concrete finishing layer 40 mm
- Slab on ground with reinforced concrete 500 mm (placed on protective film covering)
- High density extruded polystyrene (XPS) 150 mm (placed on water resistant barrier)
- Light weight concrete - 300 mm

Furthermore, to eliminate heat flow from the building to EHX2 placed in vicinity of the building one added a 1000 mm wide 150 mm vertical layer of the extruded polystyrene thermal insulation.

Figure 4: *Schematic cross-section through temperature measurement for EAHX 1 and the reference soil temperature over one-year time. Measurement points are located at dept of 10 mm, 510 mm (below concrete slab), 610mm, 670 mm (below thermal insulation) 1770 mm and the last at 3370 mm*



One can observe that 500 mm thick concrete layer modify the temperature but does not provide a smooth curve such as one obtained under 150 mm thick layer of a thermal insulation. The first meter of soil is assisting in a significant manner the provision of a stable and slowly varying temperature in summers, much lower than the air temperature. Differences between the three lowest curves in Figure 4 are small indicating that any advantage of deeper placement of the EAHX pipe may not be justified by an increased cost of the deeper installation.

5. Temperature in the EAHX pipe versus the reference curve

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Having established the reference temperature curves one may compare temperatures of the earth-to-air heat exchanger (EAHX) with those in the soil on similar depth under the building. This is shown in Figure 5.

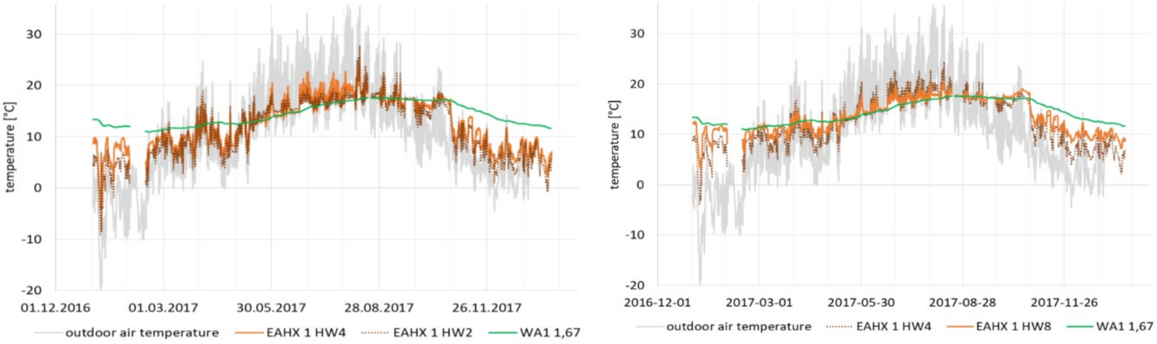

Figure 5a. Temperatures in the beginning (left) and Figure 5b Temperatures in the middle of the EAHX pipe (right) with the reference temperatures on two levels and air temperature (gray back ground).

Figure 5b shows that temperatures in the middle of the EAHX are much closer to the soil reference level than in the beginning of the heat exchanger pipe. Yet, all air temperatures in the EAHX pipe show oscillations, perhaps small, but still large enough to indicate that only a partial modification of air temperature took place. Yet, one often forgets that temperature field under the building varies in 3 dimensions, two of them being the distance from the edge of the building and the third a depth below the slab.

To highlight this point, we show in Figure 5b the profile of temperature on similar depth but at a different distance from the building's edge.

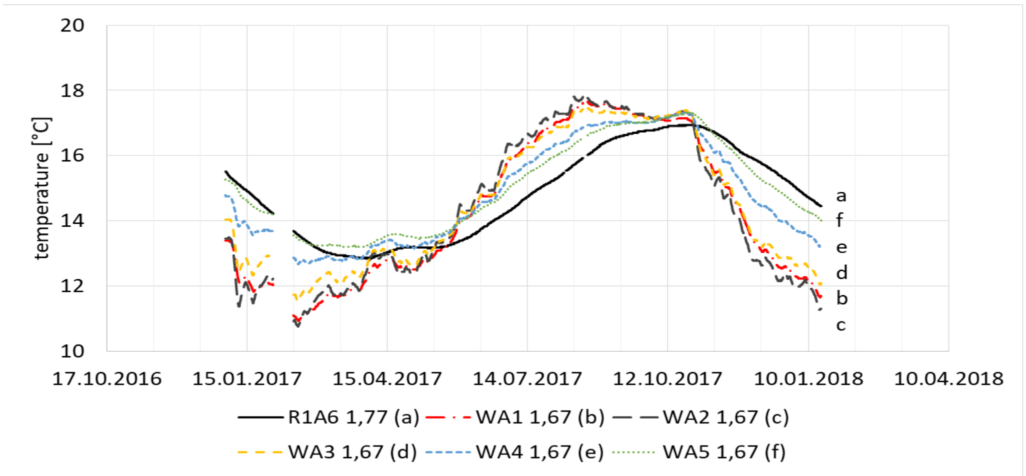

Figure 6. Measurements on the axis WA (as shown in Figure 2, it is under the house) show the variation on the first three measurement profiles and coming closer to the reference temperature at some distance.

As Figure 6 show the temperature profile in the soil surrounding the EAHX pipes, we realize that there a multidirectional temperature field and a small but visible temperature change as a function of the distance from the building edge. Furthermore, temperature variations inside the EAHX pipes were reflected by the temperature of the soils and only at a certain distance (curve f) the effect of the EAHX pipe disappeared leaving the smooth curve of the soil temperature changes. These factors must be taken into consideration when evaluating the optimum length of the EAHX pipe.

6. EAHX length with multibranch pipe arrangement

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Amanowicz [17] analyzed EAHX with a few low diameter pipes finding the influence of geometrical parameters on the flow characteristics and on the total pressure losses in particular.

His sensitivity analysis considers variable number of parallel pipes, pipes length and main pipe diameter. He showed that if the main pipe diameter is 40% larger than that of the parallel pipes a significant reduction of total pressure losses and improved airflow uniformity is obtained. Branch-pipe length affects the air flow uniformity but also increases resistance. These observations [7] are in a good agreement with our experimental observations (Figure 7).

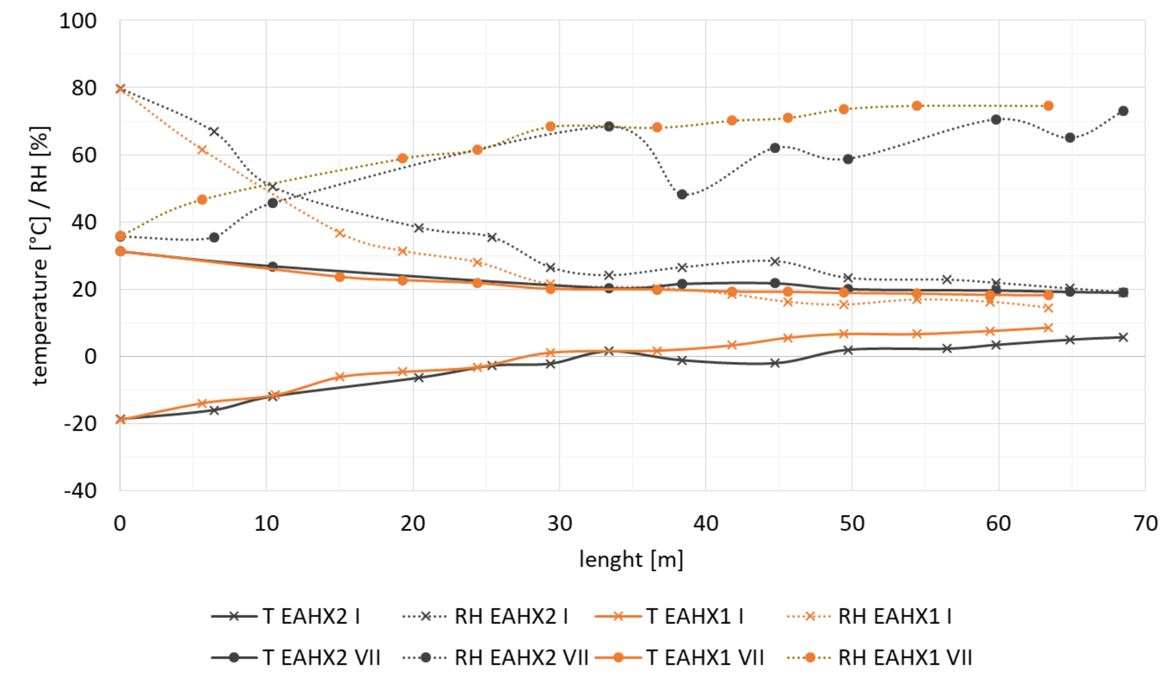

Figure 7. *Effect of distance from the inlet measured every 5 m on temperature and relative humidity of air in the EAHX pipe at CUT. The graph shows these relations measured on July 20, 2017 (filled circles) and on January 7, 2017 and values for booth EAHX tested (marked with x).*

Figure 7 shows the whole length of the EAHX from ground level to the ground level that exceeds the 60 m. This Figure explains some differences reported previously, namely the differences between measured values of temperature and relative humidity in the EAHX pipes. System 1, placed under the building has more uniform soil conditions that system 2 that is exposed to the exterior climate.

In summer, there appears to be no difference in the temperature measured by both heat exchangers that drops from the initial 30 to 20 °C over the first 30 m of the path. Finally, even though one may observe slow changes of temperature over the whole 60 m of the EAHX length the change on the first 30 m is much higher than on the second 30 m. For both the summer and winter we got about 75 -80 percent change in the first 30 m distance. Thus, we may conclude that in the studied case the length of 30 m was sufficient for the design purposes.

Yet the requirement for the EAHX length cannot be answered without addressing the floor area that the studied case relates to. When considering the reduction of air speed to a typical of 2 m/s from the current 4.1 m/s and for the current floor area of 423 m^2 and using the air change rate of 0.35 ACH (air change rate that is a minimum for health purposes) for the room height of 2.7 m one obtains about 225 m^2 floor area.

7. Comparing performance of EAHX 1 with EAHX 2

Figure 8 shows temperature and relative humidity in the outdoor air as well as in the two EAHX systems in one week of January 2017.

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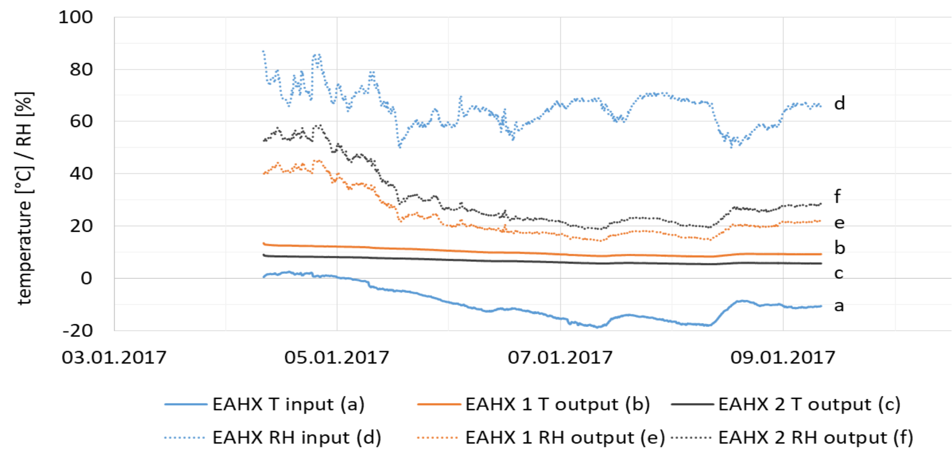

Figure 8. *Temperature and relative humidity in the outdoor air (EAHX input, color: blue) as well as the output from the EAHX1 (color: orange) and EAHX2 (color: black) during five days in January 2017.*

One may observe that with the outdoor temperature falling from near zero to minus 19 ^{o}C, there is a slight decrease of the temperature in the EAHX pipes. The absolute humidity appears to be constant and relative humidity follows the temperature changes in the EAHX pipes. The temperature of the EAHX 1 that is under the building is somewhat higher in the winter.

8. Calculating performance of the EAHX

In this section we will calculate the ability to provide the heating or cooling energy by the EAHX 1 and 2 on the base of measured temperature and humidity and mean air velocity of the air coming and leaving the EAHX.

In these calculations φ – is the relative humidity of air, p – atmospheric pressure of air [Pa], x – absolute humidity of air [kg/m^3], T - air temperature [°C] (T_{inlet} – on inlet to EAHX and T_{outlet} – on exit from EAHX), M- rate of the air mass flow [kg/s], V- mean flux [m^3/s] here 0,11111m^3/s that corresponds to 400 m^3/h, I – Enthalpy [kJ/kg] (I_{inlet} – on inlet to EAHX and I_{outlet} – on exit from EAHX), P-power [kW] and the following equations were used:

$$x=0,622((\varphi p_s) / (p-\varphi p_s))$$

Where:

$$p_s = 611,2e\text{^}((17,58*T) / (241,2*T))$$

$$I=1,0049T+(2486,5+1,905T-0,0016T^2)\ x$$

$$P=(I_{outlet}-I_{inlet})M,$$

Where:

$$M=Vp/(287,05((T_{inlet}+T_{outlet})/2+273,15))$$

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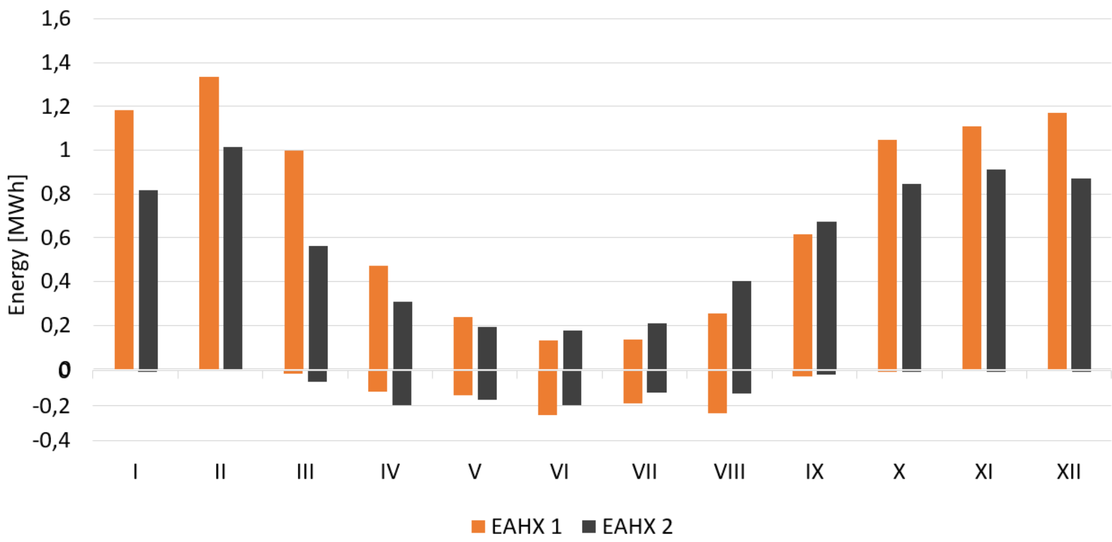

Figure 9. *Monthly calculation of heating (+) and cooling (-) capability (indexes) of each of the tested EAHX.*

Figure 9 shows the calculated capabilities of both EAHX 1 and 2 showing that EAHX 1 located under the building produced more heating energy in winter and cooling in summer than EAHX2 located in the ground adjacent to the building. We have called it heating index because in months March through September we may observe that both heating and cooling capability should be used and as previously discussed by Romanska-Zapala [1] one needs to employ an automatic steering for either heating or cooling and selection of outdoor inlet or EAHX.

9. Discussion on performance of EAXH1 and EAHX 2

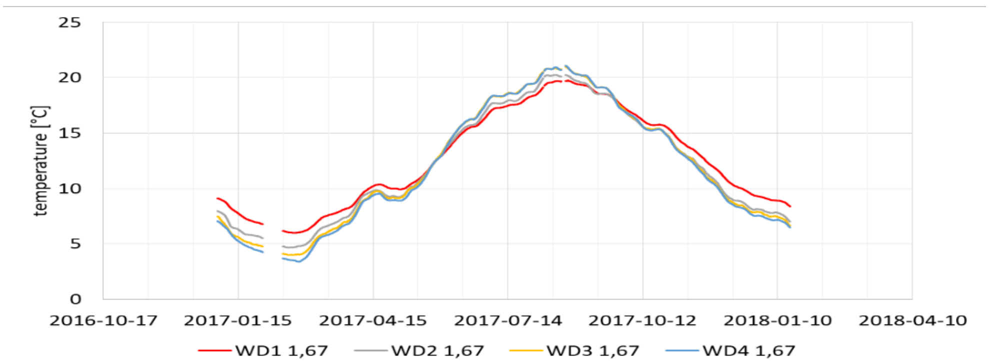

Figure 10. *Measurements on the axis WD (as shown in figure 2 it is outside the house) show the smaller variation between different temperature profiles but much larger differences between winter and summer than measured on the axis WA.*

The above presented permit drawing a few conclusions. The exit temperature of both heat exchangers varied throughout the year. During the spring, temperature steadily increased reaching in the summer 17 - 19°C, while in the autumn it decreased reaching in the winter 6 – 7 °C. The differences in construction of two tested heat exchangers were small, namely two 45 degree connectors instead of two with 90 degree angles, ascending EAHX 1 versus descending EAHX 2, however, the difference in performance between persisted through all seasons. As EAHX system 1 (located under the house) showed better performance than system 2, located outside the house one may conclude that the main reason was use of 150 mm thick, high-performance thermal insulation.

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Looking at the variation of performance between different parallel segments of the EHAX 1 pipes (under the house) one may also observe that they were located too close to each other.

Finally, one may observe that placing the EAHX under layer of thermal resistance of Rsi about 5 (m^2k)/W or U-value 0.2 K/(m^2K) is comparable with the effect of the deeper placement of the EAHX. This is shown in Figure 11 on temperature profiles measured in the axis D (open soil) on depth of 2.67 and 3.67 m.

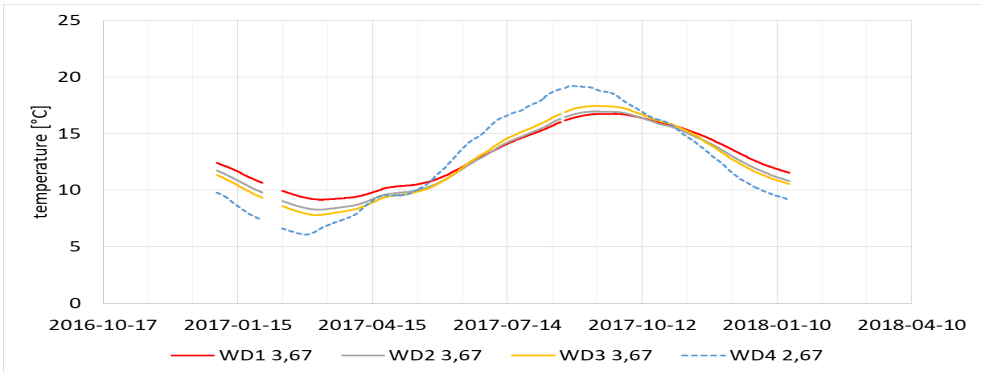

***Figure 11.** Temperature measured on the axis WD outside the building.*

One can observe in Figure 11 that deeper placement of the EAHX slightly increases the thermal lag and flattens the yearly temperature oscillation to the amplitude displayed by the EAHX 1, i.e., come closer to the optimal comfort conditions.

10. Discussion on the air preheat technology

If there is no soil gas (radon) an EAHX can be placed directly under insulated concrete slab place on ground or in the basement floor. Figure 8 shows that in winter temperature of air coming from the EAHX number 1 is significantly warmer than that from the EAHX number 2. Figures 10 and 11 show that the depth of 2 m or more is needed to fully benefit from EAHX placed in uninsulated ground, yet the same performance was achieved with 0.7 m depth under the basement of the building (Figures 4 and 5). If EAHX is placed under the building it should be located as much as possible in the central area of the basement slab. Effect of the distance from the building edge was shown in Figure 6.

So, if placement under the building is not possible, placement next to the drainage pipe at the foundation is the preferred location. In the latter case, a traditional practice of insulating the basement wall on the first 60 cm below ground and also placing a 1.2 m strip of 50 mm thick, extruded polystyrene almost horizontally i.e., with a slope of 2 – 3 percent. (One can also use any water-resistant foam with a similar U-value)

The length of the EAHX pipe should be at least 25 – 30 m. Figure 7 support literature findings [17] and shows that 30 m length provided a sufficient reduction of air temperature variation. The length of EAHX may further be shortened if one uses wide collecting pipe with two to four much smaller branches. For instance, in one NY demonstration house [18] we had 3 m pipe with 100 mm diameter with two 45-degree dividers collecting four 10 m long with diameter 25 mm PVC pipes placed 200 mm apart.

In another NY demonstration project [3, 4] where no drainage was needed on three sides of building that was located on a slope, the underground pipe was very short and the bulk of the pre-heat was achieved on an interior heat exchanger built on the return pipe connectors from the hydronic heating. This type of solution can also be used in retrofitting buildings without basement. In case of water seepage through the basement wall, one must excavate soil next to the building to locate exterior thermal insulation and drainage [19] and this facilitate either water or an earth-air heat exchanger.

Use of EAHX has an obvious appeal: they can reduce the energy needed for air conditioning. Yet the EAHX requires a bypass taking air directly from the outside; to select the source of a fresh air requires a control system. It could be based on differential temperature sensors with a motorized valve to control the mixing of air coming from two sources. This valve should also have a manual override. The other devices in the mechanical room are dehumidifier and dust particle removal, both to improve air quality.

Figure 9 shows that during 6 months for EAHX 1 and 8 moths for EHAX 2 one needs both heating and cooling. That indicates the need for switching between the two air sources. The power available from the EAHX1 in Figure 9 is calculated per hour, it shows variability from 4 kW to zero, while the fan operation took 75 W, so the control system must include two elements: (a) fraction of time when fresh air is delivered, and (b) the mixing ratio between air delivered from the EAHX and air delivered from the direct air intake. One must remember that the ventilation air is added to the unplanned air flow (UAF or air infiltration ratio) an this means that in ideal case the UAF is experimentally determined for specific building.

Elsewhere [20], we have discussed what criterion of air-tightness should be set to permit significant role of natural (uncontrolled) air infiltration to the building. This obviously will decide upon the setting of the criteria for (a) and (b) as much as cost of installation and operation versus potential to save electrical energy. One should also remember that using EAHX in cold climates, requires equipment that does freeze up in the winter and cost of maintenance, and in particular that air filters typically need cleaning or replacing every 6–12 months.

On the advantage side of EAHX technology is the capability to increase the amount of ventilation air during the periods when the temperature of the outdoor air is within a few degrees of the desired room temperature. Experience form the state of California indicates that over-ventilation of dwellings with outdoor air has multiple positive effects: it replaces a night cleaning of the dwellings, improves their feeling of thermal comfort and reduces the need to open windows when the weather is not suitable for it. As in integrated hydronic heating or cooling systems always comes with a water buffer tank, placing an air coil in each of them for some pre- conditioning intake air permits to broaden the range of air temperatures in which the occupant may use the over-ventilation feature.

Finally, there is another consideration with importance related to the size of the building, namely the complexity of the ventilation system. While making a central mechanical ventilation with a controlled supply and uncontrolled exhaust is easy for a small building, it is not easy for a multi-story residential building and may require use of neural network models [21].

Concluding remarks

With growing requirements on indoor air quality de-humidification and dust removal, with the selection of air from different air intake sources (EAHX or direct outdoor supply) an advanced control system becomes a part of the building design [22, 23]. If a building has a basement, including the EAHX system is always beneficial, while the contribution of the EAHX system can vary from taking 100 percent of the preheat to a small addition. The above paper assists in making this decision.

As the modern hydronic heating system becomes the main means of thermal energy delivery, increased role of air re-circulation in the indoor space integrates a modern, computerized system of outdoor air delivery. Effectively, computer-based informatics has recently joined the building science to respond jointly with to the need of holistic evaluation of building energy performance.

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