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Thermal Comfort Analysis in the Smart Sustainable Building with Correlation Development

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Abstract. The paper presents the results of the experimental study of thermal comfort in the smart building of Kielce University of Technology (Poland). The experiments were conducted throughout four seasons of the year and focused on developing a modified thermal comfort correlation that could determine the thermal sensations of room users more accurately than the standard methodology. Twelve groups of volunteers participated in the study, and thermal sensations were analysed for both genders separately. Even though the thermal environment was not considered overwhelmingly favourable (with 75% of men and 60% of women providing positive assessment), thermal acceptability was high. It amounted to 90% (the same for both genders). The air temperature of 22°C proved to be most preferable. The BMI index and CO_2 concentration were found to influence thermal sensations and were incorporated into a modified correlation, which provided more accurate results than the original Fanger model of thermal comfort.

Keywords: indoor environment, thermal comfort model, thermal sensations

1. Introduction

In urbanised areas, a typical person spends most of their time in closed spaces. Therefore, more and more attention should be paid to the optimal internal environment conditions. At the same time, smart buildings are being developed to provide an appropriate microclimate and thermal comfort. The parameters related to heat generation, energy consumption and lighting in the building are controlled using the Building Management System (BMS), the primary indicator of sustainable construction. Thermal comfort determines if people are comfortable under given thermal environment conditions (e.g. if they feel neither hot nor cold). This sensation is influenced by many variable parameters, including, among others: air temperature, air humidity, thermal insulation of clothing, current physical activity, etc. O. Fanger proposed a mathematical description of these phenomena in the 1970s, and it is still the basis for the international standard (ISO 7730 2005). According to the use of his research as well as results from the literature, Fanger (Fanger 1974) developed a method based on two indices: PMV – Predicted Mean Vote and PPD – Predicted Percentage of Dissatisfied. The thermal sensation is defined as a function of the mean ambient radiant temperature, physical activity level, air temperature, clothing insulation properties, airflow velocity and water vapour partial pressure. PMV is expressed as a value in a seven-point scale, where "-3" means "too cold", while "+3" means "too hot", and "0" is the most favourable and neutral state. The value of this parameter (calculated according to a complex methodology) should equal the average thermal sensation of a group of people located in a particular room when each person expresses their subjective sensations on the scale from "-3" to "+3" (as described above). However, it has turned out not to be entirely true in many cases. In (Becker & Paciuk 2009), a study of 189 apartments in winter and 205 in summer was described. The authors found that the experimental results differed from the calculated PMV values.

Moreover, the study showed that the fundamental assumption of the model – of the proportional relation between thermal response and load – was incorrect (because, in reality, thermal comfort was achieved at much lower loads than predicted). Moreover, the second assumption of the model (related to the issue that the symmetrical responses both in the positive and negative regions of the scale represent similar comfort levels) was also challenged. A field study in Tokyo office buildings conducted during the summer on over four hundred people (Indraganti et al. 2013) revealed that the PMV values largely overestimated the actual sensations of the participants because of an extensive range of adaptations by the room users. The tests also showed that the comfort temperature was 27.2°C, while thermal acceptability amounted to 89% (with 50% of the environments experiencing indoor air temperature above 28°C). Similarly, the research in 25 climate-controlled buildings (Broday et al. 2019) proved that the PMV values did not reflect the real feelings of the respondents. The authors modified the thermal comfort model and produced two alternative equations, of which the one based on the concept of multiple linear regression proved to be more accurate. The sensitivity analysis (Dyvia & Arif 2021) showed that the values of metabolic rate and clothing thermal resistance significantly impact thermal comfort in such a sense that at low metabolic rates, the PMV index seemed to be very sensitive to the mean radiant temperature. While at higher metabolic rates, thermal comfort sensitivity to metabolic rate became so intense that other parameters had a less significant effect. The analysis of thermal comfort sensations conducted in Brazil aimed at determining the accuracy of the Fanger model (Niza & Broday 2022) revealed that the PMV model did not correctly represent the thermal reality of the tested environments.

Similarly, a lack of unity was also indicated in an earlier study (Manu et al. 2016). The authors claimed that the Fanger model overpredicted thermal sensations into the warmer side of the scale. Due to the shortcomings of the Fanger model, a recent study (Laouadi 2022) presented a new and more general formulation of the PMV index, which does not involve the need to consider the mean skin temperature and evaporative heat loss. The new model was based on the research results of a broad spectrum of age groups. It also incorporates non-shivering thermogenesis in the human body.

It needs to be stated that thermal comfort is highly subjective, but it also depends on the climate – the same indoor air parameters can evoke different sensations in people from other parts of the world. In Poland, studies of the indoor environment are occasionally conducted, e.g.: (Amanowicz & Wojtkowiak 2021, Dudkiewicz & Jeżowiecki 2009, Maliszewska et al. 2019, Wojtkowiak et al. 2019), mainly with the view of determining the most efficient heating, ventilation or air conditioning strategy. Undoubtedly, ventilation air filtering processes (Dąbek et al. 2012, Kuśmierek et al. 2014) and proper heat transfer characteristics (Koshlak & Pavlenko 2019, Pafcuga et al. 2021, Pavlenko 2019, Pavlenko & Koshlak 2021) can also influence thermal sensations of room users as well as the SBS symptoms – as considered by the authors of the present study (Krawczyk et al. 2023).

Although studies of thermal comfort and the applicability of the Fanger model can be found in the literature, many problems remain to be addressed in this area. Namely, many authors challenge this model and consider it to be inaccurate. The model was designed half a century ago and was based on the test results available then. At the same time, the buildings and human expectations regarding indoor environment have changed over fifty years. The present paper aims to develop a modified correlation of thermal comfort based on analysing this phenomenon throughout all four seasons and considering the impact of the BMI index and CO_2 concentration. Both of these parameters are not present in the original thermal comfort model.

2. Experimental Set-up and Testing Method

In the experiments, two methods of data acquisition were used, namely anonymous questionnaires completed by the volunteers and measurements of the physical parameters within the rooms (globe and air temperature, relative humidity, air speed, and CO_2 concentration). The study covered the analysis of the questions related to thermal sensations, acceptability and preference, while the mathematical modelling of the thermal comfort phenomenon was based on the Fanger model. Figure 1 presents how the microclimate meter was situated in the rooms. It also shows the location of the probes and the meter on the tripod.

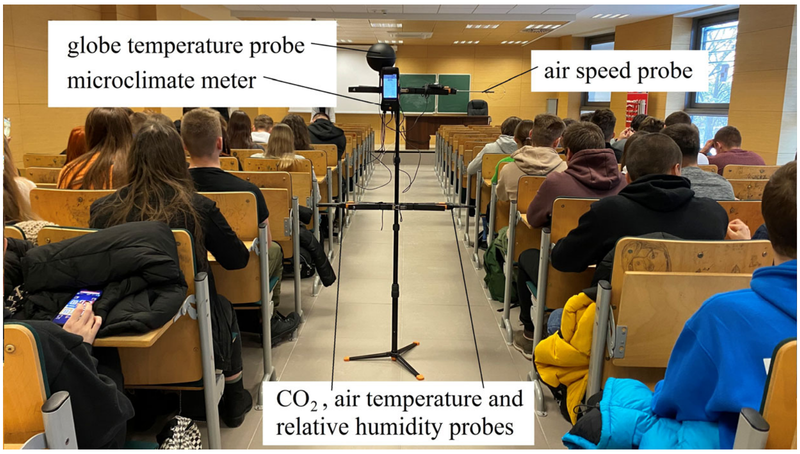

Fig. 1. Microclimate meter with probes on the tripod in a lecture room

The tests were performed with the Testo 400 microclimate meter (manufacturer: Testo AG) and five probes (connected to the meter with a cable or Bluetooth). Table 1 presents the technical details of the device regarding the measuring accuracy under the testing conditions of the present research and the connection type of the probes used in the experiments.

Table 1. Details of the Testo 400 microclimate meter with the probes, according to the manufacturer's data [Testo 2023]

No	Parameter	Measuring accuracy	Connection type
1	Air temperature	+/-0.3°C	Bluetooth
2	Relative humidity	+/-0.6%+0.7% of the value	Bluetooth
3	Globe temperature	+/-1.5°C	Cable
4	CO$_2$ level	+/-50ppm+3% of the value	Bluetooth
5	Air velocity	+/-0.03 m/s+4% of the value	Bluetooth
6	Illumination	6%	Cable
7	Ambient pressure	+/-3hPa	Built-in

The tests were conducted in twelve rooms equipped with a mechanical ventilation system with cooling. The HVAC system is controlled by BMS (Building Management System) and manually with control panels in each room. Room users can set the temperature and lighting conditions. Cooling is provided with the chilled water system. On the other hand, heating is made possible with traditional radiators, floor heating, and air heating. The air supply is done with the 4-duct cassettes and swirl diffusers, while air removal is conducted with swirl exhausts located in the suspended ceiling. The windows can be opened; thus, they provide fresh air if needed.

No columns or other objects within the rooms can cause problems with the arrangement of air movement. The mixing of air is relatively uniform. Solar radiation through windows is the only source of possible issues influencing peoples' thermal perception. Table 2 presents the geometrical details of the rooms together with the windows' data. The meter was located in the centre of the area where the respondents were seated (they usually occupied the back seats of the rooms, as seen in Figure 1). The meter was situated on the tripod at the height of the seated people. Consequently, it was usually not located in the geometrical centre of the room.

Since the windows faced East and West, solar radiation was not typically a significant problem during the experiments, especially since the windows are equipped with blinds that can be used and adjusted manually to block intense solar radiation, if needed. During the tests, the blinds covered up to 42% of the windows' surface area. Moreover, the rooms are large enough, so the students typically choose seats in the shade. Thus, solar radiation might not have influenced the obtained results of thermal comfort measurement in the present study.

In the tests, twelve different groups of volunteers participated. They occupied eight rooms (some were used more than once). The details of the rooms and the recorded indoor air parameters (at the moment of completing the questionnaires) have been presented in Table 3.

Table 2. Details of the rooms where the tests took place

No	Floor area, m^2	Cubature, m^3	Windows' surface area/ window orientation	Direct sunlight during the test	Percentage of window area covered with blinds during the test
1	145.8	422.8	20.1 m^2; W	no	20%
2	62.4	180.9	8.6 m^2; W	no	5%
3	47.2	136.9	6.4 m^2; W	no	0%
4	47.2	136.9	6.4 m^2; W	yes	25%
5	91.6	265.7	14.8 m^2; E	yes	35%
6	62.4	180.9	8.6 m^2; W	no	3%
7	47.2	136.9	6.4 m^2; W	no	0%
8	47.2	136.9	6.4 m^2; W	no	5%
9	91.6	265.7	14.8 m^2; E	yes	42%
10	458.2	1466.4	46.8 m^2; W	yes	30%
11	91.6	265.7	14.8 m^2; E	yes	15%
12	145.8	422.8	20.1 m^2; W	no	14%

Table 3. Details of the room types and the measured indoor air parameters

No	Room type	Air temperature °C	Relative humidity, %	CO_2 concentration, ppm	Air speed, m/s	Illumination lux	Number of people
1	lecture room	21.4	28.4	888	0.09	226	17
2	classroom	22.7	32.2	1540	0.08	148	10
3	classroom	24.8	30.5	1781	0.07	237	13
4	classroom	23.8	30.7	1633	0.10	33	12
5	lecture room	23.4	49.4	678	0.06	417	13
6	classroom	22.9	48.6	1607	0.06	337	12
7	classroom	24.9	33.0	1037	0.05	268	12
8	classroom	25.1	29.7	1500	0.09	278	16
9	lecture room	24.4	29.1	724	0.10	375	14
10	lecture room	23.4	49.7	438	0.08	120	16
11	lecture room	26.7	47.1	695	0.09	105	12
12	lecture room	19.8	46.3	822	0.08	313	16

In total, 163 people (57 women and 106 men) took part in the study, which occurred in all four seasons of the year, to provide a thorough insight into the subjective assessment of the thermal environment by the room users. The age of the volunteers ranged from 19 to 32 y.o. (the average: 22.1 y.o.), their height from 155 to 196 cm (the average: 176.2 cm), their weight from 45 to 115 kg (the average: 74.9 kg), while the BMI index from 17.31 to 33.95 kg/m^2 (the average: 23.94 kg/m^2). The thermal resistance of clothing that the volunteers had on them during the study ranged from 0.31 to 1.15 clo (the average: 0.64 clo).

3. Results and Discussion

High precision microclimate meter was placed within each room and determined the physical parameters of the indoor environment. The details of the parameters recorded when completing the questionnaires are presented in Table 1. However, it must be noted that they changed during the occupation of the rooms (due to breathing, heat transfer, etc.). Figure 2 presents an example variation of carbon dioxide level, air temperature and relative humidity (with error bars of each measurement) in the space of over 20 minutes from the beginning of the lecture. In this case, the carbon dioxide concentration and relative humidity increased due to breathing, while air temperature decreased – probably due to reduced heating and less intense solar irradiation through the windows. These measurements occurred in spring (at the beginning of April).

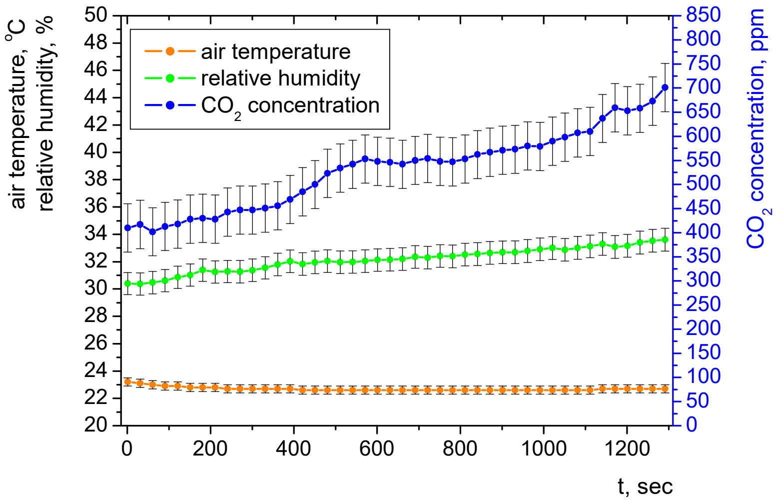

Fig. 2. Variations of air temperature, relative humidity, and CO_2 concentration with error bars (recorded in spring conditions)

The most crucial question in the questionnaire related to the actual feelings of the respondents considered their thermal sensations. They could choose from the answers on the scale from "-3" to "+3", where "0" is the neutral state of comfort when people are neither cold nor hot, while "-1" and "+1" refer to a favourable state of "pleasantly cool" and "pleasantly warm", respectively. The answers "-2", "-3", "+2", and "+3" describe the negative feelings of "cold" and "too cold" as well as "hot" and "too hot", respectively. The results have been presented in Figure 3, separately for women and men.

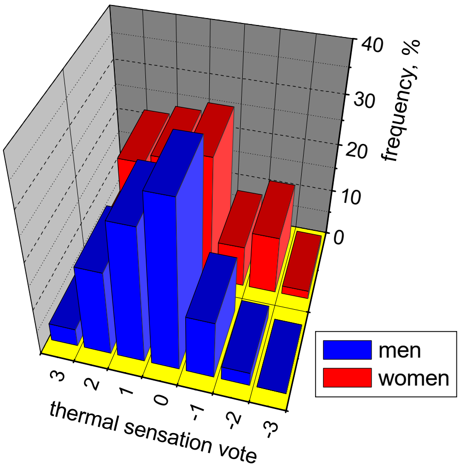

Fig. 3. Thermal sensation vote of the respondents throughout all four seasons

As can be seen, men were typically more pleased with the thermal environment. The share of their positive answers regarding the microclimate (the total share of the answers "-1", "0", and "+1") amounted to 75%, while in the case of women, it was 60%. Slightly over 3.5% of both men and women considered the environment as "too hot" ("+3"), but no men marked the answer "-3", while 1.8% of women did it. This fact, together with a larger number of dissatisfied women (40%) than men (25%), seems to prove that women are more sensitive to their thermal environment. The study also shows that generally, the respondents were not satisfied with the thermal conditions in the smart building because the number of dissatisfied is beyond the limit of 10% set out in the international standard (ISO 7730 2005).

The second question in the questionnaire was designed to collect information about a possible preference of a respondent to either maintain the current thermal conditions in the room (which would require marking "0" in the questionnaire) or change the temperature. If a person would like a reduction in the temperature, they would choose the answer "-1" for a small change or "-2" for a significant change. The same applies to a willingness to increase the air temperature (answers "+1" and "+2". Figure 2 presents the percentage share of the answers regarding the thermal preference of the room users.

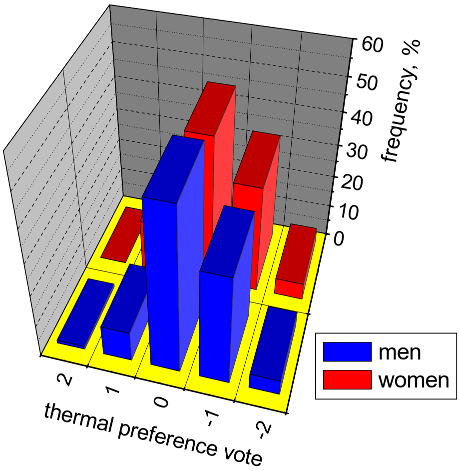

Fig. 4. Thermal preference vote of the respondents throughout all four seasons

Data in Figure 3 indicates that many respondents assessed their thermal environment as "warm" or "hot". Thus, many people would like to see a reduction in the air temperature. This phenomenon reveals itself in Figure 4. Here, the total share of the answers in favour of reducing the temperature ("-1" and "-2") amounted to 39%. This number is the same for both men and women, despite apparent differences observed in Figure 3. Only about half of the respondents opted for no change in the thermal environment of the smart building (indicating satisfaction with the indoor environment). It further backs the claim that the thermal conditions in the smart building thought the year might not have been proper for the overwhelming majority of the volunteers participating in the study. Naturally, it could have been caused by individual preferences, health conditions, past activity level or other factors.

The respondents were also asked a separate question if they accepted their current thermal environment and chose from the following answers in the questionnaire: "-2": certainly unacceptable, "-1" unacceptable, "+1" acceptable and "+2" comfortable. The results of the survey are shown in Figure 5.

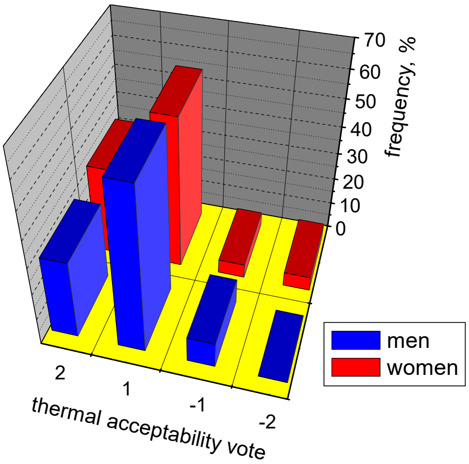

Fig. 5. Thermal acceptability vote of the respondents throughout all four seasons

Despite the test results presented in Figures 3 and 4 (which indicated widespread dissatisfaction), the respondents' thermal acceptability was high (Figure 5). The total share of the favourable answers "+1" and "+2" amounted to 90%. It was the same for both genders. However, a study in India (Indraganti et al. 2015) observed significantly higher acceptability of women than men. That large 90% acceptability might be explained by the fact that the volunteers had studied in the building long enough to get used to the conditions and must have learnt to accept them. However, thermal acceptability is also influenced by air temperature in rooms. Figure 6 presents a possible correlation between the mean value of the acceptability vote calculated for each of the twelve rooms where the tests took place – based on the answers provided in the questionnaires and the air temperature recorded with the microclimate meter at the moment of completing the questionnaires.

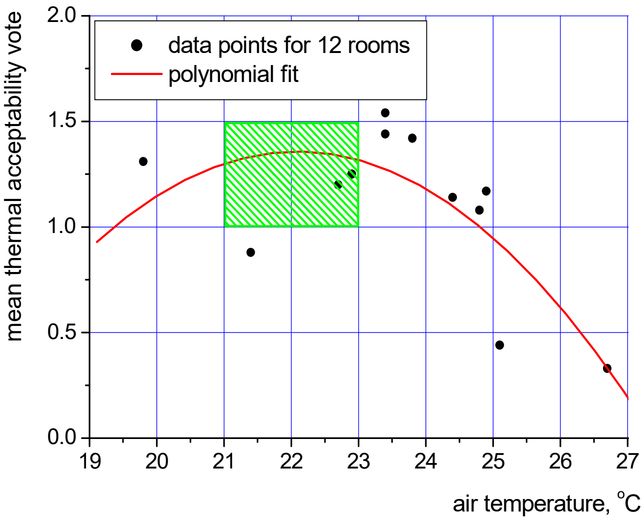

Fig. 6. Mean thermal acceptability vote vs air temperature – data for 12 rooms

The polynomial fitting function in Figure 6 takes the following form:

$$\mathrm{TAV} = -\,0.0482\mathrm{T}^2 + 2.1289\mathrm{T} - 22.1525 \qquad (1)$$

where TAV is the mean thermal acceptability vote of a group of people and T is the air temperature. The value of the coefficient of determination R^2 is 0.56. The respondents' acceptability seems to peak at the indoor air temperature of 22°C and would be considered highest in the 21-23°C range, as indicated by the green box on the graph. Lower and higher temperature values led to reduced acceptability levels of the respondents. Despite the relatively low value of the coefficient of determination, the most preferable air temperature that ensures the highest thermal acceptability seems to be 22°C. If this claim is valid, a correlation between the thermal sensation vote and air temperature would indicate that the value of "0" for the thermal sensation vote (which is the most favourable condition) will occur for the air temperature of ca. 22°C. It has turned out to be true – as presented in Figure 7.

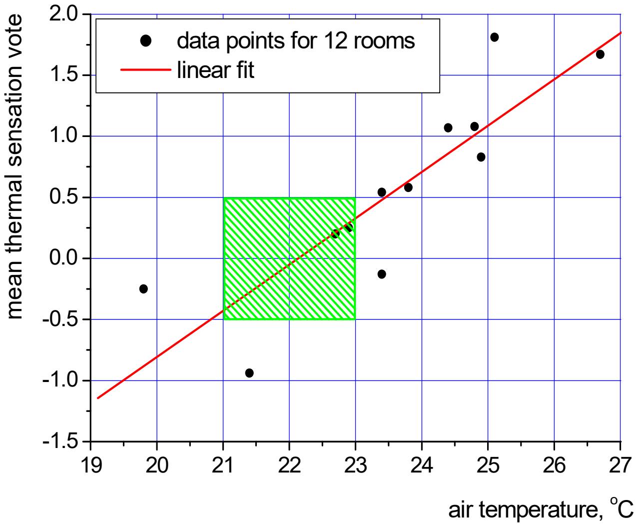

Fig. 7. Mean thermal sensation vote vs air temperature – data for 12 rooms

The most favourable thermal conditions occurred in the same temperature range as mentioned earlier, namely: 21-23°C. For these values, the mean thermal sensation vote equalled 0±0.5, which is the comfort area according to (ISO 7730 2005), while "0" occurred for the temperature value of slightly over 22°C. According to (Indraganti et al. 2015), the comfort temperature value might differ due to gender, age and BMI. However, these differences are not of much engineering significance.

The obtained linear fit equation for data presented in Figure 7 for mean thermal sensation vote (TSV) takes the following form:

$$\mathrm{TSV} = 0.3789\mathrm{T} - 8.3854 \qquad (2)$$

In this case, the coefficient of determination R^2 is relatively high considering the number of parameters that might affect the thermal sensations in rooms (of objective and subjective nature) and equals 0.74. This proves that the above correlation is relatively strong.

Apart from the thermal environment, many other factors can influence the sensation of human well-being in buildings. In the present study, the respondents also assessed their general feelings associated with occupying the rooms where the tests took place. They expressed their opinion about their general sensations in the form of the following marks in the questionnaire: very well ("+2"), well ("+1), neutral ("0"), bad ("-1") and very bad ("-2"). Figure 8 presents the test results separately for women and men.

As shown in Figure 8, the respondents generally felt well or neutral in the considered smart building throughout all four seasons. The total share of the positive answers ("+1") and ("+2") amounted to 39% in the case of women and 57% in the case of men. The volunteers provided no very negative answers ("-2"). However, there were some ("-1") responses – mostly from women (17.5%), which further supports the claim that the analysed "Energis" building failed to provide overwhelmingly positive sensations to the respondents in the present study.

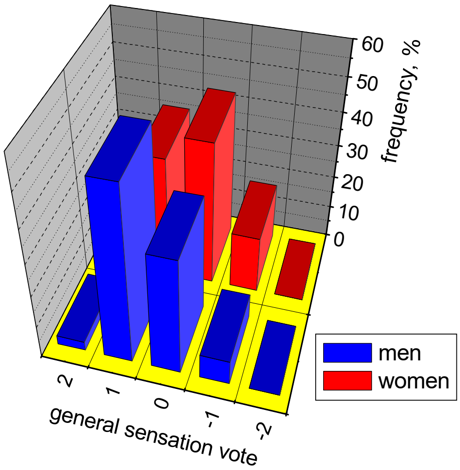

Fig. 8. General sensation vote of the respondents throughout all four seasons

The general well-being of the people might be linked with their subjective thermal assessment of the room in which they are situated. If someone considers their thermal state satisfactory, it would also mean that they would be more generally pleased. A relation between thermal sensation and general sensation votes has been considered and presented in Figure 9 to verify this claim.

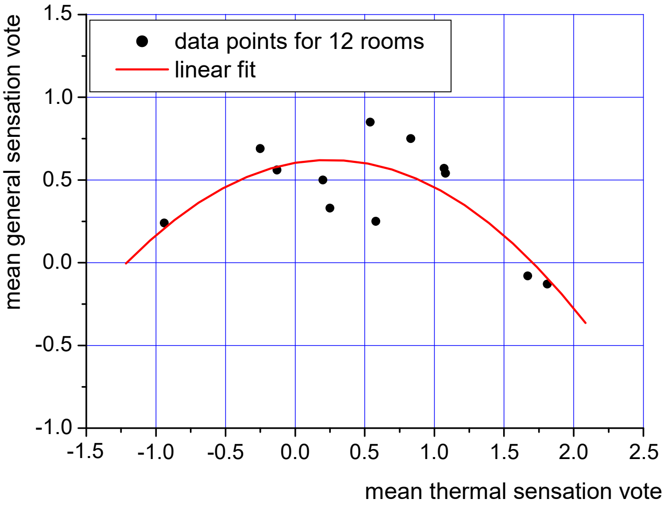

Fig. 9. Mean general sensation vote vs mean thermal sensation vote – data for 12 rooms

Based on the polynomial fit function, the highest general sensation votes occur in the $0 < TSV < 0.5$ range, with the peak at TSV = 0.25. This range of thermal sensation vote can be considered optimal and indicates that the people tended to favour slightly warmer environments relatively than slightly cooler (with TSV below zero). The generated polynomial fit takes the following form for general sensation vote (GSV):

$$GSV = -0.2921TSV^2 + 0.1452TSV + 0.6032 \tag{3}$$

The coefficient of determination equals 0.62, indicating a relatively high correlation level. The well-being of room users can be largely dependent on their thermal sensations. Thus, it might be quite important to provide a proper thermal indoor environment so that the residents would achieve and maintain a high level of well-being.

Since thermal sensation is a crucial element in indoor environment studies, it might be necessary to investigate the interconnection between it and two factors that could influence thermal sensation vote to a larger or smaller extent, namely the BMI (body mass index) of people in the room and carbon dioxide concentration there. Figure 10 presents the relations between thermal sensation votes and mean values of BMI of the groups of volunteers occupying the rooms and the CO_2 levels recorded there.

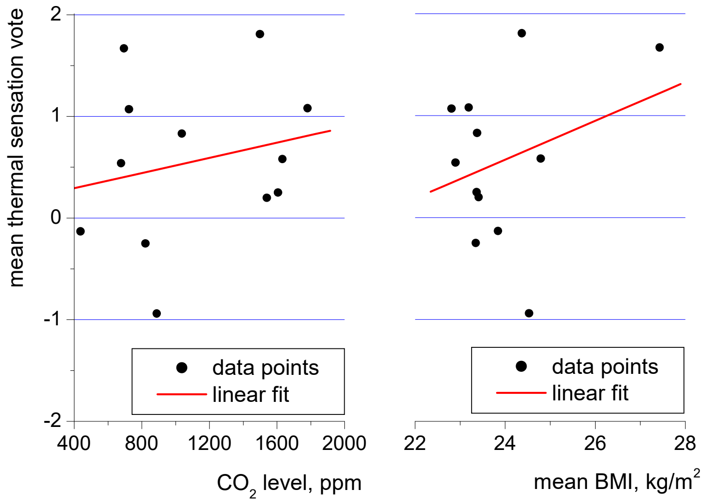

Fig. 10. Thermal sensation vote vs CO_2 concentration in the rooms and mean BMI of the groups

The test results reveal that as the carbon dioxide concentration rose, the respondents considered the indoor environment warmer (the mean thermal sensation vote calculated based on the questionnaires in a given room increased). The same phenomenon can be observed regarding the mean BMI value of people in the rooms. An increase in the mean BMI led to higher thermal sensation votes. The following linear fit equations were obtained considering the influence of the CO_2 level – denoted as (COL) and the BMI index (BMI):

$$TSV = 0.0004COL + 0.1433 \tag{4}$$

$$TSV = 0.1906BMI - 4.0056 \tag{5}$$

The above graphs might indicate the possible influence of these parameters on subjective thermal sensations experienced by the room users. It needs to be noted that the commonly used Fanger model of thermal comfort does not consider the parameters mentioned above in the calculation methodology. Because this model is often challenged, a modified correlation has been developed based on the equations in (ISO 7730 2005), incorporating the two parameters discussed above (CO_2 level and the BMI index) into this calculation methodology.

In the modified correlation, a term $1.6 \cdot 10^{-8} \cdot COL \cdot BMI^3$ (obtained through mathematical best-fitting calculations) has been added to the original equation adopted from (ISO 7730 2005), and the following formula has been proposed for the predicted thermal sensation vote ('predicted mean vote' PMV):

$$\mathrm{PMV}=1.6\cdot 10^{-8}\,\mathrm{COL}\cdot \mathrm{BMI}^{3}\left[0.303\exp(-0.036\mathrm{M})+0.028\right]\begin{Bmatrix}(\mathrm{M}-\mathrm{W})-3.05\cdot 10^{-3}\left[5733-6.99(\mathrm{M}-\mathrm{W})-\mathrm{p_a}\right]+\\ -0.42\left[(\mathrm{M}-\mathrm{W})-58.15\right]-1.7\cdot 10^{-5}\mathrm{M}(5867-\mathrm{p_a})+\\ -0.0014\mathrm{M}(34-\mathrm{t_a})+\\ -3.96\cdot 10^{-8}\mathrm{f_{cl}}\left[(\mathrm{t_{cl}}+273)^{4}-(\mathrm{t_r}+273)^{4}\right]+\\ -\mathrm{f_{cl}}\mathrm{h_c}(\mathrm{t_{cl}}-\mathrm{t_a})\end{Bmatrix} \tag{6}$$

where the parameters in this equation are as follows (ISO 7730 2005):
f_{cl} – factor of the clothing area, -
h_c – convection heat transfer coefficient, W/(m^{2}K)
M – rate of metabolism, W/m^2
p_a – partial pressure of water, Pa
T_a – air temperature, °C
T_{cl} – surface temperature of clothing, °C
T_r – average radiation temperature, °C
W – mechanical power, W/m^2.

The accuracy of the original and modified correlations has been assessed graphically in Figure 11. It shows the experimental results (x-axis) vs the calculation results using the original Fanger model (denoted as black stars on the graph) and the modified equation (6), represented by red squares. The green line shows the perfect match between the model and the experiment. Ideally, all the data points should be located on this line, and the closeness to it refers to how the calculation results reflect the actual test results.

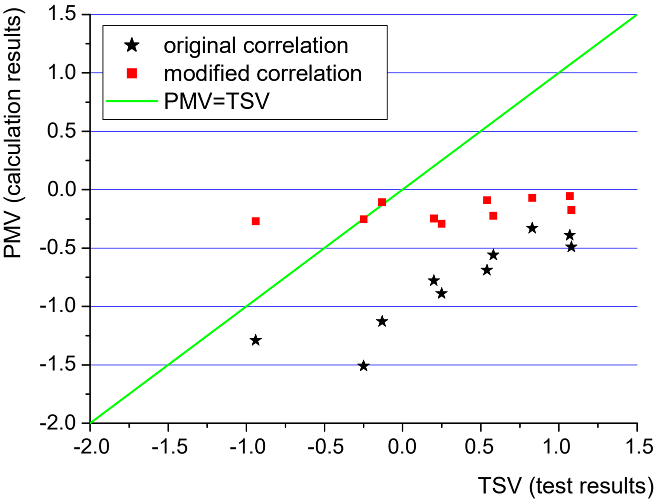

Fig. 11. Comparison of the calculation results according to the original and modified correlations and the experimental data

As can be seen, the original model could not precisely predict the respondents' thermal sensations. The congruence might be considered adequate only in one case (when TSV was slightly above -1.0). The modified correlation provided more accurate results. Two data points are located precisely on the green line, indicating perfect conformity and almost all the others are closer than in the case of the original correlation.

Developing an even more precise thermal comfort model might require obtaining more insight into the physical mechanisms of heat exchange between a person and the surroundings. Moreover, lighting conditions in the rooms as well as the past activity level (namely, the type of activity occurring earlier than 30 minutes before entering the room where the tests take place – for example, running, lifting heavy objects) can potentially influence the subjective thermal sensations of the people. Incorporating these factors into the model could further improve its accuracy, which can be the subject of future works.

3. Summary and Conclusions

Thermal comfort analysis conducted at the smart building "Energis" enabled data collection on the subjective thermal assessment of the indoor environment during all four seasons of the year. Based on the experimental study, the following can be stated:

- the thermal environment was not considered overwhelmingly favourable, with 75% of men and only 60% of women providing positive assessments;
- about half of the respondents opted for no change in the thermal environment, while 39% wanted indoor air temperature reduction;
- thermal acceptability was high and amounted to 90% (the same value for both genders); acceptability peaked at the air temperature of 22°C, and it was highest in the range of 21-23°C;
- a relatively strong correlation was found between the mean thermal sensation vote and air temperature and a quite strong correlation between the mean general sensation vote and thermal sensation vote;
- women assessed their general well-being in the smart building less favourably than men;
- the modified correlation, which considered the proportional impact of the CO_2 concentration in rooms and the mean BMI index of the group members on their thermal sensations, enabled more accurate calculation results than the original model.

The performed tests provided more insight into the thermal comfort phenomenon in smart buildings. Since many literature reports challenge the Fanger thermal comfort model, a more precise model or correlation should be developed and possibly implemented into the international standards.

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