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Maintaining thermal comfort and air quality in buildings

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ABSTRACT:
Maintaining the proper indoor microclimate and the correct level of thermal comfort is extremely important due to the impact of the surrounding environment on people's satisfaction, well-being, health, and work. This problem is particularly important in rooms where children spend long periods as the environment has a stronger influence on their still-developing organisms. The study assessed the microclimate parameters, the state of human thermal comfort, and the level of carbon dioxide concentration, as well as the maintained levels of comfort and air quality after the application of improvements aimed at rationalizing heat consumption in educational buildings. The results of basic thermal and personal microclimate parameter measurements, as well as carbon dioxide levels, were presented. The assessment of human thermal comfort was based on measured values, the Predicted Mean Vote, and Predicted Percentage Dissatisfied. The average rating of thermal comfort in the observed environment was within the acceptable comfort zone, but high concentrations of carbon dioxide indicates low efficiency of the ventilation system.

KEYWORDS:
indoor microclimate conditions; carbon dioxide concentration; thermal comfort; PMV and PPD indicators

1. Introduction

Thermal comfort expresses the satisfaction of a given person or group of people from the thermal conditions of the environment in which they reside. Obtaining and maintaining thermal comfort is possible by achieving specific microclimate parameter values. The basis for ensuring proper indoor microclimate parameters is the knowledge of heat exchange processes between the human body and the environment. Heat exchange between humans and the surrounding environment depends on a number of factors involved in shaping the heat balance of the human body. These aim to maintain the body's internal temperature at a constant level [1-3]. The main factors determining the increase and loss of heat in the human body are the so-called microclimate thermal parameters, namely air temperature, average ambient radiation temperature, airflow speed, and relative humidity. The second group of parameters to be considered are specific to the person in a given environment, i.e. the metabolic rate and thermal insulation of the clothing worn. Psychological parameters, such as the individual expectations of each person or their ability to acclimatize, also have a strong impact on the impression of thermal comfort [1-3]. During studies on thermal comfort in humans, it was found that maintaining optimal values of thermal microclimate parameters does not guarantee that the user is satisfied with the environmental conditions. Equally important is the air quality in the rooms. Sources of indoor air pollution include actions such as cooking or smoking, building materials and interior design elements, microorganisms (fungi, molds), as well as outside air [4]. Due to the existing biological differences between people, it is not possible to construct an interior that satisfies all.

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The goal should be to achieve thermal comfort conditions that would be acceptable to as many people as possible. In practice, a neutral state is achieved in a room when an ideal state of thermal comfort is reached [1-4].

The quality of a building's indoor environment is essential because this quality has a considerable impact on the well-being and health of the people staying there [5, 6]. Since people spend most of their time in buildings, the quality of the indoor environment must not negatively affect them. Both Polish law and the EU Directive on the energy performance of buildings indicate the need to ensure appropriate hygienic and health conditions in rooms [7]. Also, the World Health Organization has presented guidelines for the protection of health against many substances commonly found in indoor air [8].

The large number of factors affecting well-being makes it extremely difficult to determine comfort conditions exactly. To assess the human thermal comfort in buildings, a steady-state model or an adaptive model can be used [9, 10]. An adaptive model relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters. This model is mainly based on the theory that the human body adapts to its outdoor and indoor climate [11, 12]. So far, several indicators have been proposed defining the human thermal environment. The Fanger comfort equation calculates the predicted average thermal comfort rating PMV and the number of people dissatisfied with the existing conditions PPD [4]. The obtained value of PMV is compared with a 7-point scale of thermal feelings.

The study assessed the microclimate parameters, the state of thermal comfort and the level of carbon dioxide concentration, as well as the maintenance of comfort conditions and air quality after the application of improvements in energy performance for educational buildings. The state of the interior environment in these types of buildings affects not only the well-being and health of the people staying there, but also the comfort of work. Conducting research in buildings designed for the long-term residence of children is particularly important due to the strong impact that they have on those children's organisms [13-17].

2. Parameters important in creating human thermal comfort

Proper shaping of the values of individual interior microclimate elements is a basic condition for achieving thermal comfort by persons staying in a given environment. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality and thermal environment are specified in the standard PN-EN 16798 [18].

The air temperature and average ambient radiation temperature are correlated with each other and their effect on thermal sensations is combined. The resultant of these two elements is the perceived temperature. The lower temperature of the surrounding surfaces means that even the optimal air temperature is perceived as uncomfortable. The average ambient radiation temperature should not differ from the air temperature by more than about 3°C. Various factors affect the room air temperature. In summer, the impact of the local climate is most pronounced. During the heating season, it is largely neutralized by the operation of the heating system. When assessing thermal sensations, the gradient vertical temperature is also important [4, 9, 19].

Air movement affects the state of human thermal comfort by changing the conditions of heat exchange by convection. Excessive airflow speed causes discomfort. The feeling of airflow speed is subjective and depends on the air temperature in the room and the difference between the temperature of the airflow and the ambient temperature. Usually, air, with a temperature lower than the air in the room adversely affects a person, disrupting his thermal sensations. Air movement with a speed less than 0.20 m/s is usually received positively. Analyzing the PMV tables contained in ISO 7730 [20] it can be concluded that at a given air temperature and activity, the assessment of thermal comfort does not change with an increase in speed by 0.1 m/s, if the thermal insulation of clothing increases by 0.25%. Such an increase in air velocity can also be compensated by a 0.2-meter increase in physical activity [4].

The air relative humidity affects the removal of heat from the body through the evaporation of sweat. A person who is in clean air with a temperature of 15÷27°C is not able to feel changes in relative humidity to a significant extent. Only high relative humidity and air temperature together cause discomfort. From the shortness of breath curve elaborated by Fanger, it follows that with a humidity of 60%, people begin to sweat at 25°C, while at 50% only at 28°C. Therefore, when setting the upper comfort limit, the relative humidity should be taken as lower, the higher the air temperature [4, 9, 19].

The role of clothing in the heat exchange process consists of the thermal insulation of the body and transport water vapor. Thermal insulation of clothing depends on the material from which it is made and the amount of still air therein. Lowering the temperature by 1°C with clothes with 1 clo insulation can be compensated by increasing the thermal insulation of worn clothing by about 15÷20%. The value of thermal insulation of typical summer clothing is about 0.6 clo, and winter clothing about 1 clo [19-21].

Metabolic rate is the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. People have different metabolic rates depending on activity levels and environmental conditions. Physical activity enhances metabolic heat production. Increasing human activity causes a decrease in the air temperature that he previously considered comfortable [19, 20, 22].

With simplified air quality testing, the carbon dioxide content is taken as a reference. There are carbon dioxide thresholds that are considered a measure of air quality. It is assumed that the carbon dioxide content in indoor air should not be more than 1000 ppm. The carbon dioxide content in clean atmospheric air is around 350÷450 ppm. By the level 2000 poor air quality and sleepiness are already observed. At values 2000÷5000 ppm headaches are possible. Values over 5000 ppm lead to discomfort and rapid heart rate, over 15 000 to problems with breathing and over 30 000 to dizziness and indisposition. Concentrations above 60 000 may cause a blackout [23]. The highest permissible concentration in the work environment is 9000 mg/m^3 i.e. about 5000 ppm [24].

3. Evaluation of thermal comfort feeling in educational buildings

The subject of the conducted research was the assessment of the indoor environmental quality based on selected parameters and its impact on human thermal comfort. The research was carried out in educational buildings located in Czestochowa city, in typical study rooms designed for the long-term residence of children, during the heating season. The average room size was about 60 m^2 and there were, on average, about 20 people in the room.

First of all, the air temperature, air relative humidity, and airflow speed in rooms, as well as average ambient radiation temperature, were measured. At the same time, estimated basic parameters of the local climate, temperature and relative humidity of the air as well as wind speed. The measurement results are shown in Table 1.

Table 1
Parameters of the external climate and internal microclimate (own research)

External parameters	Average	Standard deviation	Internal parameters	Average	Standard deviation
air temperature [°C]	–1.3	5.7	air temperature [°C]	20.6	2.8
air relative humidity [%]	84	12	radiation temperature [°C]	21.2	3.1
wind speed [m/s]	3.3	1.5	air relative humidity [%]	46.4	10.7
cloudiness	7	2	air flow speed [m/s]	0.08	0.04

Figures 1-3 show the average distribution of indoor thermal microclimate parameters during the day in given buildings.

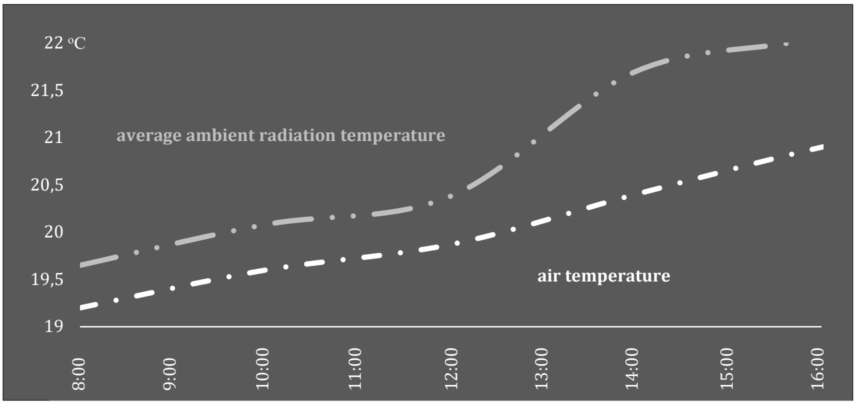

Fig. 1. The average distribution of air temperature and average ambient radiation temperature in buildings (own research)

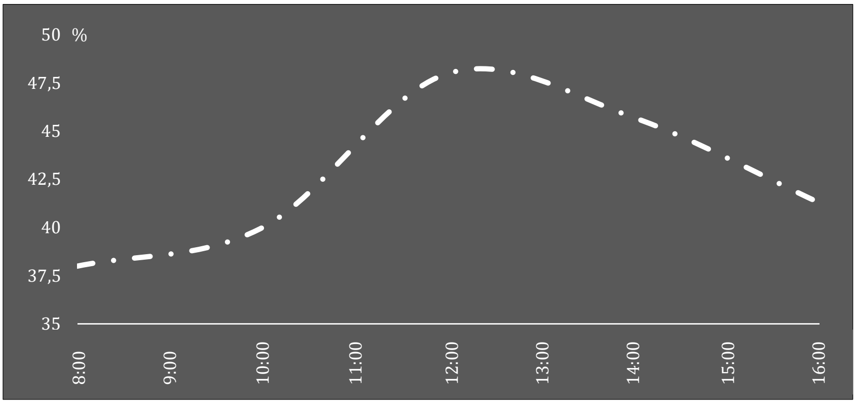

Fig. 2. The average distribution of air relative humidity in buildings (own research)

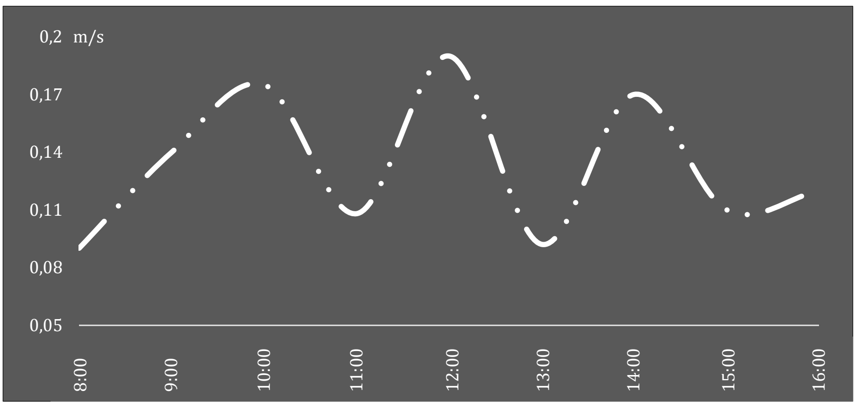

Fig. 3. The average distribution of airflow speed in buildings (own research)

Then, the personal factors of the microclimate were followed (Table 2). Thermal insulation of clothing and the value of metabolic energy related to the physical activity of the individual person were analyzed. In determining the metabolic rate and the thermal insulation of clothing, the values and formulas contained in the literature were used [21, 22].

Table 2
Thermal insulation of clothing and the value of metabolic energy (own research)

Parameters	Children		Teachers	
	Average	Standard deviation	Average	Standard deviation
Thermal insulation of clothing [clo]	0.86	0.08	0.89	0.11
Metabolic energy [met]	2.10	0.35	1.40	0.20

In addition, the carbon dioxide level in the air was also measured. During the study, the value of outside carbon dioxide fluctuated in the range from 400 to 480 ppm. The level of carbon dioxide in the rooms changed dynamically (Fig. 4). The initial content in the air was about 500÷750 ppm and increased depending on the number of people. Within an hour, this increase was, on average 500÷600 ppm. The largest measured value was 2428 ppm.

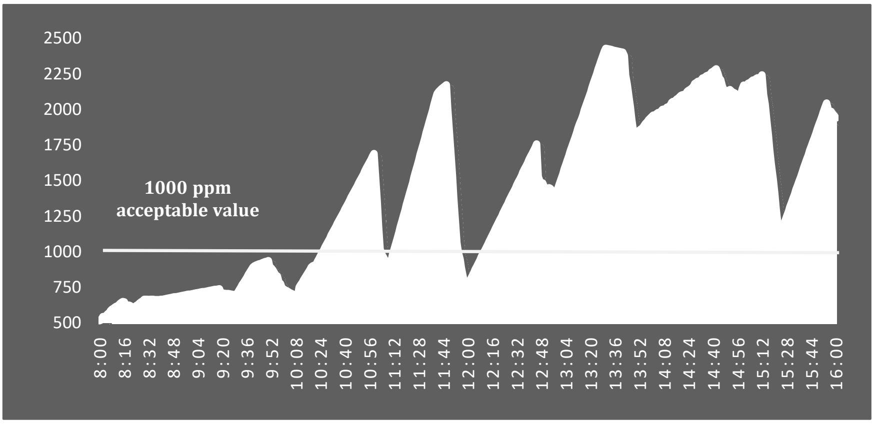

Fig. 4. Carbon dioxide level in the air (own research)

The assessment of human thermal comfort was based on measured values, the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied people with existing conditions (PPD). PMV describes human thermal sensations on a 7-point scale from −3 to +3. The value PMV = 0 is identified with a neutral reception of environmental conditions. However, the percentage of dissatisfied people PPD is then 5%. The results of the measurements are presented in Table 3.

Table 3
Human thermal comfort evaluation indicators (own research)

Thermal comfort indicators	Children		Teachers	
	Average	Standard deviation	Average	Standard deviation
Predicted Mean Vote	0.72	0.63	−0.52	0.65
Predicted Percentage Dissatisfied [%]	18	16	11	17

In the comfort zone (−1÷+1) were 84% of the value of PMV indicators estimated for children and 86% for teachers. About 15% of room users were dissatisfied with the thermal comfort conditions.

4. Energy consumption rationalization and maintaining human thermal comfort in buildings

Extensive energy-saving actions currently carried out on a large scale do not always lead to the improvement of microclimatic conditions existing in closed rooms or even their maintenance in their original condition. Permanent sealing of the building envelope often leads to malfunctions of the gravitational ventilation system, limitation of the amount of ventilated air exchanges or even loss of ventilation. A high concentration of indoor air pollution, among others carbon dioxide, usually causes pathogenic sick building syndrome and malaise or illness among users of such buildings [25-28].

The evaluation of the interior microclimate state in educational buildings was carried out, in which activities were carried out to rationalize the heat consumption for their heating. The buildings met the current requirements regarding thermal insulation and energy saving. In this group of buildings, air temperature and average ambient radiation temperature were, on average about 1.5°C higher, while air relative humidity was, on average lower by about 8÷10%. The airflow speed in rooms and person parameters remained at a similar level. Whereas, a significantly higher level of carbon dioxide was recorded (Fig. 5). The largest measured value was 3228 ppm. Intensive airing of the rooms caused a rapid drop in carbon dioxide levels.

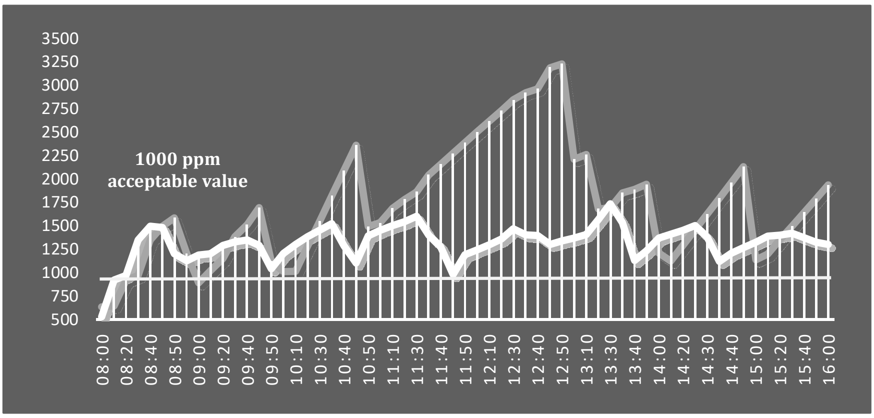

Fig. 5. Carbon dioxide level in the air measured over two days (own research)

The high content of carbon dioxide in the air has exacerbated some of the symptoms of sick building syndrome, which the occupants related with bad air quality in the rooms. Increased overall malaise, difficulty in concentration, fatigue and sleepiness. Poor air quality in the room has been reported by about 90% of people staying in rooms. The lack of fresh air created the necessity of additional airing of rooms by opening windows. It was the reason for the increase in heat loss and temporary deterioration of human thermal comfort, due to the lowering of the temperature and the increased speed of the cold airflow.

Human thermal comfort evaluation indicators in this group of buildings are shown in Table 4.

Table 4
Human thermal comfort evaluation indicators (own research)

Thermal comfort indicators	Children		Teachers	
	Average	Standard deviation	Average	Standard deviation
Predicted Mean Vote	1.12	0.72	0.11	0.38
Predicted Percentage Dissatisfied [%]	38	18	7	8

In buildings with high envelope thermal insulation, adults evaluated the interior environment as neutral, PMV ≅ 0. On the other hand, the children assessed the environment as slightly warm, perhaps because of the high insulation performance of the clothes they wear.

5. Conclusions

Proper shaping of the values of individual elements of the interior microclimate is a basic condition for the persons staying in a given environment to achieve thermal comfort and general well-being and health. The average thermal comfort rating of PMV in the considered environment was within the acceptable comfort zone. The children preferred a lower air temperature in the environment in which they stayed than the adults. The value of thermal insulation of clothing often depends not only on the air temperature in the rooms or the level of metabolism but on stereotyped habits related to the wearing of a particular type of clothing at certain times of the year.

Even though the aim of thermal protection of buildings should also be to provide appropriate conditions for indoor microclimate and human thermal comfort, attention should be paid to the deterioration of indoor air quality in connection with the implementation of improving the energy performance of buildings. Rationalizing energy consumption in buildings also partly improves the indoor microclimate conditions and the feeling of thermal comfort for residents, and also contributes to the elimination of some problems, i.e. moldy or moisture partitions due to the elimination of, for example thermal bridges or reduction of relative air humidity. However, in buildings with high envelope thermal insulation, some of the symptoms of the sick building syndrome were intensified, which residents associated with the deterioration of indoor air quality. There has been also a significant increase in carbon dioxide after prolonged use of the rooms. It was found that in many cases commonly used gravitational ventilation was not able to ensure the proper conditions of the interior microclimate. The introduction of a constant, gradual supply of fresh air in the amount necessary to ensure adequate hygiene and health conditions would eliminate the need for ventilation by opening windows and contribute to improving the conditions of human thermal comfort.

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Utrzymanie komfortu cieplnego i jakości powietrza w budynku

STRESZCZENIE:
Utrzymanie właściwego stanu mikroklimatu wnętrz oraz prawidłowego poziomu komfortu cieplnego osób jest niezwykle ważne ze względu na wpływ otaczającego środowiska i zadowolenie ludzi z warunków, w jakich przebywają, na ich samopoczucie, zdrowie i komfort pracy. Problem ten jest szczególnie istotny w pomieszczeniach przeznaczonych do długotrwałego przebywania dzieci ze względu na silniejszy wpływ otoczenia na nie w pełni jeszcze ukształtowany organizm. W pracy dokonano oceny parametrów mikroklimatu, stanu komfortu cieplnego i poziomu stężenia ditlenku węgla, a także oceny utrzymania warunków komfortu i jakości powietrza po zastosowaniu ulepszeń mających na celu racjonalizację zużycia ciepła w budynkach edukacyjnych. Przedstawiono wyniki pomiarów podstawowych termicznych i osobowych parametrów mikroklimatu oraz poziomu stężenia ditlenku węgla. Ocenę komfortu cieplnego ludzi oparto na zmierzonych wartościach przewidywanej średniej oceny komfortu cieplnego i przewidywanego procentu osób niezadowolonych z istniejących warunków otoczenia. Średnia ocena komfortu cieplnego w obserwowanym środowisku mieściła się w dopuszczalnej strefie komfortu, ale wysokie stężenie ditlenku węgla wskazuje na niską wydajność systemu wentylacji.

SŁOWA KLUCZOWE:
warunki mikroklimatu w pomieszczeniach; stężenie ditlenku węgla; komfort cieplny; wskaźniki PMV i PPD