Verification of the selected thermal comfort model in real and simulated conditions

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Abstract. The article below aims to analyze the feeling of thermal comfort model in real and simulated conditions. The research and survey were carried out on a group of students in the lecture hall, “Energis” intelligent building, Kielce University of Technology. The respondents assessed thermal impressions in real situation. In the climate chamber, the climatic room quality were simulated. Particular attention was paid to temperature and humidity, which were set at the same values as in the room. Two comfort states were compared, and the results are presented in individual charts. Based on the tests, it can be stated the Fanger model is not accurate in describing thermal sensations of people – especially in the case of simulated (laboratory) conditions.

1 Introduction

In the modern world, thermal comfort plays a huge role due to the occurrence of ever higher temperatures in all climatic zones. Such climate change also changes the heat preferences of people who strongly tend to cooler temperatures in workplaces, schools, colleges and shops, so as not to feel bad deteriorate their effectiveness. Therefore, it is so important to conduct research that will update the generally imposed temperature ranges. The most common way to learn about people's warm feelings is to conduct subjective surveys, from which one can find out the acceptability of temperature, humidity or general well-being, etc. Nevertheless, the most important question in the survey concerns thermal sensations, because it informs about people's thermal preferences (Predicted Mean Vote - PMV). These impressions are described on a seven-point scale [1] from -3 (too cold), -2 (to cool), -1 (pleasantly cool), 0 (comfortable), +1 (pleasantly warm), +2 (to warm), +3 (too hot). The PMV calculated on the basis of the questionnaires is the average of all respondents' answers ranging from -3 to +3. Average PMV is then compared to the PMV calculated on the basis of the ISO 7730 standard, based on the Fanger model. The Fanger model that allows for the understanding of PMV in the standard is presented below [1]:

\[
PMV = [0.303 \cdot \exp(-0.036 \cdot M) + 0.028] \cdot [(M - W) - 3.05 \cdot 10^{-3} \cdot (5733 - 6.99 \cdot (M - W) - p_a) - 0.42 \cdot (M - 58.15)] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M (34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot h_c \cdot (t_{cl} - t_a) - (t_r + 273)^4 \cdot f_{cl} \cdot h_c \cdot (t_{cl} - t_a) - (t_r + 273)^4 \cdot f_{cl} \cdot h_c \cdot (t_{cl} - t_a)]
\] (1)

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In the conducted research, feelings depend on the following parameters: metabolic rate – $M$ [W/m$^2$], effective mechanical power – $W$ [W/m$^2$], partial pressure of water vapour – $p_a$ [Pa], air temperature – $t_a$ [˚C], clothing area ratio – $f_{cl}$ [-], surface temperature of clothing – $t_{cl}$ [˚C], average radiation temperature – $t_{r}$ [˚C], heat transfer coefficient – $h_c$ [m$^2$K/W]. The conditions are considered comfortable if, the PMV index is within $-0.5 \leq PMV \leq +0.5$ [1].

Thermal comfort, apart from the places where people stay every day, can also be tested in the climatic chamber. A huge range of temperatures and humidity can facilitate the selection of parameters adequate to the expectations of people of various activities. After analyzing the literature, it was noticed that there is little research related to thermal comfort in a climatic chamber and comparison with the feeling of comfort in other closed rooms. One such proposal is the research of Ji et al. [2] who proposed and conducted an experiment in a climate chamber. For this purpose, three starting temperatures 20$^\circ$C, 25$^\circ$C and 30$^\circ$C were selected. The idea of this experiment was a time lasting from a few minutes to several hours and the temperature changes to lower and higher than the starting temperatures. It turned out that the feeling of comfort and discomfort depends on the current and previous temperatures. In addition, a year later, the same authors, in an enlarged composition, examined the metabolic rate and thermal comfort in a hermetic chamber during physical activity, based on CO$_2$ measurements. Ji et al. [3] invited 31 people for testing, tasked with cycling for 8 minutes at a variable speed, followed by a rest time in a seat for 22 minutes. The analysis showed, based on the responses from the questionnaires and measurements, that the time of metabolism increase started after 5 - 6 minutes, and the time it took for the body to stabilize its vital signs in order to achieve equilibrium after exercise was longer from 7 to 9 minutes. The authors' conclusions showed that such changes in metabolism can and do influence the subjective assessment of thermal comfort. It is worth mentioning that P.O Fanger [4] conducted research in a chamber with three-week cycles in which constant microclimate conditions were maintained. The temperatures taken into account in the tests were 21.1$^\circ$C, 23.3$^\circ$C, 25.6$^\circ$C, 27.8$^\circ$C at 30% relative humidity and 70% at an air speed of 0.1 m / s. Eight people from each group were asked to carry out the research: students, elderly women and elderly men. Soebart, Zhang & Schiavon [5] proposed a comparison of the warm feelings of older and younger people in the environmental chamber. The study involved 22 elderly people with an average age of 69.7 years and 20 young people with an average age of 29.6 years. The temperatures varied from slightly cool to slightly warm. Then, the questionnaires were analyzed and completed by the respondents from whom they noticed. Another idea came from Zhang et al. [6] from China, who tested 60 people from two buildings with centralized air conditioning and a split air conditioner. Two groups of 30 people were formed, which were subjected to temperatures from 20$^\circ$C to 32$^\circ$C, at 50% and 70% humidity. It turned out that for two groups the temperature covered was 26.8$^\circ$C and 26$^\circ$C. A similar test was performed by Zuo, at al. [7] except that the temperature range was from 26$^\circ$C to 37$^\circ$C. Li et al. [8] undertook the evaluation of the influence of humidity on thermal comfort in the airplane cabin in passengers. They stimulated the three temperatures 20, 25 and 28 and the humidity changing during the test (from 50% to 20% and again to 50% and 80% to 20% and again to 80%) in the environmental chamber. Using the questionnaires, it was concluded that the humidity influences the feeling of thermal comfort at a temperature of 20 for the combination of humidity 80% -20% -80%. However, one cannot forget about thermal comfort in classrooms or offices, as in the case of the Dębska & Krakowiak [9] research, which examined 3 buildings with different types of ventilation. 83 volunteers completed the questionnaires, which showed at what temperature the students felt best. The most satisfactory temperature was 22.5$^\circ$C, still acceptable was 25.3$^\circ$C, and unacceptable was 27.6$^\circ$C. However, later the same authors [10] tested one randomly selected room in order to
find out about people's thermal preferences. The study was carried out in the "Energis" intelligent building, where 9 people described the microclimate parameters. Temperature 25.7°C turned out to be comfortable for 50% of people, and pleasantly cool for the other half. 100% of people would not want any change in temperature while the test was performed. People who stayed in this room were satisfied with this temperature value. A similar study was conducted by Wang et al. [11] in China in a cold climate, at many universities, where 1973 questionnaires were analyzed. The research showed the range of temperatures preferred in the ground from 21.3°C to 25.4°C and in the summer on 29.6°C. Majewski et al. [12] conducted an in-depth computational analysis of the PMV value calculated from the questionnaires and calculated from the standard. People's actual feelings did not match Fanger's calculations. According to these studies, people were dissatisfied with the prevailing conditions, undermining the intelligence of the building under study. Krawczyk [13] also proposed a modification of the Fanger model based on the responses of the respondents. Kong et al. [14] proposed an interesting study using a climatic chamber for people who have lived in the Chongqing area of China for more than 20 years with high humidity, and for people who moved there shortly before testing from low-humidity areas. Two temperatures 25°C and 28°C were created in the chamber for humidity ranging from 20% - 90%. Due to the fact that the human factor was investigated here, questionnaires were used to assess the simulated conditions and the skin temperature was measured for any changes taking place. People living in higher humidity showed better acceptability and adaptation to the simulated parameters than those accustomed to lower humidity.

Referring to the analyzed literature, in order to undertake research, it was decided to create questionnaires that would allow to learn about the thermal feelings of people at a given moment in a selected room and for the reconstructed conditions that were previously obtained in the tested lecture room for the climatic chamber. For the room and the climatic chamber, the use of a microclimate meter is also planned for the climatic chamber, as is the case with many studies from the literature.

Taking into account the literature review, no comparative studies were carried out on thermal comfort in educational rooms and thermal comfort in a climatic chamber. The main aim of the article is to conduct comparative studies of thermal comfort with the parameters obtained in the lecture hall and then to introduce the same parameters to the climatic chamber. It is quite an important topic to know if people's thermal sensations in the lecture hall are similar or different from the simulated parameters in a climatic chamber and where people could feel better. The aim of the work is related to the Fanger model to check its accuracy.

2 Materials and methods

The research was carried out in central Poland, in the Świętokrzyskie Voivodship, at the Kielce University of Technology, in the 'Energis' intelligent building and in the climatic chamber. The Energis building was built in 2012 on the principles of sustainable development. Moreover, by using appropriate thermal insulation, the building becomes close to the idea of a passive building [15]. The main idea behind the creation of this project was its self-sufficiency through the production of electricity using photovoltaic panels, windmills and heat using heat pumps and solar collectors. Additionally, an important role was to be played by the building management system (BMS) controlling the work of all installations responsible for the comfort in the building. Currently, this system constantly monitors parameters inside the lecture halls. The climatic chamber consists of two chambers. The first one is bigger, with dimensions equal to 2.70×1.80×2.30 [m³] and the operating range for the set temperature is from -25°C ± +80°C. The area of the second
smaller chamber is equal to $2.25 \times 1.80 \times 2.30$ [m$^3$]. The temperature that can be set is $+5°C \pm +50°C$. Both research points are presented in Figures 1 and 2.

Fig. 1. Building of Environmental Engineering, Geomatics and Power Engineering, 'Energis' of the Kielce University of Technology.

Fig. 2. Climatic chamber.

The first test was carried out in a lecture hall, the second in a climatic chamber. The same research concept was used in both cases. The authors of the study used an accurate environmental meter that measures air temperature, relative humidity, carbon dioxide concentration and other parameters depending on the probes installed, and specially designed questionnaires for participants in the study. The questionnaires included 13 questions assessing the subjective feelings of people, such as, for example, thermal sensations at a given moment, the assessment of temperature, humidity or lighting intensity, assessment of their general well-being in the room under study, along with the determination of their ability to acquire knowledge, preference for cooler or warmer temperatures, etc. The first thing to do after entering both rooms was to turn on the meter and place it in the centre of the room / chamber at the height of the seated people and to stabilize the parameters collected from the closed environment. After approximately 15 minutes, the results were saved. During this time, the questionnaires were distributed to the respondents to be completed and then collected for analysis. The Testo 400 environmental gauge is shown in Figure 3.
In the lecture hall, 7 people participated in the study, including 2 women and 5 men, aged 22 to 23 years old, and in the climatic chamber one person aged 26. For clarification, the questionnaires were carried out on 01 July 2021 in room 1.14 of the Energis educational building. The results of the surveys are presented in the charts below.

3 Results

In the tested room, the environmental measurement showed the temperature of 25% and 56% of relative humidity. Then, for the purpose of the analysis, the same parameters were applied in the environmental chamber to check whether the microclimate perception of the room is closer to the PMV value according to the Fanger model, or to the microclimate created in the environmental chamber. Figure 4 shows how the respondents felt when taking measurements. As a reminder, it is summer in Poland, the outside temperature is above 30°C. In the room, the thermometer reads 25°C. The recommended temperature for offices in the summer period, for people with light work, is 23-27°C. For these thermal sensations vote question, respondents answered on a seven-point scale from -3 (too cold), -2 – too cool, -1 – pleasantly cool, 0 – comfortable, 1 – pleasantly warm, 2 – too warm, 3 – too hot.

From the chart above, that the respondents generally feel comfortable in the room - this is what 71.43% of the respondents say, 14.29% think it is pleasantly warm and the same
number (14.29%) think it is too warm. The responses of the last two groups are considered as dissatisfied with the prevailing conditions in the room. The next question was aimed at clarifying: how do you assess the current temperature in the classroom - the respondents assessed the prevailing temperature according to definitely unpleasant (-2), unpleasant (-1), acceptable (+1), comfortable (+2). The results are shown in Figure 5.

![Figure 5](image)

**Fig. 5.** Thermal preferences vote based on student responses in the classroom: -2 – definitely unpleasant, -1 – unpleasant, 1 – acceptable, 2 – comfortable.

Exactly 42.86% of the respondents considered the temperature to be comfortable, and the majority of respondents (57.14%) found the temperature to be acceptable. It can be assumed that most of them felt a slightly increased temperature in the room. Most of the respondents are men who prefer cooler temperatures. Taking into account the age of the respondents, it can be concluded that the room is comfortable.

The respondents were also asked if they would like to change something in the room. Most, as many as 71.43%, do not want to change anything. A minority, 28.57%, said they would prefer the temperature to be lowered. The thermal preferences vote (TPV) are presented in Figure 6, where respondents answered that the room could be definitely warmer (+2), warmer (+1), no change (0), cooler (-1) and definitely colder (-2).

![Figure 6](image)

**Fig. 6.** Thermal preferences vote (TPV) by the respondents: -2 – definitely cooler, -1 – cooler, 0 – no change, 1 – warmer, 2 – definitely warmer.

The question of humidity in the room was also mentioned in the questionnaires. In the lecture hall, the measuring device showed a humidity of 56.43%. This value is in the range of 40-60%, which is the optimal level for the human body. Figure 7 shows the results of the questionnaires in which the feeling of humidity in the room was assessed (assessment of...
humidity vote – AHV) : too dry (-2), quite dry (-1), pleasantly (0), quite humid (1), too humid (2).

Fig. 7. Assessment of humidity vote (AHV) according to the respondents: -2 – too dry, -1 – quite dry, 0 – pleasantly, 1 – quite humid, 2 – too humid.

Most of the respondents, 42.86%, found it pleasantly and quite humid. On the other hand, only 14.29% of respondents stated that the room was quite dry. As it is known, in the building in the summer, the humidity has a resultant value, i.e. there is no humidity control in this period. It can be concluded that the outside air quality was also within the normal range. The optimal result was obtained in the questionnaires. Figure 8 shows the respondents’ humidity preference vote (HPV) preferences, assessing it as more dry (-1), no change (0), more humid (+1).

Fig. 8. Humidity preferences vote (HPV) according to the respondents in the classroom: -1 – more dry, 0 – no change, 1 – more humid.

Most respondents stated the no change condition, as high as 57.14%. Slightly less, 42.86% said they would prefer the air to be more humid. Nobody spoke about the dryness of the air in the room. All the figures confirm that in the state of high temperature and high humidity, the human body would feel much more discomfort, for example by excessive sweating. In the case of our room, you can see that the respondents felt good, did not feel any discomfort and did not want to change anything in the environment.

The calculated PMV will provide us with information whether the parameters set in the climatic chamber (temperature: 25°C and relative humidity: 56%) created better microclimate conditions or whether the thermal sensations indicated a feeling of discomfort. Table 1 presents the calculated PMV from the ISO 7730 standard [1] and the
PMV calculated according to the respondents' answer: „How do you assess your thermal feeling at the moment?” obtained from the mean thermal sensations vote (TSV). The thermal sensations vote (TSV) average is calculated by averaging the responses of respondents who mark their readings on a seven-point scale from -3 (too cold), -too cool (-2), pleasantly cool (-1), comfortable (0), pleasantly warm (+1), too warm (+2) to too hot (+3).

<table>
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<tr>
<th></th>
<th>PMV (ISO 7730 standard)</th>
<th>PMV (surveys - TSV)</th>
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<tbody>
<tr>
<td>Room</td>
<td>0.08</td>
<td>0.43</td>
</tr>
<tr>
<td>Climatic chamber</td>
<td>0.15</td>
<td>2</td>
</tr>
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The PMV value calculated according to equation (1) (as given by the standard ISO 7730) for the room was 0.08. However, the real PMV (TSV) for the room was 0.43, which is definitely in the range from -0.5 to +0.5. In the case of the climatic chamber the PMV result from the Fanger's model was 0.15, and from the survey for it was 2. Such results exceed the range of thermal comfort. The Fanger model reflects the conditions in the room better than in the climatic chamber, despite the same simulated parameters. It also has to be noticed that the differences between the real and calculated values are larger for the climatic chamber conditions (possibly due to the number of people tested). It also proves that the Fanger model might not be very accurate (both in actual and simulated conditions).

4 Conclusions

The above studies on the respondents confirm the optimal values of summer temperatures of +23 °C + 26 °C, with a relative humidity of 40 % to 70%. It should also be taken into account that the human body is able to sense temperature fluctuations at the level of ±1 °C. The study showed differences between the values of PMV in the real and simulated states. The climatic conditions in both rooms were identical. Therefore, other factors influenced the results of the study. In the lecture hall, during the examination, the window was open and you could feel gusts of wind inside the room. Students were dressed in summer clothes. The feeling of a breath of cool wind on they bodies probably contributed to the result of 0.43. Quite significant in the analysis is the obtained result of the 2nd indicator for the climate chamber. Therefore, the conditions in the chamber clearly cannot be called a comfortable environment. In this case, the interior of the chamber, perfectly isolated from the environment, no perceivable air movement, tightness and size of the chamber, influenced the test result. Additional the feeling of one person cannot be decisive for the diagnosis of the problem. Thus, this issue has to be studied further and it will be continued on a larger number of people.

References

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