Civil and Environmental Engineering
Vol. 21, Issue 2, 852-863, DOI: 10.2478/cee-2025-0062

# THERMAL COMFORT ANALYSIS IN THE SMART EDUCATIONAL BUILDING TOGETHER WITH MODIFIED MODEL DEVELOPMENT

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**Abstract**

Thermal comfort is currently one of the most important aspects that should be taken into account so that people could feel good in indoor spaces. The following article focuses on the issue of thermal comfort measurements in the smart building as well as on improving the Fanger model of thermal comfort. The research was conducted during the heating and transitional seasons at the Kielce University of Technology (Poland). Internal measurements were made using a high-precision microclimate meter and questionnaires describing the current thermal sensations of people in 12 educational rooms. 75.37% of people found the environment comfortable, pleasantly warm or cool. The acceptance of the temperature was about 90%, while about 44% of the respondents related their preference to either a warmer or cooler environment. At the same time about 50% felt that a change in temperature was not necessary. The optimal temperature range proved to be from 21.5°C to 23.5°C (with the peak at 22.5°C). Moreover, the Fanger model of thermal comfort was modified by considering two additional parameters: $CO_2$ level and BMI index in the model. This significantly improved the accuracy of the model in terms of predicting thermal sensations of the respondents.

**Keywords:**

Smart building;
Thermal sensations;
Fanger model;
Microclimate;
$CO_2$ level.

## 1 Introduction

Modern times are currently a challenge for building designers, due to the increasing awareness of people regarding their thermal needs and internal conditions in which they feel good. That is why smart (intelligent) buildings, whose aim is to create the best possible conditions for learning, working or resting may turn out to be so important [1]. The most common technical solution used there is a building management system (BMS), which controls lighting, the use of energy for the needs of the building, or generating the right amount of heat. All this has an impact on the fact that a person feels good in a closed space, so that he/she is not cold or warm, the lighting is neither too weak or strong. Thermal comfort, according to P.O. Fanger [2], is influenced by the parameters of the microclimate environment, such as air temperature, relative humidity, insulation of clothing or any active activity performed. In the 1960s and 1970s, this led to the creation of a model describing the PMV (Predicted Mean Vote) index, and the PPD (Predicted Percentage of Dissatisfied). These indicators are important due to their nature, which makes it possible to check whether there are good conditions in a given room that meet the thermal requirements of people and the percentage of people who experience discomfort. This method is used in the international standard ISO 7730 [3], according to which thermal comfort is described using a seven-point scale from -3 to +3, where negative values mean a cold environment, and positive ones a hot environment. The values: –1, 0 +1 are pleasant and comfortable environment values [2, 3]. On the other hand, dissatisfaction is related to values between: –3, –2 and +2 and +3, because they describe the discomfort experienced.

Krawczyk [4] examined 54 people in terms of thermal sensations and found that there was an impact of the carbon dioxide concentration on thermal sensations. Dębska [5] analyzed 263 questionnaires collected from 22 rooms. In the conducted analysis, it was noted that the PMV and thermal sensations of people are very different from each other. In this way, a new parameter has been introduced in the model – BMI (Body Mass Index), which provided better calculation accuracy than the original formula. Inaccuracies in the Fanger's model were also noticed by Omidvar and Kim [6], who took sweating into account when creating a new model proposal. The results showed that the model based on experimental data turned out to be better than the original model from the 1970s. Similar inaccuracies were shown by the authors of works [7, 8].

Stokowiec et al. [9] examined 6 rooms during the winter at temperatures from 22.4°C to 25.1°C. It turned out that the PMV cannot fully predict the real thermal sensations of people. Similar conclusions could be formed based on other studies [10, 11]. Further inconsistencies between PMV and thermal sensations of people (Thermal Sensation Vote - TSV) can be found in the author's research [12]. Moreover, Balbis–Morejon et al. [13] studied thermal sensations of students in a tropical climate in air-conditioned buildings. It turned out that the PMV overestimated the cooler temperature compared to the TSV, and the thermal acceptability of the students was in the range of 23°C to 24°C. Alfano et al. [14] conducted research in nearly 200 Italian schools, thus receiving over 4000 questionnaires on thermal sensations. Selected buildings were ventilated in a natural way, i.e. through opening windows or doors. And in these studies, it was also confirmed that the PMV computational model deviates from the relative thermal sensations of people (while these conditions were assessed well). Broday et al. [15], decided to modify the Fanger's model, due to the lack of consistency between the predicted and real thermal sensations, he created two proposals, of which the better option was to use multiple linear regression.

Undoubtedly, the thermal comfort is influenced by the type of ventilation systems, as presented by Ameen et al. [16] in their research at one of the Swedish universities (Gavi University) in terms of $CO_2$ content over a wide time range. The results showed that even a small number of people can cause the carbon dioxide content in these rooms to increase above 1000 ppm, which will negatively affect the assessment of their comfort. Similar studies [17, 18] also focused on the need to provide the occupants with high quality indoor air, considering the fact that proper and effective cooling is also a necessity [19]. Recently, Torriani et al. [20] focused on 24 classes during the winter period, analysing 1548 questionnaires, for all educational stages from primary school to university. It was noticed that the temperatures that are comfortable and preferred for the subjects will increase with a given educational stage. In addition, it turned out that the greatest differences between TSV and PMV were experienced during tests in elementary school. According to the authors analysing the results, they showed that the PMV is not accurate to the real thermal sensations felt by students. Moreover, the suggested correction of metabolism was not sufficient to improve PMV predictability. Lamberti et al. [21], while conducting research in the thermal chamber, noticed that additional aspects should be taken into account that may affect the performance of students. Additionally, the sick building syndrome symptoms can affect the human sensations during the infield measurements as studied by Krawczyk et al. [22]. Equally unpleasant to humans can be the noise pollution [23]. Moreover, issues related to energy consumption of buildings should be a priority nowadays [24, 25]. However, it is very difficult to provide people with adequate level of indoor environment comfort while keeping the energy needs to the minimum.

Studies of thermal comfort in smart buildings are very rare. Thus, this paper will provide new experimental data in this area. Moreover, the literature clearly confirms that the model of thermal comfort proposed by P.O. Fanger is not able to properly indicate the real thermal sensations of people in all rooms, which proves its defectiveness due to the fact that it is based on the algorithm that might be incorrect – at least to some extent. In order to provide a solution, a modified model will be developed, taking into account $CO_2$ and BMI indices, which were not considered in the original model.

## 2 Experimental set-up and testing method

The building, where the tests occurred, is located in Kielce on the campus of Kielce University of Technology. It is called "Energis" and it is a smart (intelligent) building. It is relatively new (completed in the year 2012). Its structure is simple, enclosed in a rectangle, and the windows face East and West. Due to the fact that it is a modern building, its main idea was to minimize energy and heat costs, and therefore it was equipped with a number of devices that obtain electricity and heat from renewable sources (photovoltaics, solar collectors, heat pumps and wind turbines) and managed by BMS, aimed mainly at controlling the consumption of this energy and its use for further needs (power supply for office equipment or lighting, etc.). In fact the use of heat pumps and advanced HVAC systems can be very beneficial in terms of energy consumption in the Polish climate conditions [26, 27]. To better illustrate the appearance and location of the building, Figure 1 is provided below.

Fig. 1: Photo of the smart building „Energis".

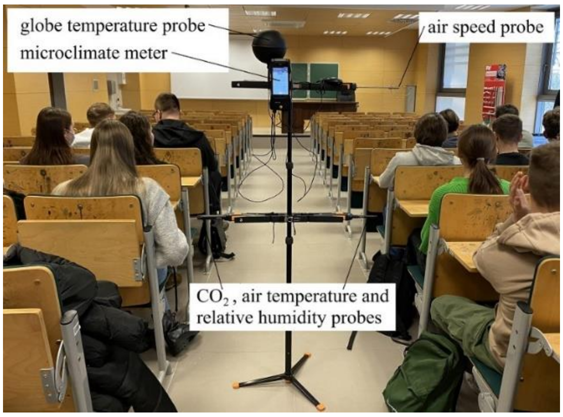


Fig. 2: Microclimate meter with the probes on the tripod in a lecture room.

The methodology of conducting this study was important throughout the experiment. Two methods were used: one based on the use of equipment to measure microclimate parameters, and the other focusing on thermal sensations, their acceptability and preferences (a questionnaire study). The meter acquires many useful parameters needed for further analysis, such as the temperature of the air and the radiant temperature, relative humidity or carbon dioxide level. The second method, on the other hand, uses anonymous surveys in which the surveyed person answers questions about feelings. Figure 2 shows the location of the meter and an example of the room where the test was conducted.

The microclimate meter used in the study was Testo 400 portable device with the probes. Two types of probes were applied: attached to the meter with wires (air speed and globe temperature probes) as well as wireless probes (carbon dioxide probe, combined air temperature and humidity probe). Details of the measuring accuracy of the applied system has been provided by one of the co-authors in her open-access paper [4]. The measurements in each room took about 25 minutes. It covered the preparation of the device and explanation of the testing procedure, however this time was also necessary for the participants to accommodate to thermal conditions within the given room.

A total of 12 tests were performed on different groups of students in various rooms. The temperature in the tested rooms ranged from 19.3 to 25.1$^{o}$C, relative humidity from 26.4 to 50.5%, carbon dioxide content from 471 to 1255 ppm. It should be noted that in the lecture halls the relative humidity was higher than 30% (except in room no 9 - the relative humidity for the lecture room was 26.40%) reaching the value of 50.5%. However, for smaller rooms these values were below 30%. Taking into account previous studies [28], the $CO_2$ content exceeds the value of 1000 ppm, as can be seen in six ordinary smaller halls, and in the current study only in one lecture hall with a value of 1255 ppm.

A total of 134 students participated in all 12 studies. Women accounted for 41.79% of the entire group, while men accounted for 58.21%, which was 3/5 of the group. The minimum age of students was 18 years and the maximum age was 41 years (this applies to part-time students), and the average age was 22.2 years (standard deviation 3.3 y.o.), the height of students ranged from 154 to 196 cm (average: 175.9 cm, standard deviation 10.3 cm). The clothing insulation value was from 0.44 to 2.66 clo (average: 0.73 clo, standard deviation: 0.19 clo) (in a similar study of the authors [28] the average value was 0.64 clo (from the range 0.31 to 1.15 clo). The weight of the students ranged from 42 to 115 kg (average: 72.2 kg, standard deviation 15.3 kg), while the lowest BMI was 15.41 kg/m$^2$ and the highest 36.26 kg/m$^2$, with the average of 23.12 kg/m$^2$ and standard deviation 3.46 kg/m$^2$). The respondents generally felt fine and well, only 2 people complained about a low intensity headache and some (four people) indicated that noise was a source of distraction.

For each test in each room, the meter was placed in the central part (as presented in Figure 2). The meter collected environmental parameters there. An example of the variability of selected parameters, i.e. air temperature, relative humidity and carbon dioxide concentration, was illustrated in

Figure 3. This variability resulted mainly from the density of people in the room (related to breathing and heat generation) and the surface area of the rooms. The results in Figure 3 come from a study that lasted over 20 minutes and the period in which the measurement was made fell at the end of November (autumn conditions in Poland). It indicates that the indoor environmental conditions in real rooms are not steady and for further analyses the values of the parameters at the moment of completing the questionnaires were considered.

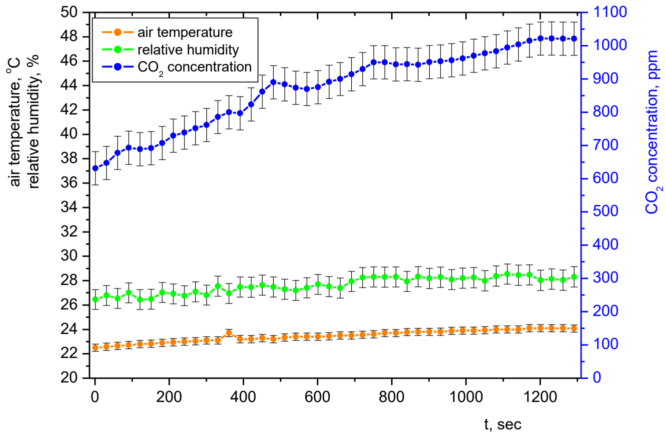


Fig. 3: Variability of selected parameters, i.e. relative humidity, air temperature and carbon dioxide together with the presented measurement error bars.

## 3 Results and discussion

The results of the parameters that were obtained during the measurements in all 12 rooms are summarized in Table 1.

Table 1: Internal environmental data regarding the tested rooms.

| No | Window orientation and room type | Air temperature [°C] | Relative humidity [%] | $CO_2$ level ppm | Air speed [m/s] | Number of people |
|---|---|---|---|---|---|---|
| 1 | W; lecture room | 19.4 | 46.9 | 728 | 0.11 | 10 |
| 2 | W; lecture room | 19.3 | 48.2 | 664 | 0.08 | 15 |
| 3 | W; lecture room | 20.0 | 50.5 | 995 | 0.07 | 13 |
| 4 | W; lecture room | 20.9 | 30.0 | 1255 | 0.05 | 13 |
| 5 | W; lecture room | 25.0 | 38.5 | 556 | 0.06 | 15 |
| 6 | E; lecture room | 23.0 | 34.5 | 471 | 0.05 | 10 |
| 7 | W; lecture room | 25.1 | 45.5 | 760 | 0.06 | 11 |
| 8 | W; lecture room | 21.9 | 43.3 | 950 | 0.03 | 18 |
| 9 | E; lecture room | 21.7 | 26.4 | 643 | 0.10 | 7 |
| 10 | W; classroom | 21.9 | 28.6 | 790 | 0.07 | 5 |
| 11 | W; classroom | 22.3 | 27.2 | 718 | 0.06 | 8 |
| 12 | W; classroom | 24.1 | 28.1 | 919 | 0.10 | 9 |

The most important question in the survey is the question relating to the actual thermal sensations (Thermal Sensation Vote – TSV) at the moment of the examination. More precisely, students can choose from a 7 – point scale those answers: "–3": too cold, "–2": too cool, "–1": pleasantly cool, "0":neutral, "+1":pleasantly warm, "+2":too warm, "+3": too hot. The value "0" indicates the comfort of the surveyed people, however, the values "–1" and "+1" (pleasantly cool and warm) can also be included in this positive range, because in people's minds they are also treated as positive feelings. Therefore, in general, all tests from the rooms were collected, and the results of thermal sensations are presented in Figure 4.

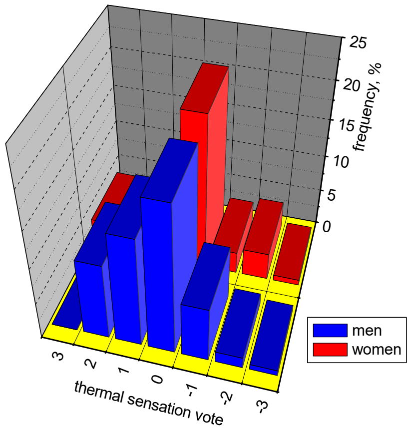


Fig. 4: Frequency count of thermal sensation votes assessed by the respondents in 12 rooms.

It turns out that a similar percentage range of men (20.15%) and women (20.90%) felt thermal comfort ("0"). Pleasantly cool and warm environment was also rated high with an overall rating of 34.34%. Nevertheless, it should be noted that as many as 14 men rated the thermal environment as too warm ("+2"). A total of 6.72% of people identified themselves as being too cool and too cold. Comparing to the authors' pervious research [28], men also marked the answer "+3" and the percentage together with women was 3.5%, while the "–3" environment was rated by only 1.8% of women. The dissatisfaction with the prevailing temperature during the research for men was 13% and for women about 12%, which is relatively low compared to [28]. However, it should be remembered that according to ISO 7730 [3] the dissatisfaction of the surveyed people spending time in the room should not exceed 10%. In previous studies [28] and those present in the same percentage range, approximately 75% of people considered the environment as comfortable (–1, 0, +1). Knowing the thermal impressions of the students, in the next step, they were asked about their preference for temperature (Thermal Preferences Vote – TPV), i.e. whether they would leave the temperature as it was, or whether they would like to increase or decrease it. In this question, students rated on a scale from "–2" to "+2", where "–2": definitely cooler, "–1": cooler, "0": no difference, "+1": warmer and "+2": definitely warmer. Based on their assessment, the results are summarized in Figure 5 below.

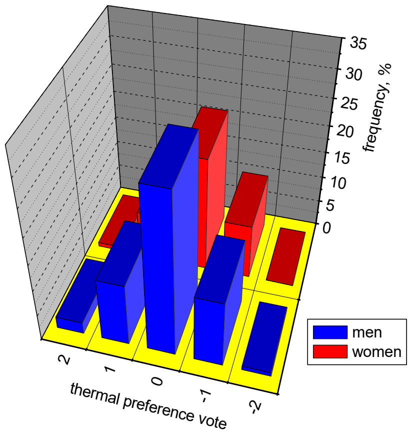


Fig. 5: Frequency count of respondents' assessment of their thermal preferences in 12 rooms.

Based on the results obtained and illustrated in Figures 4 and 5, a certain tendency can be noticed in which people who described their impressions of the temperature as cool indicated in this question that they would prefer it to be warmer or definitely warmer (+1 and +2) (Figure 5) in the overall assessment of the whole group it was 23.88%, while when they rated the temperature as warm or too warm/hot, in this question they chose that their preference was towards cooler temperatures, with an overall rating of 23.88% (while for previous studies [28] this value was about 39%). To sum up evenly 23.88% of people would like to change the temperature to warmer or cooler, while for the rest of the group marking the answer "0", no change would be needed.

The last question of the perception of temperature in the room concerns the acceptability of the temperature (Thermal Acceptability Vote – TAV) by the respondents. In this case, the range of answers concerned the temperature, which is according to the scale: "–2": definitely not acceptable, "–1": not acceptable, "+1": acceptable and "+2": comfortable. The respondents' answers are presented in Figure 6.

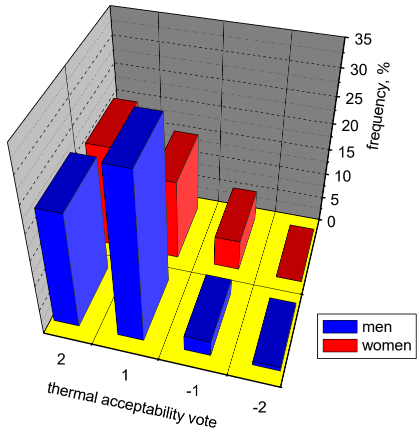


Fig. 6: Frequency count of respondents' assessment of their thermal acceptability in 12 rooms.

In total, 90.30% of people marked the answers "+1" (21 women and 43 men) and "+2" (27 women and 30 men), which proves high acceptability of the temperature in the tested rooms. More similar results were obtained in [28], where this acceptability was also about 90% for all. Such a high percentage may be due to the fact that the tests were carried out at different hours and times of the day, and those people who had already spent a long time studying in the classrooms acclimatized their bodies to the conditions in which they were currently staying. Not many, about 9.70% of people, decided that the conditions are unacceptable. Staying with acceptability, below in Figure 7, the average responses from each test regarding the acceptability of temperature for previous tests (blue) by the authors [28] and current tests (black) as well as the air temperature values in each room obtained as a result of measurements using a device for measuring the indoor microclimate are presented.

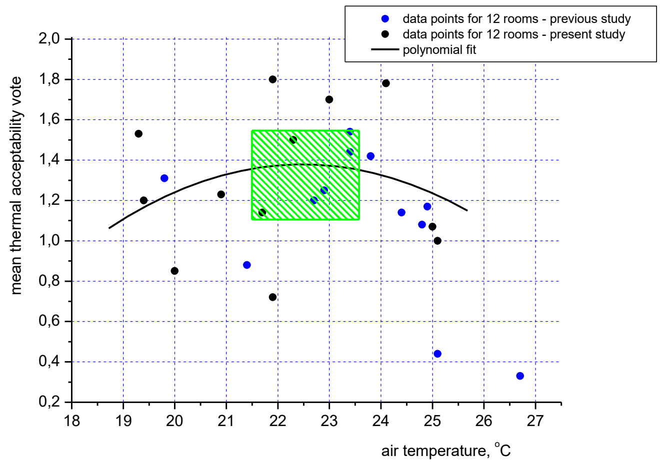


Fig. 7: Influence of temperature on the average thermal acceptability for the 24 tested rooms: present study – black colour, previous study [28] – blue colour.

The highest acceptability of air temperature of the studied groups is marked with the green box and ranges from 21.5°C to 23.5°C (this range has shifted by 0.5°C compared to the study [28]). However, its highest acceptability is at the peak point of T= 22.5°C. Temperatures that were lower or higher were less acceptable by the people. The $R^2$ value of the fitting function is very low (0.05), which might result from the low number of measuring points taken into account. Thus, no equation was provided.

Below, in Figure 8, the air temperature and the average rating of thermal sensations are compared.

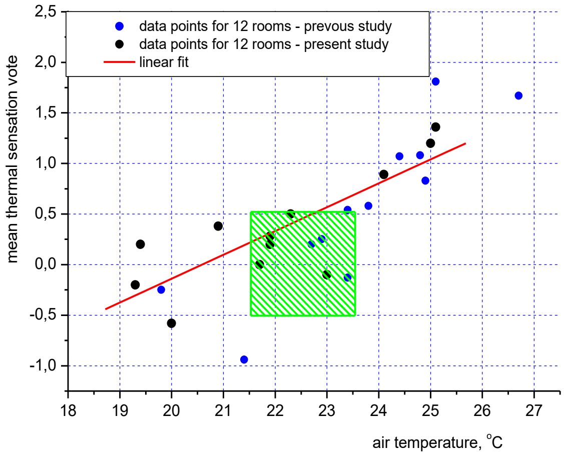


Fig. 8: Influence of temperature on thermal sensations for each tested room for 24 rooms: present study – black colour, previous study [28] – blue colour.

Based on ISO 7730 [3], the comfort range is –0.5 to +0.5. In the figure, the most favourable temperature range is 21.5 –23.5°C (marked as the green box). However, the temperature that had the highest acceptability in Figure 7 has no support for the value of 0, which ISO 7730 considers comfortable. However, it received the value of +0.5. This is a significant change compared to the previous study [28]. The matching formula for TSV is shown by the following equation:

$$TSV = 0.2357T - 4.8537 \quad (1)$$

The correlation resulting from this relationship is moderately strong and clearly visible ($R^2$ is 0.67). As the temperature moved higher, the thermal sensations go towards an overly warm or hot environment.

An important and conclusive question is the assessment of the respondents' well-being (GSV). This question is strongly related to the previously discussed thermal sensations. It can indicate how good or bad the people in the room felt. The scale from "–2" to "+2" was again used for this purpose, where "–2": very bad, "–1": bad, "0": normal, "+1": good and "+2": very good. Figure 9 presents the results obtained from students' answers broken down by gender.

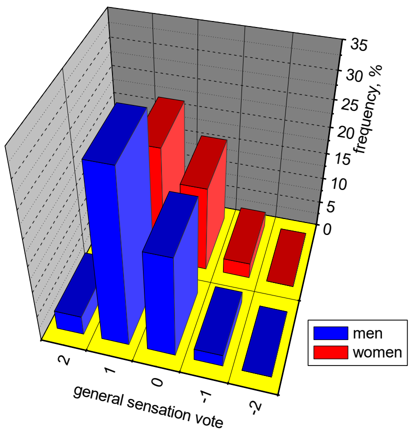


Fig. 9: Frequency count of respondents' assessment of their current well-being in 12 rooms.

As can be seen, in the overall assessment of well-being, "+1" and "+2" values for men combined were 36.57%. None of the women felt very bad or very good in the examined rooms. 30 of them felt good choosing "+1". Normal well-being was declared by 19.40% of men and 16.42% of women. Only 2.24% of men and 2.99% of women chose the answer "–1". This assessment may be influenced by the time spent in the rooms, the duration of classes and their number, but also by other health problems that may have occurred, as in the study [22].

It seems logical that well-being should be related to thermal factors in the rooms. If people are too cold or too warm, they should automatically feel bad, and if the conditions are favorable, higher values from “+1” to “+2” can be expected (feeling good and very good). Therefore, Figure 10 presents the average values of thermal sensations and average well-being responses along with the correlation.

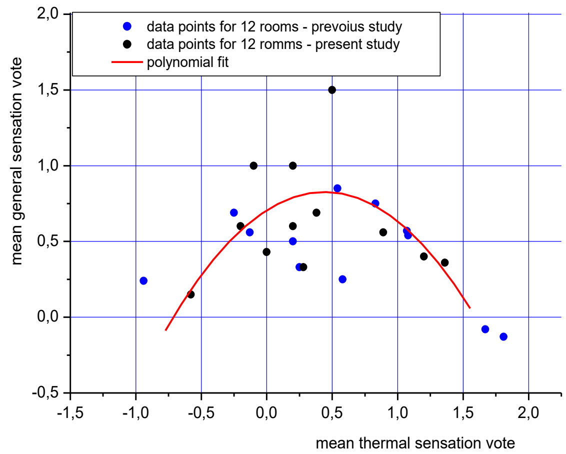


Fig. 10: Evaluation of thermal sensations in relation to well-being for 24 rooms: present study – black colour, previous study [28] – blue colour.

The highest satisfaction with general sensations of well-being occurs in the range of 0.25<TSV<0.75, with the peak point being TSV = 0.5. Comparing this to the study [28], this range has shifted by 0.25, because in the previous study this range was 0<TSV<0.5, where the peak point was TSV = 0.25. The range given above suggests that respondents prefer a warmer environment than a cooler one (similar to [28]). The parabolic fitting for GSV is shown by the following formula.

$$GSV = -0.6203TSV^2 + 0.5471TSV + 0.7063 \quad (2)$$

The relation is quite weak ($R^2$=0.33), however it provides valuable information. The respondents seem to prefer warmer environments (where TSV is about +0.5) in the present study, possibly due to the influence of other factors such as fitting the clothing level to the weather conditions.

In the last step, the two factors BMI and $CO_2$ were analyzed for average thermal sensations. The results are shown in Figure 11.

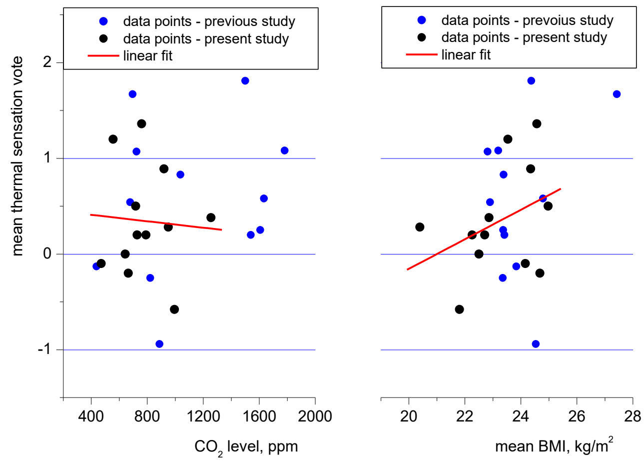


Fig. 11: The influence of $CO_2$ and BMI on thermal impressions for current (black) and previous (blue) tests: present study – black colour, previous study [28] – blue colour.

The first graph (on the left) shows the relationship between $CO_2$ content and average thermal sensations. The students generally found the environment to be comfortable or pleasantly warm in the present study. However, the fit indicates that the higher the $CO_2$ content, the thermal sensations will be directed towards a cooler environment. What's more, in studies [28], the average of thermal sensations increased with the increase in $CO_2$, i.e. the higher the $CO_2$ value, the warmer people felt. It is also interesting that in other studies there is no such dispersion in thermal sensations as in the case of the previous study.

The second graph (on the right) shows the dependence of the influence of BMI on thermal sensations. It turns out that the higher the BMI, the warmer people feel, which is in line with the authors' works [4, 5, 28].

The presented above experimental results form a basis for the modification of the model that will include the carbon dioxide level and the BMI index. To create a new formula, the COL designation for carbon dioxide content was used as in [28]. The expression that has been added to the Fanger's formula is $1.89 \cdot 10^{-8} \cdot COL \cdot BMI^{2.99}$. The modified model equation for PMV (based on [3]) is presented below:

$$PMV = 1.89 \cdot 10^{-8} \cdot COL \cdot BMI^{2.99} [0.303\exp(0.036M) + 0.028] \cdot \begin{Bmatrix} (M-W) - 3.05 \cdot 10^{-3}[5733 - 6.99(M-W) - p_a] - 0.42[(M-W) - 58.15] - 1.7 \cdot 10^{-5} M(5867 - p_a) + \\ -0.0014M(34 - t_a) - 3.96 \cdot 10^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} h_c (t_{cl} - t_a) \end{Bmatrix} \quad (3)$$

where each of these parameters means [3]:
$f_{cl}$ – factor of the clothing area,
$hc$ – convection heat transfer coefficient,
$M$ – metabolism rate,
$p_a$ – partial pressure of water,
$T_a$ – air temperature,
$T_{cl}$ – surface temperature of clothing,
$T_r$ – average radiation temperature,
$W$ – mechanical power.

The original model was modified on the basis of the above formula. Figure 12 presents the results obtained for the original formula [2, 3] (black squares) and the results obtained from the above modification (orange stars). The X-axis presents the thermal impressions of people, which were calculated on the basis of student surveys expressed in the questionnaires, while the Y-axis presents the calculated PMV values. The green line represents the ideal agreement between PMV and TSV (namely, the model provides perfect determination of thermal sensations).

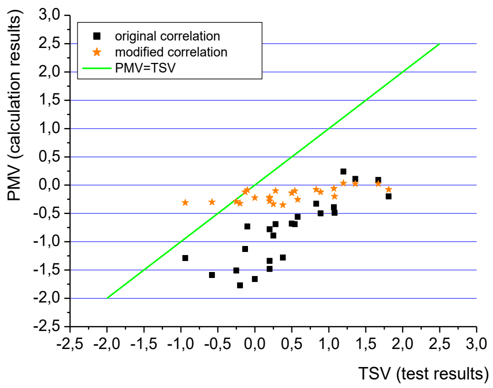


Fig. 12: Comparison of the test results obtained according to the original model [2, 3] and the modified model.

The model that has been presented in the current research much better reflects the thermal sensations of people than in the case of the original model. Almost all of the tested examples "moved closer" to the match line between PMV = TSV. The algorithm of the Fanger model did not generate the results that matched data obtained in real life measurements, which is clearly demonstrated in Figure 12 (large distance of the experimental points from the green line of the ideal agreement between the model and the experiment), however, this and possible future modifications of this model could help with better description of the thermal sensations of room users possibly using other calculation algorithms based on various mathematical and experimental concepts [29 - 35].

The mean difference between the experimental results and those calculated with the modified model turned out to be smaller than that calculated with the original model. However, it needs to be noted that the modified model seems to follow a different trend than the original one and the ideal match (PMV=TSV) line. Thus, despite better performance, it might require additional modifications so that it could be more useful for the wide range of parameters' variations (it seems to be especially important to determine how the modified model could perform with high carbon dioxide levels).

Despite the fact that the $CO_2$ level was included in the modified model, it needs to be stated that the concentration of this gas during the measurements was not particularly high. According to Borowski et al. [36] carbon dioxide concentration below 800 ppm means that the air quality is "very good", below 1000 ppm "good", while the range 1000-1400 ppm indicates "moderate" air quality (it is in agreement with the IDA categories of air quality, where very good conditions are described as IDA1, medium as IDA2 and moderate as IDA3 [37, 38]). In the present study only in 1 room out of 12, the $CO_2$ level exceeded 1000 ppm, thus the overall indoor conditions could be considered satisfactory.

## 3 Conclusion

The tests were performed in twelve rooms of the smart building under its normal usage. 75.37% of people considered that the environment was either comfortable, pleasantly warm or cool. The level of acceptance of the temperature was high and amounted to about 90%, while about 44% of the respondents related their preference to either a warmer or cooler environment. At the same time about half of the people surveyed felt that a change in temperature was not necessary. The optimal temperature range was found to be from 21.5$^{o}$C to 23.5$^{o}$C (with the peak at 22.5$^{o}$C).

A modified thermal comfort model was created (taking into account the $CO_2$ level and BMI index). It proved to be more accurate than the original one, at least for the experimental data collected in the smart building.

**Acknowledgement**

The work in the paper was supported by the project: "REFRESH – Research Excellence For REgion Sustainability and High-tech Industries, (VP2), (Reg. No.: CZ.10.03.01/00/22_003/0000048) co-funded by the European Union".

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