The Influence of Air Heating and Lighting on the Comfort Conditions in NZEB Buildings’ Rooms

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Abstract. Near zero energy buildings (NZEB) and passive buildings are designed to minimize the energy consumption. The building’s "almost zero energy demand" standard, which will be in force in Europe from 2021, additionally imposes an obligation on buildings to use the energy from renewable sources. It should be remembered that in addition to the applicable criteria for NZEB buildings, the comfort of use of the rooms is equally important. The development of low-energy buildings resulted in new products and technologies on the construction and installation materials market. Radiator heating is increasingly being abandoned for surface or air heating. In the lighting industry, which also generates the energy consumption, products based on LED technology are developing. Both new heating and lighting systems have a very large impact on the comfort of using NZEB buildings. In this article, the Authors will present the results of "in situ" research regarding the feeling of comfort in an office space heated using fan coil units. The ventilation system also influences the feeling of comfort. The location of the ventilators in the room and the stream of supply air may cause discomfort. The authors will check the comfort conditions in different places of the room, including the propagation of the air stream. Additionally, the Authors will determine the minimum operating temperature of work comfort in the tested room, with the air heating. The second research task of this article will be to determine the visual comfort of people, when using recommended illuminance. The aim of the article is to answer the question of how to design workplaces in an air-heated room and how to design lighting to optimize the work comfort and energy consumption. The conclusions from the article will allow formulating the principles for the design of NZEB buildings.

1. Introduction
Designing buildings with nearly zero energy demand (NZEB) are associated with big challenges for designers. In addition to ensuring energy consumption at a low level, care should be taken to ensure the comfort of use of such buildings. Because Poland has no experience in NZEB buildings' projects and projects, every analysis and study regarding the provision of comfortable use conditions for NZEB buildings is important for designers and building contractors.

The comfort of using buildings includes many aspects [1]. It is thermal, acoustic, visual (lighting) comfort, air quality and vibration comfort (figure 1).
In the article, the Authors focused on two criteria of comfort: thermal comfort and lighting comfort. Research on thermal comfort has allowed to determine optimal comfort conditions in the conference room in the NZEB building. Research on lighting comfort carried out on a group of surveyed students, allowed to formulate conclusions regarding optimal lighting conditions for office work. Applications developed on the basis of the article are an important contribution to the NZEB buildings design guidelines.

2. Thermal comfort

2.1. Methodology

Providing the appropriate thermal comfort in NZEB buildings is one of the most important elements in designing and constructing buildings. Thermal comfort is also affected by design errors, such as leaks in the building envelope, thermal bridges, unevenly heated surfaces. The PN-EN ISO 7730 [2] standard introduces a division into room categories due to the PMV factor achieved. The classes are shown in Table 1.

| 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    |

The methodology for determining thermal comfort is based on PN-EN ISO 7730 [2].

The study of the thermal comfort of a room in a public utility building made in NZEB technology was carried out on 17-22.2018. The study was carried out in the building of the Malopolska Laboratory of Energy Efficient Buildings (Figure 2), in the lecture hall on the third floor. The aim of the study was to determine the optimal temperature for thermal comfort.
Figure 2. Malopolska Laboratory of Energy Efficient Buildings

Ventilation and heating installations account for 40 to 60% of energy consumption in buildings. It is therefore justified to strive to reduce the energy consumption of the above technical facilities of facilities. Due to the growing expectations of people regarding the comfort of use of premises and taking into account legal requirements and guidelines and recommendations of institutions such as the World Health Organization, National Labor Inspectorate, National Institute of Hygiene, one should also remember the thermal comfort of man. This leads to the optimization of air distribution solutions in the rooms and its parameters.

The test room has been cooled to +17°C. Initial conditions were maintained 24 hours before the start of the study.

Multifunctional hall, in which in-situ tests were conducted, has mechanical supply and exhaust ventilation with heat recovery. The ventilation unit has a heating and cooling function (heater, cooler). In the room, 4 supply points were used for air heating (ceiling diffusers with plenum boxes) and 3 extraction points.
In addition, the room is equipped with 3 heating-cooling ceiling ceilings, each with the following parameters:

- total cooling power of 8 kW,
- a total heating capacity of 16.9 kW,
- air flow 1393 m³/h.

The arrangement of air supply elements from the supply and exhaust ventilation unit is shown in Figure 3a, and fan coils - Figure 3b.

![Figure 3. a) exhaust ventilation unit, b) fan coils](image)

During laboratory tests, the target temperature was set in the BMS system, which was to be achieved in the room. For this purpose, both the supply-exhaust ventilation system and the fan coil units have been activated. The building control system was able to separate the power (heat, cold) delivered by individual systems so that the energy consumption was as low as possible.

Measurements of air parameters included:

1. The temperature in the room, measured by a wall sensor at a height of 1.5 m
2. The temperature of the air blown from the ventilation unit
3. The temperature of the exhaust air from the ventilation unit
4. Humidity of the air blown from the ventilation unit
5. Moisture of the exhaust air from the ventilation unit
6. Supply the airflow from the ventilation unit, regulated by variable flow regulator (VAV)
7. Exhaust the airflow from the ventilation unit, regulated by variable flow regulator (VAV)

In addition, power consumption by fan coil units for the above data was determined. The following behaviors of the ventilation and heating system were observed: In the event of a sudden change in the set temperature from 17 °C to 30 °C, the air handling unit increased the air flow from 300-400 m³/h to the quantity of over 1200 m³/h. At the same time, the fan coil units were started with the maximum
fan capacity. The room temperature reached the set value of 30 °C after 8-9 hours, using air heating from the supply and exhaust ventilation unit and fan coil units. Fan coils behaved in a similar way when the set temperature changed from 24 °C to 35 °C. Graph of air room temperature changes (Figure 4):

![Air temperature values](image)

**Figure 4.** Air temperature values

Diagram of cooling power of fan coil units (Figure 5) during testing (17-22 November 2018)
Figure 5. Cooling / heating power of a fan coil unit

The measurement of thermal comfort was made using comfort meters (Figure 6). The measurement methodology is based on PN ISO 7726 [3].

Figure 6. Description of sensors connected to a testing device dedicated to thermal comfort measurements

The measured parameters were:
- ta—air temperature measurement;
- tg—temperature of blackened sphere (heat radiation meter)—the black sphere, in agreement with the norms, should be 15 cm in diameter;
tnw—natural wet-bulb temperature measurement;
RH—measurement of relative air humidity;
Va—measurement of air flow speed.

The frequency of data collection was every 1 min.
The data from the sensors are given in Table 2.

### Table 2. Sensors’ data

| Type of Sensor        | Measurement Range                                                                 | Scale       | Accuracy                |
|-----------------------|----------------------------------------------------------------------------------|-------------|-------------------------|
| Temperature sensors   | –200°C + 500°C (wet thermometer 0 °C + 50 °C)                                    | 0.01°C      | ±0.4°C                  |
| Humidity sensors      | 0–100%                                                                          | 0.1 RH (relative humidity) | ±2% RH (relative humidity) |
| Air velocity sensors  | 0–5 m/s                                                                          | 0.01 m/s    | +/0.05+0.05 x Va m/s,   |
|                       |                                                                                  |             | for 0-1 m/s             |
|                       |                                                                                  |             | for 1-5 m/s ±5%         |

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

\[
PMV = \left[0.303 \times \exp(-0.306 \times M) + 0.028\right] \times \left((M - W) - 3.05 \times 10^{-3} \times [5733 - 6.99 \times (M - W) - p_a] - 0.42 \times [(M - W) - 58.15] - 1.7 \times 10^{-6} \times M \times (5867 - p_a) - 0.0014 \times M \times (34 - t_a) - 3.96 \times 10^{-8} \times f_{cl} \times \left([t_{cl} + 273] - 0.028 \times (M - W) - 35.7\right) - f_{cl} \times h_c \times (t_{cl} - t_a)\right]^{-3.96 \times 10^{-8} \times f_{cl} \times \left([t_{cl} + 273] - 0.028 \times (M - W) - 35.7\right) - f_{cl} \times h_c \times (t_{cl} - t_a)}
\]

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

For measurement of PMV and PPD values, parameters were adopted, corresponding to the conditions in which respondents were surveyed:

- insulation of clothing at \(I_{clo}\) level = 1.2 \([\text{clo}]\),
- energy expenditure incurred for the work carried out MET = 1.21 \([\text{met}]\), which corresponded to the work carried out by the respondents (sitting work).

**2.2. Results**

Figure 7 shows the dependence of thermal comfort on temperature.
2.3. Conclusions of thermal comfort

Near zero energy buildings (NZEB) and passive buildings are designed to minimize the energy consumption. A very important aspect in this type of buildings is to ensure thermal comfort. In low-energy buildings, there are installed systems of modern ventilation as well as heating and cooling, controlled by BMS systems. Optimizing the operation of ventilation / air heating systems with the use of supply and exhaust ventilation and fan coil units requires constant control and ongoing verification of the set parameters. The building control system is primarily aimed at achieving set air parameters in the room. The paper presents the results of experimental temperature measurements to achieve the level of optimal thermal comfort. The air heating system in 8-9 hours allowed the temperature to change from 17 degrees to 30 degrees. At the same time, a thermal comfort test was carried out in the room using measuring equipment - a microclimate meter. The measurements showed a very close relationship between thermal comfort and temperature. The results of the measurements showed that the optimal temperature at which the comfort level was reached - PMV = 0 is in the range of 24-26 °C. At 17 degrees, the PMV [-] indicator reaches -1, which means "quite cool" in the Fanger scale. At 30 degrees, the PMV indicator reaches a value from 1.26 to 1.6, which in Fanger's scale is between "quite warm" and "warm". Other parameters, such as human activity or clothing insulation, also influence the result. In order to determine the level of thermal comfort for different levels of human activity and for the different insulating properties of clothing, it is recommended to continue the tests.

3. Visual comfort

3.1. Introduction

One of the basic functions of the building is to provide comfortable working conditions for people. This function is carried out by electric lighting installations, having a 20-40% share in the total energy consumption of buildings [4]. Among the existing sources of light, the semiconductor LED sources have become particularly popular in recent years. They are characterized by high luminous efficacy, and when dimmed they consume approximately proportionally less energy. Therefore, their use in lighting control systems using dimming lamps allows for significant energy savings [5]. Striving to reduce energy consumption in NZBE buildings should not come at the expense of deterioration of people's lighting comfort [6].

3.2. Current recommendations regarding the lighting of office workstations

Current recommendations regarding the lighting of office workstations are presented in the European standard EN 12464-1 [7]. The standard specifies, among others, the requirements for illuminance and its uniformity, glare, color rendering, and color temperature depending on the utility function of a room.
type, and difficulty of visual activities performed. The standards have been derived from the time of traditional offices, where mainly paper documents were used. Therefore, the dominant parameter in the design of the lighting installation is the horizontal illuminance in the area of the task [8]. In offices, for the type of interior, task or activity such as writing, typing, reading, data processing, CAD workstations, and meeting rooms an average illuminance in the task area of at least 500 lx is required, with uniformity equal to 0.6. It should be noted that the guidelines for illuminance specified in the standard constitute a certain compromise between ensuring comfortable visual conditions for people and architectural, economic, technical, and environmental factors [9].

3.3. Individual lighting preferences of people

Studies carried out so far show that the lighting intensity preferred by individual people is strongly varied as well as changeable depending on the activities performed or the psychophysical state. There is no one illuminance that can satisfy everyone, as well as one air temperature will not provide everyone with thermal comfort [10].

The literature describes studies in which people were able to adjust the brightness of artificial lighting and set the most convenient illuminance for them at a workplace with a computer monitor. The studies were carried out, among others in laboratory conditions in arranged open-plan office environments, without or with minimal the participation of daylight. In [9] participants adjusted the dimming level of the lamp, which illuminated the single-person cubicle workstation occupied by them. On the desk surface, illuminance in the range of 83-725 lx was preferred, with 725 lx being the upper limit of the regulation range. There was no age or gender influence on lighting preferences. In turn, in [11] people set mean desktop illuminance in the range of 252-1176 lx. Similar studies were conducted in [12], where private offices were considered. Participants preferred lighting at 80-630 lx or 110-1230 lx depending on the available dimming range of lamps. In [13], the field study was conducted. For one year, 9 cubicle workstations occupied by individuals carrying out office tasks were monitored. The median of preferred illuminance was 600 lx, with 7 people preferring lighting below the recommended level of 500 lx, while 10 preferred above 500 lx. In turn, in [14] people working mostly with computers preferred illuminance of 100-300 lx, while spending less time with a computer preferred 300-600 lx.

3.4. The importance of comfortable lighting conditions in an office

Lighting in offices affects the comfort and productivity of employees. People who perceive the lighting of their workplace as high quality, assess the office space as more attractive, have a better mood and well-being, feel more comfortable, and are more satisfied with the work environment and the work itself. Interestingly, these people report less frequently that the temperature disturbs them during work. In addition, artificial lighting is one of the factors influencing the overall rating of the work environment quality. When this rating is high, people are more motivated, they work more efficiently, and they report less frequently symptoms of physical or psychological discomfort [15-17].

3.5. Subjective evaluation of illuminance at workstations with a computer monitor in modern office spaces

A study on the subjective assessment of illuminance produced by LED sources at an office workstation with an LCD monitor was carried out. The aim of the study was to answer the question how people working in modern office work environments feel the recommended illuminance (500 lx) [7]. A 5-grade evaluation scale of the lighting level at the workstation was prepared:

- definitely too bright,
- too bright,
- optimal,
- too dark,
- definitely too dark.
Considering the aforementioned literature, it was expected to receive responses covering all grades. A correlation analysis was also performed, the aim of which was to determine the relationship between the ratings of the workplace lighting level and the gender of participants.

3.5.1. Characteristics of the experimental room. The study was carried out in an experimental room, in the Małopolska Laboratory of Energy Efficient Building of the Cracow University of Technology. The room uses a variety of materials, glazing with large surfaces, as well as sunblinds, which are often characteristic elements of modern office buildings. General lighting is provided by a system of 28 direct, dimmable LED luminaires. Applied KTM2 600 luminaires from ES-SYSTEM are characterized by color rendering index >80 and color temperature 3000K [18]. The room was arranged in 20 identical office workstations, equipped with a PC, monitor, bench, chair, keyboard and mouse (figure 8, 9). Monitor display parameters have been unified and could not be modified by participants. Placement of workplaces in the right part of the room resulted from the location of sensors and measuring equipment. In order to eliminate the dynamic effect of natural light, the external blinds were completely closed. Lighting conditions were prepared in the room in accordance with the recommendations for office rooms with computer monitors [7]. The luminaires were dimmed to provide mean illuminance at workplaces a little over 500 lx.

![Figure 8. An arrangement of lighting fixtures (yellow) and workplaces (orange) with chairs in the experimental room](image1)

![Figure 9. A layout of a single office workstation during the experiment](image2)

3.5.2. Participants and the course of the experiment. Participants of the experiment (n = 195, including 98 women and 97 men, 18-25 years, median: 21, mean: 21.49, SD: 1.72) performed office tasks on a
computer monitor for at least 30 minutes, and then they assessed the intensity of the workplace lighting (via a computer questionnaire).

3.6. Results and discussions
The results of the participants’ feelings of illuminance at the workplace are shown in figure 10. As many as 73.3% of respondents said that the lighting intensity of their workplace is optimal and meets their expectations. The research results show that definitely more people said that the lighting is too bright or definitely too bright (18.5% and 5.1% respectively, which gives a total of 23.6%) than too dark or definitely too dark (3 respectively, 1% and 0%, which gives a total of 3.1%). This confirms earlier assumptions about the distribution of grades only partially – none of the participants indicated that the lighting of its position is definitely too dark. However, the results confirm that the preferences of people regarding the illuminance at the office workstation are varied. Only young people took part in the study, however, due to the lack of dependence of preferred illuminances from age [6], the presented results can be considered adequate for people of all ages. There was no correlation between the assessment of workplace lighting levels by men and women.

Because over seven times more people (23.6%) prefer illuminance at a workplace less than 500 lx, than people who would prefer illuminance higher than 500 lx (3.1%), thanks to the dimming of lighting, there is a potential for lower energy consumption and simultaneous improving the comfort of a large group of people. This regulation, however, cannot cover the whole room, because of the comfort of people who considered lighting to be optimal or even too dark. The regulation should be carried out locally at the level of individual workstations, enabling the adjustment of lighting to individual preferences. Due to this, energy flows for the lighting of individual stands will be directed according to demand. In addition, because of the comfort, also people who want to increase the lighting intensity of the workplace should be able to do it. This will increase the energy consumption of some workplaces, however, due to the low percentage of people expecting more intensive lighting, the final energy balance may be more beneficial than in the case of traditional lighting installations. Because, locally produced illuminance will meet the expectations of all employees, their comfort and satisfaction will increase, as well as motivation and work efficiency. Due to the high costs of employees in office buildings, this solution can also be economically advantageous for the employer.

![Figure 10. A feeling of illuminance at the workplace by the participants of the study](image)

4. Conclusions
Slightly more than 73% of the respondents consider illuminance at a desk at 500 lx level recommended by EN 12464-1 [7] as optimal while working at a workstation with an LCD monitor, in a modern office.
space illuminated with LED lamps. Nearly 24% of people prefer lower illuminance, and only slightly above 3% would prefer the lighting to be brighter. Therefore, there is a potential for lower energy consumption and simultaneous improvement of people's comfort by providing local lighting control at the level of individual workstations, allowing adaptation of the illuminance to the individual preferences.

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