E3S Web of Conferences **286**, 02008 (2021) https://doi.org/10.1051/e3sconf/202128602008
TE-RE-RD 2021

The comparison of thermal comfort test results in selected traditional and modern buildings

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Abstract. The use of renewable energy sources in buildings is more and more common (both for heating and cooling purposes, as well as electricity generation). The paper focuses on the thermal comfort tests in two buildings: the traditional one (that uses non-renewable sources of energy) and the modern intelligent building "Energis" of Kielce University of Technology. The thermal sensations of students in these two buildings have been compared based on the questionnaire survey and conclusions have been drawn regarding the differences between the feelings of thermal comfort in those two buildings. Apart from subjective feelings of the volunteers, the measurements of indoor air parameters were conducted in both buildings and have been presented in the paper.

1 Introduction

Nowadays, the concept of thermal comfort is becoming more and more common. We spend more and more time indoors. Thermal comfort is a state in which a person is satisfied with the prevailing thermal conditions. This means that it does not feel cold or too warm. By providing the right thermal conditions, we feel good in the room, which affects our immune system and productivity. Therefore, in the existing and future intelligent buildings, the guarantee of thermal comfort has been increased. The main element of designing an artificial climate inside buildings is thermal comfort. It has a significant impact on human health and its safety in the building. Failure to provide good conditions can adversely affect our health, well-being and productivity. It makes us feel tired and makes us less productive, and consequently our effectiveness of the activities performed drops significantly. It is worth paying attention to the current situation in the world. The current coronavirus (Covid-19) pandemic has changed our private, social and economic lives. Most of us have changed our lifestyle to remote. This is due to the fact that when working in closed rooms, we want to feel comfortable in them. Overall, the feeling of thermal comfort significantly affects the work efficiency. Therefore, it is important to ensure appropriate conditions in a given room by using appropriate air-conditioning and heating devices. The supply of heat to the building can be produced with the use of conventional methods as well as alternative methods, including the use of renewable energy sources. Energy storage systems are important for renewable energy sources. A large part of the energy is used for thermal

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comfort in buildings. It is important to ensure thermal comfort and thus reduce energy costs. A review of progress is essential in terms of thermal comfort. The main parameters influencing the determination of thermal comfort are, first of all, air temperature, relative humidity, air velocity, average radiation temperature and physical activity. The thermal comfort model was developed in the 1970s by O. Fanger on the basis of the applicable standards: ISO 7730 [1] together with PN-EN 16798-1: 2019 [2]. Fanger [3] determined two indicators: PMV - Predicted Mean Vote and PPD - Percentage of Dissatisfied people. According to the American standard ASHRAE 55 [4], the PMV index is expressed on a seven-point scale, from -3 to +3, where negative is cold and positive is hot. For the thermal environment to be acceptable, the PMV value must be between -0.5 and +0.5. The PMV index was expressed by the following equation according to [1]:

$$PMV = [0,303 \cdot exp(-0,036 \cdot M) + 0,028] \cdot \{(M - W) - 3,05 \cdot 10^{-3} \cdot [5733 - 6,99 \cdot (M - W) - p_a] - 0,42 \cdot [(M - W) - 58,15] - 1,7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0,0014 \cdot M \cdot (34 - t_a) - 3,96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \quad (1)$$

where: M - metabolic rate [W/m^2], W - effective mechanical power [W/m^2], p_a - partial pressure of water vapour [Pa], t_a - air temperature [°C], f_{cl} - clothing area ratio [-], t_{cl} - surface temperature of clothing [°C], $\bar{t}_r$ - average radiation temperature [°C], h_c - heat transfer coefficient [m^{2}K/W]. The projected percentage of dissatisfied people (PPD), describes the number of people who feel their environment is too warm or too cold. The PPD index is calculated according to the following equation [1]:

$$PPD = 100 - 95 \cdot exp(-0,03353 \cdot PMV^4 - 0,2179 \cdot PMV^2) \quad (2)$$

In recent years, an increasing number of scientists have studied the differences between PMV and thermal sensation voices. Biyik et al. [5] carried out research on the storage of energy from photovoltaic panels, which can then be used and thus maintain thermal comfort in the building. Aghniaey et al. [6,7] conducted research on thermal comfort on a university campus in the United States. They measured the temperature and air velocity in the room, the average radiant temperature, the CO_2 concentration and the relative humidity. The authors showed that the respondents preferred higher temperature ranges, especially women accept a warmer environment. The authors [8] analysed the thermal comfort by comparing the real feelings of people with the Fanger model. Xu et al. [9] studied the problem of electricity management for a shopping center. They showed that it is possible to simultaneously ensure thermal comfort and minimize operating costs by using renewable energy sources (photovoltaic and wind energy). In the article [10] a study on thermal comfort in a climatic chamber was carried out. 15 women and 15 men participated in the study. They concluded that thermal sensations are significantly influenced by air temperature and the body's thermal adaptability. Moreover, a significant correlation was observed between skin temperature and thermal sensations. Almeida et al. [11] analysed thermal comfort in school buildings. They showed a significant relationship between PMV and Mean Thermal Sensation (MTS) and the operating temperature. Vilcekova et al. [12] on the basis of research conducted in primary school, they showed a discrepancy between the results of PMV calculations and the actual feelings. They also observed an increase in CO_2 concentration during school activities. Homoda et al. [13] conclude that the air temperature and humidity have the greatest impact on the feeling of thermal comfort. The tests of the author and other co-workers [14-17] indicate that the thermal environment in modern buildings is largely influenced by the heating, ventilation and air conditioning systems installed there.

The article discusses the research on thermal comfort in two buildings: the traditional and the modern building “Energis” of the Kielce University of Technology (using renewable energy sources). The respondents' thermal sensations in the presented buildings were compared on the basis of the surveys carried out, and the parameters of the air in the rooms were examined.

2 Material and method

The research was carried out in June 2019 in the intelligent building "Energis" of the Kielce University of Technology and in the school building. The "Energis" building has mechanical ventilation, in which it is possible to control the operation of the ventilation. On the other hand, the school building is not ventilated in the rooms where the research was conducted. An intelligent building is equipped with solar collectors, heat pumps and photovoltaic cells that use solar energy to heat water and generate electricity to illuminate the building. On the roof of the building there are photovoltaic panels and solar collectors, thanks to which the building has the ability to accumulate heat and use energy. In terms of energy, the building is self-sufficient. The picture below shows a photo of solar collectors and panels.

Fig. 1. Solar collectors and photovoltaic panels on the roof of the "Energis" building.

The discussed Energis building has been designed to ensure adequate air parameters for people staying in it. The designed air-conditioning and heating systems should ensure appropriate parameters depending on the purpose of the room, because they significantly affect the conditions in the room. The second room does not have any kind of ventilation. The inflow of fresh air is possible by opening windows and doors, thanks to ventilation and by infiltration through leaks in the window and door joinery. This room is on the first floor and the windows were ajar during the research.

The study consisted of two research methods. The first was to measure the air parameters. A microclimate meter was used for the performed tests, on the basis of which air parameters in the rooms were determined. The temperature and air velocity, black sphere temperature and relative humidity were tested. Figure 2 below shows the Testo 400 gauge that was used for the tests.

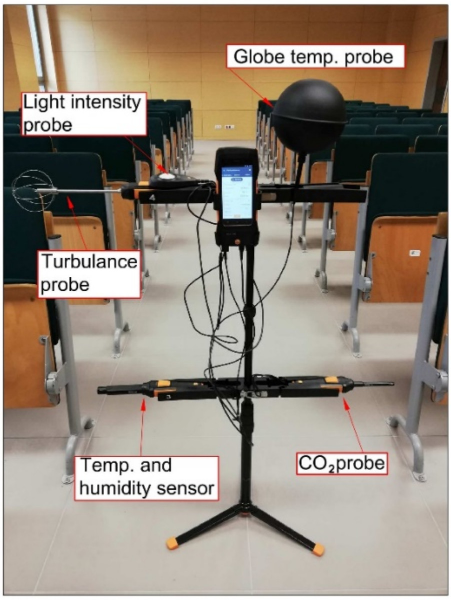

Fig. 2. Testo 400 microclimate measuring device.

The parameters were read from the meter after 15 minutes of stabilization of the measurements. During the tests performed, the measurements were characterized by high atmospheric air temperatures ranging up to 28°C, at an atmospheric pressure of about 985 hPa. Parameters indicated by the meter were read for both objects. Then the values in the given intervals were averaged and the average radiation temperature was determined. The table below shows the air parameters for the rooms in question.

Table 1. Air parameters for the tested rooms.

	Room 1: Intelligent building powered by renewable energy sources	Room 2: Traditional building
Air temperature, °C	27.60	27.70
Black ball temperature, °C	27.09	25.72
Air speed, m/s	0.01	0.05
Air humidity, %	53.15	47.60

The second method consisted in filling in the questionnaires by the respondents concerning the thermal impressions of the microclimate in which they stayed. The survey allowed for a clear assessment of thermal comfort, thermal preferences regarding the conditions in the room and thermal sensations. The questionnaire contained a question related to clothing, thanks to which it was possible to determine the average level of insulation of the garment. The thermal resistance of the office chair was added to the value of thermal resistance for clothes, which is 0.1 clo. The total value of thermal resistance for the first room was 0.49 clo, and for the second one - 0.62 clo. At the end of the questionnaire, there was a certificate which provided information on the sex, age, height and weight of the respondents. People aged 18 to 21 and one woman aged 52 participated in the study. Based on the height and weight, the BMI (Body Mass Index) was calculated. It is the ratio formed by dividing the body weight given in kilograms by the square of the height given in meters. The survey also included a question about health. When someone answered “yes” and “I do not know”, such a questionnaire was rejected due to the thermal feelings of the sick, which are not reliable.

3 Results and discussion

The tests of the two rooms were carried out in June. In the first room (Energis intelligent building), 12 respondents took part, 4 of which were rejected, 3 due to ignorance about their health condition and 1 due to illness. Thus, there are 8 reliable questionnaires for the first room, including 3 women and 5 men aged 19 to 21. The first room has mechanical ventilation with an air parameters control panel. It was not used during the research. For the second room, 19 people were examined, 3 questionnaires were rejected, one due to selecting the answer “yes” to the question about the health condition, and 2 by selecting the answer “I do not know”, therefore 16 questionnaires were taken into account for further analysis, including 15 women and 1 man. The subjects in the second room were 17 to 18 years of age and one woman was 52 years of age. The second object does not have any kind of ventilation, but the windows were ajar during the tests. The chart below shows the frequency of the given answer regarding thermal sensations vote experienced by the respondents in a room powered by renewable energy sources and in a traditional room (Fig. 3).

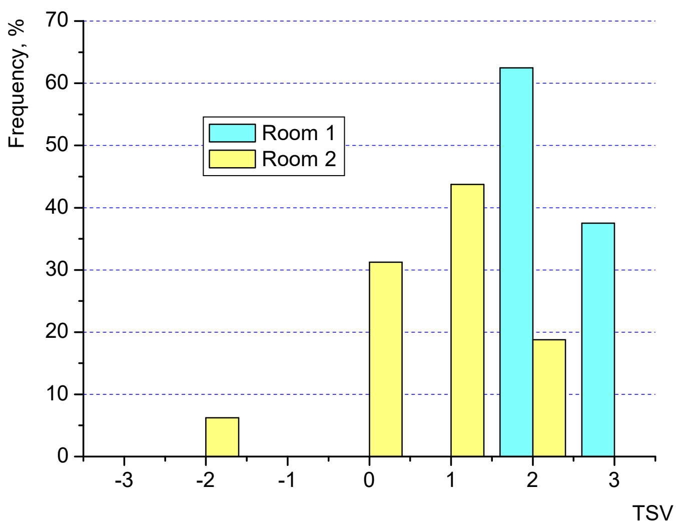

Fig. 3. The frequency of responses given by the respondents regarding thermal sensations vote (TSV): “-3” - too cold, “-2” - too cool, “-1” - pleasantly cool, “0” - comfortable, “1” - pleasantly warm, “2” - too warm, “3” - too hot.

The research on thermal sensation showed that the response “too cool” was 6.25% for a traditional building. The most frequently given answer was “too warm” for building 1 (Energis), which amounted to 62.50% for 5 responses out of 8. However, for a traditional building - “pleasantly warm” was the most frequently given answer, which corresponds to 43.75%. The answer “comfortable” for building 2 was marked 5 times which corresponds to 31.25%. The "too warm" option was repeated 3 times and amounts to 18.75%. For an

https://doi.org/10.1051/e3sconf/202128602008

intelligent building, the response “too hot” was 37.50%. Taking into account all the answers, it can be concluded that the respondents did not feel well in the rooms where they stayed. This means that there was no thermal comfort in the places where they stayed. The percentage of choice of answers -3, -2, +2, +3 was greater than 10.00% and amounted to 50.00%. The next figure shows the frequency of the answers given regarding the thermal acceptability vote.

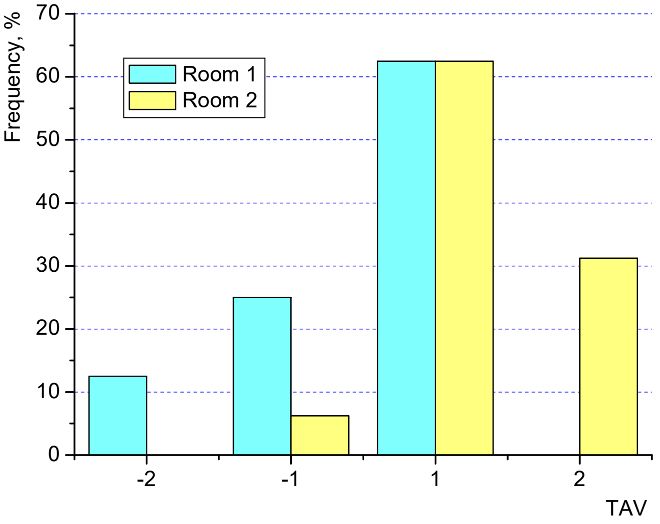

Fig. 4. The frequency of responses given by respondents regarding thermal acceptability vote (TAV): “-2” - definitely not acceptable, “-1” - no longer acceptable, “1” - still acceptable, “2” - definitely acceptable.

The above chart shows that for room one, the answer “definitely not acceptable” was 12.50%. In turn, for “no longer acceptable” it was twice as high, which corresponds to 25.00%. The most common answer for both rooms was “still acceptable”, which is 62.50%. For the second room, 31.25% of respondents believe that the air is definitely acceptable. To sum up, the answers given by the respondents show that 62.50% of all respondents are satisfied with the conditions in the rooms. Only 16.67% of the respondents did not correspond to the temperature of the environment in which they were located. The next figure shows the frequency of the given answer regarding thermal preferences vote.

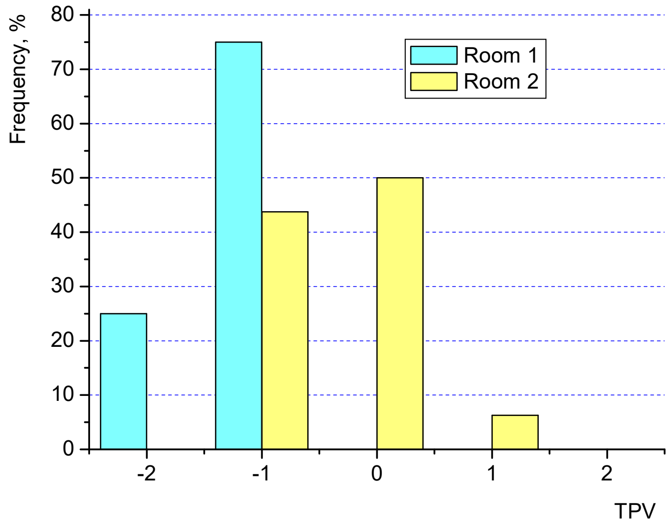

Fig. 5. The frequency of answers given by the respondents regarding thermal preferences vote (TPV): "-2" - definitely cooler, "-1" - cooler, "0" - unchanged, "1" - warmer, "2" - definitely warmer.

Of the respondents' responses to room one, the most common response was "cooler" and it was 75.00%, meaning 6 out of 8 want it to be cooler in the room. And 2 people (25.00%) selected "definitely cooler". However, for the second room, the situation is as follows: 50.00% of the respondents answered "unchanged", and 43.75% - wanted it to be "cooler" (7 people out of 16 chose this answer). The least frequently given answer for the second room was the answer "warmer" and it amounts to 6.25%. Only one person indicated that she wanted it to be warmer. It can be concluded that the respondents did not feel well in the examined rooms. When comparing all the results, 62.50% of respondents believe that the conditions in the rooms are poor. The figure below shows the frequency graph for the assessment of humidity for the tested rooms.

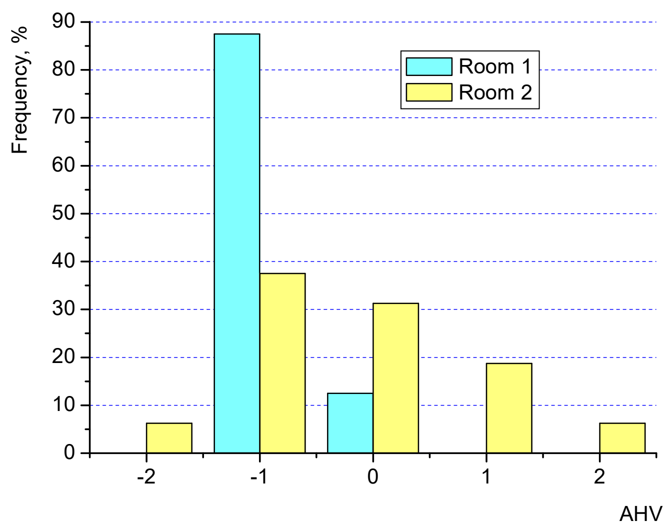

Fig. 6. The frequency of the answers given by the respondents regarding air humidity vote (AHV): "-2" – too dry, "-1" - fairly dry, "0" - pleasantly, "1" - quite damp, "2" - too humid.

From the chart above, it can be seen that for room 1, the most common answer was “fairly dry”, which is 87.50%. This means that 7 out of 8 rate the air humidity as fairly dry. Only one person was satisfied with the air humidity in the tested room. Similarly, for the second room, the most frequently given answer was also “fairly dry” and it is equal to 37.50%. This answer was chosen by 6 out of 16 people, and 5 people chose the answer “pleasantly”, which constitutes 31.25%. For 4 out of 16 people there was too much humidity in room 2. So, the percentage of “quite damp” and “too humid” responses is 25.00%. In general, it can be concluded that the tested rooms were quite dry. The next figure 7 shows the humidity preferences vote.

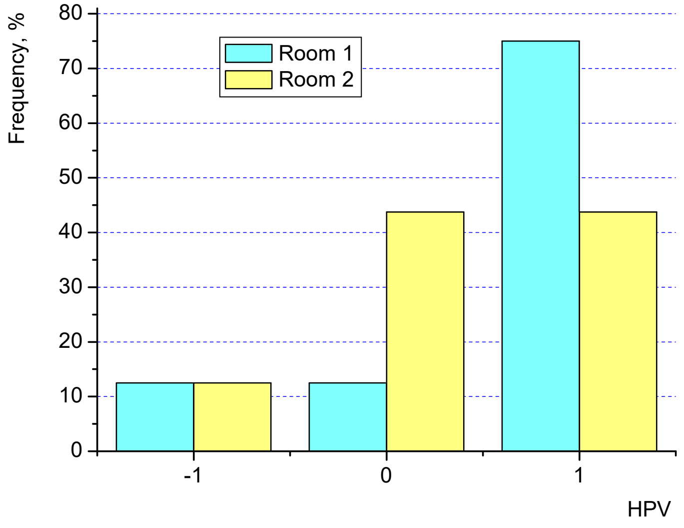

Fig. 7. The frequency of answers given by the respondents regarding the humidity preferences vote (HPV): “-1” - more dry, “0” - no change, “1” - more humid.

For the rooms studied, it can be seen that the respondents would like the air in the rooms to be more humid, which is 54.17%. The most frequently chosen answer for the first room was the answer “more humid”, 6 of the 8 respondents chose this answer (i.e. 75.00%). The same number of responses was for “more dry” and “no change”, it was 12.50% for both responses. The same percentage of the “more dry” answer was given to the second room. For the “no change” and “more humid” responses, the response rate was 43.75%. An analysis of the graph above shows that the room is quite dry. Figure 8 shows a comparison between TSV (Thermal Sensations Vote) and PMV (Predicted Mean Vote) for the rooms under study.

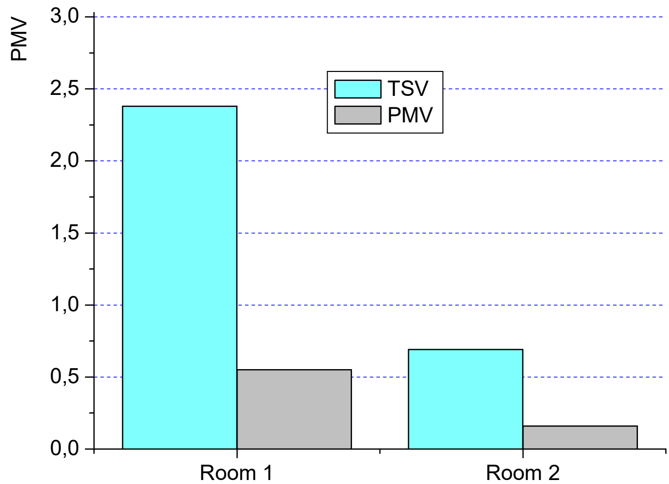

Fig. 8. Comparison of actual test results with calculated.

The above figure shows a comparison of the average thermal comfort rating from the questionnaires and that calculated according to the formula (1) from the standard [2] for the rooms under study. For the first room, the thermal sensations vote is 2.38. This value is inconsistent with the calculated one, i.e., PMV is 0.55. The values differ by 1.83. However, for the second room, TSV from the questionnaires is equal to 0.69. This answer is inconsistent with the standard, because PMV according to the standard is 0.16. These values are different and different from each other. Both tests were conducted at the same outside and room temperature. The ratio between TSV and PMV for the first and second room is as follows: for room 1 the ratio of TSV to PMV is 4.33, and for the second room 4.31. This means that both values are around 4.30. The thermal feelings of percentage of Dissatisfied people for the examined rooms are presented below.

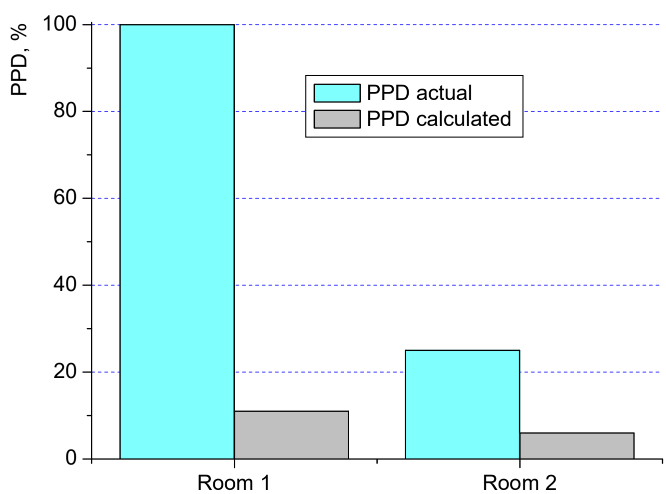

Fig. 9. Comparison of actual survey results with calculated results for PPD.

The parameters were read from the meter after 15 minutes of stabilization of the measurements. When analysing the above chart, a significant difference was noticed between the percentage of dissatisfied people according to the questionnaires and that calculated in accordance with the standard [2]. The percentage of dissatisfied with the prevailing conditions for the first room was analysed and the obtained value was 100%. You can see that all people find it too warm or too hot. According to the calculations from the norm, it is 11%. This is a significant difference in relation to the answers according to the respondents. According to the polls, for the second room, the percentage of dissatisfied people is 25%. PPD calculated according to the standard is 6%. There are 4 times more people dissatisfied for the second room than according to formula (2). The standard states that the percentage of dissatisfied people should not exceed 10%. The figure below presents the calculated BMI for the respondents and compares it with the thermal preferences voices.

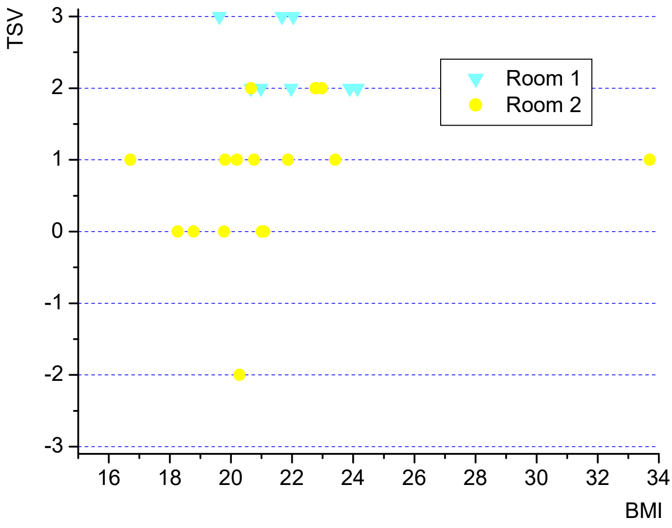

Fig. 10. Dependence of TSV on the BMI mass index for two rooms.

In the presented diagram, the first room (Energis intelligent building) is marked in blue, while the traditional building is marked in yellow. Figure 10 shows the calculated BMI for the respondents, which was compared with thermal sensations voices (TSV). Based on the results, it can be concluded that people with a higher BMI have higher thermal sensations. This means that they prefer lower indoor temperatures.

4 Conclusions

The measurement results from the microclimate meter were compared with the survey results. This showed that there was a significant difference between these results. There was a much smaller difference between the results from the microclimate meter and the results from the questionnaires for Room 2, which was 0.53. While for Building 1 it was 1.83. Both buildings had similar air temperature (for Room 1 - 27.6°C, Room 2 - 27.7°C). Research conducted in an Energis intelligent building with renewable energy sources and a traditional building showed that the number of people dissatisfied with the thermal conditions exceeded 10%. In an intelligent building, closed windows could have a significant impact. And in the traditional building, the windows were open, which made the number of dissatisfied people smaller. Thus, it might not be so important if the building is very modern and equipped with state-of-the-art technological solutions, but how these systems are used for the benefit of the people there. In addition, the survey showed that the respondents prefer the indoor environment to have higher relative humidity. This may be due to the time of year that the survey was conducted (summer). The presented survey will be continued to collect more data on thermal comfort. This will allow the current temperature settings in smart buildings to be changed to more accurately suit the occupants and will also serve to modify the Fanger model. It is important to ensure proper thermal conditions in educational spaces because it has a significant impact on productivity and will also reduce energy costs.

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