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Buildings with environmental quality management, part 2: Integration of hydronic heating/cooling with thermal mass

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Abstract

The quest for a sustainable built environment brought dramatic changes to architectural design because of the integrated design process. The integrated design process is the modern way to realize "performance architecture," that is, design with a view to field performance. Integrated design process permits merging of concepts from passive-house designs, solar engineering, and an integration of the building enclosure with mechanical services. In part 1 of this series, the emergence of many new multi-functional materials was discussed. Yet, current innovation is guided by lessons from history. Thermal mass in heavy masonry buildings allowed periodic heating. The authors postulate integration of a hydronic heating system with the walls and the use of smart temperature control of the heating system to modify and optimize the thermal mass

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contribution. To use the mass of a building, one must accept transient temperature conditions where the indoor temperature varies but is confined by comfort requirements for both summer and winter conditions. On the other side, resiliency requirements dictate that in the absence of electricity the air temperature does not fall below about 12°C over a period of several hours. This requirement implies that summer cooling will likely be separated from the heating systems and that operation of a low-energy building is heavily dependent on the design of smart control systems. Analysis of control systems provided in this article for earth-to-air heat exchangers and cooling of houses with lightweight walls lead us to the requirements of separation between heating and ventilation and needs for different sources of fresh air. Finally, a new concept emerges.

Keywords

Sustainability, integrate heating, ventilation, and air conditioning, low-energy buildings, multi-functional materials, thermal mass, control system

Introduction

During the 1930s, commercial thermal insulation as well as air and moisture barriers were introduced on the North American prairies. In the late 1970s, in the same region, the first 10 passive houses were built (Bomberg et al., 2016). The lessons from these passive buildings in Europe and North America are as follows:

- Not a single material or building component improvement but many small, interacting improvements are needed for a significant reduction in energy use. For example, the application of vacuum insulation panels that minimizes the impact of thermal bridging on heat transport requires skill in designing an assembly.
- There is also a consensus that a high level of thermal insulation and airtightness are necessary for a low-energy building.
- A low-energy building must be designed so that heating and cooling are combined with thermal mass to eliminate or reduce the peak utility demands.
- The use of hybrid (mechanical and natural) ventilation is preferred because delivery of fresh air to specific places will also be required in the absence of buoyancy forces.
- An affordable low-energy design requires that all passive measures be fully implemented before solar thermal or geothermal measures are considered.

To achieve these goals, we need to redirect the focus of design on the occupant, and for achieving high-quality environment advocate for buildings with environmental quality management (EQM). We have also learned from history that builders follow only the clients' wishes even if it conflicts with available information (Bomberg and Onysko, 2002). It is therefore important that building science presents and explains the application of new technology.

Finally, we recommend that while one uses all passive-house design measures to reduce energy level to 70 kW h/m^2 per year (a criterion from Central Europe), one also increases the area of windows to the level desired by the occupants. The design should combine utilization of thermal mass with geothermal and solar sources of energy.

Pre-conditioning air with the earth-to-air heat exchanger

The use of earth heat exchangers for supply air in mechanical ventilation systems is among the different geothermal measures used to increase the contribution of renewable energy in buildings. In this article, the acronym EAHX for earth-to-air heat exchange is introduced. This section is not to teach how to design or build EAHX, but explain why despite all its advantages we need to maintain duality of air-intake methods.

Literature review

A number of publications on this topic exist; Pfafferott (2003) and Szymanski and Wojtkowiak (2008) analyzed 1 year of EAHX performance, Żukowski (2012) discussed different applications, and Gan (2014) focused on dynamic interactions between EAHX and the environment. Incidentally, as observed by Ionescu et al. (2015), geothermal energy was used in ancient Greece and Persia.

Recent publications deal with the efficiency of EAHX based on laboratory work of Skotnicka-Siepsiak and Wesołowski (2016) and computational fluid dynamic (CFD) calculations (Congedo et al., 2016). Finally, two recent papers review various studies (Kaushal, 2017) and life-cycle analysis of EAHX in a developing country (Uddin et al., 2016).

Kaushal (2017) focused on heat flow, Gan (2014) focused on interaction with surrounding soil, and Żukowski (2012) and Szymanski and Wojtkowiak (2007) dealt with possible applications, benefits, and risk of poor design; there are few papers dealing with evaluation of EAHX for annual cycles of actual performance. Pfafferott (2003) examined three cases in Germany, Kaushal (2017) examined a case in Bangladesh, and Flaga-Maryanczyk et al. (2014) as well as Skotnicka-Siepsiak and Wesołowski (2016) examined cases in Poland. These publications highlight potential for reduction in 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 Romańska-Zapała et al. (2017).

Figure 1. EAHX that is placed next to the drainage pipe.

Experimental work

Typically, EAHX is located as deep in the earth as practical. This can be under the building, in a drainage layer of the basement slab, or next to the drainage pipes as shown in Figure 1.

Figure 1 shows a few pipes have different diameters and flow resistances, that is, EAHX with unpredictable thermal performance. It was, therefore, of interest to compare measurements performed in the same weather conditions on two similar EAHXs. This laboratory of Cracow University is in a separate building with a shallow foundation (slab on ground with a perimeter thermal insulation in surrounding soil) so that EAHX systems to be studied were installed by digging a ditch at specified locations.

The experimental setup includes a supply-exhaust system with direct intake of outdoor air through a wall and two intakes, each of them dedicated to one EAHX system. Each of the EAHX is provided with temperature and humidity sensors connected to the datalogger. Measurements of earth temperatures are performed in two ranges: (1) $-25°C$ to $0°C$ with precision of $\pm 0.3°C$ and (2) from $0°C$ to $40°C$ with precision of $\pm 0.1°C$. Relative humidity is measured in the range of 10%–90% with precision of $\pm 2\%$. Measurements are recorded every 15 min. One of these ground heat exchangers is located under the building (EAHX 1) and the other outside the building (EAHX 2, see Figure 2). The heat exchangers are made of approximately 60 m of 200-mm-diameter polyvinyl chloride (PVC) pipe starting at a depth of 1.5 m with a downward 2% slope to a depth of 2.5 m where water collecting wells were installed. Both air inlets are on the north side of the building. An exhaust for air is located on the roof.

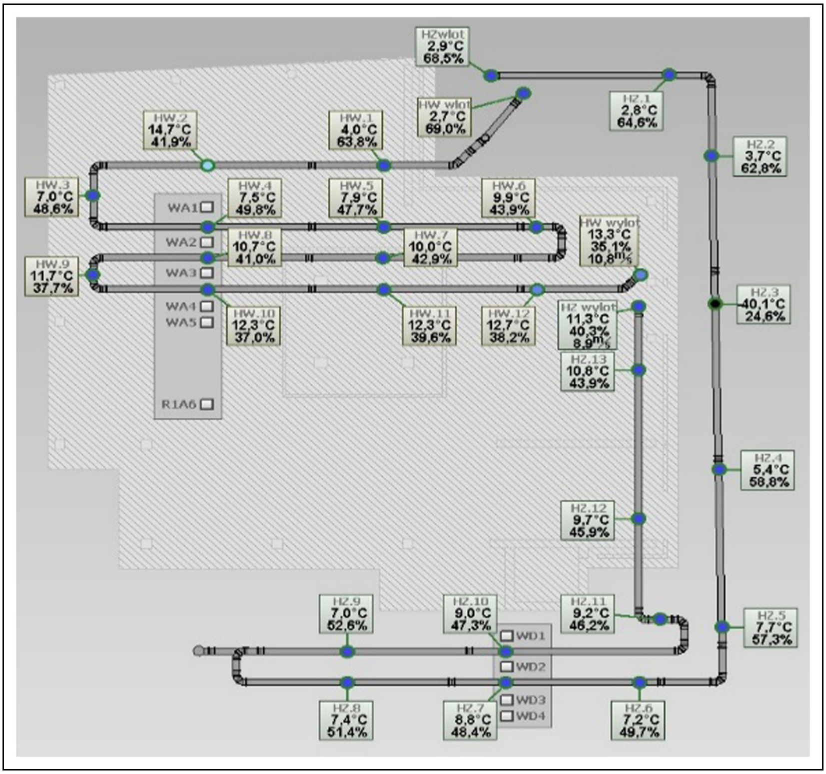

Figure 2. Schematic layout of two EAHX systems tested at MLBE; lighter gray denotes the area of building and numbers represent different soil temperature measurements.

The ventilation center (CW1) is shown in Figure 3. It operated with constant temperature on exhaust and air flow of about 450 m^3/h. This equipment included an 80% efficient rotational heat recuperation using nominal power of 3.25 and 4.22 kW, in winter and summer, respectively. The maximum air flow was 1850 m^3/h. CW1 has its own automatic control system. The choice of fresh air intake is made by power-supported valves.

The measurements were performed in September (at time of daily cooling/heating changes) and in two winter periods. Figure 4 shows 60 m of 200-mm-diameter pipe that can accommodate a flow rate of 450 m^3/h (the design flow was 300 m^3/h). Both EAHXs show similar performance, but EAHX 1, placed under the house, has somewhat lower output temperatures than the one placed outside the building. The weather similar to that shown in Figure 4 lasted until 16 September, followed by signifant cooling.

Figure 5 shows a comparison of EAHXs 1 and 2 during the period of cooling, when the outdoor temperature falls from 18°C to 8°C.

Figure 3. Mechanical room (CW1), reflective jackets on pipes from wall air intake and EAHX.

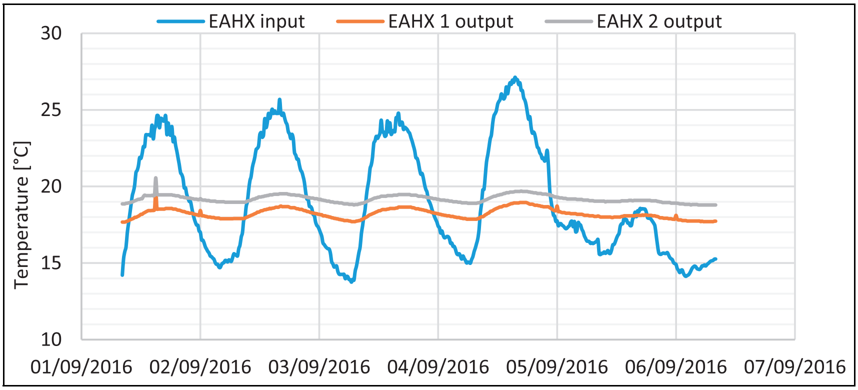

Figure 4. Temperature of air on entry (blue) and exit from EAHX 1 (orange) and EAHX 2 (green) during the period 1–7 September 2016.

Figure 5 shows the effect of cooling outdoor temperature on the performance of the EAHX. Comparing Figures 4 and 5, one may observe that EAHX 1 shows better performance, that is, lower temperature during the fall. Figure 6 shows the worst period of winter (at this location) when outdoor temperature decreased from 2°C to −18°C over a period of 3 days. At this time, when the outdoor air temperature falls to 20°C, the output from EAHX 1 is reduced by 5°C and from EAHX 2 by only 3.5°C indicating a good thermal storage capacity of the surrounding soil.

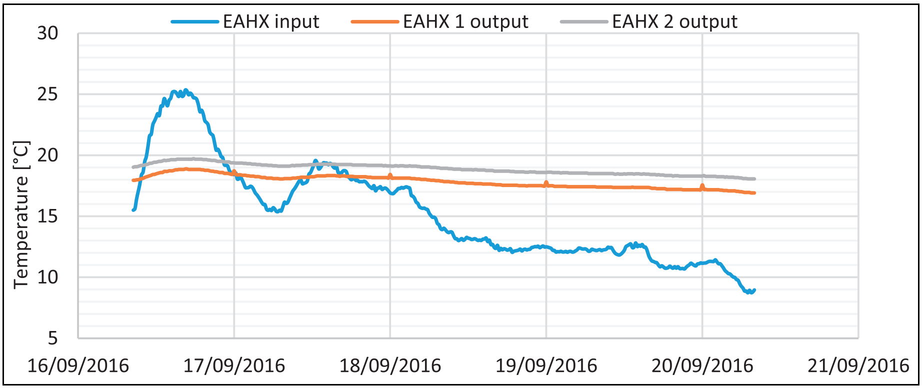

Figure 5. Temperature of outdoor air on entry (blue) and temperature on exit from EAHX 1 (orange) and EAHX 2 (green) during the period 16–21 September 2016.

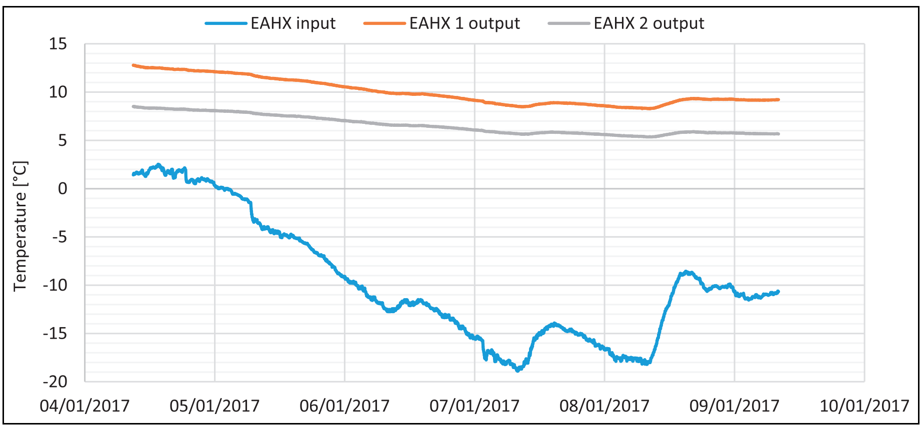

Figure 6. Temperature of air on entry and exit from EAHXs 1 and 2 during the period 4–10 January 2017.

The difference between EAHXs 1 and 2 being different during the transient and steady-state conditions can be caused by two different reasons:

1. Different moisture content of soils under the building and outside the building.
2. Heat flow from the building to the ground. As the building is already in its third year, one may consider that the temperature in the ground under the building is slightly higher than the outside temperature.

Finally, we have also examined relative humidity of the supply air from the EAHX system. Figure 7 shows temperature and relative humidity in a transition

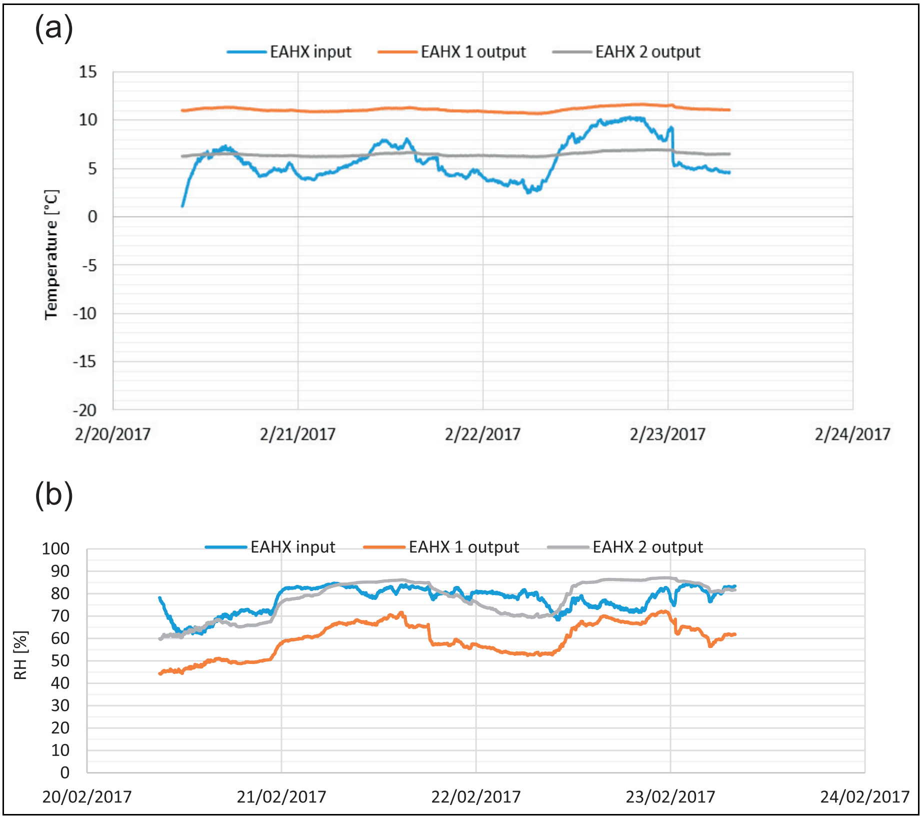

Figure 7. (a) Temperature of air on entry and exit and (b) relative humidity on exit of EAHXs 1 and 2 during the period 20–24 February 2017.

period between winter and spring. One can observe that one of the EAHX has exit temperatures about the same as outdoor temperature and does not modify the moisture content in the incoming air. During the whole period of measurements shown in Figure 7, moisture contained in the incoming air; whether it is from the outside or from the EAHX is too high for comfort and provides a risk of mold growth.

Figure 7 shows that even in the moderate climate of Kracow, Poland, some dehumidification of incoming air may be needed.

Comparison of EAHXs 1 and 2

This article compares the performance of heat exchanger placed in two different locations. The design parameters for the EAHX were identical, the period of testing was the same, measurements were performed simultaneously, and the only difference between the units was location. The difference in performance of these two units is significant. At the end of summer, the temperature of EAHX 1 (under the building, see Figures 4 and 5) is about 1°C lower than EAHX 2, while in February the temperature of EAHX 1 (under the building, see Figure 6) is about 4.5°C higher than that of EAHX 2. If one did not know that they were located at the same depth, one would assume that EAHX 1 was placed much deeper in the ground.

One can speculate that the heat flow from the building can drive moisture out of the soil filling the ditch material making it more thermally effective. If the presence of the building 1.5 m above made significant difference, one should examine whether placing a strip of nearly horizontal (slope for water management) thermal insulation on 30–50 cm depth from the soil surface but above the EAHX could also make it more efficient.

The primary conclusions from this section deal with the control systems as follows:

1. Except for the extreme cold weather, there will be periods during the day when switching to direct outdoor air is economically justified and one should design two means of fresh air intake in low-energy buildings.
2. Dehumidification should be provided in the location when both air supply streams come together and before they enter the building ventilation system.

Cooling of buildings: theory and practice

Pogorzelski and Golembowicz (1965) examined cooling rates of two light, test buildings: (a) "plastic demonstration house," where the load-bearing structure and enclosure were made entirely from plastics and thermal insulating foams and (b) a panelized system with wood-based panels and foam insulation. This comparison (Figure 8) is interesting because house (a) tested in the winter of 1962/1963 had mechanical ventilation, while house (b) tested in winter of 1964/1965 had natural ventilation.

Analyzing Figure 8(a) and (b), one may observe that cooling process comprises two stages: the initial stage where the cooling progresses from the wall surface to a certain depth of the material. The next stage represents a quasi-steady state where thermal energy is extracted from all points of the wall and the rate of cooling becomes constant and identical to theoretical cooling of concentrated mass with equivalent thermal capacity.

Figure 8 uses a semi-logarithmic scale and normalized, dimensionless temperature $[(t - t_e)/(t_i - t_e)]$ where t_i is the interior air temperature, taken to be 20 °C. Normalization permits better comparisons of the cooling phenomena. Despite different materials and varying exterior temperature, normalized curves shown in Figure 8 are similar.

These curves show the effect of indoor-air temperature equalization introduced by mechanical ventilation. Curves I and II in Figure 8(b) represent air in the

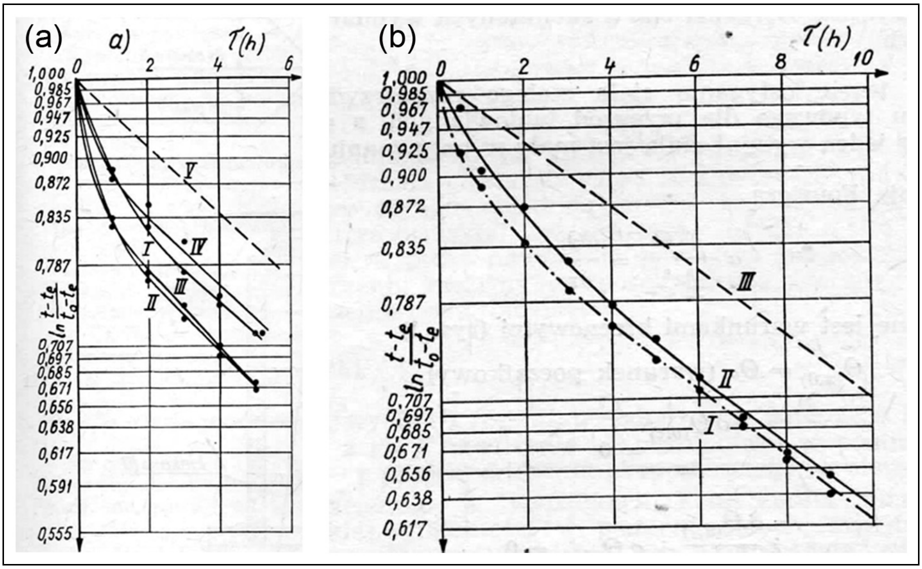

Figure 8. (a) Cooling of the house with wood-based panels: I—surface of the interior wall, II—air in the middle of the room, III—air at the exterior wall surface, IV—surface of the exterior wall, and V—theoretical curve for concentrated mass equivalent to the whole building. (b) Cooling of the plastic house: I—indoor air in the middle of the room, II—interior surface of the exterior wall, and III—theoretical curve for concentrated mass equivalent to the whole building.

vicinity of interior and exterior walls that are next to each other when mechanical ventilation is used, while curves II and III in Figure 8(a) (natural ventilation) are far apart. Figure 8 also presents the effect of thermal impedance of both buildings. It leads to an interesting conclusion, namely, if our resiliency criterion is a period of cooling from 20°C to 12°C when electricity is interrupted and the outside temperature is 0°C, this on Figure 8(b) corresponds to dimensionless temperature of 0.6°C.

The time to reach the value of dimensionless temperature 0.6°C is more than 10 h for very light plastic house construction under conditions of mechanical ventilation. It highlights the fact that the critical effect on cooling of the whole building has the internal mass. Comparing Figure 8(a) and (b), we can also observe that recirculation of interior air by mechanical ventilation helps maintain smaller temperature differences than it was under natural ventilation (Figure 8(a)). The demonstration plastic building shown in Figure 8(b) is probably more airtight than the standard residential house built in 1960s, and both of them are much less airtight than the currently built houses. Yet, it is clear that if we want a modern building to have a period of cooling from 20°C to 12°C to be at least 12 h, we need to increase both the airtightness and the mass in the interior of the building.

The above example shows that while mechanical ventilation provided equalization of temperature in the whole space, significant difference in the rate of temperature changes exists between the same mass whether dispersed or concentrated. This difference in response of air and thermal mass leads us to the next question—should buildings with EQM be required to separate heating from ventilation?

Need for separating heating and cooling from ventilation

One may wonder why we are bringing information from an introductory course in building physics to an advanced journal. One reason is that most people designing and building dwellings did not attend such a course, but there is also another more important reason. Currently, most of our heating and cooling controls are placed in one location and are supposed to serve many different rooms.

The small variation in indoor-air temperatures measured in a house with mechanical ventilation (Figure 8(b)) shows that it is possible to use centralized control on supply air. We know from experience with low-energy buildings that the quantity of supplied air depends on the manner in which air is re-circulated and exhausted from the building space. The two best options used for exhaust air are as follows:

1. Balanced, ducted exhaust ventilation;
2. Individual exhaust ventilation.

Can mechanical ventilation control the effect of thermal mass?

The above question was posed by Mattock (2010) who designed, built, and evaluated a net zero-energy house in Vancouver (Figure 9). The house design is based on the principles of the passive house combined with solar radiation input as most of the windows are located on the south facade. Excluding the solarium, 4.6% of the heated floor area is positioned to receive solar radiation from these windows.

The total area of the windows was 19.7% of the wall area, while south-facing windows occupied 45% of the south wall area. Even though we want as much solar as possible in winter without the active cooling in the house, one must limit the solar radiation to avoid summer overheating. Mattock (2010) used a forced-air heating system with air handler located in the basement to distribute the solar gains over the whole house and recover the thermal energy during the night.

It was calculated that the thermal mass of the building contributes about 20% of the space heating on an annual basis. Heat collected from solar panels is stored in a water tank and then distributed by a forced-air system. Furthermore, parallel to the forced-air heating system, there is an air-to-air heat pump for back-up.

An important part of the design was elimination of summer overheating using a combination of different measures. The first was an air cap on the chimney. Independently of the wind direction, air cap creates suction (negative air pressure)

Figure 9. South elevation of the house called “harmony equilibrium.”

that exhausts from the house. Next, as shown in Figure 10, there is an open space joining the main and top floors on the right side of the house. Since all rooms are connected to the open space, air pulled through the ventilation chimney will cool the interior of the building when windows on the main and top floors are open.

In the design of daylighting, tall windows, clerestories, skylights, light from two directions, and light-colored walls and ceilings are used to optimize the use of natural lighting. Light-sensing controls minimize the use of electric lighting.

The exterior walls used 50-mm-thick polyisocyanurate foam board and 15-mm-thick vacuum insulation panel that are encapsulated in spray foam insulation, yielding nominal thermal resistance of the exterior walls, RSI of $10.7\,m^2\,K/W$. After correcting for thermal bridges, the average RSI of $6.8\,m^2\,K/W$ implied thermal efficiency of 64% (a ratio of actual to nominal thermal resistance) for the wall. Basement walls also had RSI of $7\,m^2\,K/W$ and slab-on-ground RSI of $3.5\,m^2\,K/W$. Top of the line windows were selected. They were triple-glazed, double low-E coated, argon-filled, with an insulated space bar, fiberglass frame, and casement opening. Windows had RSI of $1.05\,m^2\,K/W$.

A high-efficiency air-source heat pump with forced-air distribution and central air handling unit located in the basement was used to ensure re-circulation of solar and internal heat gain as well as high quality of the indoor air that was filtered before coming to the heat-recovery ventilator (HRV).

The heat pump uses phase change in the refrigerant gas that takes place at different temperature/pressure conditions. This limits the efficiency for air-to-air heat pumps in cold climates (Vancouver is in a mild climate zone). On the exhaust side

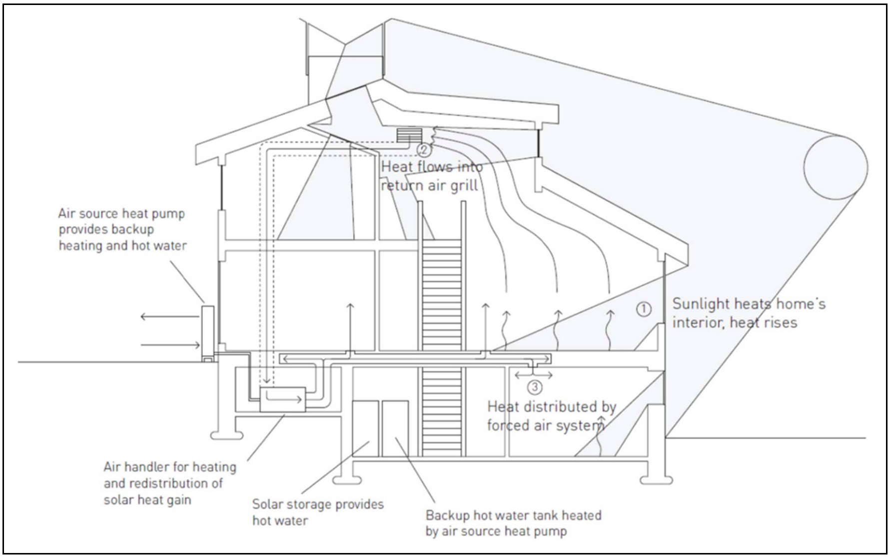

Figure 10. Heating and ventilation system working on a winter day (from Mattock, 2010).

of the ventilation loop, there is an HRV. The HRV has an efficiency of 80% and is equipped with high-efficiency direct current (DC) motors, humidity-based proportioning controller, and power grills for the zoned ventilation. In the summer operation mode, the terminals are reversed and the cooling terminal is indoor.

Figure 10 shows heating and ventilation patterns in a winter when the wind tower is closed and the return air grill redirects air to the air handler and air is distributed by the forced-air heating system. The air-to-air heat pump provides additional heating to ventilation air as well as to the hot water tank.

This case study was selected for review because it shows a next generation of low-energy house. It combines controlled solar gains with passive-house design.[1] It combines mechanical and natural ventilation with utilization of wind and solar power to reduce effect of solar overheating and includes a 20% energy saving attributed to internal thermal mass. The designer has accentuated the need to optimize the use of different technologies for heating, cooling, and ventilation, and despite being forced by the rules of competition to use only those solutions that existed in Canada's market place in 2010 it was able to achieve a healthy and durable building with net zero energy.

Interesting is also the solution of roof structure spanning in both directions. It is well known that gas-filled polyisocyanurate after long-term aging may not have dimensional stability sufficient to avoid small cracks next to wood members and thereby do not provide airtightness needed. Using open-cell polyurethane that is applied between "I" beams spanned in the other direction one takes care of the possible shortcomings of a single layer (Figure 11).

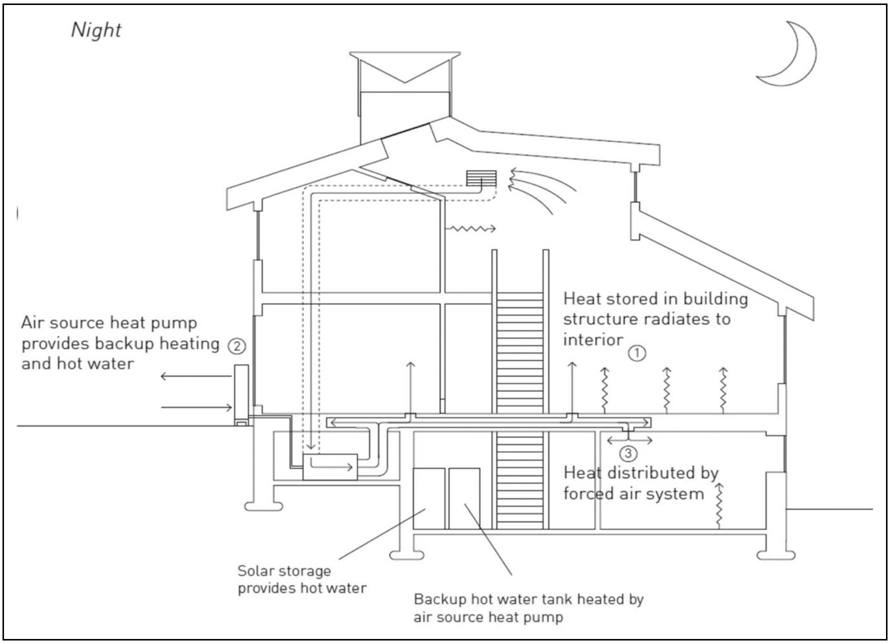

Figure 11. Heating and ventilation system working on a winter night.

What was the cost increase? The energy efficiency features increased capital cost by 8% and the renewable energy features increased cost by 10%. Use of a heat pump as the source of heating also provided an emergency cooling measure in summer if the natural ventilation was not able to provide sufficient cooling. The air-source heating has an annual coefficient of performance of 3.1. The building has been operated for 5 years now, and except for the initial problems with the solar thermal domestic water heating system that were resolved during commissioning, there were no maintenance problems.

The design and construction of the house presented above received a Canadian award as a zero-energy house that uses 2010 market-place technology. It is an interesting example of increased use of solar energy in a passive-house design. It can be considered as the first step to the next generation of buildings with high-quality environment. Why is it only a step? Because 65% energy is obtained from photovoltaic devices. In modern low-energy house, the fraction of photovoltaics (considering their price and efficiency) should not exceed 30%–35%.

Integration of hydronic heating/cooling with thermal mass

The question posed in section "Can mechanical ventilation control the effect of thermal mass?" does not have a clear answer. It was possible in a small residential house, but it does not seem easy. The whole house had to be designed in a manner that resembled old building with tall rooms (that also had ventilation connection every second floor). This is not an approach that we can use in modern multi-unit residential building.

We have seen in section "Pre-conditioning air with the earth-to-air heat exchanger" the random character of weather, and therefore one must provide means to control the contribution of thermal mass to energy balance in the building. Therefore, we propose to integrate heating/cooling systems with interior partitions. Radiative heating by means of circulating hot water that we call here hydronic heating is currently used in the United States and Germany as the system of choice. Yet, we want to locate hydronic (radiative) heating on the interior walls for the following reasons:

- Introduction of heat from the surface of floors is ineffective because of carpets and furniture.
- Use of floor panels requires a protection layer on the tubing with resulting increase in the operating temperature of the heating medium.
- One wants to integrate heating system with solar thermal panels. This limits the temperature of water to about 45°C.

There are many ways in which this can be done. One of them, a panelized solution, was shown in Bomberg et al. (2016). Another may use a moisture buffer type of interior plaster (see Bomberg et al., 2017).

Discussion on buildings with EQM

This article reviews the key lessons of the period since 1977, when the first 10 low energy demonstration houses were built in Saskatchewan. The concept of these houses came from the Architecture College at the University of Illinois, namely, a lot of thermal insulation, airtightness, and use of heat pump for heating. Harold Orr who was the designer of the Canadian house added an early version of an HRV made from plywood and polyethylene.

First, we have observed that nothing really happened until the 1990s. North American chaos in residential construction in years 1946–1990 was discussed elsewhere (Bomberg et al., 2016). At that time, the world started reacting to global warming and social pressures forced changes to codes and standard to impose energy use reductions. Initially, these reductions meant using resources better. A "High Environmental Performance" house built in New York state in 2005 and monitored for 1 year (Brennan et al., 2008; Wallburger et al., 2010) showed that without using any renewable resources one could reduce energy use by about 50%. Of course, when designing, the New York state house used the same levels of insulation and airtightness characteristic of Saskatchewan in 1977.

About that time, we discovered *what we termed* in Bomberg et al. (2015) as the energy conundrum, that is, that Vancouver multi-unit residential houses in 2002 used the same amount of energy as uninsulated buildings in 1920s. This was an effect of moving 100% of environmental controls to the realm of mechanical devices (heating, ventilation, and air conditioning (HVAC)) and neglecting the design of the building enclosure. In the meantime, in Germany, elimination of expensive heating systems by electric heating and trade-off to reproduce the passive house from 1977 became successful in the market place. So the passive house in Germany brought back the balanced construction of the building enclosure. Two issues yet unresolved in the German beginnings were the size of windows and ventilation. Only recently was it realized that use of large windows is possible. Of course, using large windows may require integration of HVAC and the building enclosure.

We decided to introduce the term *buildings with EQM* because the priorities in building evaluation are as follows:

1. Affordability;
2. Quality of indoor environment.

To control environment, one needs to separate it from the outdoor and this implies considerations of acoustic and thermal insulations, thermal bridges, airtightness, ventilation, heating, cooling, and many others. Let us define requirements for new buildings with EQM as follows:

1. Indoor-air temperature varying within the whole range thermal comfort;
2. Maximum use of thermal mass;
3. Integration of hydronic, radiative surface heating/cooling and walls;
4. Use of air-to-water or preferably water-to-water heat pumps with variable refrigerant flow technology or double loops with local controls;
5. Separation between ventilation and heating; direct outdoor air supply;
6. Air supply either through an EAHX or through a direct entry;
7. Use of multi-functional materials;
8. Traditional requirements of passive houses, but not their criteria except criterion for energy use of $70\,kW\,h/m^2$ per year;
9. Designing geothermal and solar thermal measures before photovoltaics;
10. Use of smart controls for integration of solar thermal panels and other heating devices.

Thermal mass contribution must be controlled and it is combined with surface hydronic heating/cooling. This, in turn, promotes the use of heat pump technology. Heat pumps may be small, spilt (air to water) units, or water-to-water system based on two water tanks or even a ground heat pump with horizontal or vertical heat exchangers. Water-based heat pumps are recommended for two reasons:

- They provide simultaneous heating and cooling in many climates when both functions are needed.
- They can easily interact with another source of heating or energy storage, for example, underground water tank, gray-water tanks, two-stage heating with geothermal pump providing 4°C–6°C water for the lower terminal of the heat pump.

Supply ventilation systems are based on constant air flow delivered to the whole dwelling, and a computer-based control system is used to switch between direct air supply and EAHX. The reason for using constant flow is that adjustment of air delivery to rooms, bedrooms, kitchen, or bathrooms should be checked during the commissioning of the ventilation system, and only periodically checked but not re-adjusted unless a full re-commissioning is performed. A pre-heat of ventilation air with EAHX is a mitigating factor in the energy load calculations. With a focus on controlling delivery to various spaces, we recommend constant rate of air delivery, as hydronic heating and cooling integrated with thermal mass is used for ensuring the comfort of inhabitants. As we accept up to 6 °C change in daily temperature (over a period of 6–9 h), the development of a control system that can steer mechanical devices as needed for the variable weather conditions becomes a critical part of an EQM system.

Occupants like large windows. They increase solar gains both in winter and summer, and a designer needs to eliminate summer overheating. This creates a preference for a hydronic heating/cooling system that is based on water heat pumps with surface exchangers located on interior walls. In this manner, one achieves integration of

1. Low-temperature hydronic heating with solar thermal panels;
2. Interior thermal mass with the surface heating and cooling loads.

The control system, indicated above, may be acting on heating/cooling side alone or be combined with the ventilation system. Ventilation air is taken either directly from the outside air or goes through EAHX depending on which is closer to the actual indoor temperature, while the indoor temperature must be kept in the zone of comfort for summer or winter conditions. A control of ventilation is preferred because it includes information on exterior, interior, and current air EAHX temperatures at time (1) now, (2) an hour ago, and (3) predicted for 1 h ahead. As we should to optimize use of thermal mass at the same time as we design ventilation, the preferred solution includes a computer algorithm to keep variable temperature and relative humidity of air in the zone of comfort.

Finally, buildings with EQM must include qualification as a low-energy building. In the first stage of design, one uses all design features of passive houses except that acceptance criteria for the passive house are not required. A decision about building a low-energy house, zero-energy house, or net positive energy house depends on the price of photovoltaics and available grants more than on the technology. The only requirement that we consider is now socially justified for sustainable buildings, and therefore for buildings with EQM is to achieve the level of actual energy 70 kW h/m^2 years or less.

Discussion on heating, cooling, and ventilation controls

As one progressively increases requirements for energy efficiency for buildings, the three critical elements postulated 40 years ago: (1) high thermal resistance and (2) high airtightness of building enclosure combined with (3) heat recovery from exhaust air—are necessary but not sufficient. To increase these three requirements further is futile because of diminishing returns. Counting on renewable energy sources while politically very appealing does not lead to affordable technology. One must search for improvements elsewhere and the authors decided to return to the thinking of past centuries. Using modern technology helps achieving the results.

One of the oldest geothermal technologies is a ground heat exchanger. In this article, we analyzed use of EAHXs that can give us pre-conditioning air. The analysis showed that efficient use of EAHX requires using both fresh air inlets and air passing through EAHX. For instance in Figure 4 in September, when transition to winter starts and the optimum indoor temperature is a bit higher than during winter, say between 22 °C and 24°C, the temperature on exit of EAHX is 18°C or 19°C. So during the day, as soon as outdoor air reaches 19°C, one should heat the indoor space with the outdoor air and switch it back to the EAHX when the temperature reaches 19°C on the way down. This manner of energy optimization—while at the same maintaining the required air temperature—is important for maintaining the required thermal comfort. To achieve this goal for the system EAHX—ventilation system, one must include in the steering algorithm a criterion for selection of the fresh air source. To switch between these two sources of incoming air, we need to have the following information: the temperature 2 h ago, 1 h ago, and now. The temperature history is needed to predict the next hour's temperature. In this consideration, one must also include the power used for moving air as this is a critical part of energy-saving decisions. It means we need a smart method of steering and selecting the choice of the supply air.

When using EAHX, one needs to provide dehumidification of the incoming air. The old technology requires modern controls to adjust the choice of outdoor air supply to match the requirement of indoor space and changing conditions of the outdoor climate (mezzo-climate). This statement is equally valid for design of ventilation systems based on constant volume as well as for design based on constant pressure (i.e. variable air volume). Incidentally, periodic use of EAHX gives us time for regeneration of the soil surrounding the EAHX pipes.

The control system will select the source of fresh air that is closest to the temperature required. In this process, we need to consider the following:

- Temperature of outdoor air;
- Temperature on exit from EAHX;

- Temperature required on entry to the indoor space;
- The need for heating or cooling of air to the temperature of entry to the indoor space;
- Electric energy needed for operating EAHX;
- Dynamics of temperature changes in the soil surrounding the EAHX pipes;
- Temperature of the air being removed from the indoor space and recuperation of energy.

The highest efficiency of interaction between EAHX and ventilation center (mechanical room) is achieved when one uses fully integrated control/steering systems for the low-energy building. In such a case, one may consider separate needs in different indoor spaces (different rooms), for example, presence of people in the room. Such a system will address optimization of both comfort and energy use.

Finally, in discussing this holistic approach to design, one must also consider resiliency of the building, that is, what happens when the electrical supply is interrupted. We have discussed elsewhere that buildings must be airtight but not too tight because mechanical ventilation requires supply of electricity. Experience from Finland that air leakage may provide 60%–70% of the minimum ventilation appears to be a good guidance. We also suggest using 10 Pa overpressure of buildings if the walls are designed for an adequate moisture management and delivery of fresh air is in the range of 30%–60% of time.

In summary, one can observe that while the need for high "environmental quality" is obvious, the term "management" in the description of this building system represents controls and steering mechanisms to ensure the required performance of the building.

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