Measurement and Interpretation Methodology for Determining Comfort in Passive Buildings and NZEB Buildings

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Abstract. The article contains good practise recommendations related to the proper performance of measurements of comfort in passive buildings. Passive building is a high-quality building due to impeccable construction in terms of building physics. The passive building is so well insulated that it can only be heated by supplying fresh ventilation air. Such buildings have certain features such as: balanced temperatures, there is no overheating of the rooms in summer due to the high insulation of the partitions, high insolation due to the optimal positioning of the windows, acoustic comfort, reducing pollution in the interior, high quality of thermal comfort, no aeration, high indoor air quality, permanent protection against moisture and fungiculation of partitions, etc. In all the features listed above, there was no vibration comfort, which could be a problem especially in the city centers with extensive transport infrastructure. This kind of comfort is mostly neglected during the design process, not only in the passive buildings. In this article comfort in passive buildings for all its aspects is described. The main emphasis in the article was put on the guidelines relating to the measurement of thermal comfort and measurements of vibration comfort. The recommendations contain all stages of the measurement process from the preparation of measurements with the local vision and the measurement plan, through the in-situ measurement to pre-processing and analysis of measurement data. All measurement stages are shown on the real example of passive building located in Poland. The good practise guidelines for comfort measurements could be very useful in the diagnosis of passive buildings and NZEB buildings.

1. Introduction

Construction uses about 40% of total energy consumption. The aim of the policy of the European Union is reduction of energy consumption in buildings. The EU members declared the implementation of the standards of "almost zero energy" buildings (NZEB). NZEB is 'almost zero-energy building' (in accordance with Directive 2010/31 / EU), which is a very high energy performance in the extent of renewable energy produced on-site or nearby [1]. The parameters of NZEB are determined by member countries depending on local conditions and technologies available on the market. Polish regulations impose requirements on the heat transfer coefficient of the building envelope and on the non-renewable primary energy ratio EP [kWh/m²-year]. Another example of buildings with very low energy consumption are passive buildings, more and more popular in such countries as Germany, Austria or Canada. The idea of passive buildings is to minimize the energy consumed by the building. This differs
from the idea of the Polish definition of NZEB, where the source of heat is more important. In both cases, the main focus is on minimizing energy consumption. Requirements for NZEB and passive buildings are summarized in Table 1.

| Parameter | Single-family residential building NZEB (Polish definition) [1] | Passive building [2] |
|-----------|--------------------------------------------------------------|---------------------|
| Coefficient $U$ [W/m$^2$K] - external walls | 0.20 | 0.15 |
| Coefficient $U$ [W/m$^2$K] - floor | 0.30 | 0.15 |
| Coefficient $U$ [W/m$^2$K] - roof | 0.15 | 0.15 |
| Coefficient $U$ [W/m$^2$K] - window | 0.90 | 0.80 |
| Coefficient $EP$ [kWh/m$^2$year]* | 70 | 120 |
| Coefficient $EK$ [kWh/m$^2$year]** | no requirements | 15 |

* $EP$ [kWh/m$^2$year] it is an indicator of non-renewable Primary Energy.
** $EK$ [kWh/m$^2$year] it is an indicator of Final Energy.

The implementation of this type of buildings and existing buildings show that a poorly executed building design and poor realization may result uncomfortable conditions in buildings. In the case of passive buildings, the most common is thermal comfort. This is due to the fact that the incorrectly selected ventilation system and the tight insulation of the nudinary coating lead to excessive solar profits already in the spring season. However, during designing and building process, all aspects of comfort should be taken into account [3]. The PN-EN 15251:2012 standard [4] recommends that buildings should be constructed in such a way as to satisfy, in addition to thermal comfort, the acoustic, visual comfort and air quality. The standard does not, however, capture equally important vibrational comfort [3]. Fig. 1 presents the additional principles of designing NZEB and passive buildings.

**Figure 1.** Criteria for the design of NZEB buildings complemented with comfort criteria

In the article, the Authors focused on presenting research methodology to ensure thermal and vibrational comfort. The presented research methods may be very useful for the proper construction of NZEB and passive buildings.
2. Thermal comfort measurements requirements

2.1. Measurement equipment

Thermal comfort tests are carried out in accordance with the standards [5], [6]. The standards are based on the assessment of thermal comfort proposed by the Danish scientist Ole Fanger [7]. On the basis of measurements, thermal comfort parameters were calculated from formulas (1).

Designated parameters are:

- PMV—predicted average thermal comfort rating
- PPD—predicted percentage of dissatisfied people

\[
PMV = \left[0.303 \times \exp(-0.306 \times M) + 0.028\right] \times ((M - W) - 3.05 \times 10^{-3} \times \left[5733 - 6.99 \times \left(M - W\right) - p_a\right] - 0.42 \times \left[M - W\right] - 58.15 - 1.7 \times 10^{-5} \times M \times (5867 - p_a) - 0.0014 \times M \times (34 - t_a) - 3.96 \times 10^{-8} \times f_c l \times (t_c l + 273)^4 - (t_r + 273)^4\right] - f_c l \times h_c \times (t_c l - t_a)
\]

\[
t_c l = 35.7 - 0.028 \times (M - W) - I_{cl}\left[3.96 \times 10^{-8} \times f_c l \times \left[t_c l + 273\right]^4 - (t_r + 273)^4\right] + f_c l \times h_c \times (t_c l - t_a)
\]

where:
- \(M\)—the amount of metabolism \([W/m^2]\)
- \(W\)—the density of energy loss in the form of mechanical work \([W/m^2]\)
- \(I_{cl}\)—clothing insulation \([m^2K/W]\)
- \(f_c l\)—surface of clothes \([m^2]\)
- \(t_a\)—air temperature \([^\circ C]\)
- \(t_r\)—average radiation temperature \([^\circ C]\)
- \(t_c l\)—temperature of the clothes surface \([^\circ C]\)

Measurements of thermal comfort are made using comfort meters (Fig. 2). The measurement methodology is based on PN ISO 7726 [5].

![Figure 2. A device for measuring thermal comfort](image)

The measured parameters were:

- \(t_a\)—air temperature measurement;
- \(t_{c l}\)—temperature of blackened sphere (heat radiation meter)—the black sphere, in agreement with the norms, should be 15 cm in diameter;
- $t_{nw}$—natural wet-bulb temperature measurement;
- RH—measurement of relative air humidity;
- $V_a$—measurement of air flow speed.

The frequency of measurement data collection was every 1 min.

The data from the sensors are given in Table 2.

| Type of Sensor       | Measurement Range                  | Scale             | Accuracy          |
|----------------------|------------------------------------|-------------------|-------------------|
| Temperature sensors  | $-20^\circ C + 50^\circ C$ (wet thermometer) $0^\circ C + 50^\circ C$ | $0.01^\circ C$   | $\pm0.4^\circ C$ |
| Humidity sensors     | 0–100%                              | 0.1 RH (relative humidity) | $\pm2\%$ RH (relative humidity) |
| Air velocity sensors | 0–5 m/s                             | 0.01 m/s          | $+/0.05+0.05 \times V_a$ m/s, for 1-5 m/s $\pm5\%$ |

Additionally, when making measurements, you should specify:
- insulation of clo clothes [clo],
- energy expenditure incurred for the work of MET [met].

The result can be obtained on a seven-point scale, where:

| Table 3. Fanger’s scale |
|-------------------------|
| Result | Feeling |
| +3     | Hot     |
| +2     | Warm    |
| +1     | Lightly warm |
| 0      | Comfort |
| -1     | Lightly cool |
| -2     | Cool    |
| -3     | Cold    |

The PN-EN ISO 7730 standard introduces a division into room categories due to the PMV factor achieved. The classes are listed in Table 3.

| Table 4. Room categories depending on the PMV indicator. |
|----------------------------------------------------------|
| Room category       | Coefficients: |
|                     | PMV [-] | PPD [%] |
| A                   | $-0.2<PMV <+0.2$ | $<6$ |
| B                   | $-0.5<PMV <+0.5$ | $<10$ |
| C                   | $-0.7<PMV <+0.7$ | $<15$ |
In addition, methodology allows determining the expected percentage of dissatisfied conditions (Fig. 3).

![Graph showing the expected share of dissatisfied conditions](image)

**Figure 3. PPD coefficient**

3. Vibrational comfort measurements requirements

3.1. Measurement equipment

Acceleration, velocity or displacement could be measured during dynamic in-situ tests. According to which parameter will be measured, appropriate measurement equipment should be applied. For displacements tensors should be used, but it is worth mentioned that they are problematic in use. To have reliable displacement results it good to know typical behaviour of the structure. The accelerations of vibrations are related to the easy assessment of the influence of vibrations on people. Evaluation of human perception of vibration is mostly measured in the frequency range between 1 and 80 Hz [8-10], sometimes the lower value from this range is even below 1 Hz [11]. The measurement, although in most cases the vertical direction has a decisive role, should take place simultaneously in three orthogonal directions: the "x" direction is assumed in all measurements perpendicular to extortion, the "y" direction is parallel, and the "z" direction is the vertical direction.

The problem is how to install the sensor: to the structure or on the flooring system. Because people perceive vibrations on the floor with all floor layers it is recommended to measure human perception of vibration on the flooring system in the middle of the floor [8, 10]. In British standard [9] the measurement point should be located in the zone of 1/3 from the middle of the floor.

The second problem is how to simulate human weight. It is recommended to use a measurement disk, which should have a mass of at least 30 kg and a diameter of 30 cm (Fig. 4, acc. [10]).

3.2. Signal registration and analysis

Signal recording should contain frequencies in the range from 1 to 120 Hz, so that after applying a low-pass filter the frequencies up to 80 Hz can be included in the evaluation.

Another aspect of signal registration is the duration of vibration which should be taken to the analysis. In [10] the duration of vibration it is the range in which the value of vibration acceleration amplitudes does not fall below 0.2 of the maximum amplitude value in the recorded acceleration. In the ISO standard [12] used mainly for whole body vibration measurements requires that the signal recording time should be at least 30 minutes. Standard [8] includes a reference to the duration of vibration, which states that the recorded signal should be sufficient to ensure rational statistical accuracy. In the German standard [13] the analysis takes place in cycles lasting 30 seconds, and then the data from the cycles are averaged.

The last aspect related to the analysis of measurement data is the sampling frequency of the recorded signal, which according to the Nyquist criterion. According to this criterion sampling frequency should be twice as large as cut-off frequency. In practice, the minimum is set at 2.5 times the highest registered frequency, i.e. in the case of vibration on humans, the sampling frequency should be at least 300 Hz.
4. Conclusions

In this article a good practise guidelines of methodology of measurements of thermal and vibrational comfort were described. Such some guidelines could be useful especially for young scientists which start measurement adventure. The methodology contains of the choice of a proper measurement equipment, the selection of parameter which should be measured, the proper localization of measurement points and the analysis of results obtained during thermal and vibrational comfort measurements.

In the article the aspect of comfort in the NZEB and passive buildings is shown. The comfort of room in such a building is often considered in aspect of thermal comfort (with humidity), sometimes in the aspect of indoor air quality, even less often in the aspect of acoustic comfort. The vibrational comfort is always neglected. Authors show that this kind of comfort, especially in the city centers, should not be omitted.

References

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