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ALTERNATIVE METHODS FOR PREHEATING OUTDOOR VENTILATION AIR

A. Romanska-Zapala[1a,b] , M. Bomberg[2]*, M. Dechnik[3], M. Fedorczak-Cisak[4] and M. Furtak[5]5

ABSTRACT

In the pursuit of energy efficiency one has developed a complex technology of earth-air heat exchangers (EAHX). In this process, one discovered some drawbacks such as possible entry of radon gas or high humidity in the shoulder seasons. Elsewhere, we highlighted that when the outdoor temperature changes frequently, one needs using two different air intake sources with an automatic selection of the one more appropriate for the actual weather conditions. In winter, the EAHX may be used continually but in the other seasons, the selection should be performed by a steering/ control system.

In this paper examined two nearly identical EAHX systems placed in the soil next to the building or under the basement slab. While there is an advantage in the under house placement, yet the advent of integrated system design permits replacing the EAHX by different heat exchangers located in the mechanical room (as it was done in a case study in NY) or in the exterior wall. In the latter case we propose an alternative system that permits using different ventilation patterns in summer and winter.

Key words: earth-air heat exchanger, energy efficiency, low-energy buildings, using thermal mass, smart and integrated control systems

1. INTRODUCTION

It is now a standard practice to heat or cool the fresh air between the point of intake and the entry to the mechanical room [1-3]. This can be done with earth-air heat exchanger (EAHX), see Szymański and Wojtkowiak [4] or Żukowski [5]. The use of earth for cooling air was already known in historic Greece and Persia [6, 7], yet, recently it became popular for a different reason, namely for the energy conservation.

A number of publications on this topic exist; Pfafferot [8] or Szymanski and Wojtkowiak [9] who analyzed one year of EAHX performance, Żukowski [5] discussed different applications and Peretti et al. [6] analyzed design and evaluation of earth-to-air heat exchangers and Gan [10] focused on dynamic interactions between EAHX and the environment.

Recent publications deal with the efficiency of EAHX based on laboratory work of Skotnicka and Wesolowski [11] and CFD calculations Congedo et al. [12]. Finally, two recent papers review various studies Kaushal [13] and life-cycle analysis of EAHX in a developing country by Uddin and Masudur [14].

So, while Peretti et al. [6] and Kauhsal [13] focused on heat flow and Gan [10] on interaction with surrounding soil and Zukowski [5], Szymanski and Wojtkowiak [9] deal with possible applications, benefits and risk of poor design, few papers deal with evaluation of EAHX for annual cycles of field performance. Pfeffarot, [8] who examined three cases in

[1 a,b] D. Eng., Małopolska Lab. of Energy Efficient Building (MLBE), and Automation and Information Technologies Cracow University of Technology, Cracow, Poland

[2] D. Sc. (Eng). Tech. D., Clarkson U., Potsdam, NY, USA, */ Corresponding author

[3] MSc. Eng., Małopolska Lab, of Energy Efficient Building (MLBE), Cracow University of Technology, Cracow, Poland

[4] D. Eng., Małopolska Lab. of Energy Efficient Building (MLBE), Cracow University of Technology, Cracow, Poland

[5] Prof., D. Eng., Małopolska Lab. of Energy Efficient Building (MLBE), Cracow Univ. of Technology, Cracow, Poland

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Germany and Kaushal [13] who examined a case in Bangladesh and Flaga-Maryanczyk et al. [15] as well as Skotnica and Wesolowski [11] in Poland. These publications highlight potential for reduction of energy needed for heating supply air in winter or cooling in summer but do not explain the necessity of switching between different sources of fresh air that was discussed by Romanska-Zapala [16,`17] or location o fthe EAHX.

To examine pro and con of the location, two nearly identical EAHX systemswere built at Cracow University of Technology [18]. The experimental set-up used in this research 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 drainge down pipe in ¾ distance to the mechanical room, while the other was placed outside the building and had the slope descenting 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 precison of ±3%. Measuremnts 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 symols 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.

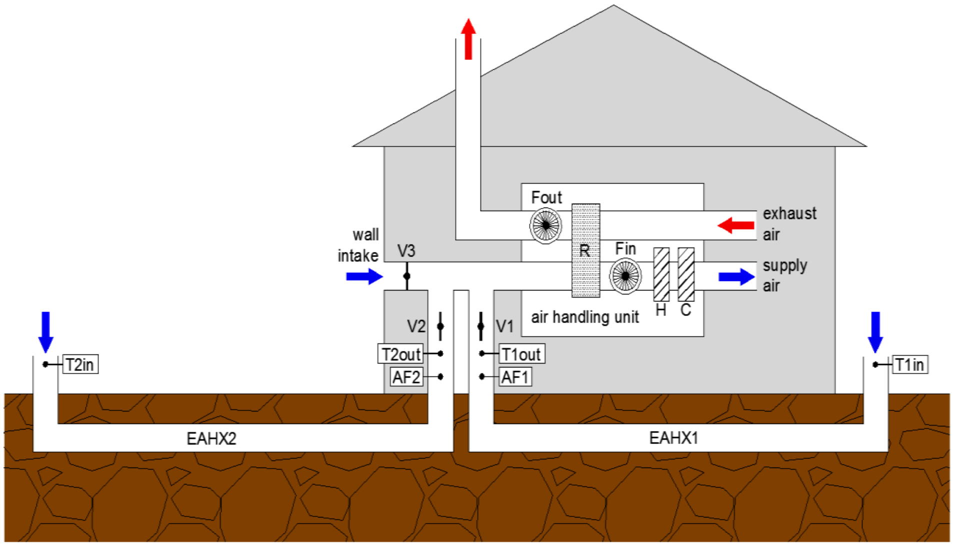

Figure 1: An experimental set-up with two ground air heat exchangers (EAHX) connected with the air handling unit. EAHX 1 is placed under the building, EAHX 2 the same system but placed outside the building. (From Romanska-Zapala [9])

The mechanical room has rotational heat eachanger with 1850 m^3/h flow and 80 percent efficiency, heating coil 3.25 kW and water cooling with 4.22 kW power. The experiments reported below were performed with air flow measured to be 400 m^3/h on average and air speed

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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. 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 charcteristics 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 technology as the exterior temperature changes combined with thermal mass of the building may cause more frequent switches between heating and cooling modes [10, 20].

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 measuremnts 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 measuremnts of soil temparatures will permit to see the effect of heat exchangers on the soil tempertureres.

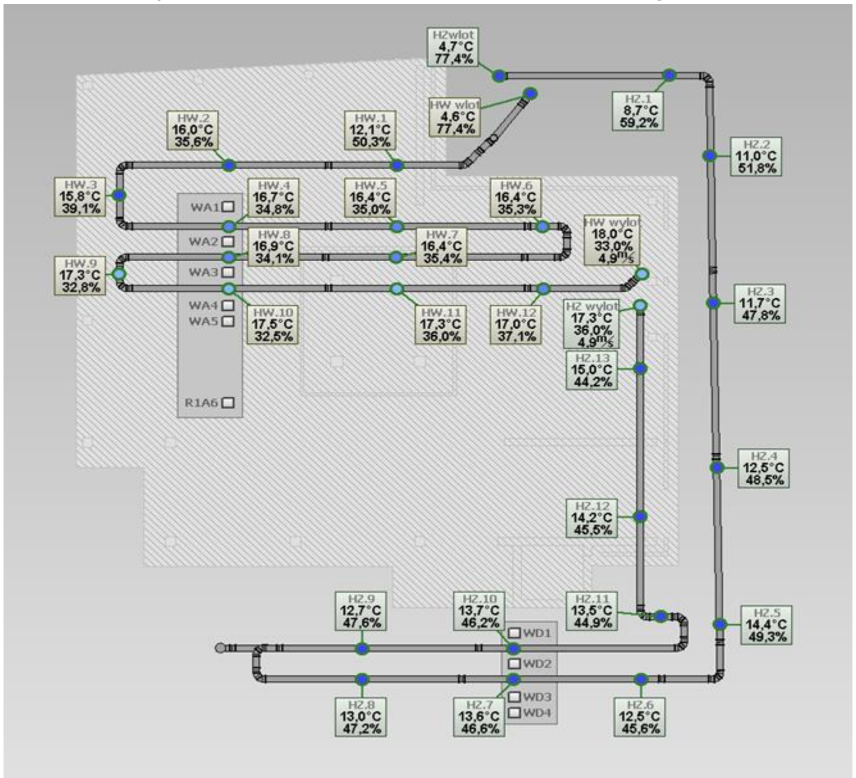

Figure 2: Schematic lay-out of both EAHX shown against the plan of the building. The temperature and relative humidity measuremnts in the EAHX pipes and their codes (HZ) are shown as well as vertical distribution of soil temperatures under the building (WA) and outside the building (WD). Temperature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

2. REFERENCE TEMPERATURE CURVES UNDER INSULATED SLAB

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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.

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)
- Keramzyt 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 isulation.

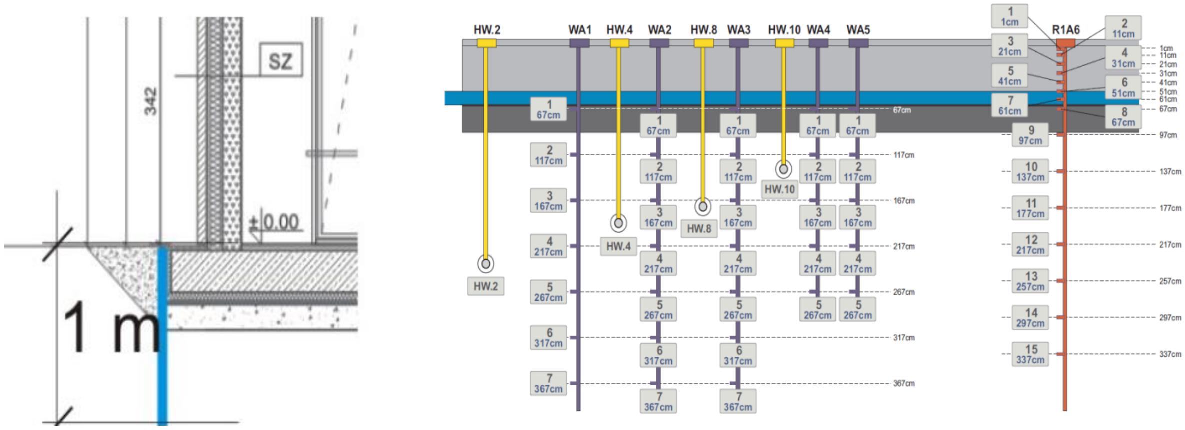

Figure 3a: vertical cross-section through an insulated slab; Figure 3b locations of vertical temperature measuring points vs the EAHX 1 pipes as well as positions of the measurement points on the reference soil temperature line

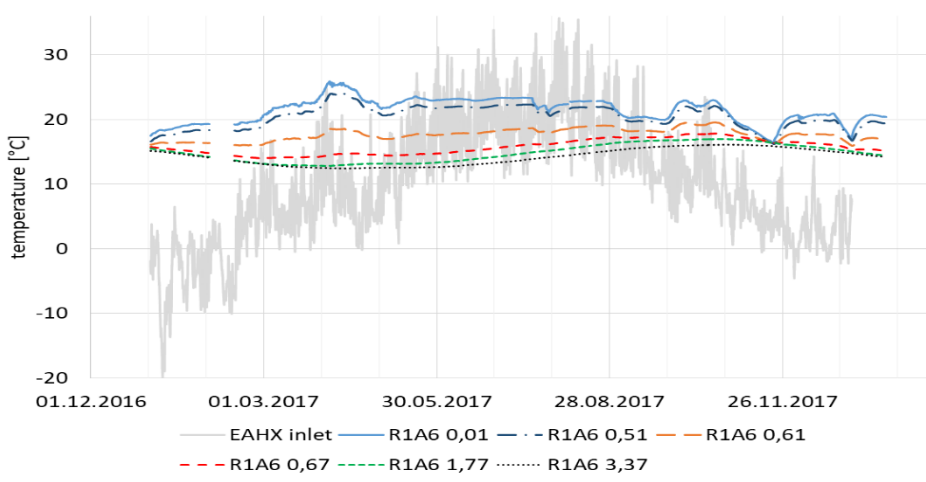

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Figure 4: Schematic cross-section through tempertutre measurement for EAHX 1 and the reference soil temperature. Measurement points are located at dept of 10 mm, 510 mm (below concrete slab), 610mm, 670 mm (below thermal insulation) 1770 mm and the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

One can observe that 500 mm thick concrete layer modify the temperature but does not provide a smoth 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 lowet than the air temparture. 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.

3. TEMPERATURE IN THE EAHX PIPE VERSUS THE REFERENCE CURVE

Having established the reference temparture 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.

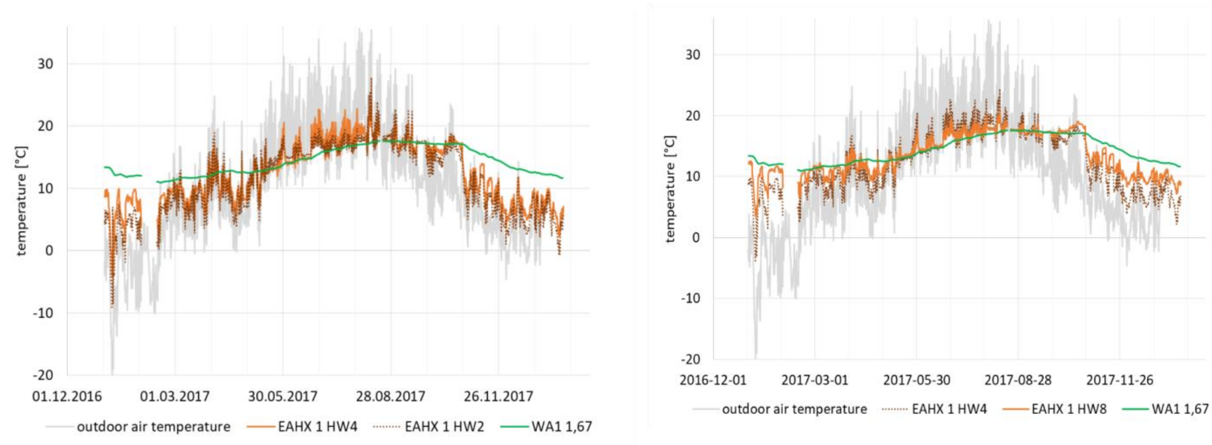

Figure 5: Tempartures in the beginning (left) and in the middle of the EAHX pipe (right) with the reference tempatures on two levels and air tempature (gray back ground)

Figure 5b shows that tempartures in the middle of the EAHX are much closer to the soil reference level than in the beginning of the heat exhchanger pipe. Yet, all air tempatures in the EAHX pipe show oscilations, perhaps smaller than their temparture but still large enough to indicate that only a partial modification of air temperature took place. Yet, one often forgets that temparture 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 5 the profile of temparture on similar depth but at a different distance from the building’s edge.

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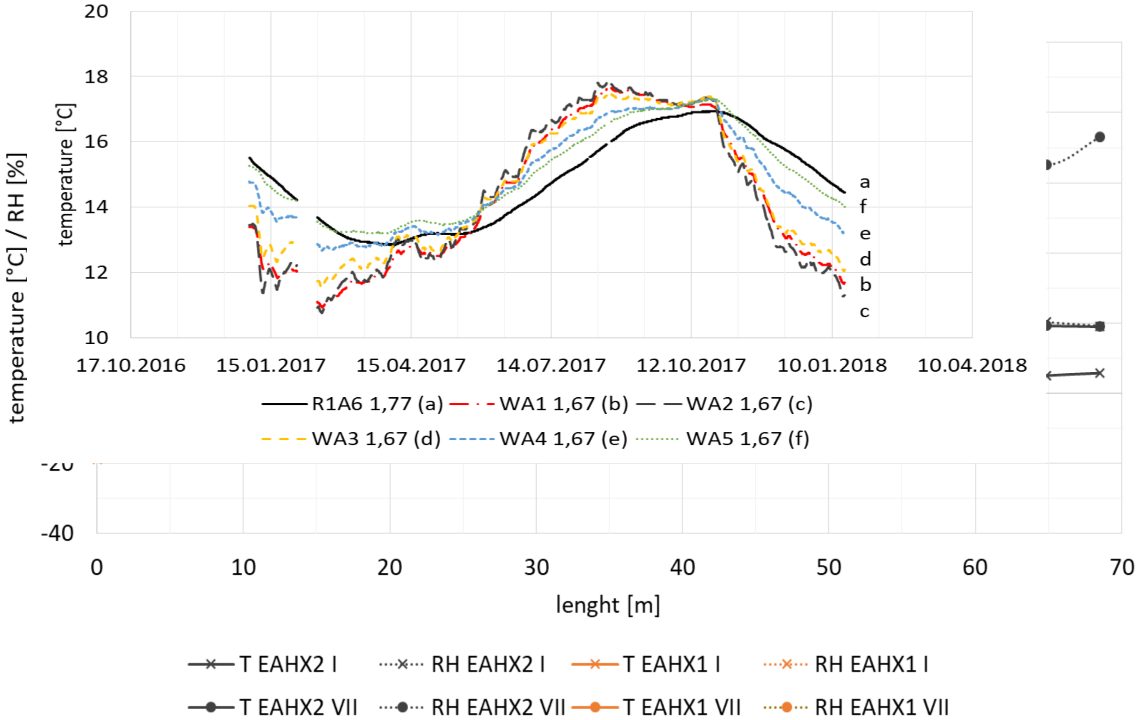

Figure 6: Measurements on the axix A (under the house) show the variation on the first three measurement profiles and coming closer to the reference temperature at some distance.

As Figure 6 show the temparture 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 temperturte changes. These factors must be taken into consideration when evaluating the optimum length of the EAHX pipe.

4. EAHX LENGTH OR MULTIBRANCH PIPE ARRANGEMENT

Amanowicz [19] analyzed EAHX with a few low diametr 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 the main pipes diameter that is 40% larger than are 1.4 the parallel pipes diameter can result in singnificant reduction of total pressure losses and improved airflow uniformity.

This was more important than branch-pipe length. Long pipes had 10- 30 percent better uniformity in the air flow division but also 15 - 30% higher resistance. These observations (experimental and CFD) are in a good agreement with our observations (Figure 7).

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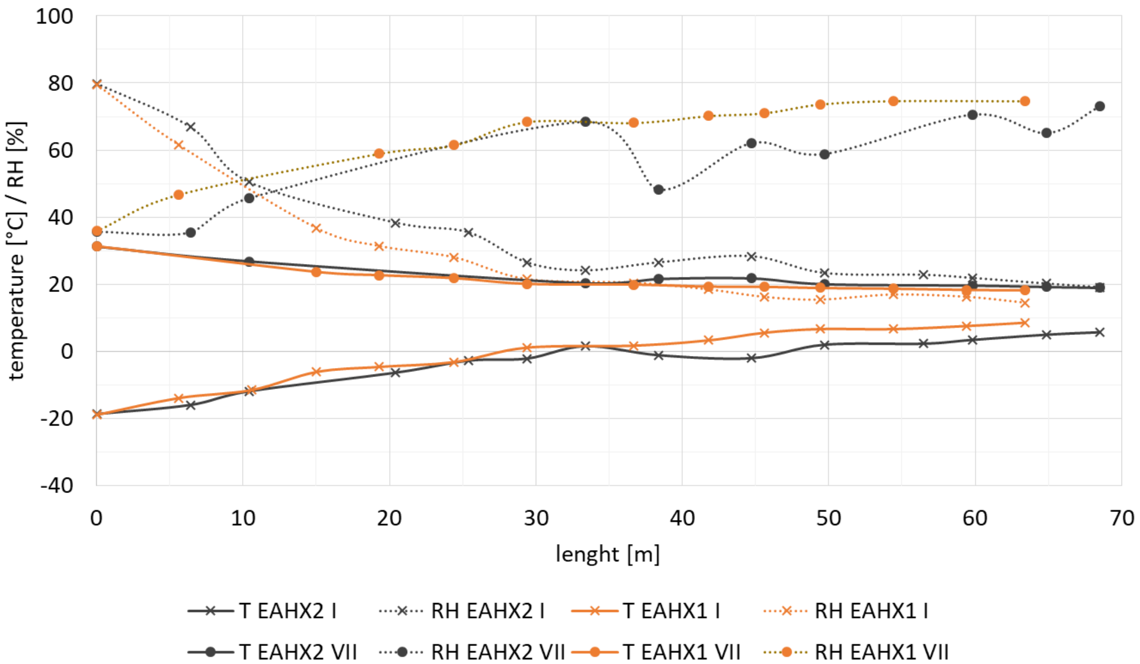

Figure 7: Effect of distance from the inlet measured every 5 m on temperature and relative humidity of air in the EAHX pipe at CUT. The graph shows these relations measured on July 20, 2017 (filled circles) and on January 7, 2017 and values for booth EAHX tested (marked with x).

Figure 7 shows the whole length of the EAHX from ground level to the ground level so the virtual length of the underground path exceeds the 60 m of the actual heat exchanger pipe. This Figure explains some differences reported in the previous paper, 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 ^{o}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 get about 75 -80 change in the first 30 m distance. We may say that in the studied case the length of 30 m is sufficient for the design purposes.

Yet this question cannot be answered without addressing the floor area that the studied case relate to. When considering the reduction of air speed to a typical 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 (minimum for health purposes) for the room height of 2.7 m one obtains about 225 m^2 floor area.

5. 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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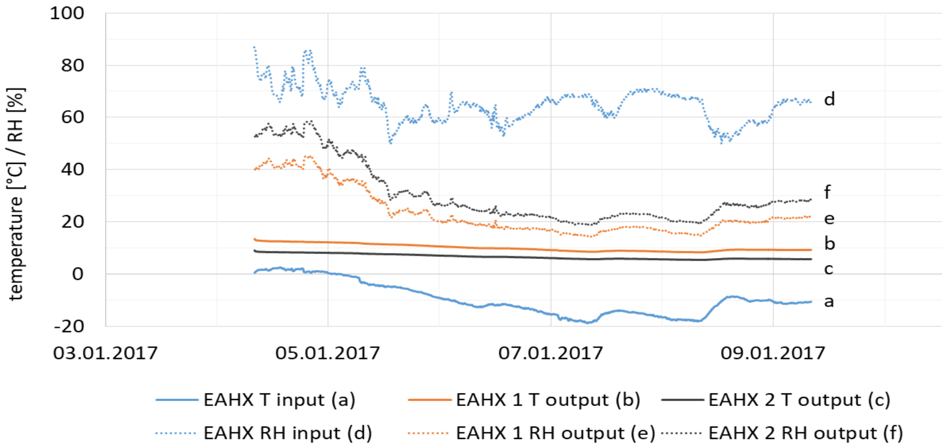
Figure 8: Temperature and relative humidity in the outodoor air (EAHX input, color: blue) as well



as the output from the EAHX1 (color: orange) and EAHX2 (color: black) during one week 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 a few degree higher in the winter.

6. CALCULATING THE 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 temparture 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/m3], 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 [m3/s] here 0,11111m3/s that corresponds to 400 m3/h, I – Entalpia [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

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

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

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

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

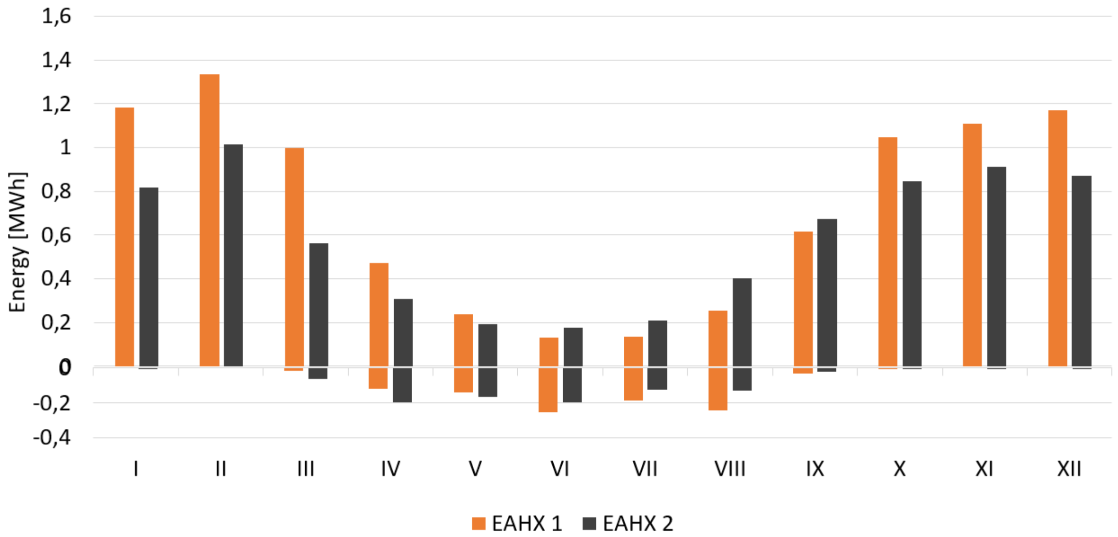


Figure 9: Hourly calculation of heating (+) and cooling (-) capability (indexes) of each of the tested EAHX

Figure 9 shows the calulated 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 the ground adjaced to the builidng. 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 [9, 10] one needs to employ an automatic steering for either heating or cooling and selection of outdoor inlet or EAHX.

7. DISCUSSION ON PERFORMANCE OF EAHX1 AND EAHX 2

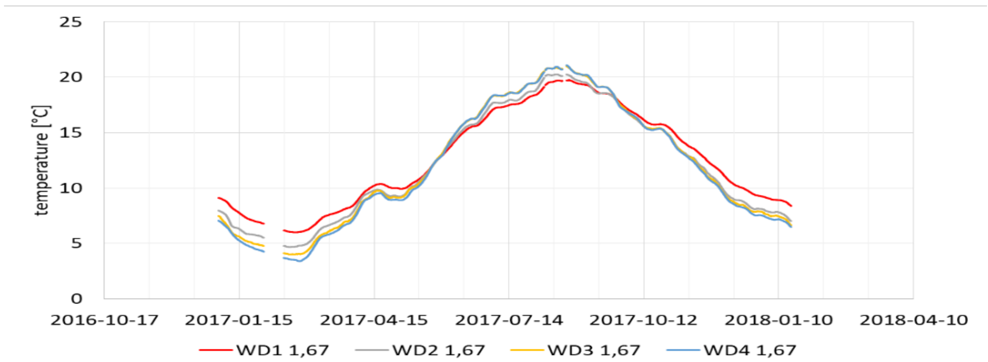


Figure 10: Measurements on the axix D (outside the house) show the smaller variation between different temperature profiles but much larger differences between winter and summer than measured on the axix A.

The above presented ten figures 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 ^{o}C. The differences in construction of two tested heat exchangers were small,

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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. 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 axia D (open soil) on depth of 2.67 and 3.67 m.

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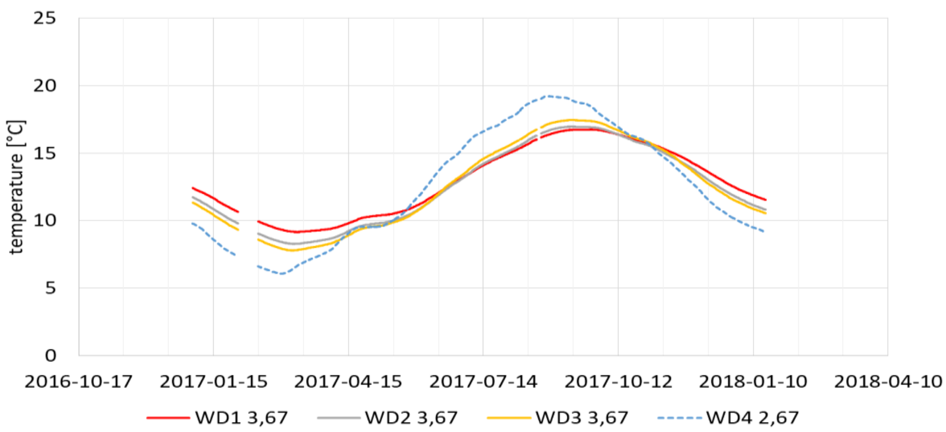

Figure 11: Temperature measured on the axix D on the depth of 2,67 and 3.37 m

One can observe in Figure 11 that deeper placement of the EAHX slightly increases the thermal lag but flattens the yearly temperature oscilation to the amplitude displayed by the EAHX 1.

8. PRO AND CONTRA FOR USE OF EAHX TECHNOLOGY

Our search for improved energy control and management continues, see [21, 22] and that includes integrated systems for control and steering of the HVAC equipment. Those will permit continuous monitoroing and smooth transition between use of EAHX and direct intake of outdoor air. In this situation an advantage of predictability of swithing between two sources of air pre-conditioning, as highlighted in Figure 12 is clearly visible. Figure 12 shows the a difference between the inlet and outlet temperature of the EAHX and indicates the need for switching between the air source.

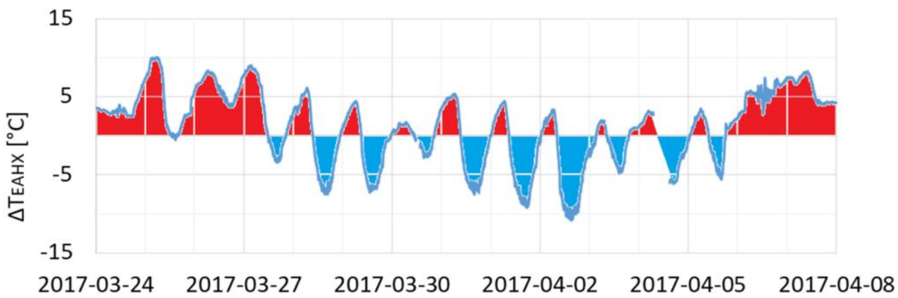

Figure 12: Temperature difference between inlet and outlet of EAHX in the spring time. Similar needs for heatig (red) and cooling (blue) in the spring day indicates a need for optimization and thereby a automatic steering of the source of the fresh air (Romanska-Zapala [9])

As high level of thermal insulation, air barriers and weather stripping reduce the unintentional air exchange between outodor and indoor environmnts [23], opening windows as the means to deliver fresh air is not a viable option any more and low energy buildings require use of a hybrid ventilation. In turn one may require pre-conditioning of the ventilation air. There are,however, many different ways for such a precondioning.

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 appears to be a good solution. For a small house, the air inlet can be located under the staircase of the entrance. One can use the main pipe of 200 mm with small-angle dividers to four pipes of 150 mm located under the concrete slab and similar collector to the main pipe with 200 mm deliverig air to the mechanical room. For larger building the diameter of pipes can be increased but the same concept may still be applied.

Use of EAHX have an obvious appeal: they can provide reduce the energy needed for air conditioning. Yet the EAHX must be ue used together with an air bypass that takes air directly from the outside. Having a choice between two sources of a fresh air requires a control system. The most unsophisticated system for a small house may comprise of a differential temperature sensor with a motorized valve can controls the mixing of air coming from two sources. This valve should also have a manual override. The next devices in the mechanical room are dehumiditier and dust particle removal. In larger instalations one talks about building management and optimization system.

On the downside, installation of EAHX can be expensive and they should not be used on continuing basis even in winter and summer when its need is the greatest. In examples discussed here, performance of EAHX varied from 4 kW to zero, while the fan operation took 75 W, so the control system must include two elemnets: (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 ventialtions air is added to the unplanned air flow (UAF or air infiltration ratio) an this means that the UAF must be experimentally determined on the specific builing.

Elsewhere [23], we have discussed what criterion of air-tghtness 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

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climates, requires equipment that does freeze up and mainatance, and in particular that air filters typically need cleaning or replacing every 6–12 months.

Finally, there is another consideration with importance related to the size of the builing, namely the complexity of the ventialtion system. While making a central mechanical ventilation with balanced supply and exhaust is easy for a single housing unit, it is not so easy for residential building with many dwellings in a multistory building. The history shows repeated failures of corridors and plenum as means of air delivery and designing multi-unit system as repetition of signle units is becoming more and more polupar. The next section of this paper can be called ''proposal for a future research" as it expands on pre-heat of the v entialtion air in the application to buildings with EQM technology.

9. SOLUTIONS FOR MULTI-UNIT RESIDENTIAL BUILDINGS

While the EHAX technology can be used in different small buildings it is not suitable for multi-unit residential buildings. Modern, energy efficient buildings, however, typically use hydronic heating / cooling [24, 25, 26] and therefore a heat exchanger may easily be placed in a mechanical room. Figure 13 shows a photo from a case study, a High Environmental Performance building in central New York [27, 28].

Figure 13: A main system panel in High Environmental Performance house [27, 28] for the return pipes from the floor heating supplied by a condensing boiler, storage tank for domestic hot water and heat exchanger between return heating (metal) pipes and ventilation outdoor supply air

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A high-efficiency, condensing, natural gas boiler provides the space heating and domestic hot water for the house. The boiler is piped in a primary / secondary piping configuration. The primary loop operates at 135°F and is used for indirect DHW production, as well as feeding the secondary heating loops. Two primary circulation pumps are used (one for the heating loops, and one for the DHW loop). The primary pumps cycle in operation with the boiler.

The boiler selected is a Viesmann Vitodens 200 WB2 8-32. The unit has a continuous variable firing rate from 37 MBtu/h to 124 MBtu/h input and has a 94.5% AFUE. The boiler panel is shown in Figure 13. Each secondary circulation pump is 1/8-hp, and the two primary loop circulators are 1/25 hp. The pumping power for this system totals approximately 0.71-hp, or 500 watts. The hydronic system secondary heating loops consists of in-slab radiant heat, hot water coils located in two small duct high velocity (SDHV) air handlers that provide a secondary conditioning of the outdoor air.

10. A LOOK INTO THE FUTURE

The future technology will deal with the building as a system that collaborate with the smart grid [29, 30] in which one of the critical subsystems is the hybrid ventilation. We may stop talking about mechanical or natural ventilation because the optimal system needs both of them and is known as hybrid ventilation.

Traditionally, over-pressurizing the indoor air was not allowed because of the risk of water vapor condensation when air is carried into the building enclosure. Yet, as the current low energy buildings can be designed with an adequate control of air flow in walls, an unbalance of indoor and outdoor pressures can easily be tolerated. So, looking from the building physics point of view, one may use an indoor air overpressure in summer and under-pressure in winter because in both cases the air transport goes from lower concentration of water vapor towards the higher one.

Such a design has two completely different air flow patterns. In summer, one takes the warm and humid outdoor air, cools it in a mechanical heat exchanger, dehumidify and remove dust particles before it enters to the air handling unit delivering air with positive pressure. The clean supply is delivered to the house of each dwelling in a multi-unit building by a valve with controlled flow rate under the 10 Pa over-pressure. The overpressure created by a programable ventilator in the air handler will result in natural exhaust ventilation through bathroom and kitchen ventilation openings and through the individual ventilation system that will be provided in the exterior walls of the solar exposed rooms. The water vapor retarder is also used to reduce moisture ingress from the interior. These ventilation cavities are also used for individual ventilation that works automatically under night ventilation scheme, and may also be operated manually.

In winter, the warm air is removed through exterior (drainable) cavities that would also act as the energy exchangers. Yet for this system to provide an effective humidity control in summer one needs a layer of capillary active material that would provide a moisture buffering capability Such materials are being developed now.

CLOSING REMARKS

In the previous paper [9], we highlighted that to optimize preheat of ventilation air one should use EAHX together with the direct air intake and to control their use one must an automatic control system. In this paper we have examined construction and performance of the EAHX systems concluding that placing EAHX under the middle part of the thermally insulated slab on ground or basement slab eliminates the need for a deep placement in the soil.

We have also observed that the design the pre-heat of ventilation air cannot be done without simultaneous consideration of the ventilation system and if we decide to use an advanced system of steering and control, we can easily integrate several components of energy management. An example given here, will also be a system that we intend to study in the next research project and because it requires an integration between HVAC and the building structure we will use an integrated control system

Note on the contributions:
Formal analysis, Anna Romanska-Zapala and Mark Bomberg; Funding acquisition, Malgorzata Fedorczak-Cisak and Marcin Furtak; Investigation, Mirosław Dechnik and Malgorzata Fedorczak-Cisak; Methodology, Mark Bomberg; Resources, Marcin Furtak; Software, Anna Romanska-Zapala; Supervision, Anna Romanska-Zapala; Visualization, Miroslaw Dechnik; Writing – original draft, Mark Bomberg

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