UNIVERSITY OF ZIELONA GÓRA

CEER CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2025; 35 (4): 0228-0249
DOI: 10.59440/ceer/214677
Original Research Article

VENTILATION PERFORMANCE AFTER APARTMENT BUILDING THERMO-MODERNIZATION

Klaudia DOMALEWSKA [1], Andrzej GAJEWSKI [2*]
[1]Students' Scientific Society "Heat Engineer" at Bialystok University of Technology, Bialystok University of Technology, Bialystok, Poland
[2]Faculty of Civil Engineering and Environmental Sciences, Department of HVAC Engineering, Bialystok University of Technology, Bialystok, Poland

Abstract

Increasing requirements for reducing energy consumption result in ther-mo-modernization of the existing buildings. Modernized buildings have significantly lower heat transfer coefficient; simultaneously the infiltration through the windows slows markedly, which may deteriorate indoor air quality (IAQ) seriously. The measurements are done in a lodging room of a three-room dwelling in a sixty-year old building after thermo-modernization; one gauge with a vane probe measures the air velocity and tem-perature at a grille in the toilet; second gauge with IAQ probe located in this room measures the mole fraction of carbon dioxide, air temperature, absolute pressure, and rel-ative humidity; moreover there are estimated the uncertainties of: the volume flow rate, mole fraction of CO2, temperatures, and humidity. Heating system ensures thermal com-fort during heating season; despite of proper ventilation performance in the toilet the IAQ in the logging room is low, for vapor condenses on the window; carbon dioxide concen-tration is too high, which curbs mental activity greatly.

Keywords: indoor air quality (IAQ), thermal comfort, mental activity, thermo-modernization

1. INTRODUCTION

Energy consumption of the buildings has been reducing since the oil crisis in the second half of 1970s (The Government of the Hong Kong Special Administrative Region, 2003); to save the energy use for space heating the buildings are more and more airtight, which leads to isolating the occupants from the outside environment; as the result they have the limited amount of the outside air, so diluting the air pollutants deteriorates. This deterioration has not to cause the additional health risk of breathing, nor should the air be perceived as stale, stuffy, or irritating (European Collaborative Action, 1992).

Pettenkofer (Pettenkofer, 1858) was the first author who expressed the ventilation re-quirements per human occupant being in a room. However, the occupying persons are not the only sources of air

* Corresponding author: Andrzej Gajewski Bialystok University of Technology, Faculty of Civil Engineering and Environmental Sciences, Department of HVAC Engineering, Wiejska 45E, 15-351 Białystok, Poland; a.gajewski@pb.edu.pl, +48 797 995 923.

pollution. Fanger et al. (Fanger *et al.*, 1988) determined the shares of the air pollutions; 20% is caused by the space materials; 42% origins from a ventilation system; 25% is generated by smoking; only 13% is produced by the occupants.

Fanger (P. O. Fanger, 1988) determined the percentage of dissatisfied persons using, de-fined by himself, new unit called olf that is the emission rate of air pollutants (bioefluents) from a standard person; other sources polluting a space are expressed as a rational num-ber of 1 olf (i.e. standard person causing the same dissatisfaction). Whereas 1 pol is a pol-lution of 1 olf that is ventilated by 1 l/s of unpolluted air, so 1 pol=1 olf/(l/s); 1 decipol equals to 1 olf ventilated by 10 l/s. The percentage of dissatisfied persons PD is a corre-spondence of the ventilation rate q as follows:

$$\begin{aligned} PD &= 395 \cdot exp\left(-1.83 \cdot q^{0.25}\right) \quad for \quad q \geq 0.32\,\frac{l}{s} \cdot olf \\ PD &= 100\% \quad for \quad q < 0.32\,\frac{l}{s} \cdot olf \end{aligned} \tag{1.1}$$

Air quality is perceived by two humans' senses; the olfaction senses the hundreds thousands odorants in the air; also the eyes are sensitive about analogous number of the irritants. The mixed reaction of these two senses is an indicator of a good or poor air quality. The average indicator of air quality is the percentage of dissatisfied persons; this percentage is the fraction of population perceiving this quality as poor just after entering a room .

Carbon dioxide production is proportional to the humans metabolic rate (Jones, 1999); also water vapour does (European Collaborative Action, 1992). Although CO_2 is inoffensively at low concentrations that occur in the rooms, it is a good indicator of other human bio-effluents that annoy humans (European Collaborative Action, 1992), (Norbäck *et al.*, 1995), (Möhle *et al.*, 2003), (Mui, Wong and Hui, 2006); conversely it is a poor indicator of the numerous perceivable pollution sources not producing CO_2 (European Collaborative Action, 1992), *e.g.* carbon monoxide or radon. Eq **Błąd! Nie można odnaleźć źródła odwołania.** shows a correspondence between the excessive CO_2 concentration χ_{co2} and the percentage of dissatisfied occupants *PD* of a room where all the pollutions are exhaled by the inactive non-smoking occupants (European Collaborative Action, 1992):

$$PD = 395 \cdot exp\left(-15.15 \cdot \chi_{CO_2}^{-0.25}\right) \tag{1.2}$$

Since the human metabolic processes generate CO_2, vapour, aldehydes, esters, and alcohols the acceptable long-term CO_2 mole fraction should be less than 3500 ppm to avoid the negative health effects (European Collaborative Action, 1992).

The ventilation system effectiveness depends also on the outdoor quality; the better this quality is the less air flow rate is needed. Table 1 shows distinguishing levels of the felt outdoor air quality in correspondence to the typical outdoor pollutants.

Table 1. The outdoor levels of air quality (European Collaborative Action, 1992)

	Perceived air quality	Air pollutant			
		Carbon dioxide	Carbon monoxide	Nitrogen dioxide	Sulfur dioxide
	[decipol]	[mg/m^3]	[mg/m^3]	[μg/m^3]	[μg/m^3]
At sea	0	680	0-0.2	2	1
In towns, good air quality	<0.1	700	1-2	5-20	5-20
In towns, poor air quality	>0.5	700-800	4-6	50-80	50-100

People perceive good air quality if the inside CO_2 mole fraction does not exceed the outdoor mole fraction by more than 700 ppm (Costanzo, Cusumano and Giaconia, 2011).

Humidity affects the occupants in a direct or indirect way; its high level, vapour condensation, or moisture penetration promotes the moulds or other fungi growth; this growth may result in malodorous or even allergy. Raised humidity may intensify chemicals (e.g. formaldehyde) emissions from the materials. Also too low humidity may cause a negative consequences for some occupants: dryness perception, skin or mucous membranes irritation (European Collaborative Action, 1992), irritation in eyes and upper airways (Wolkoff, 2018).

"Thermal comfort is defined as the condition of mind which expresses satisfaction with the thermal environment"; it is closely related to the thermal balance of an entire human's body that is in a steady state. This balance is affected by the humans' physical activity or cloth, and also by the thermodynamic parameters: the air temperature, velocity, and humidity; moreover the mean surface temperature affects the radiational heat transfer (P.O. Fanger, 1988), (Frontczak and Wargocki, 2011). However because of individual preferences it is impossible to satisfy everybody simultaneously, so the feeling of comfort should be acceptable by at least 80% of the occupants (Frontczak and Wargocki, 2011), (ANSI/ASHRAE, 2016). Thermal discomfort feeling decreases productivity (Al Horr *et al.*, 2016), (Geng *et al.*, 2017). Temperature change in the range 18°C - 30°C impacts on typewriting, learning, or reading performance. Office productivity is stable in the range 21°C - 25°C; it decreases by 2% per 1°C increase in the range of 25-30°C (Al Horr *et al.*, 2016).

Alternatively to Fanger (P.O. Fanger, 1988) the thermal comfort definition is given by de Dear et al. (de Dear, Brager and Cooper, 1997) who propose an "adaptive" thermal comfort that includes in the analysis also other factors: demographics (gender, age, or economic status), context (building design and function, season, climate, semantics, or social conditioning), and cognition (attitude, preference, or expectations). This adaptation is divided into three groups behavioural adjustment, physiological, and psychological. In brief the adaptive thermal comfort takes into consideration an interaction between a human and their closest and distant surroundings; people may change clothes or open the windows or fix the radiators, etc. (de Dear, Brager and Cooper, 1997). Thermal comfort depends not only on the individual preferences but it varies geographically according to age, sex, metabolism rate, time of the year, etc. (Al Horr *et al.*, 2016). Higher outdoor temperatures allow for higher indoor ones (Rupp, Vásquez and Lamberts, 2015). Table 2 shows the required air conditions in dependence on the season and activity.

Table 2. Being in force the indoor air parameters

Level of activity	Temperature [°C]		Relative humidity [%]	
	summer	winter	summer	winter
low	23-26	20-22	40-55	40-60
intermediate	20-23	20-22	40-60	40-60
high	18-21	15-18	40-60	40-60

Too high air temperature in summer lowers the labour effectiveness, but cooling increases operating costs (Kroner, Jakubowska and Noszczyk, 2019), (Dybiński and Mijakowski, 2016).

Development in information technology permits a personal approach to the thermal comfort by modelling the individual preferences instead of averaging large populations (Kim, Schiavon and Brager, 2018). Personal comfort models increase median accuracy from 0.51 (for conventional and adaptive thermal comfort) to 0.73 (Kim *et al.*, 2018).

Temperature, humidity, CO_2 concentration, and air speed are the measurable factors of indoor environmental quality (IEQ) (ASHRAE, 2009). The most satisfying temperature is 24°C; dissatisfaction under the lower temperatures is more significant than under the higher temperatures; the proper temperature affects IEQ feeling strongest (Geng *et al.*, 2017), (Zomorodian, Tahsildoost and Hafezi, 2016).

Al Horr *et al.* established eight physical factors affecting occupant satisfaction and productivity of an office environment: indoor air quality (IAQ) and ventilation, thermal comfort, lighting and daylighting, noise and acoustics, office layout, biophilia and views, look and feel, location and amenities; each factor interacts significantly and crosses over to others (Al Horr *et al.*, 2016); however thermal comfort is thought as slightly more significant than satisfaction with air quality (Frontczak and Wargocki, 2011). IAQ strongly influences the office productivity in the following tasks: text typing, proof-reading, or solving mathematical problems. IAQ is the complex phenomena, for to evaluate IAQ the following parameters should be measured: relative humidity, temperature, level of internal air contamination, e.g. carbon oxides mole fraction; these parameters depend on: outdoor conditions, technology of building construction, HVAC systems performance, quality of indoor space (furnishing, furniture, equipment), and occupants activity. IAQ may be improved by limiting the pollution emissions or increasing the ventilation rate which may be applied for assessing IAQ in a building; the higher rates improve IAQ; whereas to low rate, especially lower than 10 l/s, may cause Sick Building Syndrome (SBS) and decrease productivity (Al Horr *et al.*, 2016); however it is not confirmed by other researchers (Jones, 1999).

Prevention against global warming results in reducing the heat losses by the buildings, which simultaneously is a cause for sealing the windows. However the building have not to be sealed tightly, so the ventilation rates ought to be reduced according to the golden rule "build tight, ventilate right" is satisfied (Vardoulakis *et al.*, 2015).

Briefly summarizing (Dimitroulopoulou *et al.*, 2023) the national guidelines in 28 countries mostly indicate the temperature should be at the range of 20-26°C, relative humidity at 40-70%, and maximal mole fraction CO_2 is 1000 ppm.

The aim of the study is extension of the previous research into stack ventilation performance (Gładyszewska-Fiedoruk and Gajewski, 2012), (Gladyszewska-Fiedoruk and Adana, 2020), (Teleszewski and Gładyszewska-Fiedoruk, 2020). The stack ventilation performance and IAQ evaluation is researched in the different building types buildings, e.g. garage (Jermacz and Gajewski, 2019). The present study, in a lodgings ventilated by the stuck duct in a toilet, is a piece of broader research. After collecting the full set of the results the conclusions may be generalized.

The present study is focused on assessing the stack ventilation performance and IAQ in the lodgings; in particular it examines the following parameters: the volume flow rate through the grille in the bathroom, carbon dioxide mole fraction, temperature and humidity in the studied lodgings. Measurement uncertainty is estimated for every parameter. The measurements are done in every season. Each determined parameter is compared with the proper regulation, standard, or guideline.

2. MATERIALS AND METHODS

The study examines IAQ in a lodging room occupied by one person; Fig. 1 shows the floor plan of the entire three-room flat. This flat is located at the fourth level above the ground storey in sixty-year old building which was thermo-modernized and equipped in the airtight windows of the low thermal transmittance; this building is located in Białystok in the IV climatic zone in Poland; the window W1, in the studied room, is installed in the western wall.

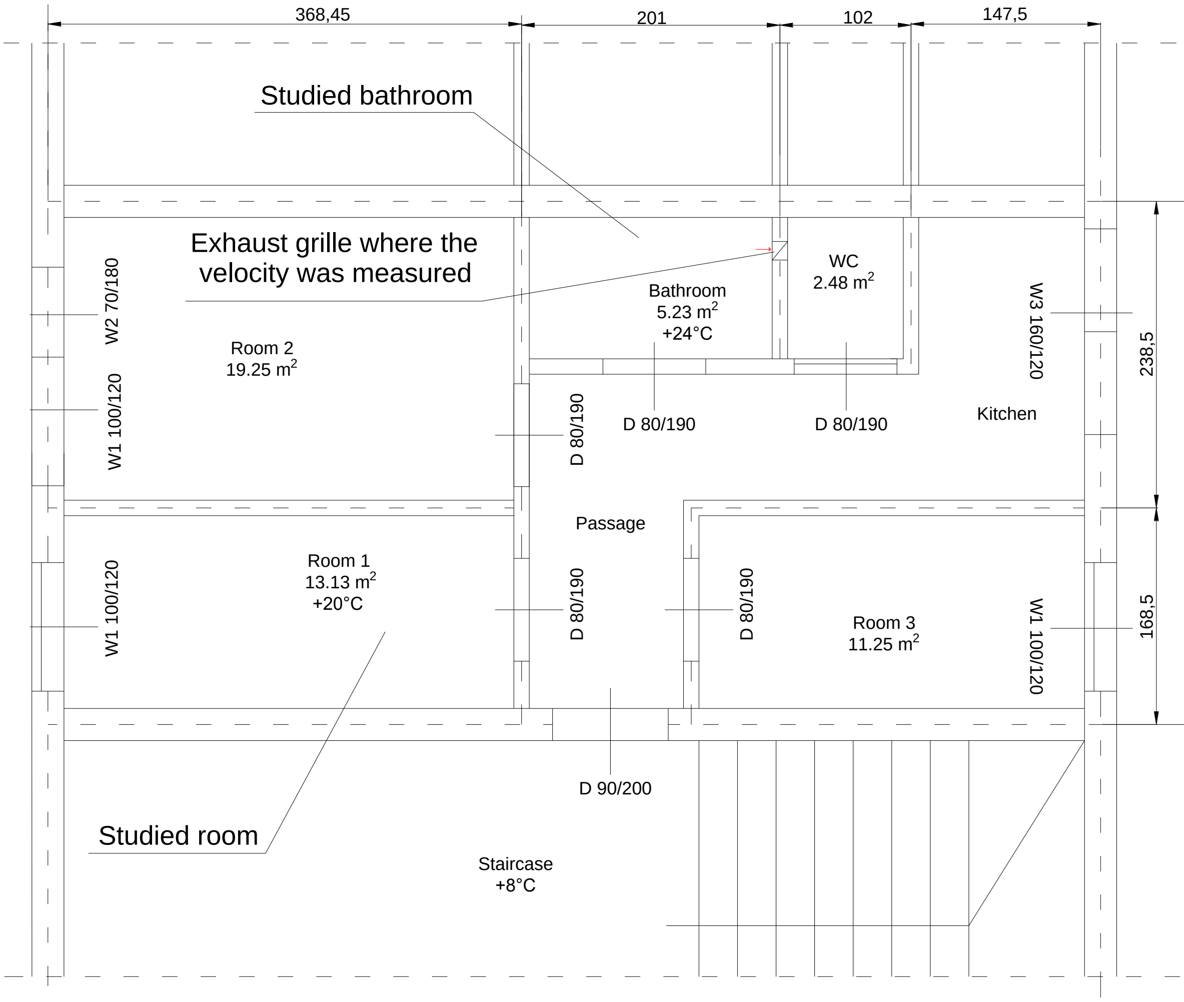

Fig. 1. The flat with the studied rooms

The volumetric flow rate of the ventilation air in this flat should satisfy the regulation (Minister of Development and Technology, 2022) which refers to the standard (The Polish Committee for Standardization, 2000); its value may not be less than 50 m^3/h in the bathroom and 20 m^3/h per the design person; the air should flow to the kitchen or hygienic-sanitary rooms from other rooms (Minister of Development and Technology, 2022).

The velocity and temperature of the exhaust air were measured, using a van measuring probe in diameter of 16 cm equipped with a thermocouple K, at the grille placed in the bathroom; IAQ probe measured the absolute pressure, dry bulb temperature, relative humidity, and carbon dioxide mole fraction in the studied room; each probe was connected with a distinct Testo 435-4 gauge. The accuracy of the IAQ measurement system is as follows: temperature in the range 0 to +50°C ±0.3°C; relative humidity in the range +2 to +98 % ±2 %; carbon dioxide concentration in the range 0 to +5000 ppm CO_2 ±75 ppm CO_2 ±3% of the measured value and in the range +5001 to 10000 ppm CO_2 ±150 ppm CO_2 ±5% of the measured value; atmospheric pressure in the range 600 to 1150 hPa ±10 hPa; air velocity and temperature at the grille were measured by a vane measuring probe which measures velocity in the

range 0.3-20 m/s with accuracy ± 0.1 m/s +1.5% of the measured value and temperature in the range 0 to +50°C with accuracy ±0.5°C (Teleszewski and Gładyszewska-Fiedoruk, 2018).
The investigations were carried out in the one-week series one in each season in the years 2022-23. The data were recorded each 5 minutes; then they were summed or averaged in the one-hour periods to plot in the charts.

The volume flow rate through the grille is determined assuming the constant velocity in every period lasting 300 s:

$$\dot{V}_g = 300 F_g \sum_{i=1}^{12} v_{gi} \quad \left[\frac{m^3}{h}\right] \tag{2.1}$$

where:
F_g- The surface area of the grille openings [m^2].
Measurement uncertainty of the volume flow rate through the grille is estimated as follows:

$$\delta\dot{V}_g = 300\sqrt{\left(\frac{\partial \dot{V}_g}{\partial F_g}\delta F_g\right)^2 + \left(\sum_{i=1}^{12}\frac{\partial \dot{V}_g}{\partial v_{gi}}\delta v_{gi}\right)^2} = 300\sqrt{\left(\delta F_g \sum_{i=1}^{12} v_{gi}\right)^2 + \left(F_g \sum_{i=1}^{12}\delta v_{gi}\right)^2} \quad \left[\frac{m^3}{h}\right] \tag{2.2}$$

where:
δF_g=0.001 m^2,
$\delta v_{g\,i}$=0.1+0.015$v_{g\,i}$ [m/s].
Mole fraction of Carbon dioxide is averaged hourly

$$\chi_{CO_2} = \frac{1}{12}\sum_{i=1}^{12}\chi_{CO_2\,i} \quad [ppm] \tag{2.3}$$

so the measurement uncertainty of the arithmetic mean determines the formula

$$\delta\chi_{CO_2} = \frac{1}{12}\sqrt{\sum_{i=1}^{12}\delta\chi^2_{CO_2\,i}} \quad [ppm]$$

where

$$\delta\chi_{CO_2\,i} = 75 + 0.03\chi_{CO_2\,i} \quad [ppm] \tag{2.4}$$

for no measurement value exceeds 5000 ppm. The minimal uncertainty equals to 17.89 ppm, and the maximal is 59.21 ppm.
Since the uncertainty of temperature measurement is fixed value, the measurement uncertainty of the arithmetic mean simplifies to

$$\delta t = \frac{\delta t_i}{\sqrt{12}} \quad [°C]$$

$$\delta t_{IAQ} = 0.0866\ °C$$

$$\delta t_{vane} = 0.1443\ °C \tag{2.5}$$

for the IAQ and vane probes respectively.

3. RESULTS

The determined quantities are plotted with the thicker lines. Whereas the measurement uncertainties are plotted with the thinner dotted lines; the upper lines show the measurement values plus the uncertainties; the down lines show the measurement values minus the uncertainties; however the δt_{IAQ} values are so small that they would blur the plotted lines, so they are not drawn in the charts.

The carbon dioxide mole fraction was measured directly, whereas the volumetric flow rate was determined as the product of the measured air velocity at the grille and the surface area; besides these values Fig. 2-Fig. 5 show also the maximal recommended CO_2 mole fraction of 1000 ppm in the room where IAQ probe was placed and the minimal ventilation air flow of 50 m^3/h in the bathroom where the velocity probe was installed. The lengths of the exceedances times enumerated further on were determined from the five-minute measurement periods, so some of them may be invisible in the charts where the one-hour results are plotted.

Between 29th October and 2nd November the occupant returned to their permanent place of residence because of the All Saints' Day, which affects the results clearly.

The carbon dioxide mole fraction was beyond the recommended limit for 22.3% of the experiment's duration in autumn (Fig. 2), 50.53% in winter (Fig. 3), 23.95% in spring (Fig. 4); in summer there was no exceedance (Fig. 5). The volumetric air flow rate failed the regulation (Minister of Development and Technology, 2022) for 62.56% of the experiment's duration in autumn, 0.19% in winter, 2.62% in spring, and 62.86% in summer.

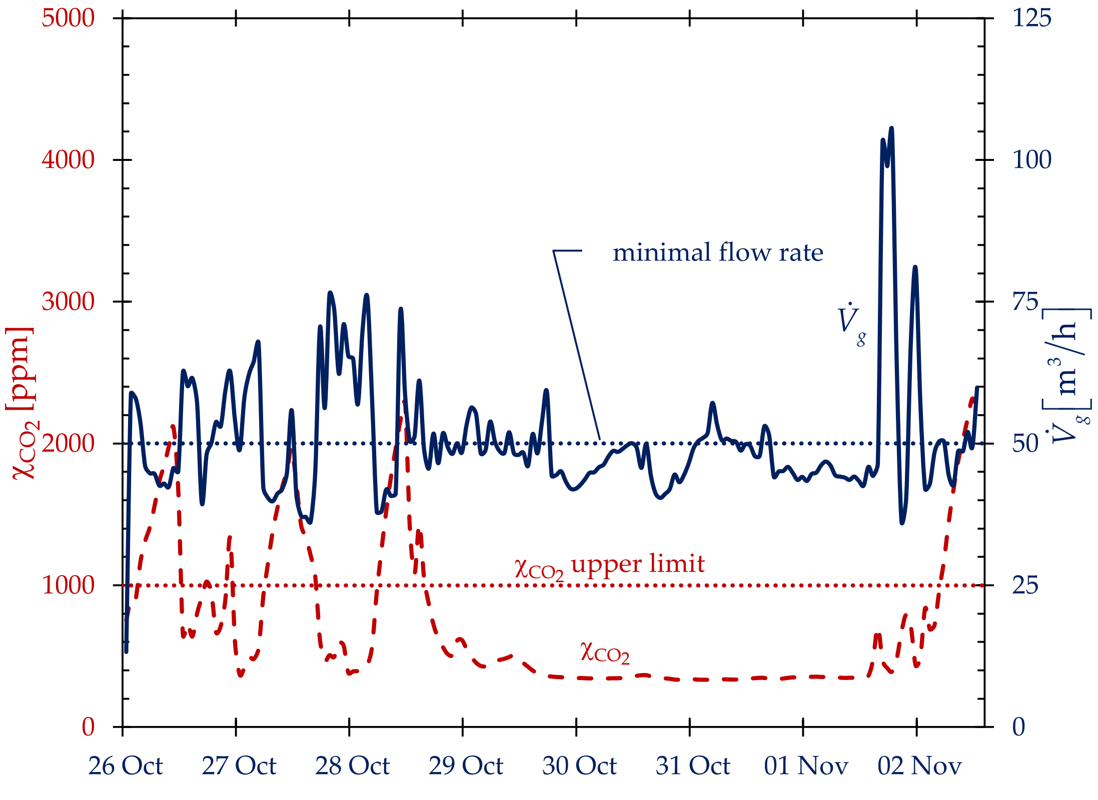

Fig. 2. The carbon dioxide mole fraction and air flow rate in the autumn 2022

The lowest uncertainty of the volume flow rate of 2.08 m^3/h was on 26 Oct at 20:00; its highest value of 10.16 m^3/h was on 2 Nov at 14:00. Its lowest relative value of 9.67% was on 2 Nov at 14:00, whereas the highest value of 21.62% was on 28 Oct at 11:00. The lowest uncertainty of mole fraction of CO_2 of 14.08 ppm was on 26 Oct at 20:00; whereas the highest one of 41.71 ppm was on 3 Nov at 7:00. Its lowest relative value of 1.76% was on 3 Nov at 8:00; whereas the highest one of 7.35% was on 31 Oct at 23:00.

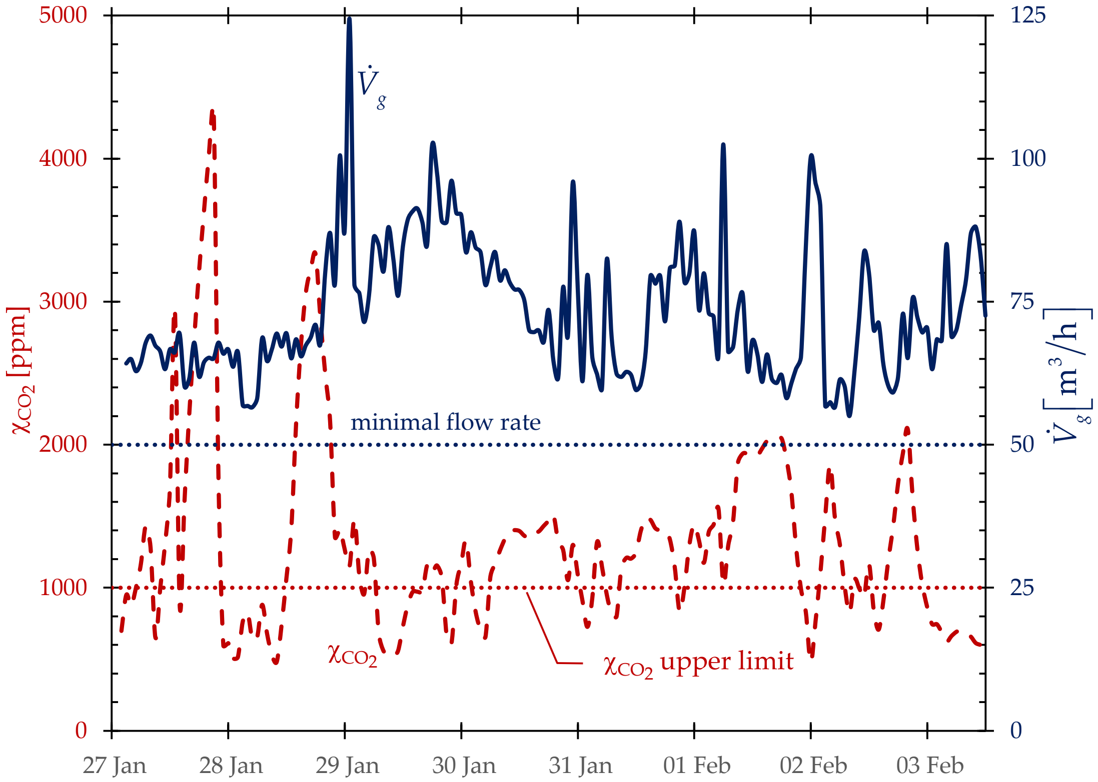

Fig. 3. The carbon dioxide mole fraction and air flow rate in the winter 2023

The lowest uncertainty of the volume flow rate of 3.57 m^3/h was on 27 Jan at 14:00; its highest value of 10.95 m^3/h was on 29 Jan at 13:00. Its lowest relative value of 8.80% was on 29 Jan at 13:00, whereas the highest value of 15.20% was on 2 Feb at 20:00. The lowest uncertainty of mole fraction of CO_2 of 17.89 ppm was on 27 Jan at 14:00; whereas the highest one of 59.21 ppm was on 28 Jan at 9:00. Its lowest relative value of 1.37% was on 28 Jan at 9:00; whereas the highest one of 5.36% was on 2 Feb at 12:00.

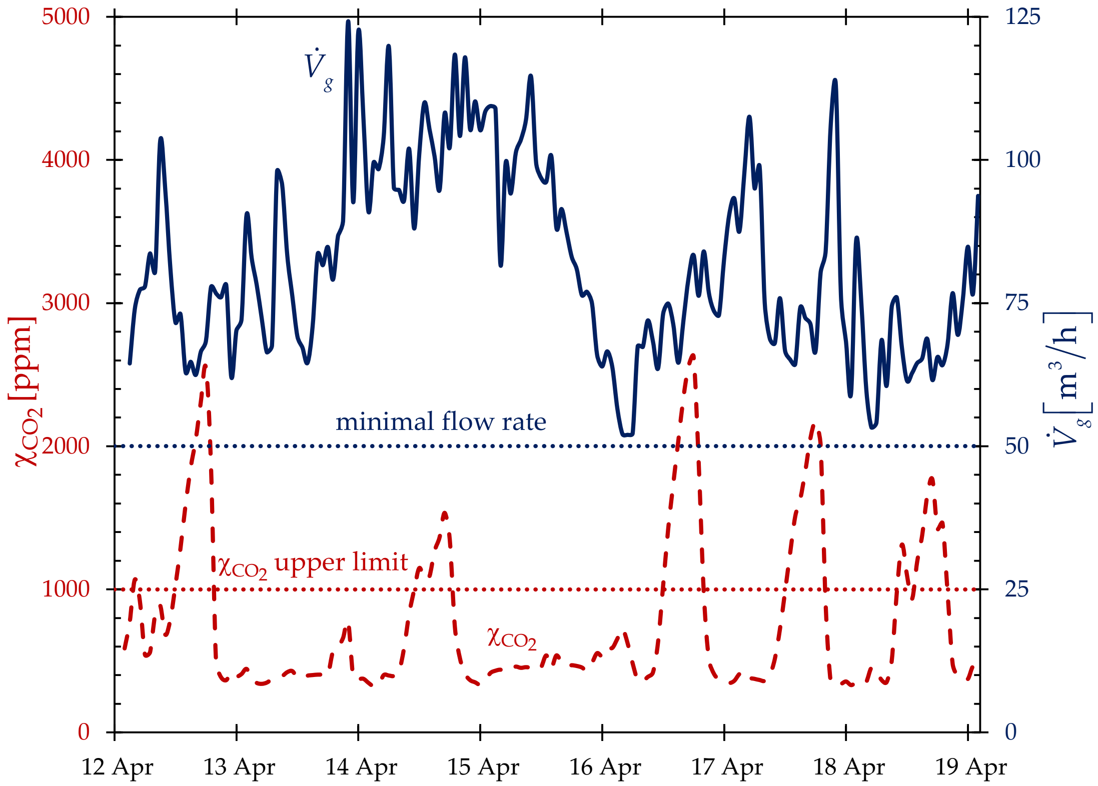

Fig. 4. The carbon dioxide mole fraction and air flow rate in the spring 2023

The lowest uncertainty of the volume flow rate of 4.08 m^3/h was on 12 Apr at 14:00; its highest value of 10.94 m^3/h was on 14 Apr at 10:00. Its lowest relative value of 8.81% was on 14 Apr at 10:00, whereas the highest value of 16.99% was on 12 Apr at 14:00. The lowest uncertainty of mole fraction of CO_2 of 18.92 ppm was on 12 Apr at 14:00; whereas the highest one of 44.41 ppm was on 17 Apr at 6:00. Its lowest relative value of 1.69% was on 17 Apr at 6:00; whereas the highest one of 7.57% was on 14 Apr at 15:00.

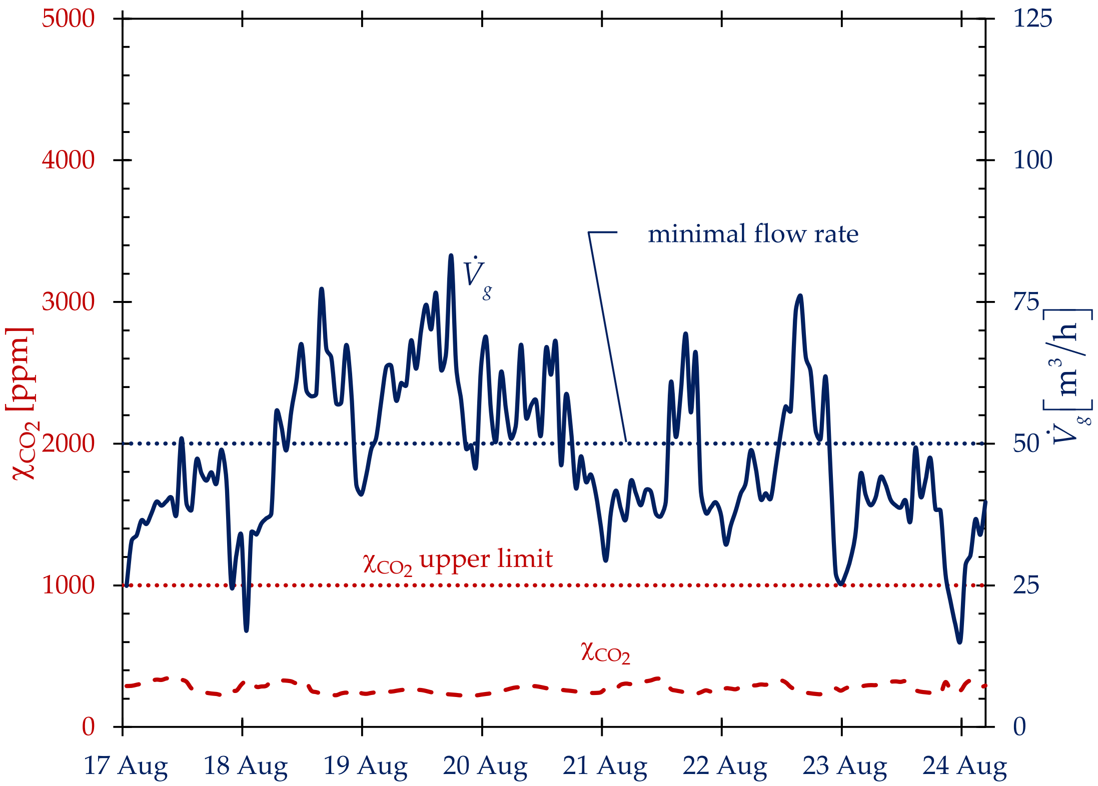

Fig. 5. The carbon dioxide mole fraction and air flow rate in the summer 2023

The lowest uncertainty of the volume flow rate of 6.38 m^3/h was on 17 Aug at 20:00; its highest value of 9.33 m^3/h was on 20 Aug at 13:00. Its lowest relative value of 11.21% was on 20 Aug at 13:00, whereas the highest value of 48.10% was on 24 Aug at 19:00. The lowest uncertainty of mole fraction of CO_2 of 22.06 ppm was on 17 Aug at 20:00; whereas the highest one of 24.79 ppm was on 18 Aug at 6:00. Its lowest relative value of 7.02% was on 18 Aug at 6:00; whereas the highest one of 10.56% was on 20 Aug at 18:00.

Temperature limits, summer or winter, were established due to meteorological data for weather station Białystok published by IMGW-PIB (Instytut Meteorologii i Gospodarki Wodnej Państwowy Instytut Badawczy, 2023) and (Instytut Meteorologii i Gospodarki Wodnej Państwowy Instytut Badawczy, 2024); because in April 2023 the outdoor temperatures rose to 21.7°C or fell to -3.8°C both upper limits were plotted.

The temperatures at the grille exceeded always the upper limits except the summer upper limit in April when it crossed this limit.

The temperature in autumn (Fig. 6) fall behind the lower limit for 10.32% of the experiment's duration; it increased beyond the upper limit for 83.9%; in the next season the respective exceedances were as follows: 8.19% and 6.34% (Fig. 7), 44.48% and 14.94%(Fig. 8), 0% and 77.16% (Fig. 9). Temperature decrease in a heating season from October to April plotted in Fig. 6- Fig. 9 was caused by airing because of the poor air quality, which was correlated with the highest amounts of CO_2.

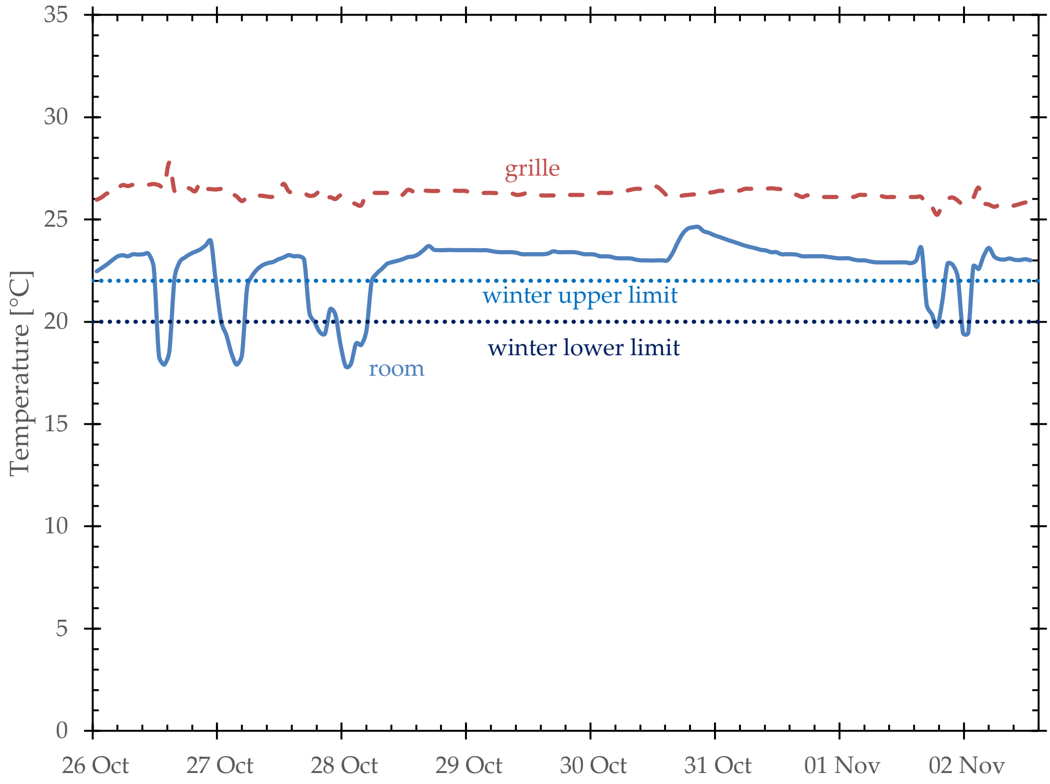

Fig. 6. The temperatures in the room and at the grille in the autumn 2022

The lowest relative uncertainty of the temperature in the room of 0.35% was on 31 Oct at 16:00; whereas its highest value of 0.49% was on 28 Oct at 20:00. The lowest relative uncertainty of the temperature at grille of 0.52% was on 27 Oct at 10:00; whereas its highest value of 0.57% was on 2 Nov at 14:00.

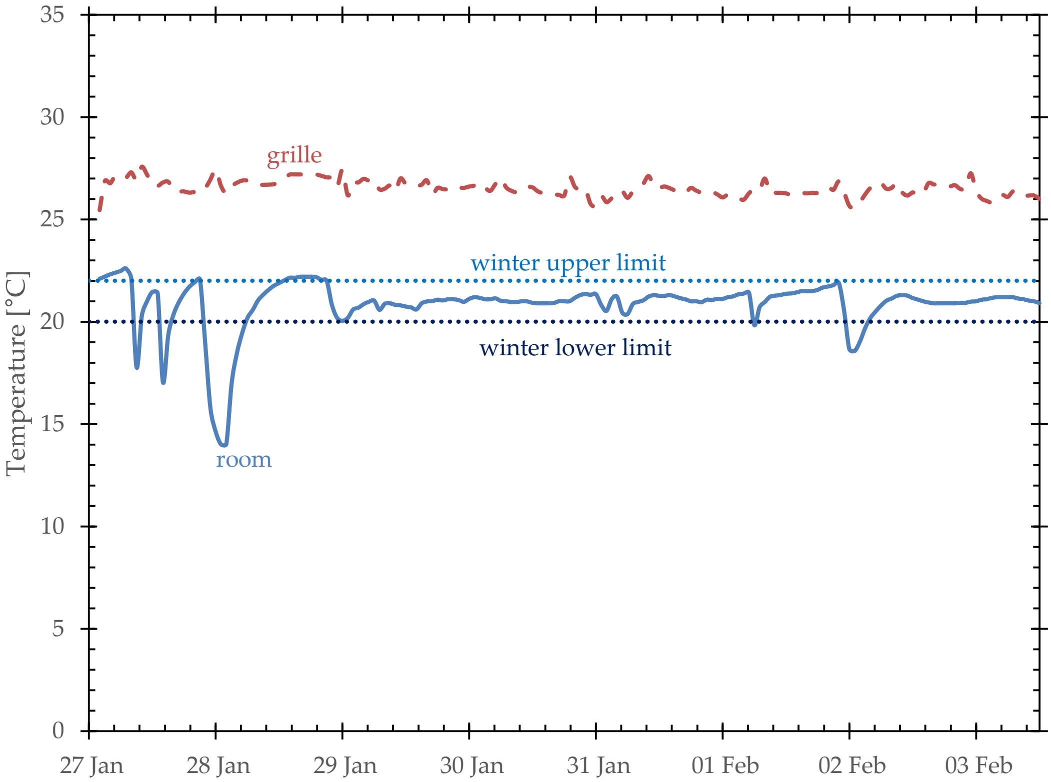

Fig. 7. The temperatures in the room and at the grille in the winter 2023

The lowest relative uncertainty of the temperature in the room of 0.38% was on 27 Jan at 19:00; whereas its highest value of 0.62% was on 28 Jan at 13:00. The lowest relative uncertainty of the temperature at grille of 0.52% was on 27 Jan at 22:00; whereas its highest value of 0.57% was on 27 Jan at 14:00.

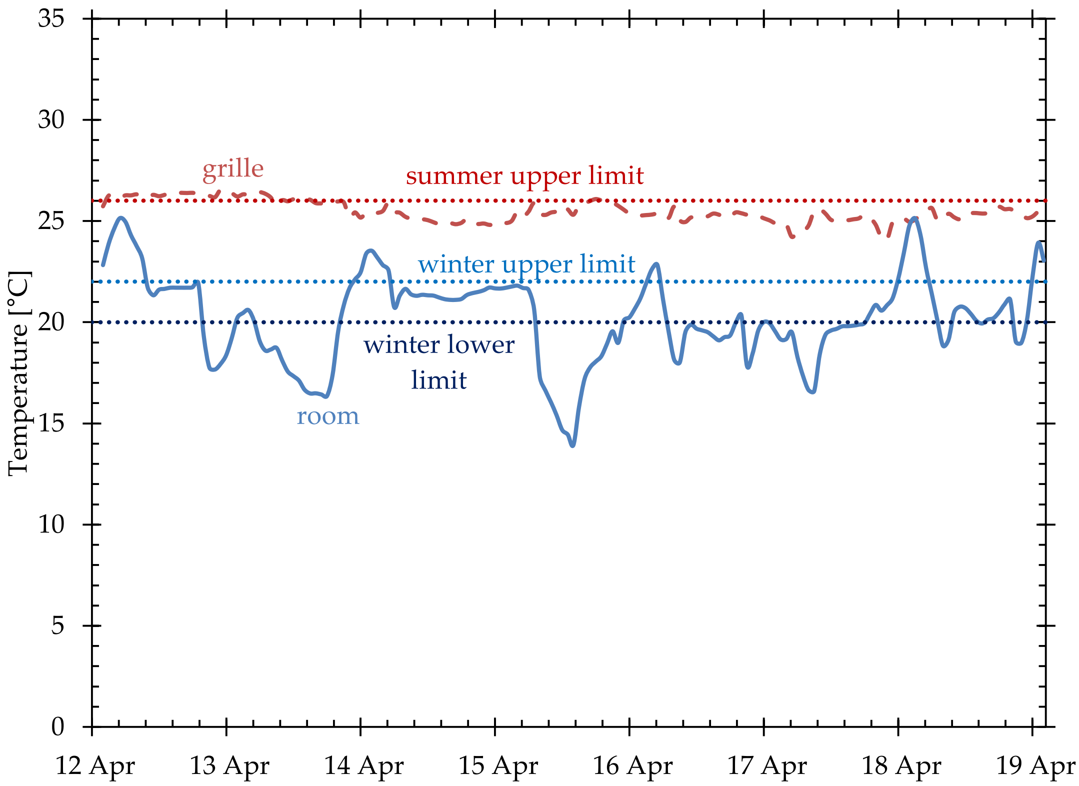

Fig. 8. The temperatures in the room and at the grille in the spring 2023

The lowest relative uncertainty of the temperature in the room of 0.34% was on 18 Apr at 15:00; whereas its highest value of 0.62% was on 16 Apr at 2:00. The lowest relative uncertainty of the temperature at grille of 0.54% was on 13 Apr at 11:00; whereas its highest value of 0.60% was on 18 Apr at 10:00.

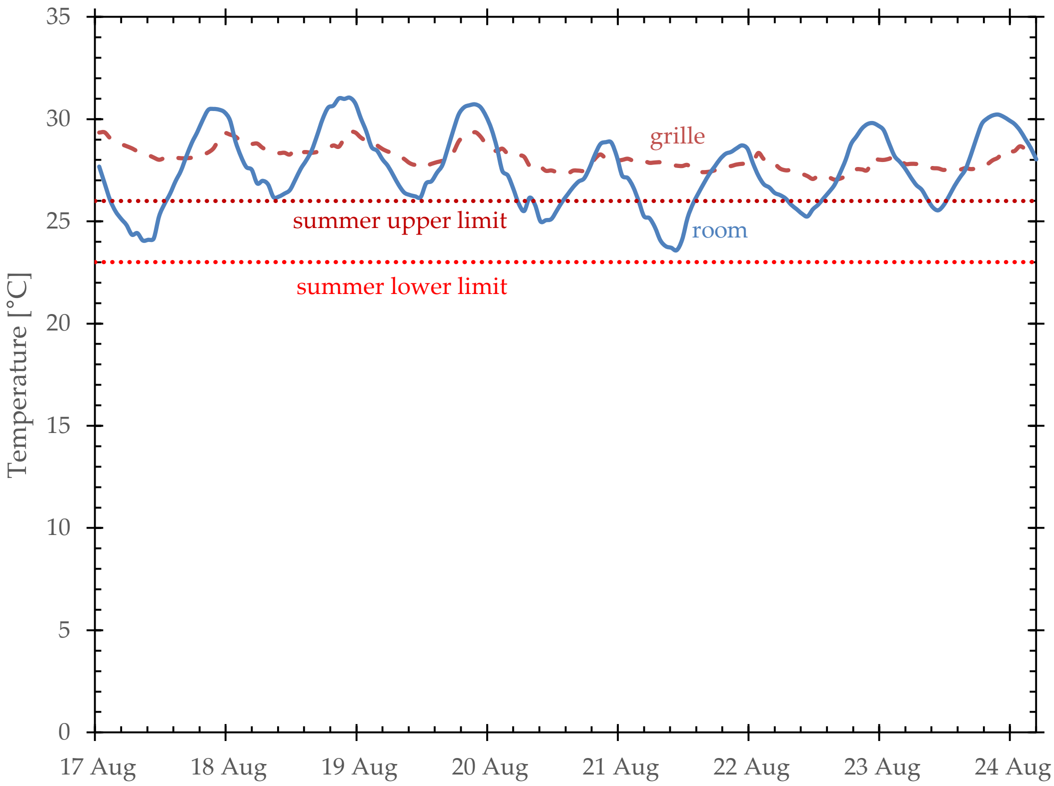

Fig. 9. The temperatures in the room and at the grille in the summer 2023

The lowest relative uncertainty of the temperature in the room of 0.28% was on 19 Aug at 18:00; whereas its highest value of 0.37% was on 22 Aug at 6:00. The lowest relative uncertainty of the temperature at grille of 0.49% was on 19 Aug at 18:00; whereas its highest value of 0.60% was on 23 Aug at 11:00.

The relative humidity in autumn (Fig. 10) rose above the upper limit for 20.31% time; in the winter (Fig. 11) it increased beyond the upper limit for 5.89% and fall below the lower limit for 32.60%; in the next season (Fig. 12) and (Fig. 13) the respective exceedances were as follows: 11.23% (in relation to the winter upper limit) and 15.49%, 35.11% and 4.60%.

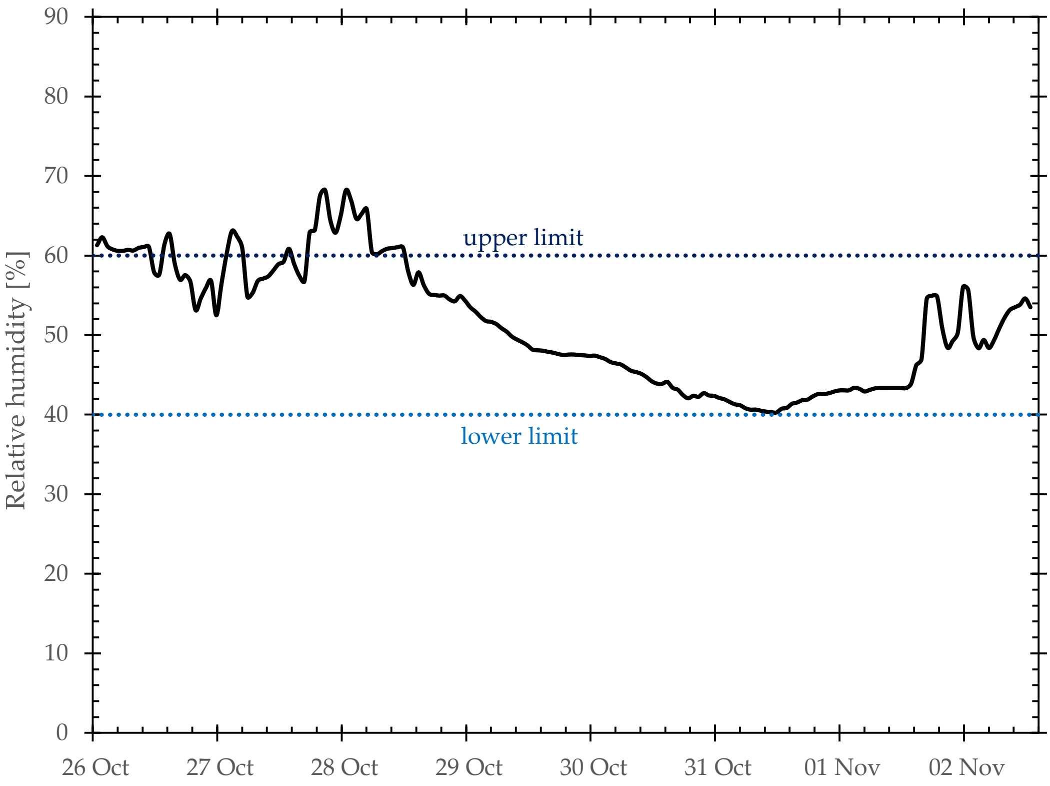

Fig. 10. The relative humidity in the room in the autumn 2022

The lowest relative uncertainty of the relative humidity of 0.00635% was on 23 Oct at 20:00; whereas its highest value of 0.01076%% was on 1 Nov at 7:00.

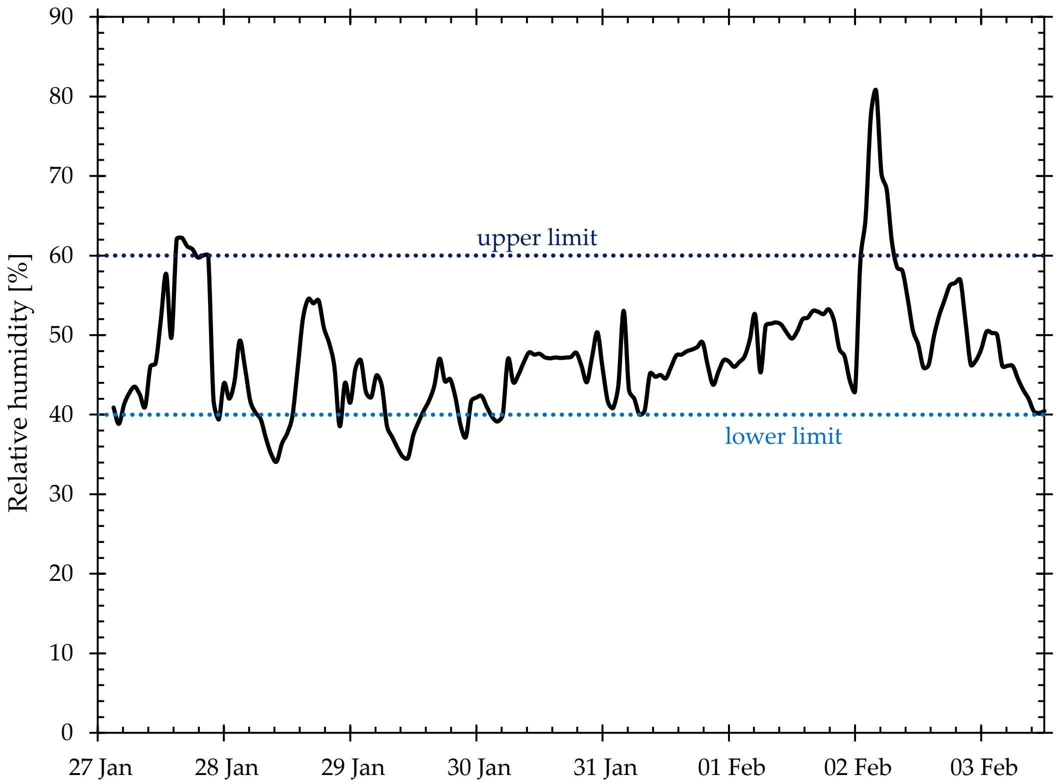

Fig. 11. The relative humidity in the room in the winter 2023

The lowest relative uncertainty of the relative humidity of 0.00537% was on 2 Feb at 16:00; whereas its highest value of 0.01270%% was on 28 Jan at 22:00.

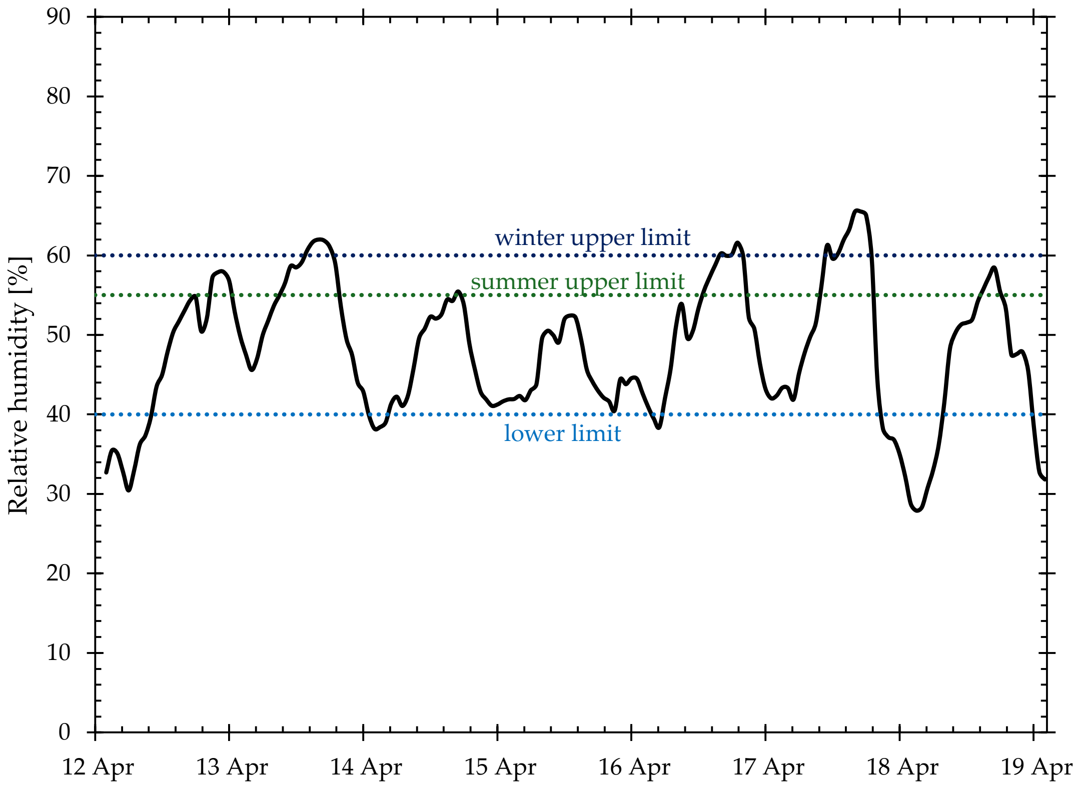

Fig. 12. The relative humidity in the room in the spring 2023

The lowest relative uncertainty of the relative humidity of 0.00661% was on 18 Apr at 5:00; whereas its highest value of 0.01551%% was on 18 Apr at 15:00.

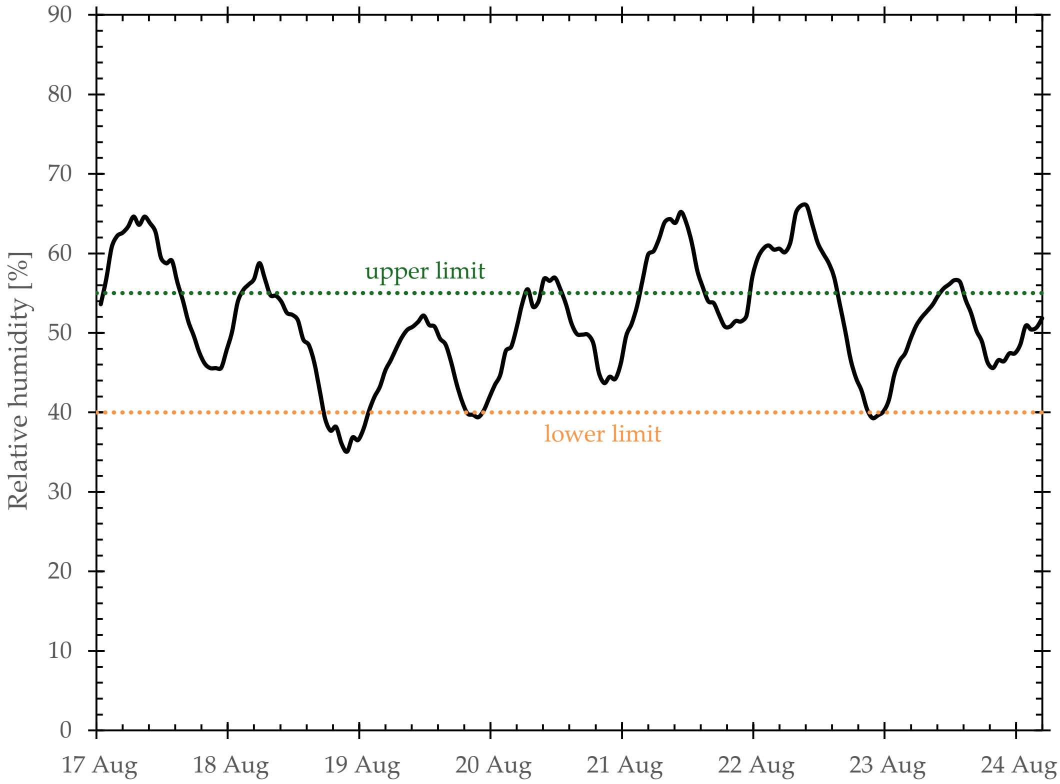

Fig. 13. The relative humidity in the room in the summer 2023

The lowest relative uncertainty of the relative humidity of 0.00656% was on 23 Aug at 4:00; whereas its highest value of 0.01235%% was on 19 Aug at 17:00.

4. DISCUSSION

The studied room is ventilated badly, for even when the minimal air flow rate is exceeded by far the CO_2 mole fraction is beyond the upper limit (cf. Fig. 3 or Fig. 4), which suggests the air to the bathroom flows in the overwhelming amount from the staircase; it leads to the conclusion that the flow from the room is severely limited because of the extremely airtight window. Although CO_2 and H_2O emissions are correlated as the products of human metabolism (Gładyszewska-Fiedoruk, 2013) the relative humidity exceeds the upper limit in the shorter time periods than carbon dioxide mole fraction, so carbon dioxide was not removed from the room. Fig. 7 shows the space heating performs excellently, for the lower temperatures were measured only amid the airings; the higher temperatures in the heating season was adjusted by the occupant; however (Wiater and Gładyszewska-Fiedoruk, 2022) suggest the poor ventilation, not overheating, causes the temperature rises.

The simultaneously performed measurements in other building showed the stack ventilation may provide the proper indoor air quality (Dobkowski and Gajewski, 2025).

The occupant reported there was observed frequently vapour condensation on the window, and liquid water flew down on the floor. In the heating season air in the room was stuffily, and it seemed dense and difficult to breath; it lacked in freshness, and also unpleasant smell was detected; hence airing was necessary often. There was observed neither moisture nor mould on the walls. Too high carbon dioxide concentration resulted in tiredness and sleepiness, which intensified after a longer occupation; these tiredness and sleepiness resulted in loosing concentration or performing the tasks required an intellectual effort.

5. CONCLUSIONS

It may be stated the heating system and stack ventilation in the bathroom in winter and spring perform correctly; the stack ventilation performance in autumn and summer is insufficient temporarily, for the minimal air flow rates fail the standard. However, the studied room is ventilated extremely poorly, which results in excessive amount of carbon dioxide or vapour condensation; this poorness curbs mental activity significantly.

Thus stack ventilation operation affects IAQ greatly, which influences on the occupant behaviour strongly.

To improve airing in the particular room a trickle vent should be installed into the window's frame.

The buildings should not be modernized thermally in a way which simultaneously impairs indoor air quality.

The study concludes the maximal mole fraction of carbon dioxide should be limited by law to 1000 ppm.

The next research should be made into measuring the air flows through the grilles in the kitchen as well as the infiltration coefficients of the windows and the door into the staircase; also it should be control IAQ in the kitchen.

ADDITIONAL INFORMATION

Research was carried out at Bialystok University of Technology as a Rector's project WZ/WB-IIŚ/4/2025 at Department of HVAC Engineering which was subsidised by the Ministry of Science and Higher Education Republic of Poland from the funding for statutory R&D activities.

The paper was prepared using equipment which was purchased thanks to either "**INNO – EKO – TECH" Innovative research and didactic center for alternative energy sources, energy efficient construction and environmental protection** – project implemented by the Technical University of Bialystok (PB), co-funded by the European Union through the European Regional Development Fund under the Programme Infrastructure and Environment or "**Research on the efficacy of active and passive methods of improving the energy efficiency of the infrastructure with the use of renewable energy sources**" - project was co-financed by the European Regional Development Fund under the Regional Operational Programme of the Podlaskie Voivodship for the years 2007-2013.

Meteorological data have been available thanks to a kindness of The Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB).

REFERENCES

1. ANSI/ASHRAE 2016. Ventilation for Acceptable Indoor Air Quality, *ANSI/ASHRAE Standard 62.1-2016*, **2016**, 1–60.
2. ASHRAE 2009. Special Report 200 - Indoor air quality guide, ASHRAE Special Project 200.
3. Costanzo, S, Cusumano, A and Giaconia, C 2011. Ventilation rates and unsatisfied percentage from indoor CO_2 concentration, *Indoor and Built Environment* **20**(2), 232–245. Available at: https://doi.org/10.1177/1420326X10373330.

4. de Dear, R, Brager, G and Cooper, D 1997. Developing an Adaptive Model of Thermal Comfort and Preference, FINAL REPORT ASHRAE RP- 884.
5. Dimitroulopoulou, S *et al.* 2023. Indoor air quality guidelines from across the world: An appraisal considering energy saving, health, productivity, and comfort, *Environment International* **178**(April), 108127. Available at: https://doi.org/10.1016/j.envint.2023.108127.
6. Dobkowski, J and Gajewski, A 2025. Stack Ventilation Performance in a Semi-Detached House After Limiting Energy Consumption for Space Heating, *Energies* **18**(17), 4616. Available at: https://doi.org/10.3390/en18174616.
7. Dybiński, O and Mijakowski, M 2016. Problemy związane z utrzymaniem komfortu w dużych halach przemysłowych w okresie letnim [Thermal comfort in huge production halls during summer], *MATERIAŁY BUDOWLANE* **2016**(1), 44–47. Available at: https://doi.org/10.15199/33.2016.01.13.
8. European Collaborative Action 1992. Indoor Air Quality & Its Impact on Man - Report No. 11 - Guidelines for Ventilation Requirements in Buildings, Office.
9. Fanger, PO *et al.* 1988. Air pollution sources in offices and assembly halls, quantified by the olf unit, *Energy and Buildings* **12**(1), 7–19. Available at: https://doi.org/10.1016/0378-7788(88)90052-7.
10. Fanger, PO 1988. FUNDAMENTALS OF THERMAL COMFORT, in *Advances In Solar Energy Technology*. Elsevier, 3056–3061. Available at: https://doi.org/10.1016/B978-0-08-034315-0.50562-0.
11. Fanger, PO 1988. Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors, *Energy and Buildings* **12**(1), 1–6. Available at: https://doi.org/10.1016/0378-7788(88)90051-5.
12. Frontczak, M and Wargocki, P 2011. Literature survey on how different factors influence human comfort in indoor environments, *Building and Environment* **46**(4), 922–937. Available at: https://doi.org/10.1016/j.buildenv.2010.10.021.
13. Geng, Y *et al.* 2017. The impact of thermal environment on occupant IEQ perception and productivity, *Building and Environment* **121**, 158–167. Available at: https://doi.org/10.1016/j.buildenv.2017.05.022.
14. Gładyszewska-Fiedoruk, K 2013. Correlations of air humidity and carbon dioxide concentration in the kindergarten, *Energy and Buildings* **62**, 45–50. Available at: https://doi.org/10.1016/j.enbuild.2013.02.052.
15. Gladyszewska-Fiedoruk, K and Adana, MR De 2020. Improving the Effectiveness of Stack Ventilation by Supplying an Outdoor Air Stream, *IOP Conference Series: Materials Science and Engineering* **809**(1), 012008. Available at: https://doi.org/10.1088/1757-899X/809/1/012008.
16. Gładyszewska-Fiedoruk, K and Gajewski, A 2012. Effect of wind on stack ventilation performance, *Energy and Buildings* **51**, 242–247. Available at: https://doi.org/10.1016/j.enbuild.2012.05.007.
17. Al Horr, Y *et al.* 2016. Occupant productivity and office indoor environment quality: A review of the literature, *Building and Environment* **105**, 369–389. Available at: https://doi.org/10.1016/J.BUILDENV.2016.06.001.
18. Instytut Meteorologii i Gospodarki Wodnej Państwowy Instytut Badawczy 2023. *Rocznik Meteorologiczny 2022*. Edited by A. Szokalska.
19. Instytut Meteorologii i Gospodarki Wodnej Państwowy Instytut Badawczy 2024. *Rocznik Meteorologiczny 2023*. Edited by A. Szokalska. Warszawa.
20. Jermacz, K and Gajewski, A 2019. Experimental lnvestigations of Carbon Oxides in an Auto Repair Shop, *Ciepłownictwo, Ogrzewnictwo, Wentylacja* **50**(1), 30–33. Available at: https://doi.org/10.15199/9.2019.I.5.

21. Jones, AP 1999. Indoor air quality and health, *Atmospheric Environment* **33**(28), 4535–4564. Available at: https://doi.org/10.1016/S1352-2310(99)00272-1.
22. Kim, J *et al.* 2018. Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning, *Building and Environment* **129**, 96–106. Available at: https://doi.org/10.1016/j.buildenv.2017.12.011.
23. Kim, J, Schiavon, S and Brager, G 2018. Personal comfort models – A new paradigm in thermal comfort for occupant-centric environmental control, *Building and Environment* **132**, 114–124. Available at: https://doi.org/10.1016/J.BUILDENV.2018.01.023.
24. Kroner, W, Jakubowska, P and Noszczyk, P 2019. Ochrona pomieszczeń przed przegrzewaniem w okresie letnim w aspekcie komfortu termicznego [Protection of rooms against overheating in the summer period in the aspect of thermal comfort], *Materiały Budowlane* **2019**(9), 54–56. Available at: https://doi.org/10.15199/33.2019.09.03.
25. Minister of Development and Technology 2022. Notice of the Minister of Development and Technology of 15 April 2022 on the announcement of the unified text of the regulation of the Minister of Infrastructure on the technical conditions to which buildings should comply and their location.
26. Möhle, G *et al.* 2003. Development and application of a protocol for the assessment of indoor air quality, *Indoor and Built Environment* **12**(3), 139–149. Available at: https://doi.org/10.1177/1420326X03012003001.
27. Mui, KW, Wong, LT and Hui, PS 2006. A new sampling approach for assessing indoor air quality, *Indoor and Built Environment* **15**(2), 165–172. Available at: https://doi.org/10.1177/1420326X06063821.
28. Norbäck, D *et al.* 1995. Asthmatic symptoms and volatile organic compounds, formaldehyde, and carbon dioxide in dwellings, *Occupational and Environmental Medicine* **52**, 388–395. Available at: http://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=emed3&NEWS=N&AN=1995181268.
29. Pettenkofer, M 1858. *Luftwechsel in wohngebäuden*. München: Der J. G. Cotta'schen buchhandlung.
30. Rupp, RF, Vásquez, NG and Lamberts, R 2015. A review of human thermal comfort in the built environment, *Energy and Buildings* **105**, 178–205. Available at: https://doi.org/10.1016/J.ENBUILD.2015.07.047.
31. Teleszewski, T and Gładyszewska-Fiedoruk, K 2018. Changes of carbon dioxide concentrations in classrooms: Simplified model and experimental verification, *Polish Journal of Environmental Studies* **27**(5), 2397–2403. Available at: https://doi.org/10.15244/pjoes/77074.
32. Teleszewski, TJ and Gładyszewska-Fiedoruk, K 2020. Characteristics of humidity in classrooms with stack ventilation and development of calculation models of humidity based on the experiment, *Journal of Building Engineering* **31**, 101381. Available at: https://doi.org/10.1016/j.jobe.2020.101381.
33. The Government of the Hong Kong Special Administrative Region 2003. Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places.
34. The Polish Committee for Standardization 2000. Ventilation in residential buildings of collective housing and public utility -- Requirements (PN-83/B-03430).
35. Vardoulakis, S *et al.* 2015. Impact of climate change on the domestic indoor environment and associated health risks in the UK, *Environment International* **85**, 299–313. Available at: https://doi.org/10.1016/j.envint.2015.09.010.

36. Wiater, J and Gładyszewska-Fiedoruk, K 2022. Idoor Air Quality with Particular Reference to Carbon Monoxide in the Room - A Pilot Study, *Journal of Ecological Engineering* **23**(6), 286–293. Available at: https://doi.org/10.12911/22998993/149284.
37. Wolkoff, P 2018. Indoor air humidity, air quality, and health – An overview, *International Journal of Hygiene and Environmental Health* **221**(3), 376–390. Available at: https://doi.org/10.1016/j.ijheh.2018.01.015.
38. Zomorodian, ZS, Tahsildoost, M and Hafezi, M 2016. Thermal comfort in educational buildings: A review article, *Renewable and Sustainable Energy Reviews* **59**, 895–906. Available at: https://doi.org/10.1016/j.rser.2016.01.033.