



Investigation of Thermal Comfort in the Intelligent Building in Winter Conditions

Łukasz J. Orman^{1*}, Stanislav Honus², Paulina Jastrzębska³

¹Faculty of Environmental Engineering, Geodesy and Renewable Energy,

Kielce University of Technology, Kielce, Poland

<https://orcid.org/0000-0002-2221-1824>

²Faculty of Mechanical Engineering, VSB – Technical University of Ostrava, Ostrava-Poruba, Czech Republic

³Faculty of Environmental Engineering, Geodesy and Renewable Energy,

Kielce University of Technology, Kielce, Poland

*corresponding author's e-mail: orman@tu.kielce.pl

Abstract: The paper analyses thermal sensations, preferences and acceptability as well as humidity sensations of students in the intelligent building "Energis" of the Kielce University of Technology (Poland). The tests were performed in 8 lecture rooms, during which the volunteers filled in the anonymous questionnaires (with 3 to 7 possible answers for each question) and – simultaneously – physical air parameters were measured with Testo 400 microclimate meter. The study aimed to determine if the intelligent building provides proper indoor environment conditions during the heating season and to assess the accuracy of the standard methodology for thermal comfort determination. Experimental analysis of thermal and humidity sensations revealed that a share of the respondents critically assessed the indoor environment: 17% regarding temperature and 30% regarding humidity. Moreover, the standard methodology for thermal comfort calculations proved overwhelmingly inaccurate compared to the experimental data (with the results for 6 rooms being beyond the 50% error range). Since smart buildings are still not very common in Central Europe, the experimental data obtained in the study can be valuable both from the scientific but also practical point of view – providing useful data for building engineers and designers.

Keywords: indoor environment, intelligent building, thermal comfort

1. Introduction

Nowadays, buildings are more advanced, equipped with sophisticated systems and even intelligent (also called "smart"). However, despite a lot of effort by designers and constructors, such buildings might not provide the proper level of indoor thermal comfort.

The number of research works on smart buildings' indoor climate is relatively low compared to traditional buildings' large databases. In (Merabtine et al. 2018), indoor air quality and thermal comfort experienced in a smart building in France were described. It was reported that dissatisfaction in the analysed space occurred, as well as a high carbon dioxide concentration value, which exceeded the allowable values. In the paper (Dębska 2021), tests with about hundred and seventy students were conducted in a smart university building. The range of indoor temperature values was 19.3-27.6°C. The study showed that over twenty per cent of the respondents were uncomfortable or did not accept the prevailing conditions. A relatively high level of carbon dioxide was also observed. The students considered humidity generally fine, but some complained that the air was too dry. A similar study (Krawczyk 2021) focused on thermal comfort in a selected lecture hall at an intelligent facility. It was reported that more than 50% of the respondents expressed neutral thermal sensations, and over 30% were pleasantly cool or warm. Thus, there were ca. 20% who showed dissatisfaction. The BMI index was also identified as a factor that impacted thermal sensations. The Fanger model of thermal comfort was challenged as being inaccurate concerning intelligent buildings. Two buildings (one traditional and one intelligent) were compared (Krawczyk & Krakowiak 2021) concerning thermal comfort performance during the summer. The authors stated that the most crucial issue is how the buildings are managed in view of providing comfortable conditions. In that paper also, the Fanger model was verified, and it failed to correctly determine people's thermal sensations. The authors (Majewski et al. 2017) claimed that the majority of the respondents in the intelligent building classrooms, which the authors investigated, were dissatisfied regarding their thermal sensations (it was especially visible with female respondents). This study was done on over a hundred people in three classrooms during the Polish summer season. The experimental study (Białek & Koltuk 2021) was also focused on a smart building. The authors stated that almost twenty per cent of the respondents in the considered room were unsatisfied with their thermal environment conditions. They indicated that it was too warm for them. Still, none regarded the temperature as unpleasant (the majority claimed it was quite acceptable). This paper also investigated lighting conditions in this building, proving that they were generally fine.



Providing proper indoor conditions for people and satisfying them is a complicated issue. It requires, among others, careful design and operation of heating systems (Wojtkowiak & Amanowicz 2020, Amanowicz & Wojtkowiak 2021) or ventilation air filtering processes (Dąbek et al. 2002, Kuśmierk et al. 2014). The phenomenon of thermal acceptability depends on indoor air parameters. Still, it might also be influenced by the proper design of the building and several other issues – for example, heat transfer problems as described in (Pavlenko 2020, Pafcuga et al. 2021, Hečko et al. 2021, Pavlenko 2021, Pavlenko & Koshlak 2022). Thermal acceptability is a subjective assessment of each person, but it could be stated that age, health condition, prior and current physical activity as well as taking medications could play a role. Based on the literature review, the current study has focused on determining thermal comfort in an intelligent building in winter weather conditions, as these seem less common. As a result, the performance of the intelligent building regarding thermal comfort conditions will be known. Moreover, a comparison will be presented between the actual questionnaire results of thermal sensation votes and the calculation results according to the Fanger model. In Poland, studies on the indoor environment are occasionally published – e.g.: (Dudkiewicz & Jeżowiecki 2009, Maliszewska et al. 2019), but in terms of thermal comfort, they are quite rare, especially when it comes to the analyses of subjective sensations in intelligent buildings.

The study aims to critically assess if the intelligent building provides proper indoor environment conditions regarding air temperature and relative humidity during the heating season in the Central European climate. Such a study, accompanied by an accurate assessment of the standard thermal comfort methodology conducted at an intelligent building during winter, can provide new insights into the phenomenon of indoor environment perception in such buildings.

2. Equipment and Testing Method

The tests were performed in the intelligent building "Energis" teaching rooms, located on the Kielce University of Technology campus (central Poland). The building is situated in the Western part of the campus and connected to the neighbouring traditional building with the bridge. The considered building and the bridge (on the left-hand side) are presented in Figure 1.



Fig. 1. Intelligent building "Energis" of Kielce University of Technology

The facility was built a decade ago thanks to significant funding received from the European Union. It has a building management system (BMS), which runs and controls various building services. It uses numerous sources of renewable energy. The wind turbine, solar collectors and photovoltaic systems are located on the rooftop, while in the basement, there are heat pumps that generate heat for the central heating and domestic hot water systems. Moreover, proper thermal insulation reduces heat losses and ventilation systems are equipped with rotational heat recovery units. Apart from its teaching role, the building is also a laboratory – all the data regarding energy generation and consumption, indoor environment, occupation times, etc., are stored and can be analysed and processed.

The study covered the analyses of the answers regarding the subjective sensations, preferences and acceptability of temperature and humidity in eight rooms given by sixty respondents in anonymous questionnaires. Table 1 presents the basic data of the rooms where the study took place (some of the rooms were used twice).

Table 1. Data of the rooms where the tests took place

Room	Window orientation	Room dimensions		
		Length	Width	Height
1	E	10.5	7.7	2.9
2	E	11.9	7.7	2.9
3	W	18.0	8.1	2.9
4	W	13.8	8.1	2.9
5	W	5.9	8.0	2.9
6	W	7.8	8.0	2.9

Usually, filling in the questionnaire took up to a few minutes so that the normal teaching activities were not interrupted. As the students were filling in the questionnaires, the measurements of indoor air temperature, relative humidity, velocity, and carbon dioxide concentration were done with the microclimate meter Testo 400 equipped with adequate probes located at the height of a sitting person in each of the analysed rooms. The measurements took place when the air parameters' readings stabilised (when the probes were thermally accommodated to the room environment). The probing time was 1 sec. and data recording was manually stopped after the questionnaires were completed and the study was finished in a given room. The system also measured other parameters, such as illuminance and ambient pressure, however, they were not used further for thermal comfort analyses. It must be emphasised that three separate probes recorded the air temperature values. However, the measurement results obtained with the most precise probe were the only ones to be considered. Figure 2 presents the meter on the tripod in lecture room no 1.14 during the measurements. The study took place in the Polish winter conditions in January with the outside air temperature in the range -1°C to $+1^{\circ}\text{C}$. Thus, low humidity values were recorded in rooms during the measurements (moisturising of air was not provided with the mechanical ventilation systems of the building).

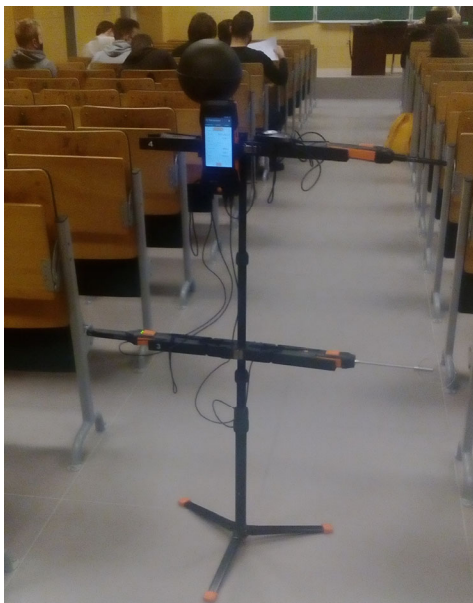


Fig. 2. Microclimate meter located in a lecture hall

3. Results and Discussion

The testing was performed in 8 lecture rooms during the winter season. They were chosen to represent typical lecture rooms (no 1-4 in Tab. 1) and classrooms (no 5-6 in Tab. 1) in the intelligent building as well as two window orientations: East and West (other window orientations do not occur in the building's teaching rooms). The microclimate meter determined the physical parameters in each room where the tests took place. Figure 3 presents example changes in air temperature, relative humidity and carbon dioxide concentration for 20 minutes (starting from the beginning of the lecture) for one room.

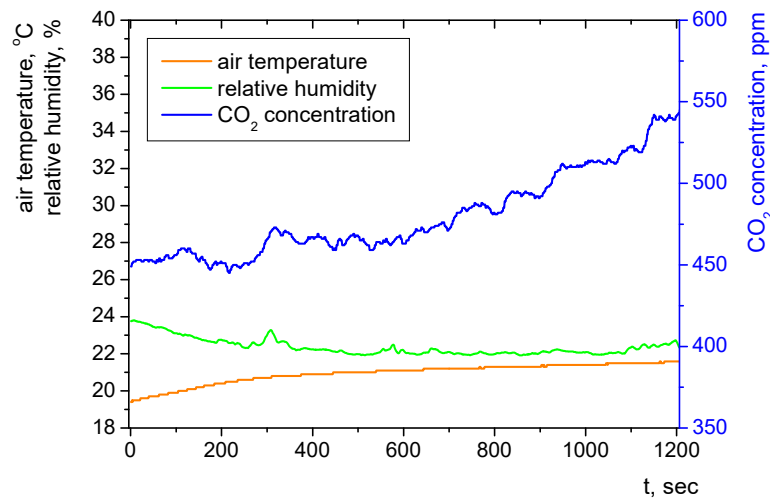


Fig. 3. Variation of air temperature, relative humidity and carbon dioxide concentration in a lecture room

It can be seen that at first – as the students enter the room – the concentration of carbon dioxide is low and amounts to ca. 450 ppm. As the lecture progresses, the level of CO₂ increases due to breathing. Variations of this parameter, observed in the graph, might be linked with the measurement uncertainties (maximally ± 50 ppm). A similar trend is visible for temperature. The presence of the students results in heating the air. The relative humidity values were typically low during the measurements due to the season (winter is characterised by dry air conditions within rooms). In all 8 rooms, the recorded air temperature was up to 24.1°C, humidity up to 34.7%, and carbon dioxide concentration up to 990 ppm. The measurement uncertainty of air temperature and relative humidity were 0.3°C and up to 1%, respectively. Concerning air temperature and carbon dioxide concentration, the measurement error was constant and the same for all the investigated rooms. In the case of relative humidity, it depended on the measured value (as a percentage of it) and, thus, it became lower for low humidity values (but – as mentioned above – the maximal error of relative humidity determination did not exceed 1%).

An important part of the study was the collection of students' subjective responses regarding the indoor environment and their sensations. They expressed their opinions on several issues using anonymous questionnaires. In terms of their thermal sensations (how they felt thermally), the results for all the rooms are presented in Figure 4. In the figure, "zero" means the neutral and, at the same time, most favourable state, while the positive values ("+1", "+2", "+3") describe that the person feels warmth "+1" or strong heat "+3", while negative ones "-1", "-2", "-3" the opposite (cool, then cold and very cold, respectively).

The smart building provided proper conditions to about 83% of the volunteers (calculated as the total number of responses "-1", "+1", and "0"). Quite many: ca. 40% felt fine ("0" – neutral), and 43% were 'still fine' and provided answers: "+1" and "-1". However, it needs to be seen that about 17% expressed negative opinions about their thermal state – the respondents felt hot (votes "+2", "+3") and cold "-2". These responses are considered unsatisfactory and are linked with negative opinions about the indoor environment. Consequently, the considered building failed to provide the students with a high level of comfort – at least in the rooms analysed in the present study.

Naturally, some differences might have been caused by the individual preferences of the students, but it is quite true that many were dissatisfied and would like to change the temperature, as presented below in Figure 5.

This figure shows how many respondents wanted to increase the temperature ("+1") and how many of them would welcome its reduction ("-1"). The biggest number of students would like the temperature to be as it was (almost 65%) and did not want any change ("0" on the graph). On the other hand, there were quite many respondents (ca. 20%) who wanted to slightly increase the temperature "+1" and ca. 15% who wanted to decrease it "-1". No willingness for considerable temperature changes was expressed by the respondents (no votes of "+2" and "-2"), even though such answers were present in the questionnaire form provided to them. The figure proves that despite a large number of satisfied people (namely 65%), quite many wanted some change in air temperature, especially its slight increase. It might indicate that people in the Central European region tend to like warmer environments, at least during the winter season when the measurements were carried out. The opposite might be true if the testing was performed in other regions where the climate is warmer.

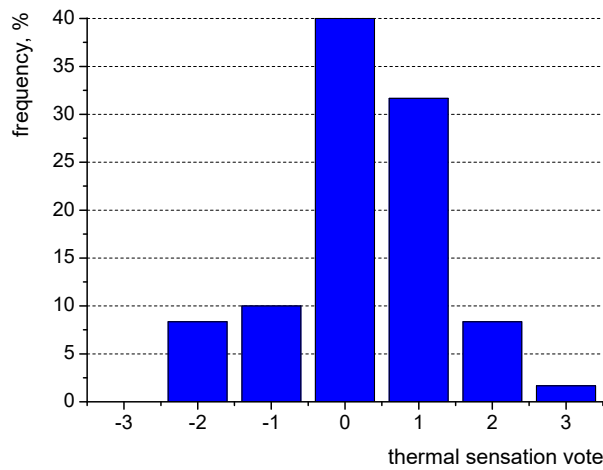


Fig. 4. Frequency of occurrence for thermal sensation vote in 8 lecture rooms

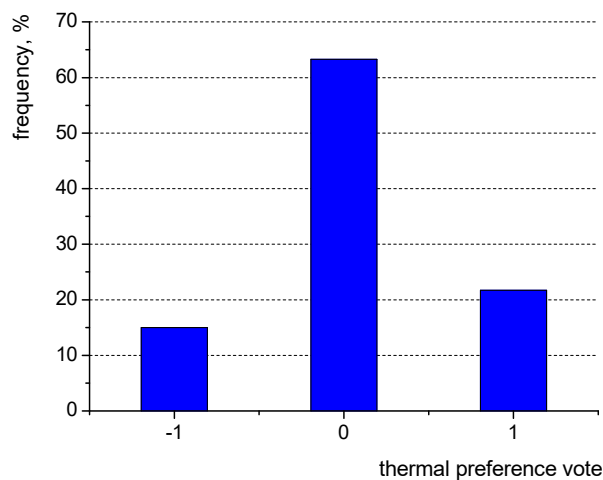


Fig. 5. Frequency of occurrence for thermal preference vote in 8 lecture rooms

Naturally, the preference to change the indoor temperature should be closely dependent on the air temperature's current value. This dependency has been presented in Figure 6 together with error bands for temperature (T) measurements and thermal preference vote (TPV) – calculated based on the individual questionnaire answers as the mean value for the whole group of students situated in a given room (of a certain ambient temperature value T).

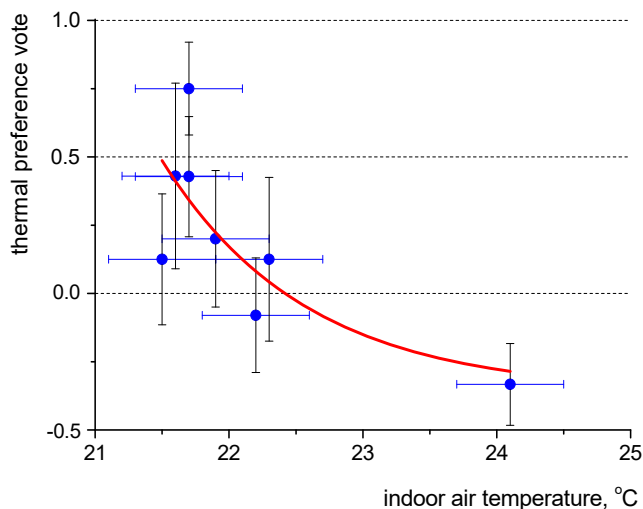


Fig. 6. Thermal preference vote vs indoor air temperature

In this graph, the mean values of thermal preferences for each room (eight in total) have been related to the air temperature prevailing there. The results have been approximated with the polynomial fit function, and the obtained function took the following form:

$$TPV = 52.9 - 4.3T + 0.09T^2 \quad (1)$$

with the R^2 value of 0.59.

It is clearly visible that in high-temperature environments, people want a reduction in the temperature value, and in the lower-temperature region, the opposite is true. However, the dependence has turned out not to be linear. In (Aghniaey et al. 2019), a slightly different trend line was applied. However, compared to the present study, the operative room temperature was used instead of air temperature. Moreover, the R^2 value was lower and amounted to 0.52. The polynomial and not the linear character of the dependence between thermal preferences and indoor air temperature in Figure 6 can be explained by the fact that people might be more sensitive to colder thermal environments and, thus, at lower temperatures, their preference towards higher temperatures is stronger (and, consequently, the curve in Figure 6 is steeper in the range of 21.5-22°C). The opposite is true for higher temperatures (above 23°C), which do not seem to cause such a strong preference for temperature reduction.

Overall, the students considered the ambient atmosphere in the analysed rooms of the smart building to be acceptable – the detailed questionnaire study results have been shown in Figure 7 for all eight rooms considered in the tests.

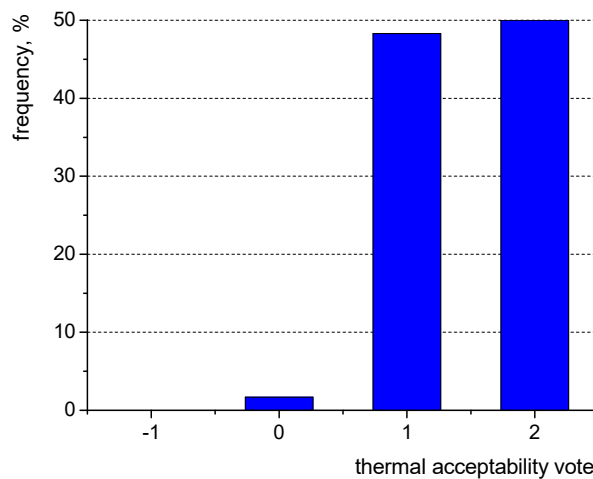


Fig. 7. Frequency of occurrence for thermal acceptability vote in 8 lecture rooms

Very negative opinions about the thermal environment (marked as "-1") were not recorded at all, and only a few students expressed a negative opinion ("0" on the graph). Almost all showed relative acceptability (denoted as "+1") or even comfort (marked as "+2"). The level of high thermal comfort was expressed by ca. 50% of students, which correlates well with Figure 4. It also proves that air temperature is not the only parameter influencing thermal comfort, especially in smart buildings where the tests were made.

The other parameter, which might somewhat impact human well-being, is the relative humidity of indoor air. Figure 8 presents the students' assessment of humidity, where the most favourable value is "0" (neutral state), while "-1" and "-2" mean that the air is 'dry' or 'too dry', respectively. Similarly, "+1" and "+2" denote 'wet' or 'too wet' air, respectively.

As can be seen in the graph, the most significant majority (over 70%) assessed the humidity as fine. However, a large group of students considered the air as 'dry' and 'too dry' (about 25%). It might be caused by the relatively low humidity level in the tested rooms (due to winter conditions and low moisture content in the outside air). Naturally, it is typical of the winter conditions but proves that the level of comfort in the analysed smart building is not high enough (despite its technical sophistication). That is the reason why quite many student respondents (about the same share as those who described the air as being 'dry' or 'too dry') wanted an increase in the value of relative humidity – as shown in Figure 9, where "0" marked by the respondents in the questionnaires means "no change", while a preference for an increase in relative humidity is denoted as "+1" and decrease as "-1".

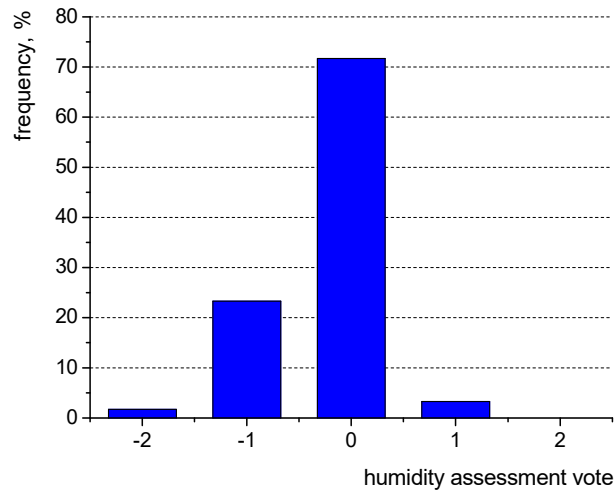


Fig. 8. Frequency of occurrence for humidity assessment vote in 8 lecture rooms

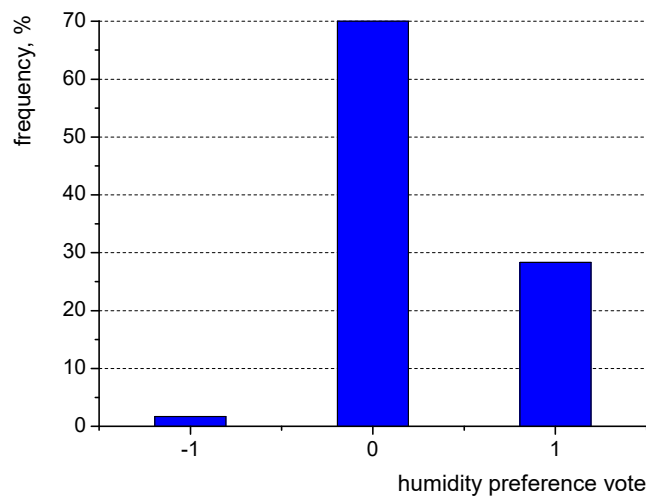


Fig. 9. Frequency of occurrence for humidity preference vote in 8 lecture rooms

This figure is a reflection of Figure 5. Those who felt fine did not want any change, while those who experienced dry air would welcome increased humidity. However, some students still considered the air as wet and would like it to be drier. However, these votes were marginal. Nevertheless, this must have been related to individual preferences.

A close correlation exists between how people feel in a certain room and their preferences. For example, if someone feels hot, they would like to reduce the indoor temperature; when they feel cold, the thermal preferences are positive (they would welcome an increase in air temperature). The same should be true for humidity – if people assess the air as too humid, they would welcome a reduction in relative humidity. Figure 10 shows how thermal sensation vote is related to thermal preference vote and humidity assessment vote is related to humidity preference vote (dots on the graph represent mean values of the considered parameters – calculated based on the questionnaires in each of the considered eight rooms).

As can be seen, there is a strong linear relation between the indoor environment assessment and the preferences for changing or maintaining it. The values of the coefficient of determination R^2 are 0.89 for thermal preference vote (TPV) vs thermal sensation vote (TSV) and 0.80 for humidity preference vote (HPV) vs humidity assessment vote (HAV), while the obtained equations have taken the following forms:

$$\text{TPV} = -1.945\text{TSV} + 0.519 \quad (2)$$

$$\text{HPV} = -0.946\text{HAV} + 0.036 \quad (3)$$

It might also be concluded that people tend to be more sensitive to thermal sensations (the fitting line is steeper) than humidity sensations. It seems to agree with the everyday experience when we consider air too wet or too dry only when the relative humidity significantly exceeds or falls below certain values.

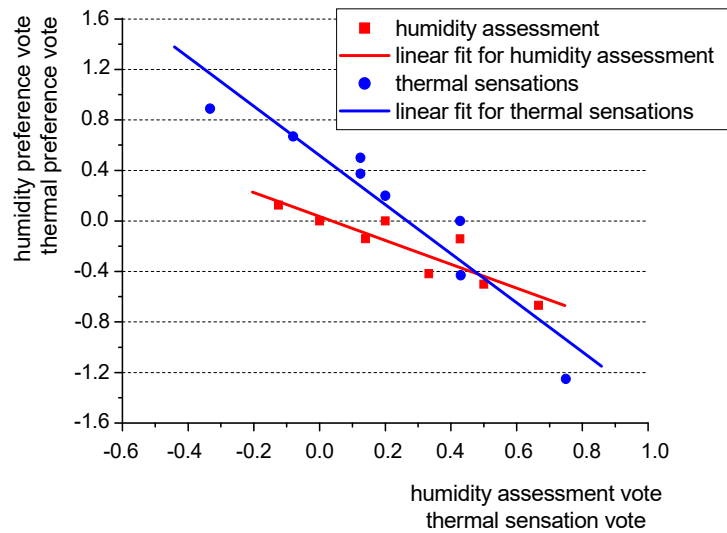


Fig. 10. Relation between thermal sensation vote, humidity assessment vote and thermal/humidity preference vote in 8 lecture rooms

Experimental analysis of the thermal and humidity sensations experienced by the students of the smart building revealed that a share of the respondents critically assessed the indoor environment – both in terms of temperature and humidity. However, another important aspect is the ability to properly determine the sensations of the people in a given room (of certain indoor air parameters) so that proper indoor air parameters are set, and the HVAC (heating, ventilation and air conditioning) systems provide adequate air treatment. Consequently, a comparison has been made between the actual thermal sensations of the students (based on the questionnaire survey data) in each room and the calculation results according to the international standard (ISO Standard 7730 2005) that enables to determine the mean value of thermal sensations (called 'PMV' – predicted mean vote) based on the indoor environment parameters such as air temperature, air velocity, water vapour partial pressure and others. The calculation methodology also requires data on the metabolic rate of the people (their activity level) and the thermal insulation of their clothing. Figure 11 compares the actual thermal sensation votes TSV (the mean value for each room based on the questionnaires) and the PMV value. The red line denotes the line of ideal congruence of the experimental data and calculation results (when $PMV = TSV$).

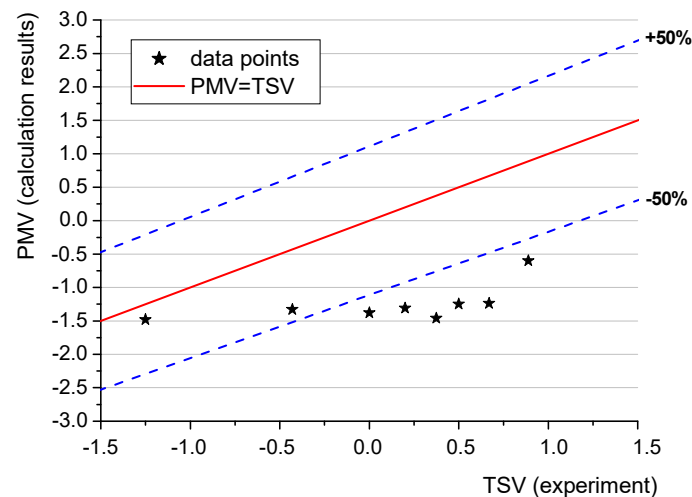


Fig. 11. Comparison of the experimental test results for 8 rooms and calculation results according to the methodology in (ISO Standard 7730 2005)

It seems that the methodology for thermal comfort determination available in the standard could not properly determine the actual thermal sensations of the room users in the intelligent building. The calculation results of PMV were close to the actual experimental data of TSV only in one case (the data point is close to the red line in Figure 11). The data points for six rooms are quite distant from the ideal congruence line of $PMV = TSV$ and beyond the 50% accuracy range. Thus, it can be concluded that the calculation method has

not been successful in determining thermal sensations in the smart building (possibly due to mechanical ventilation and indoor environment control strategies).

The study's main limitation is that it took place only in winter conditions. Additionally, the respondents were familiar with the building's indoor conditions (because they had studied there for some time), so their perceptions could have been slightly affected by the fact that they got used to the indoor environment of the considered intelligent building. However, it must be added that these two factors are unlikely to influence the obtained general results.

3. Summary and Conclusions

Thermal comfort measurements performed in winter in the smart building provided valuable knowledge regarding that kind of building. It was observed that almost all the students accepted the environmental conditions in the considered teaching rooms despite various responses about their willingness to change the temperature and humidity. However, the study indicates that even in smart and sophisticated buildings, indoor conditions might not be fine for all people – both with regard to temperature and humidity. It might be a problem or concern for those responsible for properly managing such facilities, especially during the winter, when problems with low relative humidity in the indoor air can occur.

The comparison of the calculation results according to the methodology presented in the international standard and the actual experimental results for eight rooms has shown significant discrepancies, and the calculation method has not been successful in this case. It might be related to the use of mechanical ventilation and indoor environment control strategies set by the building management unit.

Future studies of this subject should focus on broadening the experimental database to include all the seasons and possibly more varied volunteer groups. It would be most appropriate to conduct the studies for at least sixty groups (occupying sixty rooms) at an equal share in each season – namely fifteen. Detailed analysis of subjective sensations of people in modern smart buildings can help their managers to properly set the indoor conditions within those facilities for the higher comfort of their users.

*The work in the paper was supported by the project:
"SP2023/094 Specific research in selected areas of energy processes".*

References

- Aghniaey, S., Lawrence, T.W., Sharpton, T.N., Douglass, S.P., Oliver, T., Sutter, M. (2019). Thermal comfort evaluation in campus classrooms during room temperature adjustment corresponding to demand response. *Building and Environment*, 148, 488-497. <http://10.1016/j.buildenv.2018.11.013>
- Amanowicz, Ł., Wojtkowiak, J. (2021). Comparison of single- and multipipe earth-to-air heat exchangers in terms of energy gains and electricity consumption: a case study for the temperate climate of Central Europe. *Energies*, 14, 8217. <https://doi.org/10.3390/en14248217>
- Białek, A., Koltuk, B. (2021). Thermal comfort measurements in the Energis building. *Structure and Environment*, 13, 10-15. <https://doi.org/10.30540/sae-2021-002>
- Dąbek, L., Świątkowski, A., Dziaduszek, J. (2002). Studies on the utilisation of spent palladium-activated carbon (Pd/AC) catalysts. *Adsorption Science and Technology*, 20, 683-693. <https://doi.org/10.1260/02636170260504369>
- Dębska, L. (2021). Assessment of the indoor environment in the intelligent building. *Civil and Environmental Engineering*, 17, 572-582. <https://doi.org/10.2478/cee-2021-0058>
- Dudkiewicz, E., Jeżowiecki, J. (2009). Dyskomfort lokalny na stanowisku pracy. *Rocznik Ochrona Środowiska*, 11, 751-759.
- Hečko, D., Mičko, P., Holubčík, M., Kapjor, A. (2021). Experimental simulation of hydrate formation process in a circulating device. *Processes*, 9(9), 1529. <https://doi.org/10.3390/pr9091529>
- ISO Standard 7730 (2005). Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria; Geneva, Switzerland, 2005.
- Krawczyk, N. (2021). Thermal comfort in the low energy building – validation and modification of the Fanger model. *E3S Web of Conferences*, 246. <https://doi.org/10.1051/e3sconf/202124615003>
- Krawczyk, N., Krakowiak, J. (2021). The comparison of thermal comfort test results in selected traditional and modern buildings. *E3S Web of Conferences*, 286. <https://doi.org/10.1051/e3sconf/202128602008>
- Kuśmierk, K., Dąbek, L., Świątkowski, A., Syga, P. (2014). Influence of chlorine atom number in chlorophenols molecules on their adsorption on activated Carbon. *Fresenius Environmental Bulletin*, 23(3), 947-951.
- Majewski, G., Telejko, M., Orman, Ł.J. (2017). Preliminary results of thermal comfort analysis in selected buildings. *E3S Web of Conferences*, 17, 00056. <https://doi.org/10.1051/e3sconf/20171700056>
- Maliszewska, A., Szkarowski, A., Chernykh, A. (2019). Normative problems of the nitrogen oxides concentration limiting in the human residence environment. *Rocznik Ochrona Środowiska*, 21, 1328-1342.

- Merabtine, A., Maalouf, C., Waheed Hawila, A.A., Martaj N., Polidori, G. (2018). Building energy audit, thermal comfort, and IAQ assessment of a school building: A case study, *Building and Environment*, 145, 62-76. <https://doi.org/10.1016/j.buildenv.2018.09.015>
- Pafcuga, M., Holubcik, M., Durcansky, P., Kapjor, A., Malcho, M. (2021). Small heat source used for combustion of wheat-straw pellets, *Applied Sciences*, 11(11), 5239. <https://doi.org/10.3390/app11115239>
- Pavlenko, A. (2020). Energy conversion in heat and mass transfer processes in boiling emulsions, *Thermal Science and Engineering Progress*, 15, 100439. <https://doi.org/10.1016/j.tsep.2019.100439>
- Pavlenko, A. (2021). Self-preservation effect of gas hydrates, *Rocznik Ochrona Środowiska*, 23, 346-355.
- Pavlenko, A.M., Koshlak H. (2022). A new method for the rapid synthesis of gas hydrates for their storage and transportation, *Environmental and Climate Technologies*, 26(1), 199-212. <https://doi.org/10.2478/rtuect-2022-0016>
- Wojtkowiak, J., Amanowicz, Ł. (2020). Effect of surface corrugation on cooling capacity of ceiling panel, *Thermal Science and Engineering Progress*, 19, 100572. <https://doi.org/10.1016/j.tsep.2020.100572>