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Measurements and simulation of CO_2 concentration in a bedroom of a passive house

Pomiary i modelowanie stężenia CO_2 w sypialni domu pasywnego

Abstract

This paper presents the results of the measurements and simulation of carbon dioxide concentration, as an indicator of indoor air quality, inside the master bedroom of an inhabited passive house. The measurements were taken in the autumn for a period of ten days. A series of sensors placed inside of the test object wirelessly measured the contaminant concentration every thirty seconds. The measurements were taken continuously in real time, when the occupants freely used the household. The contaminant concentration shows the impact of their activity on the air quality, as they were the only indoor air source of CO_2. During the measurements, the ventilation system that the house was equipped with was manually controlled by the users according to their daily routine. Simulations were performed to determine if it was possible to recreate the measured conditions within the bedroom of the passive house. The chosen program was the CONTAM software application, a tool designed for indoor air quality and ventilation analysis, developed by NIST.

Keywords: CO_2 concentration, passive house, indoor air quality, multi-zone model, CONTAM

Streszczenie

W artykule przedstawiono wyniki pomiarów i modelowania stężenia dwutlenku węgla, jako wskaźnika jakości powietrza wewnętrznego, w sypialni zasiedlonego domu pasywnego. Pomiary prowadzono w okresie jesiennym, nie zaburzając normalnego cyklu życia domowników. Umieszczone wewnątrz obiektu testowego czujniki w sposób bezprzewodowy mierzyły poziom stężenia zanieczyszczenia co 30 sekund, przez okres dziesięciu dni. Pomiar był dokonywany w sposób ciągły, w warunkach i czasie rzeczywistym, gdy mieszkańcy swobodnie poruszali się wewnątrz budynku. Poziom stężenia dwutlenku węgla odzwierciedlał wpływ aktywności mieszkańców na jakość powietrza wewnętrznego, gdyż byli oni jedynym źródłem CO_2 w obiekcie. Podczas pomiarów instalacja wentylacyjna, w którą dom został wyposażony, była włączona i regulowana przez domowników według wypracowanego przez nich schematu. Przeprowadzone symulacje miały na celu określenie czy możliwe jest odtworzenie warunków zmierzonych w sypialni analizowanego budynku. Do modelowania wybrano oprogramowanie CONTAM, narzędzie przeznaczone do analizy systemu wentylacji i jakości powietrza wewnętrznego, opracowane przez NIST.

Słowa kluczowe: stężenie CO_2, dom pasywny, jakość powietrza wewnętrznego, model wielostrefowy, CONTAM

1. Introduction

The building sector, followed by the industry and transport sectors, is the largest energy-consuming sector [1]. To control the energy use of new buildings, European directives require that all new buildings in the European Union must be near zero energy from 31st December 2020 and public buildings must be near zero energy from 31st December 2018 [2]. Because of these regulations, and due to increasing energy prices, the trend to build more energy efficient dwellings is growing.

The passive building standard is one of the most advanced forms of energy-efficient building standards. Houses built in line with this standard are objects that maintain a proper indoor climate in the summer as well as in the winter without the need for conventional heating and cooling systems [3]. The basic goal of the passive standard is to minimise thermal loss of the object to such an extent that the heating system uses a minimal amount of energy. In central Europe, for an object to be classified as passive, the amount of energy used for heating purposes should not exceed 15 kWh/(m^2 year) and the primary energy demand for the whole object (including heating, hot water preparation, electricity, etc.) should not be over 120 kWh/(m^2 year).

To meet such high energy standards, passive objects have a very compact structure and are well insulated. The outer envelope of the building is extremely airtight in order to minimise the uncontrolled airflow between the building and the outdoor air. The air exchange is limited to n50 = 0.6 1/h (0.6 of the volume of the whole building in one hour) and is certified by a blower door test [4]. Great attention is placed on the heat recovery of such objects as it must be at least 75%. Because of these rigorous standards, air exchange through the building envelope is minimised and fresh air is no longer provided by a natural ventilation system but by a mechanical ventilation system that allows heat recovery from the discharged air. Additionally, such objects may be equipped with a ground heat exchanger that heats or cools the fresh air before it flows into the ventilation system. This allows energy savings and may prevent passive objects from overheating in the summer.

Because of their airtight structure and minimal infiltration through the building envelope, passive objects may be prone to the accumulation of contaminants; however, they are equipped with mechanical ventilation systems, which should provide proper air exchange. This paper presents the results of measurements and simulation of carbon dioxide, as an indicator of indoor air quality, inside the master bedroom of a passive house. The measurements were conducted to determine if the quality of the indoor air of the test object meets the hygienic standards. During the measurements, the ventilation system with which the house was equipped was manually controlled by the users according to their daily routine. The measurements were taken continuously in real time, when the occupants freely used the household. The contaminant concentration shows the impact of their activity on the air quality, as they were the only indoor air source of CO_2. To identify whether it was possible to reflect the measured conditions within the test object through use of a computer program, simulations were performed using the CONTAM software application, developed by NIST, which is a tool designed for indoor air quality and ventilation analysis. The results of the conducted simulations allowed discussing the influence of the changing conditions within the bedroom (e.g. the number of persons, the ventilation air flow rate, the position of doors) on the indoor air quality.

The problem of carbon dioxide concentration in bedrooms has been researched by authors in the past. Kotol et al. [5]and Bekö et al. [6] analysed the concentration of carbon dioxide within houses built in accordance with the classic building standard with a natural ventilation system. The former measured the concentration of carbon dioxide within bedrooms in seventy-nine Greenlandic households, while the latter analysed the concentration of the same contaminant inside the bedrooms of five hundred Danish children. Both studies showed that the concentration of carbon dioxide exceeded the maximum hygienic levels; the main reason, highlighted by the authors, was the lack of the proper airing out of the test objects. Sekhar & Goh [7] studied the difference in the indoor air quality in bedrooms with a natural ventilation system and an air-conditioning system. The concentration of the contaminant was higher in the latter case due to the use of split-system air-conditioning units that only recirculate air and do not provide fresh outdoor air. They also found that the CO_2 level could affect the duration of sleep: if the concentration of CO_2 was high, sleep duration would decrease. The effects of bedroom air quality on sleep and performance during the following day was thoroughly examined by Strom-Tejsen et al. [8], who conducted two field-intervention experiments in single-occupancy student dormitory rooms. They concluded that when the CO_2 level was lower during the night, objectively measured sleep quality improved significantly. The study also showed that sleepiness reported the next day was lower and the ability to concentrate and the subjects' performance during a logical thinking test improved. The authors underlined that these factors can be significantly improved by increasing the supply rate of clean outdoor air in the bedrooms. Additionally, Gładyszewska-Fiedoruk [9] analysed the concentration of carbon dioxide within the bedrooms of a detached house, built in the classic standard, with natural ventilation. The study showed that the concentration of carbon dioxide exceeded the maximum recommended value most likely when more than one person slept inside the tested bedroom. This happened regardless of the sex and age of the occupants. The author underlined the risk of accumulation of contaminants in the case when there are too many occupants in relation to the possibility for bedroom ventilation. Batog & Badura [10] measured CO_2 levels in Polish sleeping rooms (typical blocks of flats with low ventilation rates). They also conducted CFD simulations in which they studied the dynamic changes of CO_2 in bedrooms. The results of their experiment showed that in a typical small bedroom, the air quality was very bad and in most cases, the CO_2 levels significantly exceeded the recommended hygienic standards. Based on the results of their research, the author recommended applying demand-controlled ventilation using sensory information rather than systems based on designed air exchange rates. They saw it as the only proper way to provide both good air quality and good energy efficiency in buildings.

2. Background

2.1. Analysed passive house

The research object (Figs. 1, 3 and 4) is located in a small town in the south west of Poland in the Silesian region [11]. The object is a detached house with a ground and first floor with the area of 120 m^2 (Fig. 1) [12]. The building meets the strict passive house standards, certified by the Passive House Institute [13]. Its annual maximum space heating demand is below 15 kWh/(m^{2}a). The blower door test performed before the inhabitants moved in, gave the result of 0.36 1/h and later, after the house had been occupied, 0.5 1/h. The building also has the typical characteristics of a passive house. Solar heat gain is increased by placing the windows with a high solar transmittance of glazing mainly within the south elevation. An exception is one window on the west elevation, upon which the main entrance doors are also located. All windows, with the exception of a glass door leading to a terrace, are fixed with no possibility of opening. The ventilation of the building is mechanical. The object is seated on a 25 cm reinforced concrete slab, underneath which, a 40 cm layer of Styrofoam was placed; as a result, the thermal bridges that would have occurred between the ground and the house were prevented. The thick layer of thermal insulation limited the heat exchange between the house and ground to almost zero. The space-heating energy demand of the passive house is covered by the floor heating system and by the warm air of a central mechanical ventilation system. The thermal energy for heating purposes (floor heating system, air heating coil) as well as for domestic hot water production is provided by the ground-source heat pump.

Because of the lack of fresh air infiltration through the building envelope and the fact that air is supplied only by a mechanical ventilation system, it was decided to measure the concentration of carbon dioxide within the described passive house. This was done to determine if the quality of the indoor air of the test object meets the recommended standards.

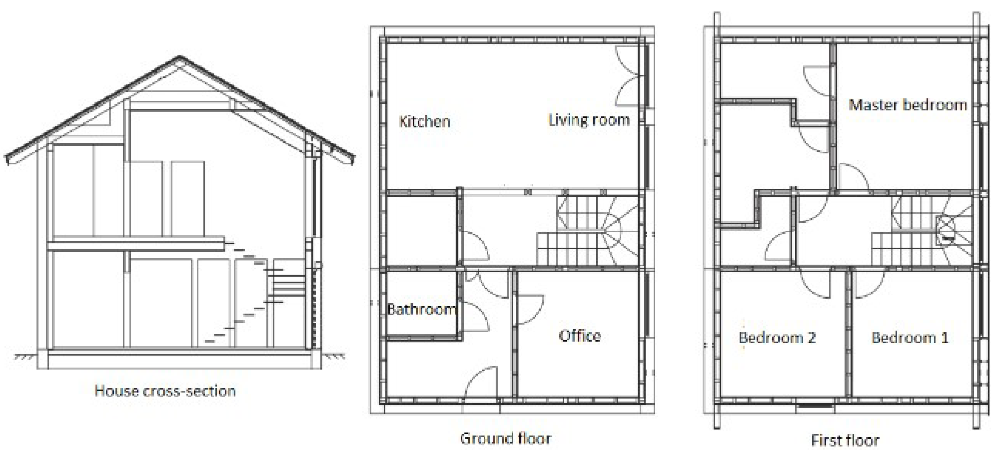

Fig. 1. Test object – plan of the passive house

During the research project, the house was occupied by a family of five: two adults and three children. One of the adults had a full time job which required his presence outside of the house, the other adult had a part time job that was done from within the house. Two of the children attended school during the research timeframe while the youngest child stayed at home under the second adults supervision. The occupants were the only indoor air source of carbon dioxide as cooking and water heating was done using an electrical system and heat pump, respectively. During the experiment, the inhabitants freely occupied the house and maintained a normal daily routine.

The research project focused on the measurements of carbon dioxide as an indoor air quality indicator. A series of sensors (Fig. 2) were placed inside the test object and measured the CO_2 concentration as well as the temperature and relative humidity. The measurements were taken in the autumn, when school activities took place, for a period of ten days. The sensors wirelessly traced the measured parameters every 30 seconds. The range of installed sensors in terms of carbon dioxide concentration was 0-5,000 ppm and their accuracy was ±50 ppm. The airflow though the inlets inside the house was measured using a Balometer that had a range of 10-400 m^3/h and an accuracy of ±3%.

Fig. 2. Measuring equipment and sensors

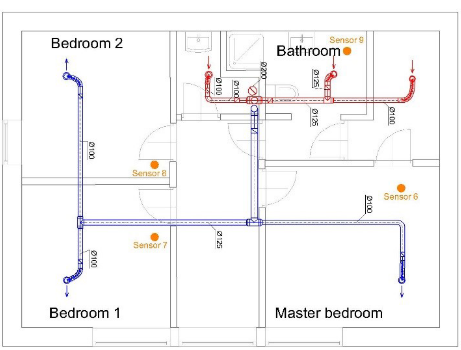

Fig. 3. First floor – sensor layout

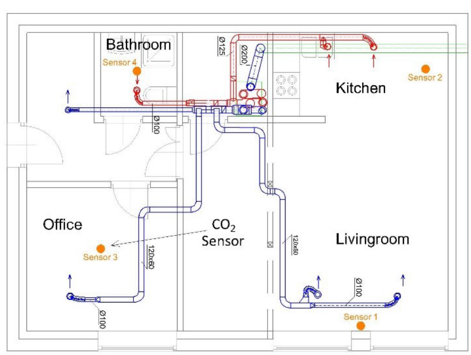

Fig. 4. Ground floor – sensor layout

The layout of the sensors (four on each floor) is shown in Figs. 3 and 4. The sensors were placed in rooms which were frequently occupied by the inhabitants. They traced the concentration of the contaminant continuously during the day and night. Measurements that took place during the night were done especially to determine if contaminant accumulation occurred in the bedrooms, as described in papers by Kotol et al. [5] and Bekö et al. [6] and Gładyszewska-Fiedoruk [9]. The risk of such an occurrence was high, as occupants reported that the night ventilation airflow rate was generally lowered to a minimum to eliminate noise.

2.2. Carbon dioxide

Carbon dioxide is a natural component of the earth's atmosphere. Its concentration in the outdoor air is around 0.04% (400ppm). The maximum indoor concentration of carbon dioxide that should not be exceeded, recommended by ASHRAE [14] and the World Health Organization, is 1,000 ppm [15]. This is also known as the *Pettenkofer* number. Higher concentrations of CO_2 have been proven to have a negative effect on human performance, the perception of poor indoor air quality and the prevalence of certain health symptoms such as the irritation of mucous membranes, headaches and tiredness [16–22]. The influence of elevated CO_2 concentration on the human body is presented in Table 1 [23, 24].

Table 1. Influence of elevated CO_2 concentration on the human body

CO_2 concentration [%]	CO_2 concentration [ppm]	Influence of elevated CO_2 concentration on the human body
0.2	2,000	occupants with respiratory disease may experience coughing or even fainting
1	10,000	increased respiratory rate
2-3	20,000-30,000	shortness of breath, deep breathing
5	50,000	breathing becomes heavy, sweating, pulse quickens
7.5	75,000	headaches, dizziness, restlessness, breathlessness, increased heart rate and blood pressure, visual distortion
10	100,000	nausea, vomiting, loss of consciousness within a few minutes
above 10	above 100,000	rapid loss of consciousness, coma, death

The results of the conducted measurements showed that the concentration of carbon dioxide in the analysed passive house remained below the level of 1,000 ppm for most of the time. However, periodically repeating exceedances of the maximum hygienic level occurred in every test room of the passive house. These periods were characterised by different lengths and times of occurrence, reflecting the rhythm of the occupants' lifestyles. A regularity in the fluctuations of the contaminant can be seen. The concentration of carbon dioxide rises during the day and lowers during the night on the ground floor while the opposite occurs on the first floor, which is strongly connected with the rhythm of the day and night.

The longest exceedances of CO_2 concentration were noted in the master bedroom of the analysed passive house, where the two adults and the youngest child slept, which is why it is studied in detail in this paper.

To see whether the outdoor air had a negative impact on the inside air quality, an additional sensor was placed in the inlet of the ventilation system. The measured concentration of the contaminant in the outdoor air differed between 312 ppm and 450 ppm, with an average of 385 ppm (which corresponds to the literature values), meaning that it did not have a large impact on the concentration of the contaminant within the house. The measured average value of CO_2 in the outdoor air was also used in the conducted simulations and described in this paper.

2.3. Simulation

The aim of the conducted simulations was to determine if it is possible to recreate the conditions inside of the test object and to what extent. The chosen simulation program, CONTAM, developed by NIST (the National Institute of Standards and Technology), is a multi-zone indoor air quality and ventilation analysis program that allows the user to determine the following factors: contaminant concentrations; personal exposure in buildings; airflows, including infiltration, exfiltration, and room-to-room airflow rates; contaminant concentrations including the transport rate of airborne contaminants due to airflow [25]. In this paper, CONTAM version 3.2 was used. A transient simulation using the impact Euler solver was conducted for a period of ten days for each case.

The influence of occupancy schedules and the effectiveness of ventilation on the contaminant concentration inside the master bedroom of the studied passive house was analysed using the CONTAM software. The computer simulations were compared to the measurement results.

CONTAM software has been applied by, among others, Yu et al. [26] where it was used to conduct a transient simulation of carbon dioxide emission from the human body. The authors analysed the variety of the concentration of indoor carbon dioxide in an office room over time under steady-state conditions of natural ventilation based on CONTAM. Alonso et al. [27] designed an airtight apartment model using the CONTAM software in which the impact of three different ventilation systems were tested. Rim et al. [28] defined the influence of outdoor particle sources on indoor air quality under three different ventilation scenarios using the same software. These examples show that the program is suitable for modelling indoor air quality.

During the simulation, the entire household was taken into consideration. The occupants had a detailed occupant schedule that determined their whereabouts inside the house. The detailed schedule is shown in [29]. This was performed to determine how the contaminants from other zones influenced the concentration inside the tested master bedroom. As stated earlier, three out of the five occupants slept in the master bedroom. In the simulation, it was assumed that the occupants were inside the test room as follows:

- The male adult: from 10 pm to 6 am;
- The female adult: from 10 pm to 6:45 am;
- The child: 2 pm to 4 pm (nap) and 9 pm to 7 am.

The occupancy schedule was discussed briefly with the occupants as well as being analysed using the measurement results. During the rest of the day, the occupants moved throughout the house or outside it. During the night, the other two children slept in their bedrooms (bedroom 1 and 2).

For simulation purposes, the amount of carbon dioxide generated by the adult occupants during the day was 0.005 L/s during the day and 0.0033 L/s during the night, these levels were adopted from Persily [30]. The CO_2 generation rate relating to the children was assumed as 0.0038 L/s during the day and 0.0025 L/s while sleeping [30].

3. Measurement results

The results of the measurements of carbon dioxide concentration in the master bedroom of the analysed passive house are shown in Fig. 5. A pattern can be observed in fluctuations of the contaminant. The concentration of carbon dioxide rises during the night and lowers during the day. Significant periods of concentration of carbon dioxide exceeded 1,000 ppm usually last 7-8 hours and are connected with the time of night rest. These distinctive periods of exceedance were recorded for most of the nights in the considered period. The maximum values of concentration of CO_2 during the night were usually around 1,200 ppm; one occurrence of 1,500 ppm and one occurrence of 1,800 ppm were registered.

To determine the influence of the ventilation system on the concentration of carbon dioxide in the master bedroom, the air supply rate, supplied by the ventilation system, and the contaminant level measured inside the bedroom were compared in Fig. 5. This figure shows that the concentration of carbon dioxide is strictly connected to the amount of air that flows through the ventilation system. When the ventilation rate is high, the concentration of the contaminant significantly lowers and the highest concentration is observed when the ventilation rate is the lowest.

The occupants could control the airflow rate of the system using a manual control panel. This panel allowed them to change the supply rate to three different levels without the option of turning the system completely off. During the measurements, the occupants freely changed the ventilation rate according to their will without any interference from the authors. The occupants reported that the night ventilation airflow rate was often lowered to a minimum to eliminate noise.

The analysed master bedroom had two doors: one leading into the walk-in wardrobe and the other into the hallway. According to the occupants, they slept with the open door to the walk-in wardrobe, but the door to the hallway was sometimes open and sometimes closed.

The measured average concentrations of the CO_2 in the master bedroom of the passive house are comparable with the measurements shown in the research done by [9], which analysed the concentration of carbon dioxide within the bedrooms of a detached house, built in the classic building standard with natural ventilation. The study showed that the concentration of carbon dioxide were most likely to exceed the maximum standard when more than one occupant slept inside the test room. This happened regardless of the sex and

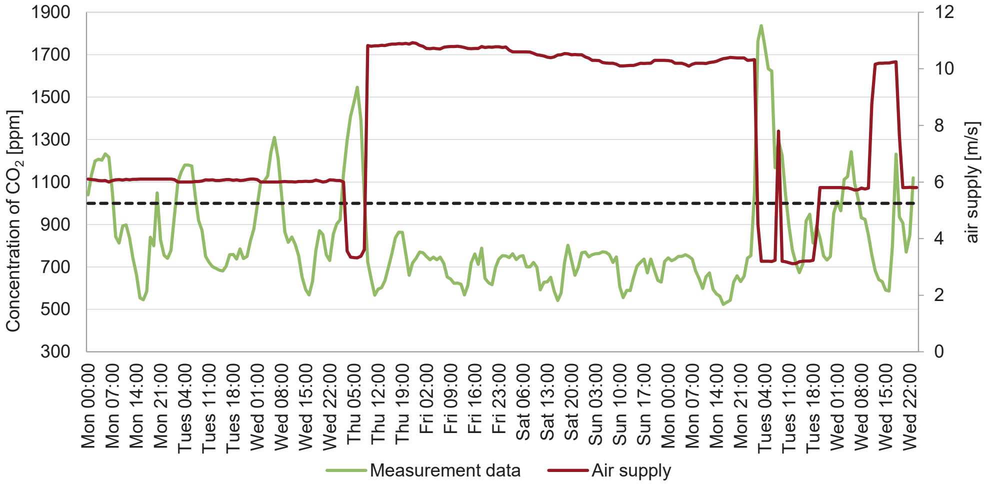

Fig. 5. Ventilation air flow rate and the measured concentration of carbon dioxide in the master bedroom of the passive house; maximum recommended level of 1,000 ppm marked by the dashed line

age of the occupants. According to Gładyszewska-Fiedoruk [9], the maximum night-time concentration of carbon dioxide in the tested bedroom (where the parent and a child slept) was approximately 1,200 to 1,300 ppm; this strongly corresponds with the values measured in the master bedroom of the studied passive house during the periods when the ventilation rate was set at the medium level.

Similar results are shown in the research of Kotol et al. [5] and Bekö et al. [6] where the concentration of carbon dioxide was measured during the night in bedrooms of buildings built in the classic standard, with natural ventilation. In his research, Bekö et al. showed that only 32% out of the five hundred bedrooms which were taken into consideration had proper indoor air quality. In the research performed by Kotol et al. [5] only 34% of the tested bedrooms had a CO_2 level below 1,000 ppm. The reason for this was the low amount of fresh air flowing into the rooms.

In the tested master bedroom, the number of occupants was higher than in a standard master bedroom as it is usually designed for two occupants and the ventilation rate in some cases was too low. When the air flow was higher, the air quality improved showing that the analysed mechanical ventilation system may provide good indoor air quality when properly controlled. Even though the houses in the mentioned research papers by Kotol et al. [5] and Bekö et al. [6] were built in a classic building standard ventilation and the test object described in this paper was built in a passive standard with mechanical ventilation, the same issues concerning contaminant concentration occur. This means that the mechanical ventilation system in the passive house does not always provide better indoor air quality than objects with a natural ventilation system. The key issue is proper control of the ventilation system (with regard to air flow rate) and adaptability to changing conditions.

4. CONTAM simulation results

The influence of occupancy schedules and the effectiveness of ventilation on the contaminant concentration inside the master bedroom of the studied passive house was analysed using the CONTAM software application. In each case, the computer simulations were compared to measurement results as different scenarios were discussed.

4.1. Simulation with minimal ventilation rate

As shown in Fig. 5, when the minimal ventilation rate was turned on, the concentration of carbon dioxide was the highest. Figure 6 shows the results of the CONTAM simulations conducted for the minimal ventilation air flow rate compared to measurement results recorded in the analysed period. Figure 7 presents the results of the CONTAM simulations for the minimal ventilation air flow rate but with the closed walk-in wardrobe.

The figures above show that the highest CO_2 peaks (Thursday from 3 am to 9 am and Tuesday from 2 am until 9 am) were in fact because of the low ventilation rate. However, they also show how occupant behaviour influenced the results. In the first simulation, where the door between the bedroom and wardrobe was open (Fig. 6), the concentration of the contaminant is lower than in the second scenario, when the door to the wardrobe was closed (Fig. 7). During the simulation with the door opened, the maximum calculated CO_2 concentration was around 1,500 ppm, which corresponds to the contaminant peak from the Thursday morning. When the door was closed, the calculated concentration increased up to 1,800 ppm. This level of around 1,800 ppm also corresponds to the CO_2 level during the second contaminant peak that occurred on the second Tuesday between 2 am and 9 am,

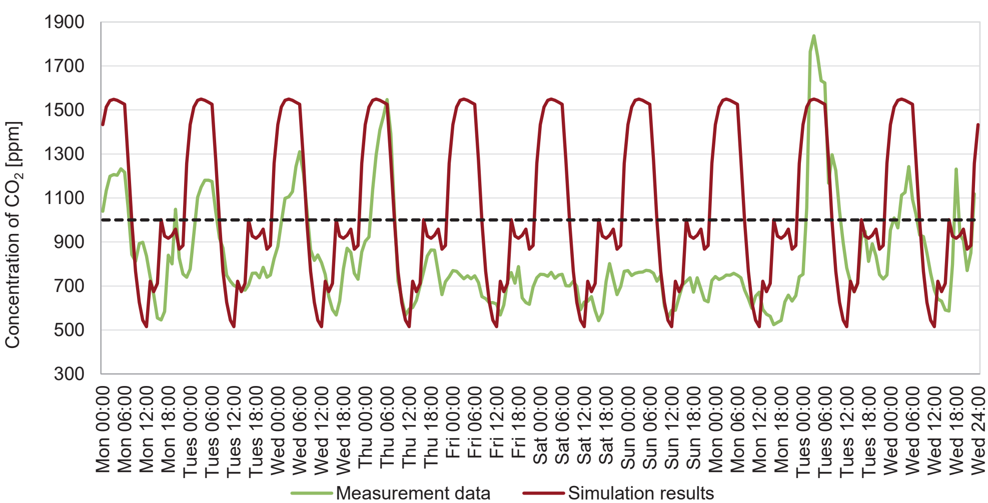

Fig. 6. Carbon dioxide concentration – simulation with the minimal ventilation rate and open door to the walk-in wardrobe; maximum recommended level of 1,000 ppm marked by the dashed line

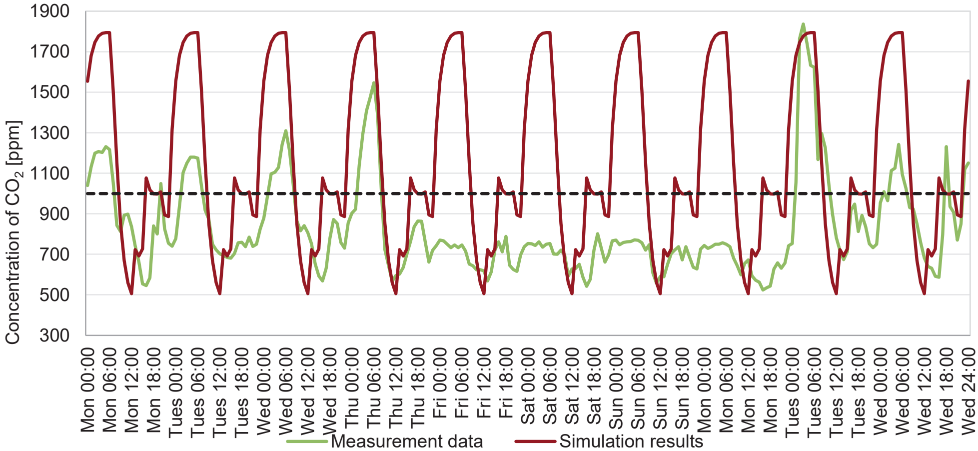

Fig. 7. Carbon dioxide concentration – simulation with the minimal ventilation rate and closed door to the walk-in wardrobe; maximum recommended level of 1,000 ppm marked by the dashed line

meaning that during this period, the occupants slept with closed doors to the bedroom. This shows how contaminant migration within a household may occur and how minor details influence the indoor air quality.

4.2. Simulation with medium ventilation rate

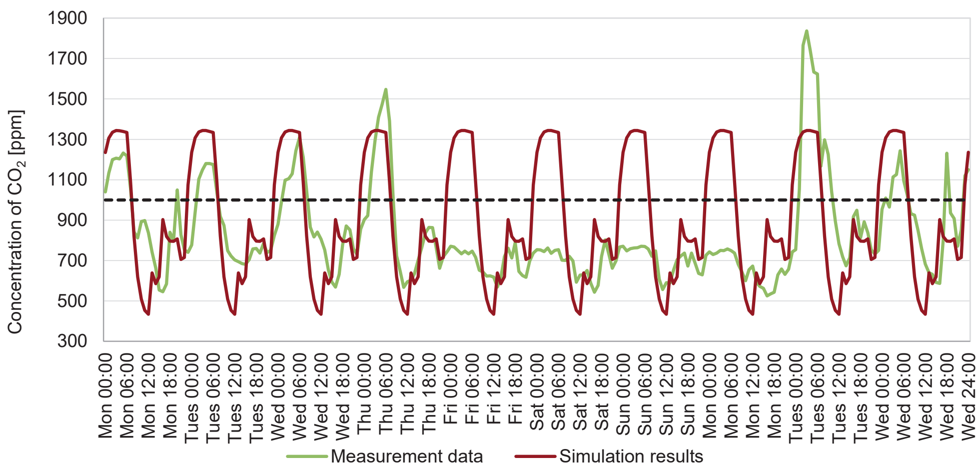

Fig. 8. Carbon dioxide concentration – simulation with the medium ventilation rate and open door to the walk-in wardrobe; maximum recommended level of 1,000 ppm marked by the dashed line

The medium ventilation rate was activated by the occupants between Monday at 12 am and Thursday at 1 am as well as from the second Tuesday at 8 pm until the second Wednesday at 10 am. In the simulation, it was assumed that the door to the wardrobe was open and the door to the hallway was closed (Fig. 8). The simulation results correspond to the measurement data as the peaks of CO_2 are noted in the same time frame. However, in most cases, the maximum concentration in the simulation is higher than real measurements and the minimal calculated CO_2 level is 434 ppm while the minimal level of the contaminant in reality was 524 ppm. Because of this discrepancy, it was decided to perform a simulation in which both of the bedroom doors were open. The results of the simulation are shown in the figure below.

The simulation with both doors open (Fig. 9) corresponds to the measurements in the period when the medium ventilation rate was set. The minimal CO_2 level corresponds to the level of the contaminant from the measurement data.

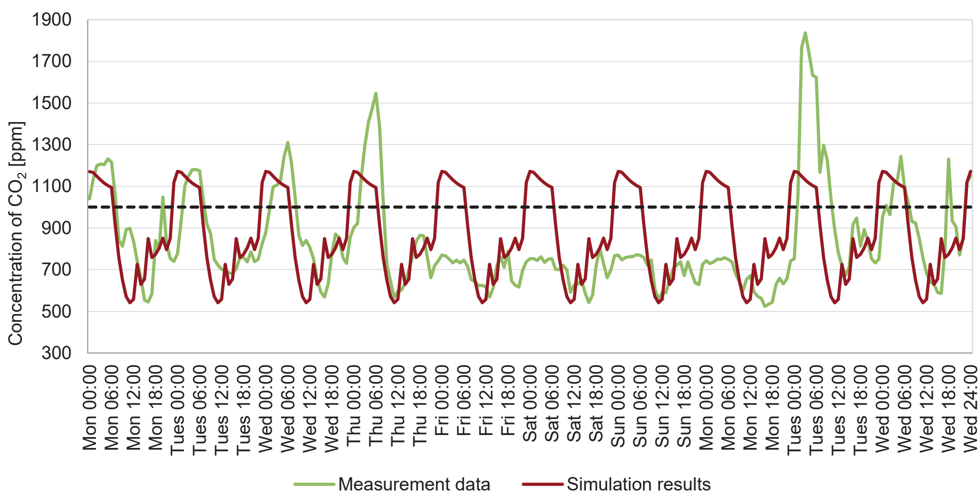

Fig. 9. Carbon dioxide concentration – simulation with the medium ventilation rate and both doors open; maximum recommended level of 1,000 ppm marked by the dashed line

4.3. Simulation with maximum ventilation rate

The maximum ventilation rate was mainly active between Thursday at 9 am until the second Tuesday at 2 am. According to the occupants' statements and analysis of the sensor results, only the female adult and the child slept in the bedroom during this period. The occupation schedule was altered during the simulations with regard to the maximum ventilation rate so as to take this change into account. The first simulation with this ventilation rate was conducted with only the wardrobe door open; this is shown in Fig. 10. However, similar to the situation with the medium ventilation rate, the real contamination level did not correspond with the simulation results, which showed a significantly lower contaminant level. This is why an additional simulation was conducted in which it was assumed that both doors to the bedroom were open. The results of this simulation are shown in Fig. 11. The results from this simulation corresponded better to the real results especially with regard to the minimal CO_2 level.

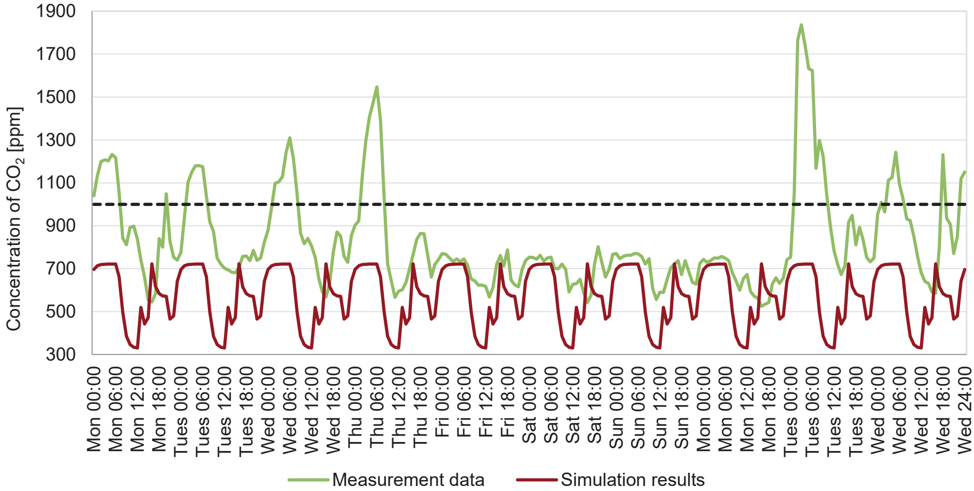

Fig. 10. Carbon dioxide concentration – simulation with the maximum ventilation rate and door to the walk-in wardrobe open; maximum recommended level of 1,000 ppm marked by the dashed line

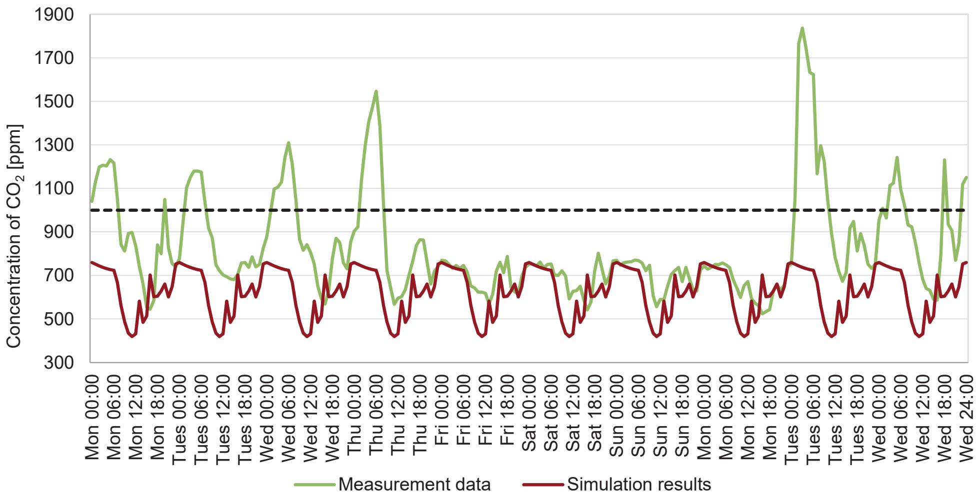

Fig. 11. Carbon dioxide concentration – simulation with the maximum ventilation rate and both doors open; maximum recommended level of 1,000 ppm marked by the dashed line

4.4. Simulation with the occupancy schedule and real ventilation rates.

After the analysis of the different scenarios, a full simulation was conducted that included the occupancy schedule and the real ventilation rates; the results are shown in Fig. 12. This figure shows that it is possible to model the conditions of carbon dioxide concentration inside the analysed bedroom based on the occupancy schedule and the real ventilation rates.

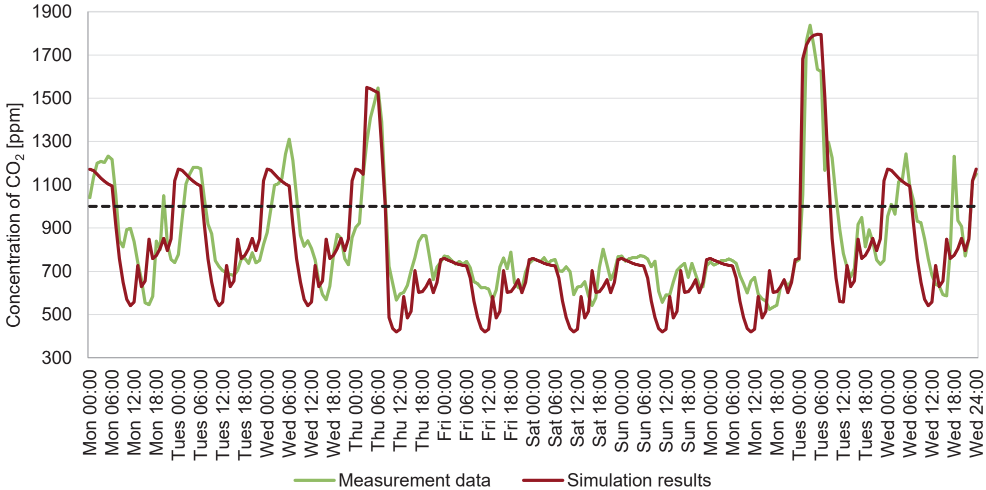

Fig. 12. Carbon dioxide concentration – measurements and the results of simulation with the occupancy schedules and real ventilation rates; maximum recommended level of 1,000 ppm marked by the dashed line

5. Conclusions

In this paper, the results of the measurements and simulation of carbon dioxide concentration as an indicator of the quality of indoor air inside of a master bedroom of the inhabited passive house have been shown. The measurements were performed to determine if the quality of the indoor air of the test object meets the hygienic standards. The aim of the conducted simulation was to determine if it is possible to recreate the conditions of carbon dioxide concentration inside of the analysed bedroom and to what extent.

The measurement results show that the concentration of carbon dioxide in the master bedroom of the analysed passive house mostly remained below 1,000 ppm – the recommended maximum indoor concentration of carbon dioxide that should not be exceeded for hygienic reasons. However, this value was periodically exceeded to a significant degree for episodes usually lasting 7-8 hours, which can be connected to the sleeping patterns of the occupants. These periods were recorded for most of the nights during the test period. The values of maximum concentrations of CO_2 during the night were usually around 1,200 ppm; on one occasion, 1,500 ppm was registered and on another occasion, the registered value was 1,800 ppm.

The maximum concentration of carbon dioxide in the master bedroom of the analysed passive house measured during the periods when ventilation rate was set on the medium level are comparable to the values reported by Gładyszewska-Fiedoruk [9], who analysed the concentration of carbon dioxide within bedrooms of a detached house, built in the classic building standard with natural ventilation. When the air flow rate was higher, the air quality improved showing that the analysed mechanical ventilation system may provide good indoor air quality when properly controlled. Even though the houses in the mentioned research papers by Gładyszewska-Fiedoruk [9], Kotol et al. [5]and Bekö et al. [6] were built in a classic building standard with natural ventilation and the test object described in this paper is built in a passive standard with mechanical ventilation, the same issues concerning contaminant concentration occur. This means that the mechanical ventilation system in the passive object does not always provide better indoor air quality than objects with a natural ventilation system. The key issue is proper control of the ventilation system (air flow rate) and adaptability to changing conditions.

This project has shown that the registered exceedances of the recommended indoor levels of carbon dioxide were associated with the regulation of the mechanical ventilation system implemented by the occupants, who freely changed the ventilation rate according to their will. The occupants reported that the night-time ventilation airflow rate was often lowered to a minimum to eliminate noise; this can be seen in the results of the conducted measurements. This underlines the importance of occupant behaviour and awareness with regard to the control of mechanical ventilation in passive houses.

Due to the nature of passive buildings, during the design phase, special attention should be placed on the fact that the number of people in different rooms and their physical activity can differ strongly from the design values. If the ventilation system does not take into account the actual amount of household members (or potential visitors), it may be insufficient in providing appropriate indoor air quality. The simplest solutions for this problem the possibility of opening the windows to periodically increase the intensity of ventilation (inflow of fresh air) – in passive houses is very limited. A potential solution could be the use of a variable air volume ventilation system (VAV) controlled individually for each room by the level of carbon dioxide. This view is consistent with the results of Batog & Badura's [10] research who recommend applying demand-controlled ventilation using sensory information rather than systems based on designed air exchange rates as the only proper way to provide both good air quality and good energy efficiency of a building. Such systems, however, are much more expensive, which certainly is a barrier to their use in objects such as a detached house.

The results of the conducted CONTAM simulation showed that it is possible to model the conditions with regard to carbon dioxide concentration inside of the analysed bedroom based on the occupancy schedule and the real ventilation rates. The prediction of contaminant concentrations can be used to determine the indoor air quality of a building before it is constructed and occupied or to investigate the impact of various design decisions related to ventilation system design.

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