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Influence of window and door opening on office room environment and human thermal sensation during different seasons in moderate climate

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ABSTRACT

Natural ventilation is commonly used in buildings because it does not require energy, and its various strategies, for example ventilation through an open window, can improve the indoor environment quality, including the thermal comfort of users. This study aimed to determine accurate environmental parameters typical for naturally ventilated rooms for three seasons: summer, autumn and winter, and to assess the occupants' thermal sensation in the mentioned conditions. Based on the measurements, the spatial distribution and time variability of air temperature and air speed in an office room with a stack natural ventilation system were assessed. The resulting data on the indoor environment parameters at different seasons and with various door and window opening configurations were used as an input to simulate human thermal sensation. Three models were used for simulation: predicted mean vote (PMV), the thermal sensation (TS) model developed by Zhang et al., and the advanced dynamic thermal sensation (DTS) model by Fiala et al., which allowed the demonstration of differences in the thermal comfort assessment depending on the method. Measurements have shown that opening the window with the door closed has a negligible impact on the parameters indoor environment parameters in summer; opening the door (cross-ventilation) changes this situation. The effect increased during autumn and winter, which affects users' thermal sensations. The assessment based on the most popular PMV model differed from the indications of advanced DTS and TS models showing significant discrepancies, which may lead to a misinterpretation of thermal comfort for individuals in the room.

1. Introduction

The thermal comfort of the occupants is one of the most important performance parameters in the built environment. The environmental parameters that influence thermal comfort are air temperature, air speed, humidity, and average surface temperature. The ventilation system in the building determines the air speed and also the indoor air temperature. Due to rising energy prices, environmental harm and growing resource scarcity in recent years, there has been a return to building ventilation solutions based on natural ventilation. Apart from the obvious disadvantages of such a system, related to the inability to recover energy from the exhaust air and the lack of control over the airflow, this system has many advantages; it does not require additional energy for fans, and the external airflow can be used for passive cooling. Furthermore, people in naturally ventilated buildings tolerate a wider range of indoor air temperatures, which are considered comfortable compared to people working in buildings with mechanical ventilation and air conditioning, resulting in a significant reduction in energy consumption for cooling [1–4]. Research and understanding of the natural ventilation process is part of the larger worldwide effort to reduce building energy consumption.

Natural ventilation depends on external weather conditions, as it occurs as a result of the pressure difference resulting from the difference in air temperature inside and outside the building and the movement of air outside (wind speed and direction). The design of naturally ventilated buildings requires in-depth knowledge and accurate airflow prediction to quantify natural ventilation rates and the associated impact on the indoor environment. There are three types of natural ventilation solutions [5]: one-sided external air supply (unilateral ventilation), airflow through the entire building (cross-ventilation), and airflow caused by the stack effect (stack ventilation). In each of the solutions, it is possible to achieve different ventilation intensity in individual zones

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of the building and thus the distribution of air parameters in the space and time (including air temperature and speed). However, even during the hot period, airflow, especially with cross-ventilation, can have a positive impact on the thermal comfort of occupants [6,7].

In recent years, the importance of ventilation in reducing cooling demand has been emphasised [5]. Currently, the energy consumption for cooling in buildings and households in the European Union averages 0.5 % of total energy consumption [8]. However, according to estimates, this consumption will grow in next years, even up to 9 % [9]. In developed countries, air conditioning can account for more than half of the electricity consumption in an individual building [10]. Along with the energy crisis and the increase in energy prices in the second half of 2022, efforts to reduce energy consumption are becoming increasingly justified. Natural ventilation solutions allow us to use the natural cool air provided by the climate without having to use additional energy for cooling. Such solutions require a temporary increase in the amount of airflow, which is typically performed by opening windows. However according to the idea of sustainability, saving energy in buildings should not be at the expense of the well-being and thermal comfort of users. All the more so because the increase in global air temperature as a result of climate change has intensified the problem of ensuring human thermal comfort in buildings, even in moderate regions [11]. Due to its economic and energy efficiency, natural ventilation is used for passive cooling and is the only such option for almost 70 % of the world's population [12].

Although natural ventilation is a low-energy consumption strategy, it still lacks a performance analysis and an operation strategy to maintain consistent indoor conditions. The impact of natural ventilation strategies on human thermal comfort in warm and hot season was assessed in various types of buildings [5]. The great potential of ventilation cooling to ensure affordable thermal conditions in rooms even in unfavourable climatic conditions has been confirmed. For example study by Li et al. [13] showed how natural ventilation can cover 60 %–100 % of the cooling demand of various buildings depending on the climate zone in China. Furthermore, a study conducted by Ramos et al. [14] in Brazilian residential buildings showed passive cooling by opening windows and doors in all climatic zones. In the article by Stasi et al. [15] the effectiveness of natural cross ventilation in a high-rise building in India was examined. A study conducted in residential buildings in Southeast Asia with a hot and humid climate showed that natural ventilation, mainly an indoor air speed of 0.04 m/s, is sufficient to ensure the thermal comfort of residents [16]. The study by Iskandar et al. [17] examined the effectiveness of six natural ventilation strategies in the cooling of a historic residential building located in San Antonio, USA, in spring and summer. All scenarios could contribute to energy savings in both seasons, especially in spring, and cross ventilation is the most effective strategy. In turn, Ran et al. [18] proposed the operation of the ventilation system in mixed mode (air conditioning and natural window ventilation), which allowed a reduction of the difference between the operating temperature of the air conditioning and the adaptive comfort temperature. The results showed that the hybrid system could reduce the number of overheating hours and building energy consumption by approximately 50 % in a residential building tested in Chinese climate. It should be noted that in buildings where ventilation through doors and windows is the main way of controlling the indoor environment, the adaptation of occupants is particularly important. This aspect has been considered in numerous studies [5]. Indraganti et al. [19,20] showed that residents in India adapted through clothing and metabolism as air temperatures increased in summer. Kumar et al. [21], Dhaka et al. [22], and Lai et al. [23,24] indicated that the window opening time tends to increase as the indoor and outdoor air temperature increases. In turn, Faheem et al. [25] found that window opening is influenced by the season, time of day, days of the week, building orientation, user type and gender.

Due to relatively poor air exchange, naturally ventilated rooms also require periodic opening of the windows in the fall and winter to dilute air pollutants. This improves indoor air quality, but may cause discomfort for users during cold periods caused by a decrease in indoor air temperature. Zhang et al. [26] indicated that thermal comfort is rarely taken into account in naturally ventilated buildings in winter. In this aspect, Li et al. [27] conducted a study on the assessment of window opening time on the indoor air quality in a residential building in northeastern China. To achieve a satisfactory ventilation rate, the window should be opened for 2–6 min in winter. Lei et al. [28] noted that a short window opening time, especially with a small opening area, may not dilute CO_2 effectively. On the other hand, a long opening time, especially with a large opening area, would drop the air temperature in the room to an unacceptable level.

The achievement of energy savings and appropriate ranges of average air temperature in naturally ventilated rooms seems unquestionable, but the evaluation of local human thermal sensations, which may be crucial in the assessment of thermal comfort, remains an important aspect. Opening windows may cause a local increase in air speed and an uneven change in air temperature in the room (mainly near the window). Most thermal comfort studies are mainly based on static models which consider steady-state heat transfer between the human body and the environment, assigning a comfort vote (i.e. PMV-PPD [29,30]) or adaptive models [29,31] taking into account human reactions and relative changes in the indoor environment. Machine learning algorithms are also used to predict human thermal sensations [32]. Analyses based on these models do not consider the distribution of air parameters in the room space and local thermal sensations in individual parts of the body. In such a case, the overall human sensation is solely used for decision-making without considering any local thermal effects in individual body regions caused by a heterogeneous spatial distribution of room parameters. There are several local thermal sensation models reported in the scientific literature that can offer such opportunity of local evaluation of thermal sensation over the human body [33,34]. These model however require as an input data the results of measurements of air parameters at different heights in the room and human physiological parameters, such as local and mean skin temperatures, core temperature as well as rate of change of the skin temperature. To obtain such an input, an adequate and accurate model of human thermophysiology and associated clothing definition is necessary to translate the environmental exposure parameters into the thermophysiological status of the exposed occupant. This is probably the greatest difficulty to overcome when trying to assess local thermal comfort under heterogeneous conditions related to natural ventilation.

2. Research gap and aim

Analysis of the distribution of indoor air parameters, combined with an appropriate model of thermal sensations, can show whether the ventilation method used does not have a negative impact on the occupants, including: draughts, local warmer or cooler areas. Currently, the main research methodologies to assess the indoor environment in naturally ventilated buildings include mainly full-scale measurements, reduced-scale measurements in wind tunnels, and computational fluid dynamics (CFD) simulations [35]. There is a scarcity of literature concerning both indoor parameters distribution and at the same time the evaluation of human thermal sensations in naturally ventilated spaces. The lack of literature is due to the wide variations and differences in the natural ventilation process of buildings, which depend on the structure of the building, construction, and the orientation of windows or other ventilation openings, as well as climatic differences. Therefore, there is a lack of general results and conclusions on this issue.

Part of currently available articles on natural ventilation ability to cool buildings shows nothing more than the air speed distribution on room air inlets/outlets (windows, doors) and based on that indicates ACH (air change rate) [36]. It seems not to be enough to formulate statements about NV cooling potential, especially given that those publications do not provide any information about parameters distribution in space. Therefore, they also do not offer reliable information about the possible thermal sensations of people in the room. Other publications [37–39] point out the good ventilation and cooling potential of natural ventilation in buildings while showing results in which air speed in naturally ventilated rooms exceeds significantly recommended velocities of 0.25–0.3 m/s [30] and reached even 4 m/s in occupied zones. Those studies concerned specific scenarios (i.e. specific year period, localization, building configuration) and did not consider thermal comfort of building occupants. Moreover, there is a lack of information on validation of the used CFD models. Third group of studies [40,41] are those which concerns natural ventilation potential based on global air temperatures in room, averaged for longer periods of time. Most of them use building energy simulations (BES) software [42] and one-node thermal comfort or adaptive models. Although these publications were prepared based on results from validated comfort models and BES-type programmes, they do not take into account asymmetry in the distribution of parameters and, therefore, allow only for an averaged determination of human thermal comfort. Currently only Zemitis et al. [43] showed analysis concerns indoor parameters distribution and human thermal sensations but only for specific Latvian winter conditions. The indoor conditions were analysed in the school building and human thermal comfort was evaluated using PPD parameter. Authors created CFD model of classroom, however their study did not include validation of results.

The aim of this study was to provide real environmental parameters typical for office rooms with natural ventilation for three seasons: summer, transitional season (autumn) and winter and to assess the thermal status of room occupants in the mentioned conditions. The spatial and temporal distribution of air parameters (temperature and speed) was evaluated based on results of in-situ measurements in the room. The aim of the study was to show not only the asymmetry of indoor parameters but also the thermal sensation of users in different positions for various ventilation scenarios (with windows and doors open or closed). This assessment was based on thermal sensation simulations using the established local thermal sensation model (TS) developed by Zhang [44–47] and the global dynamic thermal sensation (DTS) model by Fiala et al. [48].

3. Methods

To provide a dataset of indoor environmental parameters, field measurements were taken. The measurements took place in an office room located on the second floor of a five-floor university building. The room has one external wall, with a 4-sash window (typical double glazing without any blinds and shadings), oriented in the southwest direction. The window is characterised by an average degree of tightness (the air infiltration coefficient is approximately 0.2 $m^3/(m\bullet h\bullet Pa^{0.67})$), the total length of the window cracks is 18 m). The dimensions and configuration of the room in terms of window and door are shown in Fig. 1. Moreover, the furniture (desk, cabinet, bookcase and 4- leg table) are shown as grey contour. The room is a part of a building built in the second half of the 20th century, which is after thermomodernisation carried out in 2013. The building is constructed using prefabricated reinforced concrete technology. Such shapes and structures were very popular for Polish buildings built in the 1970s and 1980s. Similar buildings are often found throughout Central Europe. The layout of the room with a large window on one side and a door on the opposite side is a typical office room. In the building under consideration, the room layout is repeatable; there are dozens of such rooms and there are many buildings with a similar layout in Poland. The building is located in an urban area in southern Poland. This location has a moderate transitional climate (Dfb class according to the Köppen-Geiger classification [49]). Air exchange in the room is solely through the natural ventilation system. The room has one gravity ventilation grille connected to the roof by a chimney. The room is equipped in heating system working from September do May.

3.1. Measurement in the room

The one-day measurements were carried out in three periods of 2022 and 2023: summer, twice: August 3 and 6 ($temp_{out1}$ = 21–26 °C, $speed_{wind1}$ = 0.3–1.8 m/s, $temp_{out2}$ = 17–21 °C, $speed_{wind2}$ = 1.8–4.5 m/s), transitional, November 25 ($temp_{out}$ = 6–7 °C, $speed_{wind}$ = 0.5–1.2 m/s) and winter, February 7 ($temp_{out}$ = 2–3 °C, $speed_{wind}$ = 3.5–6.5 m/s) during working day between late morning and afternoon. The selected measurement days are representative for particular periods of the year. Taking into account the standard climate (Typical Meteorological Year [50]) for the location under consideration, the external air temperature varies throughout the year in the range of −19°C–31°C, with wind speeds of up to 12 m/s, mainly from the west. Taking into account the working time of the day, only from 7 a.m. to 5 p.m., in summer, for 80 % of this time, the external air temperature is within the range of 15–30°C, and the air speed of 0.5–4.5 m/s (half in the lower and upper values). In autumn, for 80 % of the working time, the external air temperature is within the range of 0–15°C, and the air speed of 0.5–4.5 m/s, of which a quarter is in the range of 0.5 m/s to 1.5 m/s, in winter for 80 % of the working time during the day, the outside air temperature is within the range of −5 °C to 5°C, and the air speed is within the range of 1.5–6.5 m/s 70 % of the time. The distributions of external air temperature and wind speed are presented in Fig. 1. Autumn was chosen as a transitional period. In a moderate transitional climate, the external climate conditions are very similar in autumn and spring (similar external air temperature, sun altitude and solar radiation). Therefore, it was assumed that window and door openings affect the spring measurement session similarly to the autumn session. Each measurement contained four subsequent phases. One measurement phase lasted 30 min. The differences between phases are depicted in Table 1.

The main measuring devices were twelve thermo-anemometers (SENSOANEMO 5100SF, Sensor Electronic, Poland), which measured air temperature and speed. Twelve sensors were used. The sensors were mounted on three stands, four sensors per stand at different height levels according to ISO/DIS 7726 [51] standard for both sitting and standing positions (10 cm, 60 cm, 110 cm and 170 cm) and distributed in the room in three locations (A, B and C; see Fig. 2). The second measuring device used to for long-term monitoring of the air conditions in the room

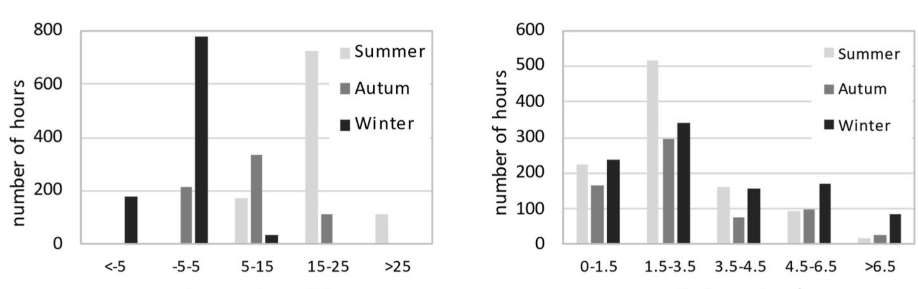


Fig. 1. Distribution of external air temperature and wind speed for three periods of year taking into account only working hours during day (7 a.m.–5 p.m.).

Table 1
Description measurement phases.

Measurement phase			
1	2	3	4
Cross-ventilation	Stack ventilation		
✓ door to corridor open *effective open area: 1.89 m²*	✓ door to corridor closed	✓ door to corridor closed	✓ door to corridor closed
			
✓ two windows ajar *effective open area: 0.34 m²*	✓ two windows ajar *effective open area: 0.34 m²*	✓ one window ajar *effective open area: 0.15 m²*	✓ all window sashes closed
			

Table 2
Sensors parameters.

Sensor type	Parameter	Range	Accuracy
Transducer with omnidirectional air speed and temperature sensor SensoTCM 5507, Sensor Electronics, Poland	Temperature Speed	−10–50 °C 0.05–5 m/s	±0.2 °C ±0.02 m/s ±1 % of readings
Digital sensor SHT31 Sensirion APAR 236.B, APAR Control, Poland	Humidity Temperature	0–100 % 30–80 °C	±2.5%RH ±0.3 °C

throughout the analysed seasons was the relative humidity and air temperature recorder (AR236.B, APAR Control, Poland), in total, four recorders distributed in the room at the height level of 80–120 cm in locations alfa, beta, gamma and delta (Fig. 2). The evaluation of the relative humidity distribution was outside the scope of this study. These additional measurement allowed the selection of representative measurement days not only in terms of external conditions, but also indoor conditions and showed the range of indoor air temperature variability in all seasons. This was also the basis for selecting appropriate boundary conditions for further simulations. Characteristics of both types of sensors are listed in Table 2.

Mean radiant temperature was assumed based on calculation done with CBE 3D Mean Radiant Temperature Tool [52] using wall parameters (internal walls temperature assumed to be equal to air temperature and emissivity), window properties and sun properties same as in measurements days as inputs. These simulations showed that the radiant temperatures differed from mean air temperature by less than 0.2 °C, which is below the measurement accuracy of the temperature sensors.

3.2. *Simulation of occupant thermal sensations indications in naturally ventilated spaces*

The resulting data on indoor environment parameters at different times of the year and with various door and window opening configurations were used as input to simulate human thermal sensation. To make the comparison reliable, each simulation, regardless of used input data, assumed one scenario of events including initial steady-state conditions with closed windows and doors and occupant sitting in the room followed by 5 min of conditions with opened window(s) and doors and final period of time with closed windows and doors where the parameters of the indoor environment naturally returned to their values from the initial period before the windows were opened. The local insulation of clothing considered body sitting posture and corresponding decreased insulation was adopted according to Fojtlin et al. [53]. The clothing parameters used in simulations are presented in Table 3. Two clothing sets were used to reflect typical seasonal office clothing including Tshirt, trousers, socks and light shoes for summer season and long-sleeve shirt, undershirt, trousers, socks and shoes for winter and transitional seasons (Table 4).

To simulate human thermal response to heterogeneous environmental parameters in the office room, three global and one local thermal sensation models were used as follows:

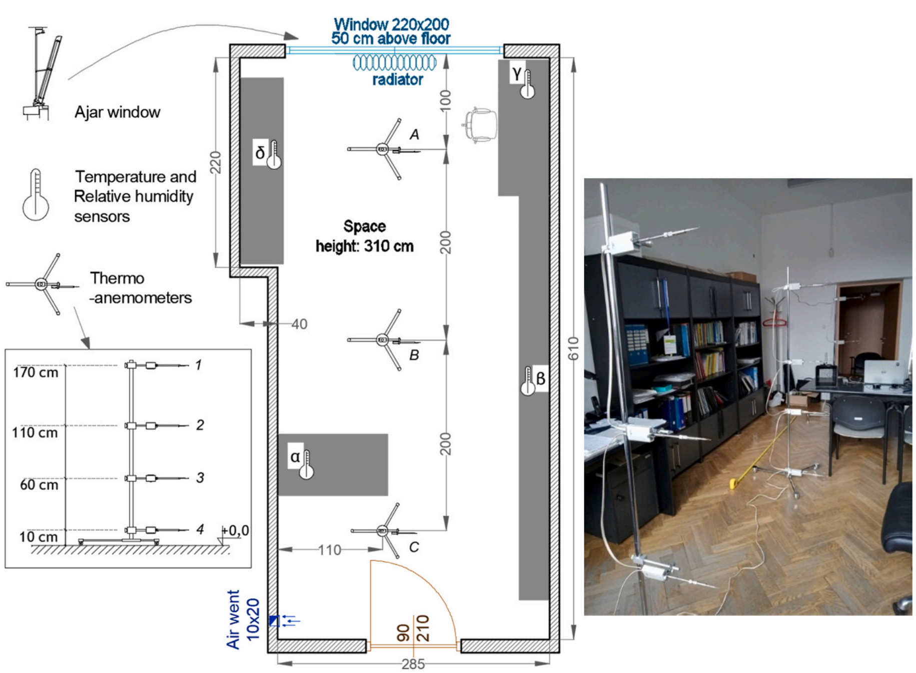


Fig. 2. Overview of the office room with its dimensions and location of the sensors.

Table 3
Body division and summary of initial input data used in the model.

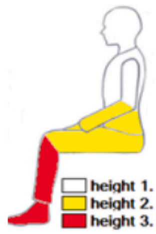
	Input type:		Summer			Autumn			Winter		
			A	B	C	A	B	C	A	B	C
	Air temp., °C	1:	28.4	28	27.8	22.2	21.9	21.5	22.2	22	21.4
		2:	27.7	27.4	27.1	21.9	21.3	21.2	21.8	21.5	21
		3:	27.6	27.1	26.9	21.6	21.1	20.9	20.9	20.7	20.3
	Air speed, m/s	1:	0.05	0.05	0.05	0.07	0.05	0.05	0.1	0.05	0.05
		2:	0.08	0.05	0.06	0.07	0.05	0.05	0.05	0.05	0.05
		3:	0.11	0.09	0.15	0.07	0.05	0.2	0.06	0.14	0.17
MRT, °C	27.6					21.5			21.3		
Rh, %	54					41			25		
Activity, met	1.3 (sitting office work)										
Clothing, clo (avg)	1.126					1.170					

Table 4
Thermal insulation properties used in simulations.

Local thermal insulation properties	Summer clo/fcl[a]	Transitional/ Winter clo/fcl[a]	Local thermal insulation properties	Summer clo/fcl[a]	Transitional/ Winter clo/fcl[a]
Head (short hair)	0.65/ 0.98	0.65/1.24	Hip – front	1.29/ 1.13	1.41/1.17
Arm - upper	0.97/ 1.51	0.97/1.40	Hip – back	3.54/ 2.00	3.54/2.00
Arm - lower	–	0.59/1.26	Thighs – anterior	0.44/ 1.26	0.54/1.36
Lumbus	3.54/ 2.00	3.54/2.00	Thighs – posterior	3.54/ 2.00	3.54/2.00
Back	3.54/ 2.00	3.54/2.00	Calves – anterior	0.71/ 1.46	0.75/1.59
Shoulders	0.46/ 0.98	0.54/1.00	Calves – posterior	0.90/ 1.78	0.97/2.17
Chest	0.46/ 0.98	0.54/1.00	Feet	0.82/ 1.54	0.82/1.54
Abdomen	1.02/ 1.21	1.25/1.25			

[a] fcl – local clothing area factor [–].

- Predicted mean vote (PMV) model as a most frequently used model in research on comfort in built environment, which is also implemented in national and international standards [29,30,54]. The environmental inputs to the model were obtained by averaging heterogeneously distributed parameters in the location of exposure. Table 3 shows the division of body into three parts and the air temperature and speed values assigned to them. The general values of air temperature and speed were obtained as weighted averages where weights were particular body part surfaces. This model can be applied to occupied spaces where users have a level of activity between 1.0 met and 2.0 met and where clothing that provides thermal insulation not exceeding 1.5 clo is worn. Although the room is mechanically conditioned only in the transitional and winter periods to be able to compare the results, this model was also used in the summer period (naturally conditioned room). The ASHRAE 55 standard [29] does not exclude this method in such case. Global insulation of clothing was calculated based on local values using the parallel method according to ISO 15831 [55]. Clothing insulation and metabolic rate are provided in Table 3. Originally this model was designed for steady-state conditions, but in practice it was proven to also work for some mildly transient conditions [33]. The result of the PMV model is provided on a 7-point scale as a global value for the entire body.
- Dynamic thermal sensation (DTS) model [48] is highly suitable for the simulation of transient conditions [56] and requires physiological parameters such as the mean skin temperature and the core temperature of the body, as well as the rate of change in skin temperature as input parameters. For this purpose, the human thermoregulation model FPCm [57] was applied to obtain these parameters for given conditions in the naturally ventilated office room. The selection of the model was guided by the available validation evidence [33,58–60] and model availability for wide audience (commercial and academic licenses available for purchase). The exposure conditions were applied individually to three regions of the body corresponding to different height levels and corresponding sensor data as depicted in Table 3. Clothing properties were also applied locally in these three regions, as listed in Table 3.
- Thermal sensation (TS) model, also referred to as the UCB comfort model (University of California, Berkeley) [44–47] developed to model spatially transient environmental conditions. It predicts both the local thermal sensation and forecasts the whole-body thermal sensation based on the local thermal sensations of individual body parts. The model local skin temperatures and body core temperature as inputs. In this study we used the same simulated data using human thermoregulation model FPCm as in case of DTS model simulations.

4. Results

The main aim of the in-situ measurements was to assess the air temperature and speed distribution in the room under various natural ventilation conditions. The results of this evaluation allowed for the creation of scenarios to simulate human thermal sensations in the next step. Example results of air speed measurements on individual measurement days for the case of a cross-ventilation at a height of 10 cm from the floor are presented in Fig. 3.

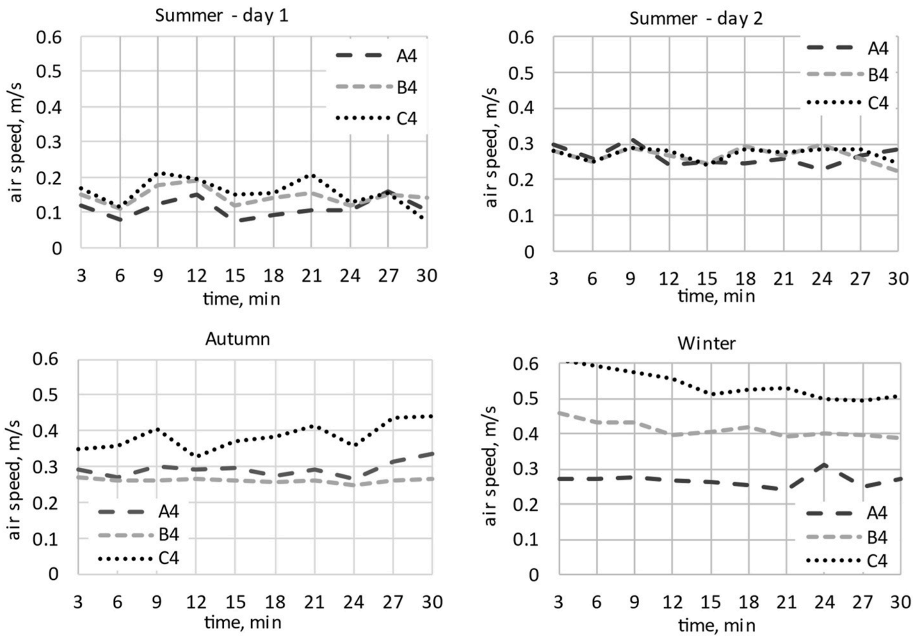


Fig. 3. Air speed depending on the distance from the window at height 4 (10 cm from the floor) – phase 1 (two open windows and an open door).

In each period, the air speed value was variable. The highest speed values occurred near the floor (location 4) and at the highest location 1. The air inflow from the corridor and windows into the room resulted in higher air speed. Even in the case of the closed windows, in location C (closest to the door) the air speed at the floor was 2–3 times higher than in the other locations. The speed distribution in the summer period was practically irrelevant. The increase in air speed was influenced by the air temperature difference between the indoor and outdoor environment; the greater the difference, the higher the speed. In summer, the air speed did not exceed 0.2 m/s; in winter, the instantaneous value reached 0.6 m/s in the case of cross-ventilation. Wang [61] demonstrated a vertical distribution of air speed and temperature similar to this study.

Regardless of the period of the year, with closed windows and door (very little air exchange caused by negligible inflow of fresh air through leaks in the windows and door – mainly the gap under them), the indoor air temperature increased slightly due to internal (e.g. computer) and external (solar radiation) heat gains (during 30-min measurement it was no more than 0.4^{o}C in summer, in the rest periods of the year air temperature was control by heating system). Irrespective of the season, opening the windows and simultaneously opening the door to the corridor reduced the air temperature if the external temperature was lower than the indoor temperature; in summer, after 30 min, the air temperature dropped by a maximum of 0.8^{o}C in location C2 on the first day of measurement and by 1.1^{o}C in the same place on the second day of measurement when the outdoor temperature was lower. In the transitional and winter periods, opening the window and especially opening the window and door resulted in a sharp drop in air temperature in the first minutes after opening, due to the delay in response of the heating control system (in winter it was even 4.6^{o}C in location C1), after 10–15 min the indoor temperature stabilised but the indoor temperature did not reach the air temperature before opening the window due to the limited power of the heating system. In all periods of the year, there was a vertical stratification of the air temperature in locations B and C of the room, with the lowest values near floor (in summer, difference between points 1 and 4 was on average 1.5^{o}C regardless of the type of ventilation, in winter even 2.5^{o}C in case of cross-ventilation). In the closest to the window location A, the vertical air temperature distribution depended on the room height only in summer and autumn when the windows were closed. With cross-ventilation, air inflows disturbed the air temperature stratification in this zone. Location near the window was also highly influenced by solar radiation (the windows did not have any sun protection). In turn, in winter, this location was under a great direct influence of the heat flow from the radiator. The passive cooling potential was only noticeable in the case of cross-ventilation, otherwise there were no significant changes in indoor temperature. This result is similar to studies reported in the literature [17,62].

Since the used models are multi-nodal, environmental parameters measured on different heights were used as initial input for different body parts. The division of the body into individual parts to which these particular inputs have been assigned is shown in the Table 3. Since the study undertakes sitting position of human body, results from 2nd, 3rd and 4th sensor in each location (A, B, C) will be used in simulations.

4.1. Relationships between indoor environmental conditions and thermal sensation

The first part of the presented results includes 3D plots (Figs. 4 and 5) showing the change in thermal comfort of a person sitting in different locations in the room (A, B, C) during three periods of the year (summer, transitional and winter), correlated with average environmental indoor parameters (air temperature and speed). The plots are used to illustrate the degree of thermal comfort changes occurring alongside indoor environmental parameter changes. To present human thermal comfort DTS model, as the good validated and proven, was used [60].

Data presentation on the charts begins five minutes before the windows are opened. Then, a decrease in air temperature and an increase in speed are observed, along with the associated change in thermal comfort. The values marked on the chart are: the last minute before the windows are opened, the last minute before the windows are closed, and after 1 h. In each period, the lowest air temperatures before the windows were opened were in location C, while the highest were in location A. Also in position C, the least visible effect of air cooling (in terms of air temperature drop) was observed regardless of the season. With windows closed, the average air speed never exceeded 0.08 m/s and there are no visible differences in distribution of average air speed between different localisations. Air speed increased significantly when two windows were opened – even up to 486 % (winter, localization A). When one window was opened, the highest speed increase was 86 % (autumn, location A).

The smallest changes in indoor environmental parameters are observed during summer. Only with both windows open, in their

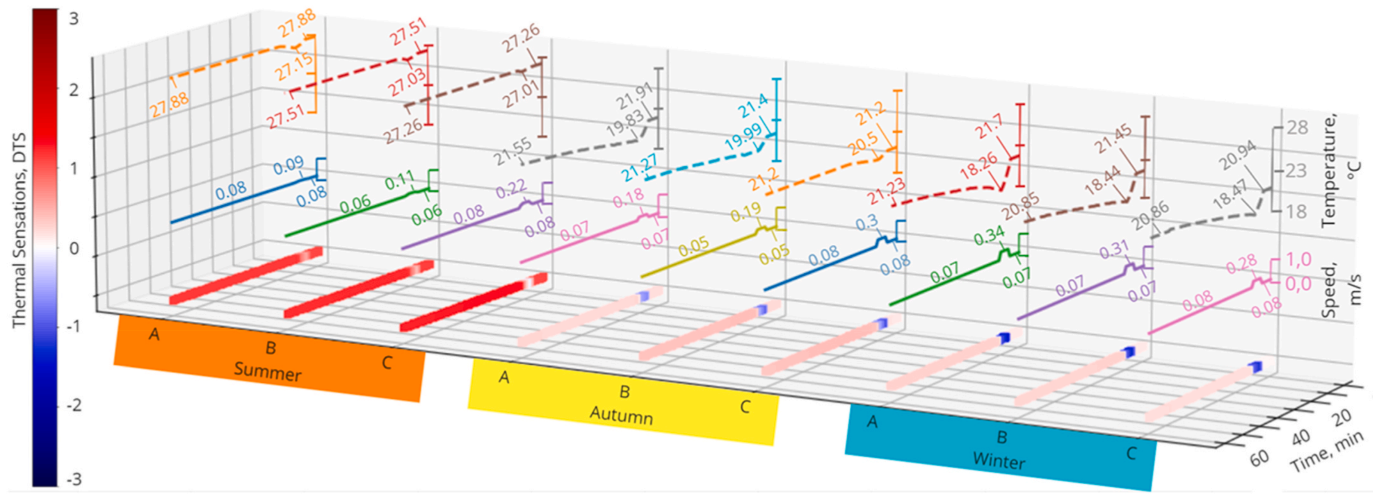


Fig. 4. Human thermal comfort (heat maps) correlated with air temperature and speed (lines). Two windows open.

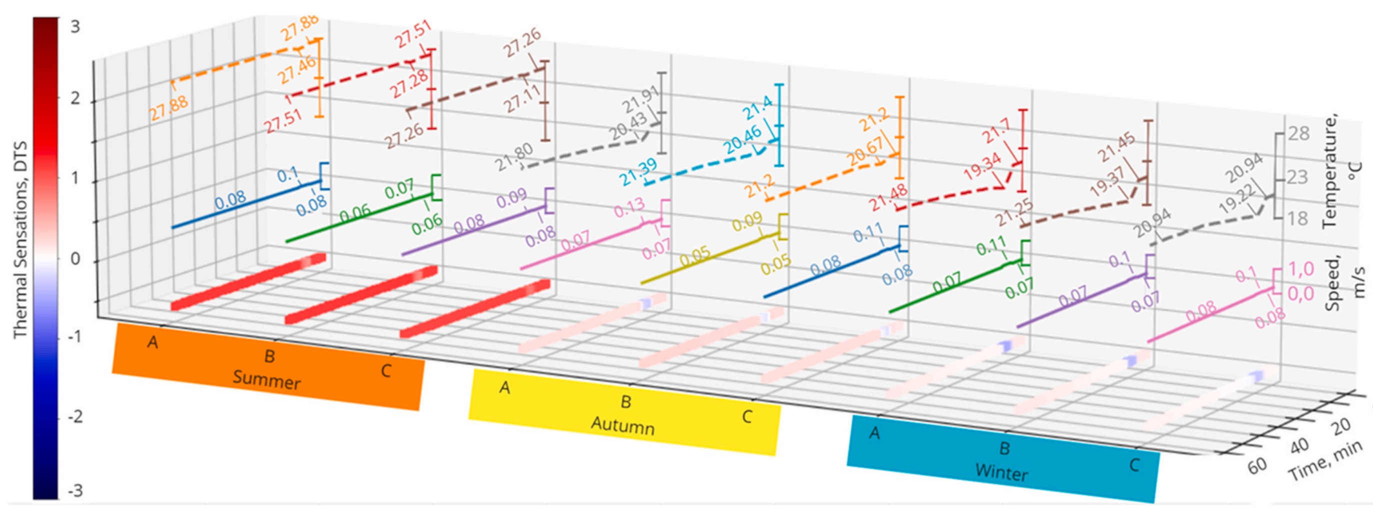


Fig. 5. Human thermal comfort (heat maps) correlated with air temperature and speed (lines). One window open.

immediate vicinity, that is, in location A, does the air temperature decrease by more than 0.5 °C. Also, the air speed changes slightly – the highest increase is recorded in location C with two open windows and amounts to 0.22 m/s. However, relatively small changes have an impact on thermal comfort. With closed windows, thermal comfort according to the DTS model is 1.11, 1.13, and 1.08 at locations A, B, and C, respectively, decreasing to 0.55, 0.40, and −0.11 with both windows open, and also to 0.65, 0.73, and 0.94 with one window open.

The greatest changes in indoor environmental parameters occurred during winter. The highest recorded average air speed was 0.34 m/s. The largest air temperature drop was 3.44 °C (winter, two windows opened, location A). In the transitional and winter period, the window opening gives opposite result as in summer. While with both windows closed, DTS remains at level 0.07–0.23, so with two windows open, the thermal sensation drops to a range of −1.30 to −1.43 in winter and −0.67 to −1.01 in transitional period.

4.2. Physiological parameters – Skin temperature, core temperature, sweating

Fig. 6 contains data related to skin temperature. Average body temperature and the temperatures of three specific body parts, hands, feet, and forehead, have been shown. Due to low differences between skin temperatures in different localizations and different window opening scenarios, area charts showing the range of body surface temperatures in specific seasons were used. The plots present the data from before the windows are opened, through the period they are open, to 3 h after they are closed again. During this time, there is a change in skin temperature caused by the opening of the window and the change in internal parameters, as well as its subsequent stabilization and return to pre-window opening values.

In summer, the average skin temperature ranges from 34.4 °C to 34.6 °C and decreases to around 34.3 °C with both one and two windows open. Only by also opening the doors does the average body temperature drop to 34.1 °C. The return to the stable body surface temperature occurs between the 30th and 50th minutes after the windows (and doors) are closed. The temperature of individual parts of the body (forehead, hands, and feet) when the windows are closed is similar. For the feet and hands, it ranges from 34.7 °C to 35.0 °C. The temperature of the forehead is slightly higher, around 35.7 °C in each location. The decrease in forehead surface temperature during room cooling is at most 0.25 °C, while the temperature of the hands decreases from 0.2 °C (one window open) to 0.8 °C (windows and door open), and the temperature of the feet decreases from 0.1 °C to 0.3 °C.

In winter and transitional season, when windows are closed, skin temperatures are on similar level (due to similar indoor conditions) and are more varied and lower in compare to summer temperatures. In transitional period average body surface temperature is 32.8–32.9 °C

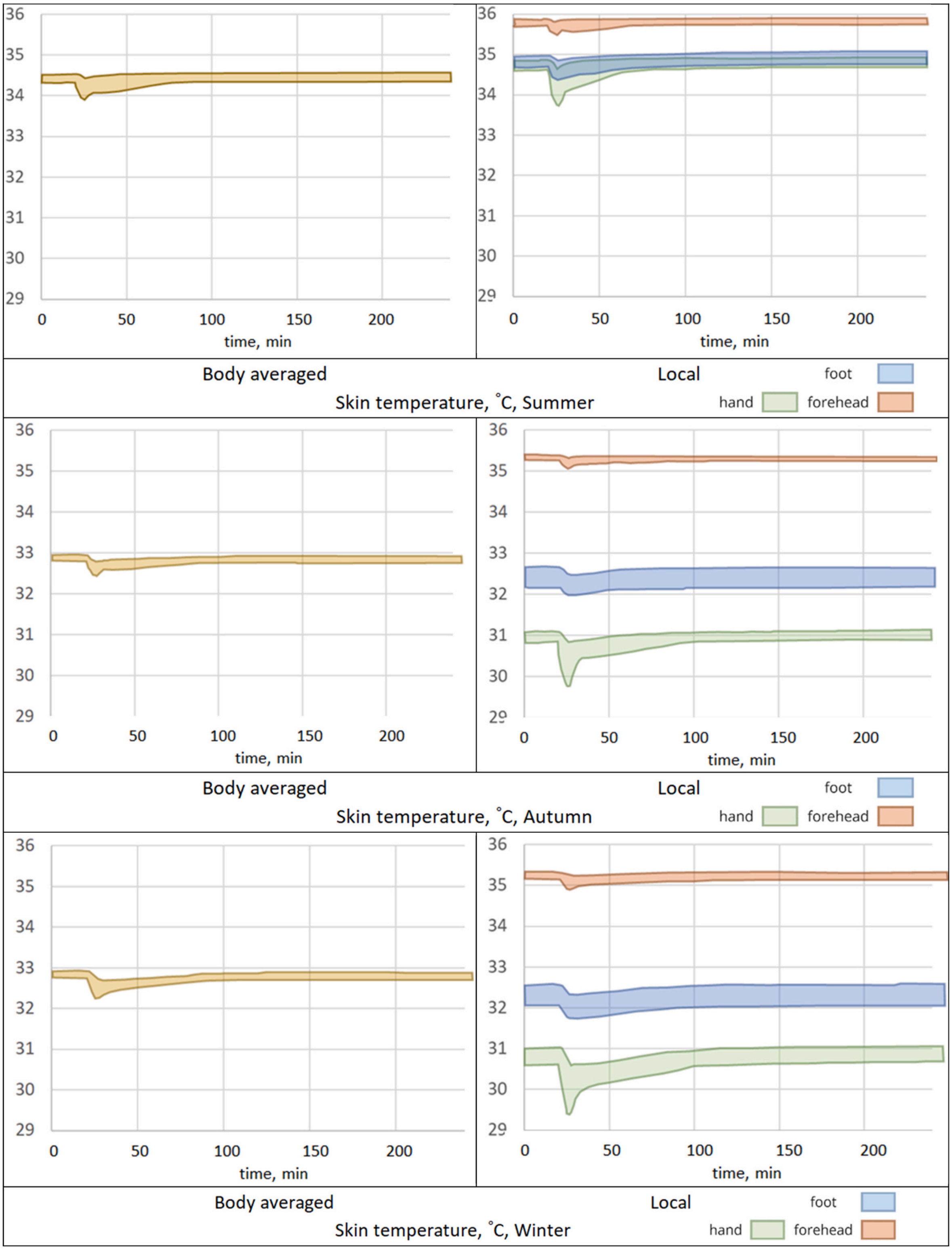


Fig. 6. Temperatures of skin for forehead, hand, feet and averaged for whole body.

and decreases to 32.7–32.6 °C during airing. The return to the initial values takes about 60–65 min. Among the analysed body parts, the forehead retains the highest temperature of 35.2 °C at each location. Also, the decrease in forehead temperature is slight – temperature does not exceed 35.0 °C. The temperature of the limbs is noticeably lower. The feet have a temperature between 32.2 °C and 32.6 °C, but their temperature does not decrease more than 0.2 °C. A lower surface temperature is observed in uncovered hands. Their temperature ranges from 30.9 °C to 31.1 °C and depending on location and scenario decreases to 29.9 °C (both windows opened, location A) and 30.8 °C (both windows closed, location B and C).

In the winter season, the average skin temperature remains within the range of 32.7 °C–32.8 °C despite of the location and the scenario of the window opening and stabilises after about 70–75 min. The temperatures of the analysed body parts are slightly lower in comparison to the transitional period. The forehead temperature is 35.2 °C either way and decreases from 0.1 °C to 0.3 °C. The feet have a temperature between 32.1 °C and 32.5 °C, and their temperature decreases depending on the location and opening of the window in the range of 0.2 °C–0.45 °C. The lowest surface temperature is observed again in hands. Their temperature ranges from 30.7 °C to 31 °C and decreases to even 29.5–29.7 °C with both windows open in each room location.

In addition to skin temperature, the Fiala model allows for the determination of other physiological parameters of the human body, such as body core temperature (Tre) or sweating intensity (sMsw). The body core temperature, regardless of the room location, was 37.4 °C in the summer period, while in the winter and transitional periods it was 37.3 °C. During the cooling of the room caused by window opening, changes in body core temperature did not exceed 0.1 °C – thus, it can be considered that the body core temperature remained unchanged.

Sensible perspiration occurred only in the summer season and is approximately 1.4–1.5 g/min. The skin humidity was estimated to be between 0.46 (location C) and 0.49 (location A), and natural 5-min room cooling did not allow this parameter to drop below 0.30, defined as the comfort limit associated with skin humidity.

4.3. Thermal sensations simulations. PMV, DTS and TS model

Figs. 7 and 8 present detailed results of thermal sensation simulations using three models: DTS, TS, and PMV. The individual points on the Y-axis correspond to specific moments: 1 – the last minute before opening the windows, 2 – 2 min after opening the windows, 3 – the last, fifth minute of window opening, 4 – 5 min after closing the windows, 5 – half hour after closing the windows, 6 – 1 h after closing the windows, 7 – 2 h after closing the windows. To facilitate comparison, the results of the TS model were rescaled to fit within the range of −3 to +3, as suggested by Koelblen [34].

Generally, there is no quantitative convergence between the indications of particular models. The only general observation that applies to all locations in each season is that the TS model consistently indicates the coolest sensations.

In the summer period, the DTS model indicates sensations at level 1.08–1.13 and only in the DTS case, during natural cooling, full thermal comfort is achieved, i.e., around point 0, in each location. In locations A and B, such conditions are achieved only when both windows and doors are open. In location C, even opening only the two windows allows for a significant improvement in sensations. After the windows are closed, the thermal sensations return to a level above +1. Right after closing the windows, there is a slight increase in the DTS values (up to 1.29 in position C) compared to the state before the windows were opened. Opening one window in position A has a similar effect to opening two windows. DTS decreases to a level of 0.62. As you move away from the outer wall, the ventilation effect caused by opening one window decreases. In location B, DTS indicates 0.73, and in C, it's 0.82.

The TS model indicates lower values when windows are closed and a smaller decrease in thermal sensations during ventilation compared to the DTS model. Again, opening both windows and doors brings about the greatest reduction in sensations, even in position C. Sensations, starting from the level of 0.83 (with closed windows), decrease to approximately 0.50 in positions A and B. In position C, they drop even further, reaching 0.10 after 2 min of ventilation. Opening two windows and one window in positions A and B yields similar results to DTS indications. Opening two windows lowers TS to the level of 0.52–0.70, while opening one window lowers it to 0.62–0.70.

The highest indications, both with closed windows and during ventilation, occur with the PMV model. In locations A and B, only opening both windows and doors leads to a decrease in indications below +1.0. In location C, opening two windows also causes such a decrease.

During transitional and winter periods, the TS model assumes the greatest sensation of cold and associated discomfort among room occupants, which occurs in the absence of room ventilation (ranging from −0.74 to −0.82) and intensifies when the windows are opened. The greatest decrease is observed when both windows are opened, both in winter and during the transitional period in locations A and B, 2 min after opening the window. Thermal sensations of the TS models drop below −1.50, indicating a significant cold sensation. In location C, the decrease in thermal satisfaction is smaller, ranging from −1.30 to −1.20. Further analysing the results of the TS model, in the last minute of window opening, there is an improvement in thermal sensations consistent with the actual physiological reaction of the body – there is an increase in thermal comfort level by 0.40–0.47 points in locations A and B. The same phenomenon is also visible in the indications of the DTS model; however, the improvement in sensations and their values are smaller. The DTS model also indicates that during the transitional period, location C is the least optimal in terms of thermal satisfaction. The thermal comfort level decreases to −1.01 in location C, while in location B it is −0.88, and in location A it is −0.67. In the last minute of

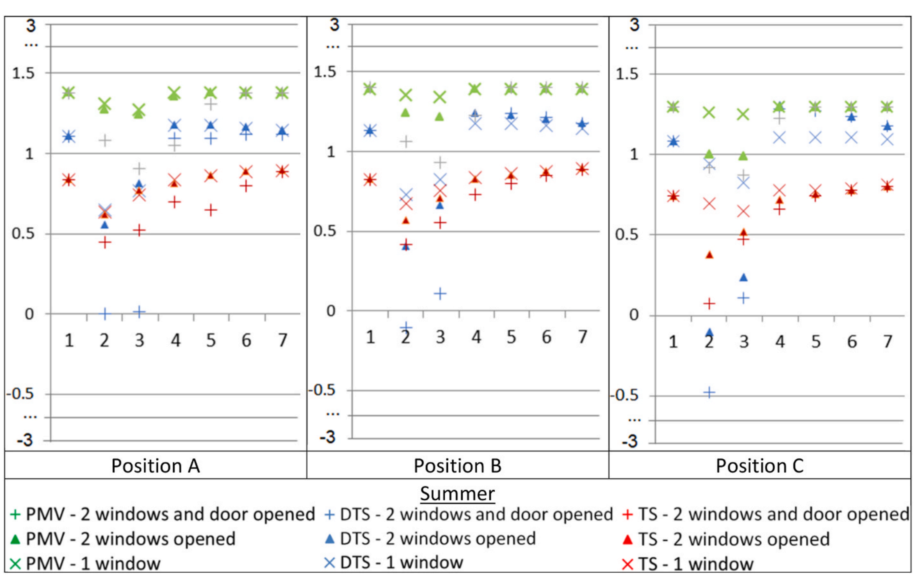


Fig. 7. Human thermal sensations in summer season according to three models – PMV, DTS, and TS.

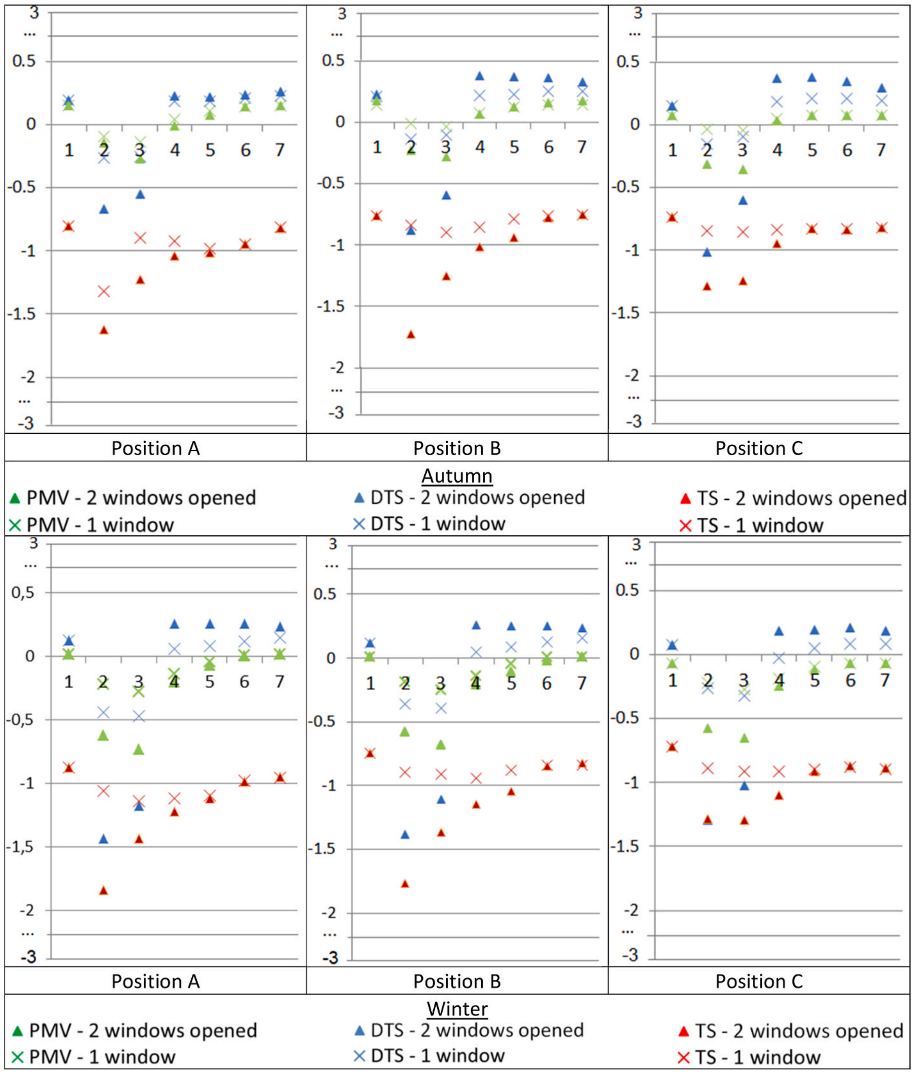


Fig. 8. Human thermal sensations in transitional and winter seasons according to three models – PMV, DTS, and TS.

window opening, comfort stabilises to a similar level at all locations, ranging from −0.55 to −0.60.

According to the PMV model, opening two windows, both during the transitional and winter periods, causes slight changes. The comfort limit is exceeded only in winter, reaching a level of −0.65 to −0.73 points depending on the location. Opening one window brings much smaller changes in simulated thermal sensations. The DTS and PMV models similarly evaluated the thermal sensations under these conditions, considering them satisfactory, falling within the range of 0.00 to +0.20 and decreasing during opening to a maximum of −0.47 in winter (location A) and −0.26 during the transitional period (also location A). Once again, the sensations were rated lowest by the TS model, below the comfort boundaries. With closed windows, satisfaction is rated −0.95 to −1.16. During the opening of one window, the greatest changes in sensations are seen at point A, with a decrease to −1.76 in autumn and −1.52 in winter. In other locations, the decrease is minimal, reaching a maximum of −1.22.

5. Discussion

The opening of windows has a different impact on indoor air parameters and the human sense of thermal comfort, depending on the season and location in the room, however it was not as significant as reported by Kumar [38]. In the summer season, when ventilation does not significantly lower the indoor temperature, air speed becomes a significant factor for cooling. In each scenario and in every location, opening windows positively affected thermal comfort, however scenarios involving the opening of two windows or two windows along with doors are more optimal. The best thermal comfort ratings in the summer occur in location C due to the higher airspeed present there. Location C is also the farthest from the window, which is the main source of heat during the summer due to sunlight radiation. As a result, the air and radiation temperature in this position are lower.

During the transitional and winter seasons, window opening negatively affects thermal sensations. However, during these periods, in a moderate climate, ventilation is not used to cool the space but rather to improve the indoor air quality. Improving air quality in the work environment is crucial; however, it should not come at the expense of deteriorating thermal conditions. In the winter, the opening of two windows significantly affects the indoor environmental parameters, leading to a decrease in thermal comfort. Two dynamic models, DTS and TS, indicate a decrease in thermal sensation below acceptable values (e.g., according to ASHRAE standard [29]). Therefore, less abrupt ventilation by opening only one window seems to be a more optimal solution in terms of maintaining thermal comfort, although it may be less effective in exchanging polluted air. On the other hand, even in the most extreme scenario in terms of thermal comfort (i.e., winter, two windows open, location A), the DTS model indicates that thermal sensation values come back to initial values from before the windows were opened and are within the comfort range just 5 min after closing the windows. However, this phenomenon is not evident in the results of the TS model. First, the TS model indicates that in the winter and transitional periods, even with closed windows, the thermal comfort sensations are determined to be below −0.50. Second, after windows are closed, thermal sensation stabilization takes longer and usually occurs between 30 min and 1 h after window closure. Discrepancies between models were already described [30], however, those studies assumed different and only steady state conditions. It should also be noted that the TS and DTS models use different scales. The DTS model uses a 7-point scale (−3 to +3), recommended by ASHRAE [29], while the TS model employs a 9-point scale (−4 to +4). Currently, we do not have sources that clearly define the relationship between the results of these two models. Some sources [30] recommend rescaling the results of the TS model to fit within a 7-point scale for comparison purposes, as was done in this study. However, there are also suggestions that the most extreme points of the TS model actually extend beyond the 7-point scale to represent the most extreme conditions.

The results of the PMV model also differ. In each scenario, it indicates the least decrease in thermal comfort. However, it should be remembered that the PMV model differs fundamentally from the DTS and TS models. PMV assumes only steady state conditions and the input data based on which PMV determines thermal sensation include: air temperature, air humidity, air speed, radiant temperature, activity level, and clothing insulation. Therefore, the return of PMV model outputs in the simulations conducted for this study to their initial values depended on changes in environmental parameters, mainly air temperature, which gradually increased after the windows were closed. Dynamic thermal sensation models such as DTS or TS, used in simulations under transient conditions, also take into account the physiological response of the human body, resulting in a greater realism of their outputs. The input data form PMV model are also averaged and uniform for the whole body. The DTS and TS models allow for the determination of environmental parameters or clothing properties for individual body parts, enabling the consideration of local discomfort in simulations caused by draughts or air temperature gradients. Another advantage of using the DTS model is the variety of information obtained as a result of the simulation. In addition to thermal sensations, physiological parameters and the body's response to changing environmental conditions are also determined. Based on this data, changes in skin temperature, body core temperature, or the occurrence of sweating can be determined. Understanding such data allows for a more precise determination of the causes of potential discomfort, whether caused by uneven air temperature distribution or excessive skin moisture, which researchers also perceive as a source of discomfort [63]. From a legal and standards perspective, physiological parameters, especially in the workplace, should also be evaluated. Sokolova [64] conducted such evaluations based on the indications of the DTS model. On the other hand, the PMV model is relatively simple to use and widely available.

6. Conclusions

The publication aimed to shed more light on the thermal sensations of people in naturally ventilated spaces by demonstrating the relationship between changes in indoor environmental parameters and thermal sensations. Additionally, various methods of assessing thermal sensations were compared, which may help better understand the thermal conditions in such spaces. The indoor environmental parameters developed based on environmental measurements were typical parameters, consistent with the results of other studies, and allowed for the simulation of thermal sensations of office space occupants in three locations and three seasons of the year.

The research conducted led to the following conclusions:

– The opening of windows or windows and doors affects room environment, but the distribution of air parameters in naturally ventilated spaces is also affected by external and internal heat gains. In the tested room, before and after opening the window(s), the highest air temperatures usually occurred in location closest to the window, despite expecting the greatest cooling effect there. The non-uniform distribution of gains from solar radiation in the room (the greatest ones near the window) contributes to this effect. In summer, the air speed does not exceed 0.2 m/s, in winter, instantaneous values reach up to 0.6 m/s during airing.
– During summer, air temperature drops due to the degree of opening of the window; however, it does not mean worse thermal sensation in location C (farthest from the window) in compared to other locations due to generally lower air temperatures and higher air speeds there (due to air flow through the gap under the door between the room and the corridor).
– Indications of the most common used, both by researchers and engineers, the PMV model differs from the indications of advanced dynamic multi-nodal models, DTS and TS. The biggest difference in compare to DTS model appears in summer and are up to 1.4 during airing of the room and 0.27 in steady state when windows are closed. In winter and transitional season, the greatest discrepancies between PMV and TS are 1.49 with windows open and 0.95 with windows closed. Such discrepancies may lead to a misinterpretation of thermal comfort for room occupants.
– The DTS indications based on the Fiala model are the most comprehensive. This model provides information related to the physiological response of the human body to environmental conditions. Knowledge of physiological parameters of the body enhances the depth of analysis.
– The PMV model is simple (due to less input data which are easier to obtain) compared to the others considered and operates under steady-state conditions, which makes it easier to use and more widely available.

Future research

Since the above study has limitations related to the adopted window opening scenarios and the use of the room, it is planned to extend the research with new variants including opening the window for longer than 5 min, also in more extreme conditions of the external environment (higher wind speed). Additionally, window blinds will be included in the measurements. The thermal sensation simulations will take into account not only the sitting position of a person, but also the standing position. The measurements of the indoor environment will also be used to validate the CFD numerical model for further analyzes of human thermal comfort in an office room with natural ventilation.

CRediT authorship contribution statement

Stanisław Kocik: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Agnes Psikuta:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Joanna Ferdyn-Grygierek:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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