OVERHEATING PROBLEM IN SINGLE FAMILY PASSIVE HOUSE

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ABSTRACT
Interior temperature significantly influences the comfort in the house. While temperatures lower than 20°C can be found in poorly insulated objects accompanied with the condensation problems, the temperatures above 26°C usually points to the overheating problem in a passive house as a highly insulated object and extremely weakly coupled to an environment. Since already a small energy input can raise the internal temperature significantly, the shadowing and internal energy sources minimization should be considered to reduce the overheating problem. To provide more information on that issue we analyzed data collected from a single Slovenian family passive house and associated different energy sources’ contributions to overheating of the passive house. Results show that cooling of the house at night in hot summer days and strict shading of the western windows is necessary to keep internal temperature on level comfortable for their residents.

INTRODUCTION
Comfort in building is a very important issue affecting not only the perception of the local environment, but influencing also an efficiency of the residents and residents’ health. Although we can identify many factors influencing the comfort, e.g. temperature, humidity, noise level, dust level, the temperature is certainly the first one to be addressed by the house regulation systems. Already Fanger’s Model from 1972 pointed out indoor conditions that contribute to comfort of people. These are physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity), and two personal variables (clothing insulation and activity level). A comfort zone in balance with the outdoor climate conditions, lies between 20 and 26°C and between 30 and 60 % relative humidity according to ANSI/ASHREA standard 55-1992. The temperature level should therefore be kept at least within the 20°C - 26°C range. Lower temperatures cause feeling of a cold, uncomfortable space since such temperatures constrict blood capillaries and efficiently slow down the blood circulation making the skin colder. On the other hand, lower temperatures also reduce the efficiency of the respiratory system protection against bacteria. However, lower temperatures are very rarely found in the highly insulated objects like passive houses as the are connected with poor insulation and thermal bridging. On the contrary, higher temperatures are not so uncommon in passive houses when the latter are located in a climate region with a hot summer and autumn like a Slovenian one. In such a case a passive house is obviously loaded at the same time with an extensive solar radiation and very high external temperatures. Since a passive house is highly insulated object, it is therefore extremely weakly coupled to environment. With a specific loss of up to maximally 60 W/K, one can imagine that an afternoon passive solar energy influx through a single unshaded western window can easily reach 500 W, requiring for a 10 K temperature gradient needed for a house to release this energy. Since such a temperature gradient is unimaginable in aforementioned climates, already a small energy inputs will have large effect on internal temperature, especially if the internal heat capacity is as low as is the case of low-weight construction which became more and more popular in Europe and also in Slovenia. Even more problematic can be reduction of an internal energy sources which can be neutralized only through an extensive ventilation during the night time, when the temperatures more or less fall below the internal temperatures.

Protection against overheating should be taken into account already when planning the house including orientation, size of windows, building elements, ventilation etc. Solar protection, solar gain, thermal mass, thermal insulation, internal heat gains, night cooling, ventilation rate, glazing properties (ratio, transmittance, orientation) are obviously all important factors that influence the overheating phenomena. Nevertheless, it is very important to know how to properly shade windows and avoid excessive internal energy release to teach the passive house residents to use their passive objects in a proper way.

The problem of the overheating has been addressed by several studies till now. According to the simulations performed by Orme et al. (2003) the most important factors for overheating in well-insulated houses are balanced mechanical ventilation They proved that mechanical ventilation system of a thermally heavy weight building normally cannot
remove heat to sufficiently prevent the overheating of the house during the daytime. Night time excessive cooling appeared to be the most effective in preventing building overheating. Also Badescu et all. (2010) identify overheating in passive houses, especially in southern Europe climate, as an important issue. According to a steady-state model they presented a simple technique to decrease the overheating rate is opening the windows during the night.

Artmann et all. (2008) investigated the most important parameters affecting night ventilation performance in preventing overheating in commercial buildings. They concluded that climatic conditions and air flow rate during night-time ventilation mode have the most significant effect on reducing overheating. Also thermal mass and heat gains have a considerable effect on thermal comfort in summer.

Lehmann et al. (2007) investigated the role of thermal mass on reducing peak cooling load while Robinson and Haldi (2008) constructed mathematical model for predicting overheating risk which considers human tolerance to overheating stimuli. The results of the simulation performed by Florides et.al. (2000) indicate that the inside house temperature, when no air-conditioning is used, varies between 10–20°C for winter and between 30–50°C for summer. Window shading in summer, resulted in savings of 8–20% of the cooling loads with the savings increasing with the amount of insulation of the construction.

Breesch et al. (2005) research results show that passive cooling has an important impact on the thermal summer comfort in the building. Furthermore, natural night ventilation appears to be much more effective than an earth-to-air heat exchanger to improve comfort.

Shaviv et al. (2001) investigation showed that in the hot humid climate of Israel it is possible to achieve a reduction of 3–6°C in a heavy constructed building without operating an air conditioning unit. The reduction depends on the amount of thermal mass, the rate of night ventilation, and the temperature swing of the site between day and night.

Although the overheating problem has already been addressed in the literature, no serious attempts has been made so far to explain the real passive house temperature dependencies during the hot summer periods from the point of view of shading and night-time ventilation. In our work an extensive data array has been acquired on a minute interval through a control system of a passive house located in northern Slovenia to estimate and allocate energy input contributions to the overheating of the real passive house. It was not our aim to only identify the possible strategies to reduce the overheating problem, but to determine to what extent the internal temperature could increase if the residents would not cool house with opening the windows at night and would not shade the windows. Our study therefore wants to contribute to an important discussion of appropriateness of a passive house strategy in hot-summer climate regions like the one of Slovenia by proving that the internal temperatures can still be kept on a comfort level without additional cooling system.

**METHODS**

**Description of test house**

In our study the data were acquired in single family passive house in Limbuš near Maribor (Figure 1), in a northeastern part of Slovenia, typical for a continental climate with a hot summer. House was constructed in 2006, and has been occupied since July 2006. The house has wood frame construction with rectangular floor plans ob both base and first floor. Concrete basement is outside of the thermally insulated volume. It has a 113 m² of a residential floor area and an approximately 260 m³ of internal volume. Walls, roof and floor towards basement are very well cellulose-insulated with U-values less than 0,1 W/m²K. Windows are triple glazed with two low emissive coatings and krypton between glass, with the effective thermal transmittance of 0,8 W/m²K. On the south side windows are shaded with the roof extension as shown on Fig. 1. This extension was calculated to prevent any solar energy influx during the summer time period. The east and west side windows are shadowed with external movable Venetian blinds, which are manually controlled by the residents. Tightness of the house falls below onetime exchange of air at 50 Pa. Air flow of the ventilation system is 80 m³/h. Counter flow heat recovery unit works with 83 % efficiency. Ventilation system includes two infrared-based preheaters of 100 W and 200 W individually controlled to enable 3-step frost-prevention in the range between 0°C and -12°C. The ventilation system is switched off below -13°C, which is considered as an average minimum winter temperature of this region. In addition, the ventilation system involves a water-air 280 W heat exchanger connected to floor heating system and places just behind the counter flow heat recovery unit to heat up for the last 2.8 K in average reaching the projected internal temperature of approximately 22 °C.

House is heated with floor heating system with maximal temperature of 29 °C and maximal power of 1800 W calculated to an average minimum winter temperature of -13°C. All mechanical engineering systems, like pumps and valves of the floor and hot-water heating systems are controlled by sensory-control system and software on a PC that is also stores the measurements each minute.
Acquisition system

The sensors acquire the following data:

- the external temperature – $T_{\text{ext}}$ [°C]; this sensor is placed on the north wall under extension of the roof to be protected against direct sunlight and eliminate the fast oscillations due to fast-heated ground; all the temperature sensors are Zenner-like diodes calibrated against absolute temperature and reaching absolute accuracy of ±0.3K;

- the internal temperature – $T_{\text{int}}$ [°C]; this sensor is placed in the middle of an open staircase in the north central part of the building to be protected from direct sunlight, direct heat source from kitchen, bathrooms and any of the home appliances as well as from direct cooling from the uncontrolled convection through the main entrance of the house;

- the solar flux – $j$ [W/m²]; the photo-diode is placed on the roof with a normal oriented to the azimuth of 183° and elevation of 55°. The real incident solar flux is calculated from the measurement flux taking into account the real direction of the solar flux, the incident angle of absorption, the supplier angular and flux sensitivity of the photo-diode and calibrated against the maximum solar flux defined in the solar noon at June 21st; The direction of the solar flux with an 1-hour accuracy is calculated within a model of the Earth motion against Sun, taking into account the position of Slovenia, which is defined with a 46° north and 16°east; Local solar time is used with an appropriate transformation to UTC, CET and CEST;

- other temperature sensors are used to measure temperature in the pipelines of the mechanical engineering systems (like the floor heating systems, heat buffers, etc).

Description of model

To characterize the overheating in the house, the internal temperature has to be measured and simulated at the same time. The analysis of the discrepancies between simulated and measured internal temperature summer time-variations finally reveals the sources of the overheating.

To model the internal temperature one has to calculate all the heating and cooling powers which altogether change the internal temperature via heat capacity $C$ of the house inside the thermal shell. Energy law gives us:

$$ C \frac{dT}{dt} = \sum P $$

(1)

The main cooling sources are the transmission and ventilation losses. Since they depend on the difference between internal and external temperature, the proportionality coefficient describes the specific heat loss ($\Lambda$ in W/K), sometimes also denoted as the heating number. Note, that such an effective specific heat loss includes the effective heat transfer coefficient, heat loss due to nonideal heat recovery in ventilation system as well as uncontrolled ventilation heat loss through the main entrance. Heat loss in passive houses can be calculated, but the most accurate numbers are gained through the fitting of the time-variations in winter. For our example, the latter was done for several winter periods and the specific heat loss of 60 W/K were determined for all the aforementioned energy-loss sources.

$$ P_{\text{loss}} = \Lambda \left[ T_{\text{ext}}(t) - T_{\text{int}}(t) \right] $$

(2)

On the other hand, the energy is firstly supplied through a heating system with a power $P_{\text{heat}}$, which was in this house during the energy balance analyzes based on the 3 electrical heaters of 300 W, 600 W and 900 W, placed directly into pipelines of the floor heating system and digitally controlled by a PC-based control system, making the incorporation into the simulation models very straightforward.

In additional, the energy in a passive house is gained also through passive, i.e. uncontrolled, absorption of solar flux through the glazing as well as through internal gains. There are many sources of the latter such as the heat generated by cooking, the metabolic activity of the human bodies of the residents, the heat generated by nonideal efficiency of electrical home appliances especially heat pumps (in refrigerating) and data processing (multimedia, computers, controllers, etc. which pay the energy to reduce the data entropy). The amount of internal energy gain varies significantly with time. For example, already one person that irradiates in average 80 W is not continuously present in a house. This makes the simulations more demanding especially in the case of real house where the occupancies are not strictly tracked. Moreover, the energy release by cooking is also very stochastic and discrete process – energy is...
not released continuously, but in big quanta imposing serious difficulties for simulations. The internal gain power is therefore approximated with an average internal gain power which was also gained through the fitting of the time-variations in winter. The aforementioned internal energy-gain sources \( P_{\text{int}} \) were determined to be in average 400 W.

As indicated previously, passive solar gains are also one of the main energy gains in the passive house. High accuracy of solar gain determination is desired in simulations due to high energy density in order to characterize the overheating problem correctly. For that purpose the analyzed passive house measures the solar current directly. The power of solar gains \( P_{\text{sol}} \) can be calculated as

\[
P_{\text{sol}} = \sum_{i, j} \alpha_s \alpha_{\text{shad}, i, j}(t) \left( \mathbf{S}_i \cdot \mathbf{j}(t) ; >0 \right) \left( 0 ; <0 \right)
\]

(3)

where \( \alpha_s \) represents the glazing transmittivity which is 50\% for the windows of the analyzed house, \( \alpha_{\text{shad}, i, j} \) the effective transmittivity of each \( i \)-th window due to the shading which obviously depends on the solar current direction and architecture, \( S_i \) the area of transparent part of each \( i \)-th window, and \( j \) solar current flux.

Firstly, the solar gain depends on the incident solar current which amplitude is measured in real time by the photo-diode taking into account the orientation of the photodiode and the direction of the solar current. The latter is calculated as described in previous subsection.

Secondly, the solar gain depends also on the direction of the solar current against each of the window. To take this into account, each of the transparent surface is defined as a vector quantity with a direction of a normal vector perpendicular to the window, defined in the same coordinate system as the solar flux is. For example, the eastern, southern and western windows have the azimuths of 90°, 180° and 270°, respectively, and a constant elevation of 0°.

Finally, the solar energy is partially restricted due to shading. This can be done in a fixed way with a roof extension, or in a manual-controlled way by external shading of Venetian blinds. The shading is taken into account by the real-time calculation of the shaded area on the outside of each window and appropriate incident solar current reduction.

Although the ventilation system of the analyzed house is also equipped with preheating and additional heating of air, the first one is operating only when the external temperature is below freezing point while the second one is effective only when the floor heating system is operational. This means that in the summer time, the two mentioned systems contribute no additional energy input to the house energy balance and will therefore not be included in the simulation model.

Finally, the internal air temperature \( T_{\text{int}} \) and therefore energy balance of the house depends on thermal losses \( P_{\text{loss}} \); heat gains due to solar radiation \( P_{\text{sol}} \); heat produced by the heating system \( P_{\text{heat}} \); and the thermal internal gains due to energy emitted by the residents electrical appliances in the house \( P_{\text{int}} \).

\[
C \frac{dT_{\text{int}}}{dt} = P_{\text{loss}}(t) + P_{\text{sol}}(t) + P_{\text{heat}}(t) + P_{\text{int}}(t)
\]

(4)

\[
C \frac{dT_{\text{int}}}{dt} = N(T_{\text{ext}} - T_{\text{int}}) + \sum_{i} \alpha_s \alpha_{\text{shad}} \left( \mathbf{S}_i \cdot \mathbf{j}; >0 \right) \left( 0; <0 \right) + P_{\text{heat}} + P_{\text{int}}
\]

(5)

Simulation of internal temperature

To simplify the simulations, one has to identify the proper time scales of all the quantities in the above equations. The external temperatures change on an hour time scale, while solar current change on a minute time scale (although the effect of solar energy influx is usually delayed by the buffer systems). Also the internal heat sources do not change faster than on a minute time scale, defining the later to be the final time scale of the simulations. For that reasons, also the data are acquired each minute.

Approximating that the quantities are quasi constant on a time scale of one minute, the above differential equation can be transformed into difference equation:

\[
T_{\text{int}}(t+1) = T_{\text{int}}(t) + \frac{N}{C} \sum_{i} P_{i}(t)
\]

(6)

As in the case of specific heat loss and average internal gain power, also the effective heat capacity of the house was gained through the fitting of the time-variations in winter, where the temperatures gradients are large and these quantities significantly affect the internal temperature time variation. The aforementioned effective heat capacity \( C \) was determined to be 20 MJ/K.

Fitting the response of the house

If the general temperature response of the house is determined (during the winter period) in terms of the specific heat loss, internal power gains and effective heat capacity, the internal temperature can be simulated and also predicted for a hot summer period.

Under conditions of heavy solar current load, very high external temperature and practically no energy release with conduction or convection via forced ventilation, the energy balance of the house significantly depends on the two factors: shading, i.e. preventing solar current entering the house, as well as...
on cooling the house during the night with opening of windows. For this purpose, the manual-control shading strategy has to be implemented in the simulation in addition to a cooling term which represents the effect of window opening. The shading strategy which was used by the residents was very simple – eastern and western windows must be strictly shaded before noon or after noon, respectively. This diminishes the solar energy influx through these windows. The southern windows

![Figure 2: Overheating problem in a passive house in Slovenia. A: Temperature dependences of internal (gray) and external (dotted) temperature are shown together with 24-h integral of external temperature (dash dotted) which is used in controller to decide about the day-variation of the weather. B: Simulated internal temperatures (black solid) are shown as a fit to measured internal temperature (gray) at real conditions taking into account the real shading and real window opening as presented in the ventilation time. In addition, to predicted internal temperatures are shown for the same house without shading (dash-dotted) and without window opening (dotted), which would clearly result in an overheating of the house.](image)
are perfectly shaded by the roof extension, that has already been introduced in the shading calculation. Cooling via manual-controlled free ventilation was utilized in a very simple way: as the external temperature felt below the internal temperature, the windows were opened manually for approximately the time, which is noted (and plotted on a Figure 2B). This effect was simulated as extensive mixing of the external and internal air at known temperatures and air exchange rate of 600 m³/h effectively representing the specific heat loss of 220 W/K.

RESULTS AND DISCUSSION

The selected period demonstrate a typical climate pattern of a hot summer with an external temperature reaching 35°C and significantly exceeding the desired internal temperatures (Figure 2A). In a period slightly shorter than a week, a 24-h average external temperature increase for almost 10 K, imposing huge load on a passive house that should keep the internal temperature within a comfort level below 26°C without the additional cooling system. On can see that the real passive house responds to a two subsequent weeks of excessive external temperatures with an increase in the internal temperature of few K. However, this is achieved by the effective shading of the eastern and western windows in addition to free ventilation achieved by the opening of the windows during the night. The later is enabled by the large daily temperature oscillations of a 15 K, in which the lower temperatures fall below internal temperatures for at least few hours during the night time. The approximate cooling time, i.e. time when windows were completely open during the night time, is presented in the Figure 2B. One can clearly see that the residents intuitively increase the free ventilation during the hot periods. Additionally, they use the cold days immediately after to restore the lower internal temperature conditions as fast as possible by excessive ventilation. These results indicate that the model is capable of explaining the time-variations of internal temperature in great detail and that the shading and night-cooling by ventilation through opened windows can keep the internal temperatures within the comfort level. The modeling clearly revealed that neglecting this strategies would result in serious overheating.

CONCLUSION

With a relatively simple model of energy flux in the passive house internal temperature dependencies were explained during the hot summer periods. Effect of the shading and night-cooling by ventilation through opened windows were determined. In such a way the problem of overheating has been addressed. Results prove that a real passive house can resist excessively hot periods in a hot continental climate of northern Slovenia and that simple strategies like strict shading during the day and excessive ventilation through opened windows can keep the internal temperatures within the comfort level. The modeling clearly revealed that neglecting this strategies would result in serious overheating.

The knowledge gained in this study is crucial to the passive house building sector, proving that the passive house concept can survive even in the climates with extreme hot and cold months if the residents implement some of the anti-overheating strategies into their way of living.

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REFERENCES


