Thermal comfort analysis in a passive house using dynamic simulations*

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Abstract. Passive houses are energy efficient constructions that are considered a good way towards a sustainable and non-polluting environment. Their impact on the energy consumption has been discussed numerous times, therefore this article targets the thermal comfort analysis during the summer period. A passive house called SES ECO was used for a detailed computer modeling and numerical analysis. This house was divided into thermal zones with different occupancy scenarios, heat gains and temperature set points. The operative temperature inside these zones was thereafter studied using dynamic simulations using the Bucharest weather data. It was found that by using a ground heat exchanger for fresh air introduction or an increased ventilation rate during night time the overheating was 9% from the total year period or 25% from the entire summer season. Despite the high outdoor temperatures, with values up to 35°C, the indoor operative temperature was lower than 28°C and only for a small period of time a cooling system would have been necessary.

Key words: passive house, simulations, thermal comfort

1. Introduction

A passive house is not a construction type which is limited to some particular building materials, but a concept for which there are multiple ways to achieve the ultimate goal [1]. The final result is a new living space with a minimum of energy consumption and enhanced interior comfort [2]. With their low energy consumption, passive houses can play an important role in reducing global warming. The heating demand is reduced through passive measures so that this kind of buildings can reach the point where there is no need for a conventional heating system (e.g. heating boiler). The concept is based on minimizing heat losses and to maximize the heat gains. The design of a passive house does not differ significantly from a conventional home and those who live in this house should not change their lifestyle. Passive houses provide a good natural light due to large glazed areas designed to optimize solar gains, and may be considered as an „healthy environment”, due to a very good air quality.

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The Passive House standard was developed by the Passivhaus Institute in Germany [3]. This standard can be achieved using a variety of design strategies, construction methods and technologies applicable for any type of building. Usually this includes optimal insulation levels, minimal thermal bridges, use of passive solar measures and the use of a mechanical ventilation system with heat recovery. Renewable energy sources are used as much as possible to meet the energy needs (electricity, heat and hot water).

The passive house concept requires certain conditions:

- Energy consumption for the heating $\leq 15 \text{ kWh/(m}^2 \cdot \text{ year)}$ or Thermal load $\leq 10 \text{ W/m}^2$
- Infiltration rate $\leq 0.6 \text{ ach}$
- Values for the coefficient of transmission of the walls $U_{wall} \leq 0.15 \text{ W/(m}^2 \cdot \text{ K)}$
- Values for the coefficient of transmission of the windows $U_{windows} \leq 0.15 \text{ W/(m}^2 \cdot \text{ K)}$
- Primary energy consumption $\leq 120 \text{ kWh/(m}^2 \cdot \text{ year)}$

The major objective of a passive house is to be energy efficient but we should not neglect the indoor comfort. The first priority is to provide occupants a healthy, clean and comfortable environment for their living. This level of comfort should be obtained using energy efficient solutions.

2. Study case on a passive house

In this chapter a passive house project, called SES ECO house, will be presented as architecture and envelope structure. The project represents a four main room house with three bathrooms, a dining area, a kitchen, an office and two bedrooms. The spatial orientation followed the premises to have perfect relationship with the outside environment and to use the natural light throughout the year. The main spaces are oriented South, East and West. The glazed areas are designed in order to ensure effective light and ventilation without compromising the global insulation of the house or to favor the appearance of thermal bridges. Facing south there is a greenhouse that provides both a pleasant space towards the living and dining areas and is built on two levels. The useful surface area is of 141.4 m$^2$ and is represented by the dinning/living area (33 m$^2$), office (12.35 m$^2$), bathrooms, dressing, kitchen, master bedroom (17 m$^2$), bedroom (13.1 m$^2$) and other spaces (hall, stairs, etc). The building has two balconies that are protected by the solar radiation with architectural shading constructions (see Figure 1). To prevent the overheating of the greenhouse there are controlled operable windows for efficient natural ventilation and window blinds for solar protection. The attic is situated over the rooms which are situated at the first floor and it represents a technical space.

For fulfilling the passive house criteria it was chosen an envelope structure with a high level of insulation. The walls are made of concrete (15 cm) with an external...
layer of insulation (35 cm). The corresponding U-value is 0.11 W/m²K. The internal walls are made of concrete (10 cm) and each face has a thin layer of plaster (0.015 cm) summing a U value of 3.38 W/m²K. The floor towards the ground is made of wood parquet concrete and insulation. The U-value of the floor is 0.14 W/m²K. The roof is well insulated with 40 cm of insulation, wood, air layer, plasterboard, and the calculated U-value is 0.09 W/m²K. The windows are energy efficient with three layers of glass and their U-value is 0.52 W/m²K.

3. Dynamic simulations of the house

The study has its support structure on the dynamic simulations with an hourly time-step realized using the TRNSYS [4] building simulation software. TRNSYS is a transient systems simulation program with a modular structure that was designed to solve complex energy system problems by breaking the problem down into a series of smaller components. For our problem the passive house was modeled using the standard library of components that exists in the software database. The TRNSYS building model, known as, Type56, is compliant with general requirements of European Directive [5] on the energy performance of buildings and has been used with success by engineers to design efficient buildings and also for scientific research [6]. TRNSYS was also found to be a good way to predict the thermal comfort inside the occupation space [7].

The building was divided in multiple thermal zones in order to better represent the particularities (e.g. heat gains, occupation scenario, heating set point temperature) of each space inside the house. Thermal zones are a fundamental part when you wish to do an energetic analysis by simulations. These areas can be considered as a room or group of rooms within the building, with similar thermal contributions, the same profiles (temperature, occupancy, etc.), or are served by the same HVAC system. For our study case there are 7 distinct zones (see Figure 1):
For each of these zones there were established the thermal loss surfaces, the adjacent surfaces between the zones (e.g. Zone 3 – wall and door with Zone 2), the heated volume and the profiles. The profiles are for the occupation (indoor heat gains from the occupants), the lighting and appliances (indoor heat gains) and the temperature set point. It is necessary to introduce the heat gains due to the presence of people in the building. These gains have a significant influence on the consumption and for the overheating during the summer season. The occupancy profiles were created specifically to each area. These were developed based on the literature and are divided into zones and periods (weekdays and weekends). There were considered 3 weeks for the holidays throughout the year. For school holiday weeks, during the weekdays the occupancy will be higher in Living area (Zone 2). The power dissipation of a person is estimated at 100 W (60 W sensible heat and latent heat 40W) and corresponds to a normal house activity [8]. The house is supposed to be occupied by four persons.

Fig. 4. Occupancy scenario for the thermal zones
The heat gains from electrical appliances are taken into account during the simulations (see Table 1). The indoor heat gains from the artificial lighting are also considered and a value of 1.5 W/m² was chosen. For the appliances a 40% heat transfer through radiation will be considered and the rest by convection.

Table 1

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Zone</th>
<th>Used time</th>
<th>Power (W)</th>
<th>Power (kJ/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freezer</td>
<td>Zone 2</td>
<td>24h/24</td>
<td>70</td>
<td>252</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>Zone 2</td>
<td>24h/24</td>
<td>16</td>
<td>60</td>
</tr>
<tr>
<td>Hi Fi (TV..)</td>
<td>Zone 2</td>
<td>During occupation</td>
<td>150</td>
<td>540</td>
</tr>
<tr>
<td>Kitchen</td>
<td>Zone 2</td>
<td>Between 7÷8 &amp; 19÷20 + 12÷13 (weekend)</td>
<td>200</td>
<td>720</td>
</tr>
<tr>
<td>Laundry machine</td>
<td>Zone 2</td>
<td>1h/2days (18:00)</td>
<td>60</td>
<td>216</td>
</tr>
<tr>
<td>Computer</td>
<td>Zone 3</td>
<td>During occupation</td>
<td>100</td>
<td>360</td>
</tr>
</tbody>
</table>

4. Thermal comfort analysis

According to the Passivhaus Institute [3], the air exchange rate of a passive house is between 0.3 and 0.4 times the volume of the building per hour, with a general recommendation to lower rates. This value will maintain a good indoor air quality while ensuring a comfortable level of humidity and an energy saving. According to the Passivhaus Institute the fresh air flow of 30m³/h/pers. is sufficient for good air quality. For the SES ECO house a fresh air rate of 0.3 ach will be considered during occupation period and 0.1 ach during the inoccupation. In this article, the main objective is the thermal comfort analysis during the summer period and therefore it won’t be discussed the ventilation strategy for the winter season. One important feature of the summer ventilation is the use of ground heat exchangers. To decrease the outside fresh air temperature such ground heat exchanger will be used. In our case the length of the tubes is 40 m, with 20 cm diameter, buried at 2 m depth and with the air velocity of max. 1 m/s.

During summer when the outside air temperature can be higher than 30°C the air is passed through the ground buried pipes decreasing this temperature up to 5°C before its introduction in the house ventilation system. Another characteristic of the summer ventilation strategy is to avoid high air temperatures inside the house with an increased ventilation rate that may go up to 3 ach. Among other strategies to reduce the solar heat gains it is mentioned the shading of the windows with blinds and a natural ventilation of the greenhouse. This zone is during the summer period the weak part of the house due to its overheating. This is due mainly because of the high amount of glazing area. To reduce the air temperature inside the greenhouse the windows are opened, leading to a natural ventilation of the space. A study case will present the data obtained for the Bucharest weather conditions. The simulation time step was of ½ hours and 17520 values/results were obtained for the entire year. The global horizontal solar radiation (W/m²) and the outdoor air temperature (°C) for Bucharest climate are presented in Figure 4.
The maximum level of the solar radiation is recorded during the summer season with a value of 989 W/m$^2$. The weather data correspond to a typical year and are METEONORM weather files. The maximum outdoor air temperature for Bucharest is 35.4 °C and the minimum of -15.6 °C according to the same weather file. The thermal comfort will be further analyzed. The definition of the thermal comfort is that it is the state of mind that is satisfied with the thermal environment; it is thus the condition of minimal stimulation of the skin’s heat sensors and of the heat-sensing portion of the brain. The temperatures of the surfaces surrounding a space are in strong relation with temperature of a body within that space. These can determine the rate and direction of radiant heat flow between the body and the surrounding surfaces. The radiant exchange can affect the thermal comfort of a person and consequently, it is mandatory to know the radiant surface temperatures or the average value. The most common used variable to evaluate this aspect is the mean radiant temperature (MRT). In the case of the SES ECO house, the MRT tends to stabilize near the room air temperature because the building is well insulated and the inside temperature of the walls is close to the indoor air temperature. The satisfaction with the thermal environment can be very complex and there are many interacting variables. Among the most important indoor climate parameters it is mentioned the air (dry-bulb) temperature, the humidity and the mean radiant temperature. To evaluate the thermal comfort of the SES Eco house the operative temperature will be used. This one is the uniform temperature of an imaginary enclosure in which the occupant would exchange the same heat by radiation and convection as in the actual environment. The operative temperature ($T_o$) is what humans experience thermally in a space and it is the combined effects of the MRT and air temperature.

$$T_o = \frac{h_r T_{mr} + h_c T_{db}}{h_r + h_c}$$  \hspace{1cm} (1)

where $h_c$ is convective heat transfer coefficient, $h_r$ is the linear radiative heat transfer coefficient, $T_{db}$ is the air (dry bulb) temperature and $T_{mr}$ is the mean radiant temperature. In its simplest form the operative temperature can also be written as:

$$T_o = \frac{T_{mr} + T_{db}}{2}$$  \hspace{1cm} (2)

The preferred temperature range for occupants dressed in summer may go to 26°C [8].
Thermal comfort analysis in a passive house using dynamic simulations

Fig. 5. Operative temperature during summer months a) zone 2 – living b) zone 3 – office c) zone 4 – bedroom d) zone 6 – master bedroom

It can be observed from Figure 5 that the operative temperature during the summer period can be higher than 26°C. This is particularly noticed for the thermal zone 2 which has the major internal heat gains. The operative temperature overpasses the 26°C limit in 9% of the year total time or 25% during four months of summer. During the periods when the thermal comfort cannot be ensured by the ventilation strategies then it is necessary to use an air cooling system. If no ventilation strategy is put in place than the overheating time would have been higher than 60% of the cases (summer months). With the chilled air from the ground heat exchanger and with an increased ventilation rate it was possible to reduce the indoor air temperatures with up to 7°C if compared to the case were no measures were taken. Taking a closer look on the data from four days of summer conditions (high outdoor air temperatures and radiation) we can notice that the operative temperature barely passes for 2÷5 hours the 28°C. Living area is a sensible zone especially because of the higher internal heat gains and proximity to the overheated greenhouse. As concerns the relative humidity inside the zones the average value is around 57% during the warmest days of the year.
6. Conclusions

In this article it was discussed the thermal comfort inside a passive house during the summer months. The SES ECO passive house project was first presented in terms of architecture and envelope insulation. Using specialized computer software the house was simulated in a virtual environment that corresponds to Bucharest weather data. The house was divided in multiple thermal zones with specific occupancy, heat gains and set point temperatures profiles. The house is adjacent to a greenhouse that is advantageous for the ventilation strategies during winter season but has the inconvenient of overheating during summer. The indoor space must assure an acceptable level of thermal comfort for the occupants. To reduce the overheating
Thermal comfort analysis in a passive house using dynamic simulations

periods several strategies were used: ground heat exchanger, higher ventilation rates (especially during night time) and controllable window blinds. In most of the cases, the operative temperature was lower than 26°C which is a proof that despite the high level of internal heat gains and risk of overheating, the applied methods have an important impact on the thermal comfort. Even if Bucharest climate can be very unfriendly during the summer period, inside the passive house a pleasant environment is achieved (average building temperature < 28°C) and only a small amount of energy would be necessary to avoid completely the overheating.

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