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CFD MODELLING OF AIR FLOW AND TRANSPORT OF CONTAMINANTS IN A PASSIVE HOUSE

MODELOWANIE METODĄ CFD (KOMPUTEROWEJ DYNAMIKI PŁYNÓW) PRZEPŁYWU POWIETRZA I TRANSPORTU ZANIECZYSZCZEŃ W DOMU PASYWNYM

A b s t r a c t

Rising costs of energy have caused the building envelope in the living sector to become tighter to improve energy efficiency. This raises questions about the quality of the indoor air as in traditional housing fresh air is supplied not only by ventilation system by also by infiltration through cracks in the building envelope. If a building is not properly ventilated, contaminants could accumulate within it and their levels could become hazardous to human comfort and health.

Keywords: *CONTAMW*, *passive house*, *mechanical ventilation*, *modelling of contaminant concentrations*

S t r e s z c z e n i e

Wzrastające koszty energii spowodowały, że przegrody zewnętrzne w budynkach stały się coraz bardziej szczelne, aby polepszyć efektywność energetyczną. Rozpoczęło to szereg dyskusji na temat jakości powietrza w pomieszczeniach, ponieważ w tradycyjnym budownictwie świeże powietrze jest dostarczane poprzez infiltrację przez nieszczelności w budynku. Jeśli budynek nie jest odpowiednio wentylowany, zanieczyszczenia gromadzą się w nim, co może tworzy niekomfortowe warunki, które mogą niebezpieczne dla zdrowia.

Słowa kluczowe: *CONTAMW*, *dom pasywny*, *wentylacja mechaniczna*, *modelowanie stężenia zanieczyszczeń*

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1. Introduction

Due to the growing costs of energy and environmental consideration, great effort is nowadays made to build more and more energy efficient buildings which under certain requirements can be named as passive houses. Such buildings are not only built from materials providing better insulation, but they are also becoming more “airtight” to prevent infiltration energy losses via building infrastructure and ventilation systems. This raises questions about the quality of indoor air in such airtight structures, for which natural ventilation is no longer the optimal solution to provide proper air quality. The reason why natural ventilation is not adequate for the energy efficient building is because it is (apart from ducts) based on airflows through leakages throughout the building envelope.

This paper reports a study based on computer simulation to examine this issue in an airtight passive house located in Poland. The simulations where performed using CONTAMW software, a computer program designed to analyse a ventilation systems, indoor air quality and occupant exposure in a multi-zone structure [5]. The program was used to analyse and compare three ventilation systems: natural ventilation, demand control ventilation based on occupant schedules and demand control ventilation based on the concentration of contaminants. The contaminants included in these simulations are: carbon dioxide, carbon monoxide, nitrogen dioxide, total volatile organic compounds and water vapour. As an indicator to compare the energy consumption of the proposed mechanical ventilation systems, their air flow rates through each air handling unit were compared.

2. Methods

This study shows the impact of three deferent ventilation systems within a passive house on the indoor air quality assesed by computer simulation. The chosen program was CONTAMW, a computer program designed to analyse ventilation systems, indoor air quality and occupant exposure in a multi-zone structure [5]. The tested ventilation systems include:

– A natural ventilation system where the air flows into the house through infiltration leakages and with two outlet fans in the bathroom and kitchen.
– A mechanical ventilation system based on zone occupancy. The airflow is maintained by an air handling unit connected to a series of inlets and outlets within the house. The proper inlets and outlets are activated when an occupant is within a zone/room and are switched off when the zone is empty.
– A mechanical ventilation system based on contaminant control. The airflow is maintained by the same system as in the one based on zone occupancy but it is activated when the concentration of carbon dioxide exceeds the maximum the permissible level, which is 1000 ppm.

2.1. Considered parameters

The test object is a one-story house located in Boruszowice, Poland, occupied by a family of four (two adults and two children). The house is heated by a heat pump system and has a central air-conditioning system [4, 9].

The contaminants considered in the study are airborne contaminants. The CONDAMW program allows the user to define traceable and non-traceable contaminants. The concentration of the latter is constant and is used to define the ambient contaminant influence [4]. Outdoor air composition is considered constant and consists of: 75.54% nitrogen, 23.14% oxygen, 1.27% argon and 0.05% CO_2 [5]. On the other hand traceable contaminants are variable and include: carbon dioxide, carbon monoxide, nitrogen dioxide, water vapour and total volatile organic compounds.

The only considered indoor source of CO_2 is human respiration. As mentioned earlier, a family of four occupy the house and they include: two adult family members, a male and female working full time, two children, which are aged 16 (child_1) and 10 (child_2). Each member has an assigned schedule. Such timetables define the whereabouts of each occupant as well as specify the amount of time spent by him or her in each room and outside of the house. This option allows to track the amount of contaminants within a zone that are produced by each individual during the day. In the following simulations the amounts of CO_2 generated by the adult male and female are 9.1 mg/s and 8.0 mg/s respectively while they are awake. The children's CO_2 generating rates when awake are lower and equal 7.8 mg/s for child_1 and 5.5 mg/s for child_2. While sleeping, the amount of CO_2 generated by occupants is equal to 66% of the rate when they are awake [1].

It was decided that a gas cooking stove would be taken under consideration as cooking on both gas and electrical stoves are equally popular in Poland and many EU countries and gas stoves generate more contaminants. Cooking on such a stove generates mostly water vapour, carbon monoxide (CO) and nitrogen dioxide (NO_2). Other contaminants caused by cooking where not taken into consideration. The generation rate depends on the time of day and its example is displayed in the table below (Table 1).

Table 1

Generation level of CO and NO_2 for gas cooking [1]

weekdays		
	Carbon monoxide [μg/s]	Nitrogen dioxide [μg/s]
6:30–7:30 am	210	28
17–17:30 pm	420	56
17:30–18 pm	830	111

Besides cooking, sources of water vapour include bathing and occupant respiration. The estimated amount of water vapour generated while showering is 3 dm^3/h. Each occupant takes a 10 minute shower daily based on his or her daily schedule [8]. The amount of moisture released by cooking breakfast or supper is equal 0.45 dm^3/h , while cooking dinner 1.33 dm^3/h [8]. Furthermore, the ratio of humidity generation from each person during the day is equal to 0.03 dm^3/h [8].The generation rate of volatile organic compounds is considered to be steady as they are emitted by building materials and furnishings. Their amount was estimated on the basis of the area of each room and is equal to 250 μg/h per each cubic meter of the house space [3].

2.2. Simulation approach

The tool used to present the contaminant migration and concentration is the computer program CONTAMW developed by NIST (National Institute of Standards and Technology, which is a part of the Technology Administration of the U.S. Department of Commerce). CONTAMW is a multi-zone indoor air quality and ventilation analysis program that helps to define airflows and pressure drops, concentration of airborne contaminants and occupant exposure to them [5]. Each zone created in the program has the assigned name, temperature, initial contaminant concentration and assigned contaminant sources. Airflow paths are created between zones to connect zones with other zones or with the outdoor space, allowing air to move between two neighbouring zones. The external air paths can be defined for example as: leakages through windows, doorways or cracks in the building envelope. The airflow through the majority of these paths is determined by the flow characteristics of the path itself and the air pressure difference between the zones [5]. The sources of contaminants can be assigned to a specific zone, as for example kitchen and bathroom appliances, or can be connected to the occupants who generate contaminants while migrating through zones. CONTAMW defines the concentration of contaminants in each room by calculating the airflow characteristics through a zone and estimating contaminant migration between zones.

2.3. Natural ventilation

The first simulation was undertaken for a natural ventilation system which consists of extraction fans that are placed in the bathroom and room_1 (which contains kitchen appliances). Fresh air is supplied through leakage paths though the building envelope. Each air vent is turned on by a schedule that lines up with occupant usage of the room. The air vent in the kitchen is turned on when cooking occurs. As the house is a passive one, the air leakages are much smaller than in a standard one, the pressure drops through the leakage paths are quite high and probably cause a draft inside of the house. To prevent this, an additional inlet flow path was placed in the bathroom and room_1 (Fig. 1).

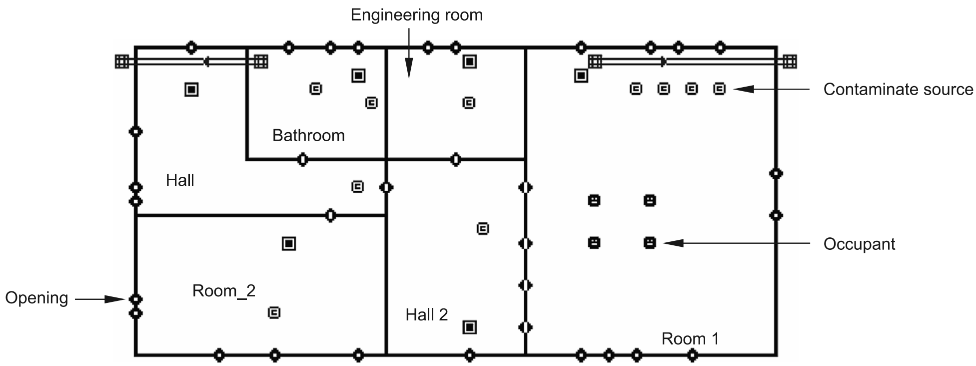

Fig. 1. Natural ventilation system

2.4. Demand control ventilation based on zone occupancy

This type of demand control ventilation system is accomplished by supplying zones with fresh air through a single air intake and divided into room_1, room_2, and the hallway. Contaminated air is removed through exhaust duct, which is connected through valves with room_1, the bathroom. The activity of the system depends on occupant schedule. When an occupant is inside of a room, the proper valves are opened and the room is ventilated. Because the occupants only attend the hallway on an limited basis, the ventilation system in this room is scheduled to activate briefly before occupants enter the room and is deactivated a period of time after the occupants exit the room. As a result, the sufficient amount of contaminants would not have been removed. The supply and exhaust fans used inside of each room have an equal capacity for maintaining air pressure balance within the building. This simulation approach does not depend on the contaminate concentration within a room and is not affected by it. According to Polish standards, when occupants are outside of a zone the ventilation system maintains a 20% airflow though the ducts [12]. The ventilation system in the engineering room is not altered as its main purpose is to ventilate the monitoring system (Fig. 2).

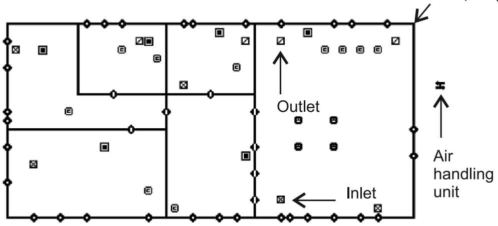

Fig. 2. Demand control ventilation based on zone occupancy

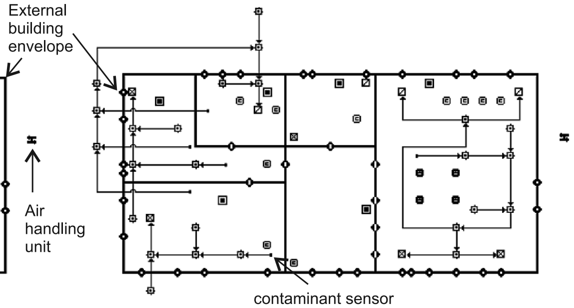

Fig. 3. Demand control ventilation based on CO_2 concentration

2.5. Demand control ventilation based on indoor air quality

This ventilation system is designed in the same way as the duct system in the previous simulation approach (Demand control ventilation based on zone occupancy). In this approach, the ventilation system was activated on the basis of the indoor air quality. The contaminate chosen as an indicator was carbon dioxide (CO_2). Carbon dioxide was chosen not only because of its negative effect on the human organism but also because it is the most variable contaminant. Its amount depends on occupant activity. Each room was equipped with a CO_2 sensor that sent a signal to proper valves when the CO_2 level was higher than the project assumptions. The CO_2 limit is equal to 1000 ppm. According to Polish standards, when occupants are outside of a zone the ventilation system maintains a 20% airflow though the ducts [12]. The ventilation system in the engineering room is not altered as its main purpose is to ventilate the monitoring system (Fig. 3).

3. Results

As explained above, the ventilation system is run by controlling it either on occupant schedules or on the concentration of carbon dioxide. This resolves the problem of altering the concentration of all of the contaminants in the building in comparison to their concentration when natural ventilation is used. The room that contains the most altering contaminant rate as well as the highest concentration of pollutants is room_1. All cooking activities take place here, and the two adult family members sleep in this room. This is why the concentrations from this room will be used to display the difference between the efficiency of the three ventilation methods. The contaminants displayed below include: carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and volatile organic compounds (VOC). These are vital contaminants that affect a person's health, efficiency and comfort level, which is why they were used in all of the simulations.

3.1. Carbon dioxide

When analysing Fig. 4, it is clear that the natural ventilation system does not meet the stated criteria and constantly exceeds the allowable maximum contaminant (CO_2) level which is 1000 ppm. However, as expected, both types of mechanical ventilation (demand control based on occupant schedules as well as contaminant concentration) meet the indoor air criteria for the maximum amount of this contaminant. Constant, higher than 1000 ppm,

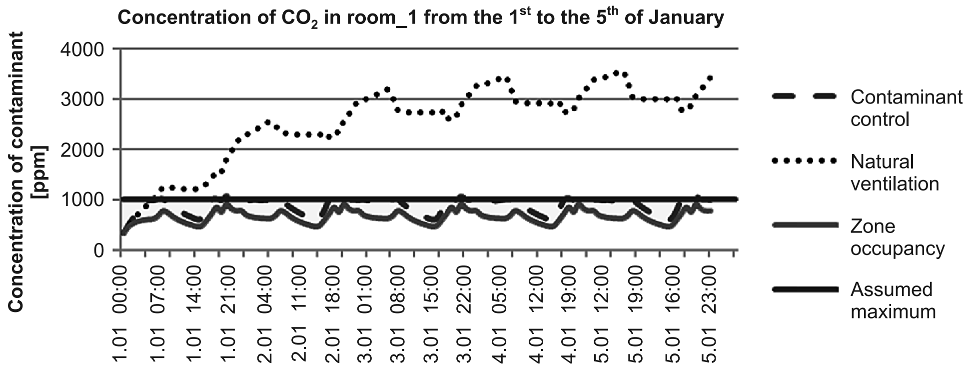

Fig. 4. Concentration of CO_2 in room 1

concentration rate of carbon dioxide may cause, among others, headaches, tiredness, dizziness, elevated heart rate and in extreme cases suffocation [13]. Though the concentrations less than 3500 ppm of carbon dioxide dose not threaten the human wellbeing, it is important to remember that the source of carbon dioxide inside of this house is strictly associated with occupant physical activity.

3.2. Carbon monoxide

Since carbon monoxide is a toxic gas it is vital to keep its concentration below a certain level. Even at low concentrations it causes mild effects that are often mistaken for the flu, which include dizziness, disorientation, nausea and headaches [13]. In higher concentrations it is deadly. Furthermore, because of the lack of colour and smell it is practically impossible for humans to detect increased CO levels without instruments.

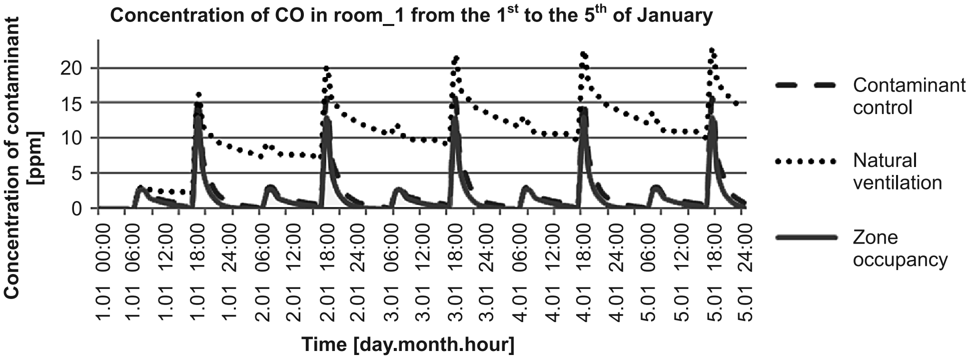

Fig. 5. Concentration of CO in room 1

Figure 5 shows, that the maximum established rate of CO – 4.3 ppm [2] is constantly exceeded while using the natural ventilation system and occasionally by both mechanical ventilation systems (demand control based on occupants schedules and the one based on contaminant concentration) while cooking dinner. This is why natural ventilation is not an acceptable option if a gas stove is used inside an air-tight house as the one considered in this research.

3.3. Nitrogen dioxide

In Figure 6 it is noticeable that the rate of nitrogen dioxide is almost instantly and constantly surpassed while using natural ventilation as its limit was specified as 0.058 ppm [2].

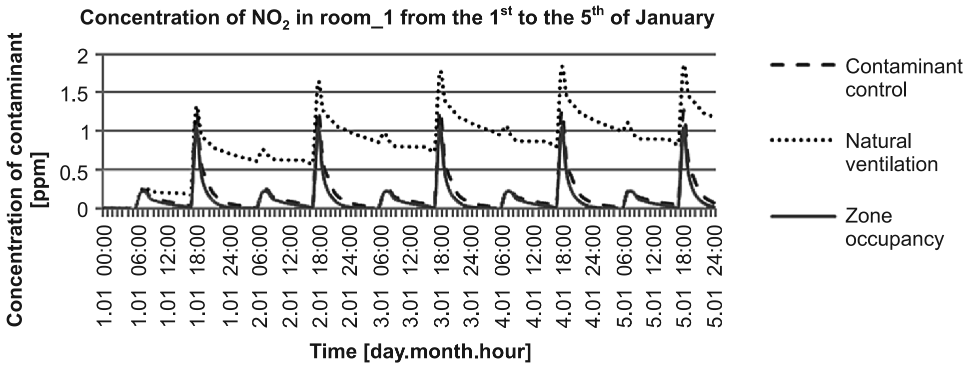

Fig. 6. Concentration of NO_2 in room 1

Similarly to the Fig. 5 for carbon monoxide, nitrogen dioxide rates are occasionally exceeded for both mechanical ventilation systems (demand control based on occupant schedules and contaminant concentration). It takes place while cooking dinner. Nitrogen dioxide may cause irritations of the respiratory system and can be hazardous to young children causing respiratory infections [13]. This is why natural ventilation is not an acceptable option if a gas stove is used inside an airtight house as it is in this case.

3.4. Water Vapour

In Figure 7 it is visible that the rate of water vapour concentrations are almost instantly and constantly exceeded while using natural ventilation, as its limit was specified between 30–60% [11]. On the other hand, the relative humidity inside of the house, while using the mechanical ventilation systems, is below the lower limit. When a house is too dry, the occupants may experience aggravation of allergy and asthma symptoms, frequent colds, flu, sore throats, nose bleeds, dry skin and dry coughs [14]. This can be easily altered by using a humidifier.

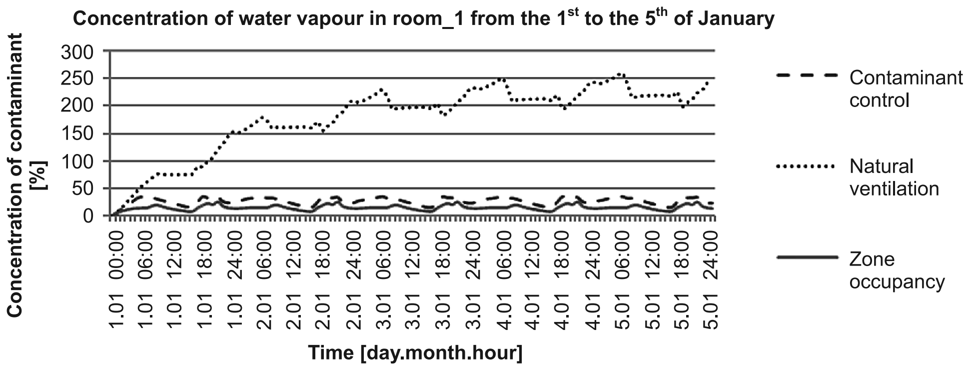

Fig. 7. Concentration of water vapour in room_1

The symptoms of excess indoor moisture are more hazardous. They include: odours, frost and ice on cold surfaces (such as windows), surface discoloration and texture changes and deformations of wooden surfaces [15]. It is common for mould and mildew to appear when the relative humidity is above 70%. Mould can lead to a series of health problems that include: development of asthma, coughs, allergic reactions, and respiratory ailments [15].

3.5. Total volatile organic compounds

The indoor concentration of volatile organic compounds is higher (up to ten times higher) than outdoors [13]. The reason for this is that these compounds are emitted by a wide range of products such as: paints and lacquers, paint strippers, cleaning supplies, pesticides, building materials, furnishings, etc. At high concentration they may cause: nausea, headaches throat, eye and nose irritation, damage vital organs such as the kidneys, liver and central nervous system [13]. They can also by carcinogenic. The maximum assumed in this paper is 0.95 ppm [2] which is exceeded when using natural ventilation.

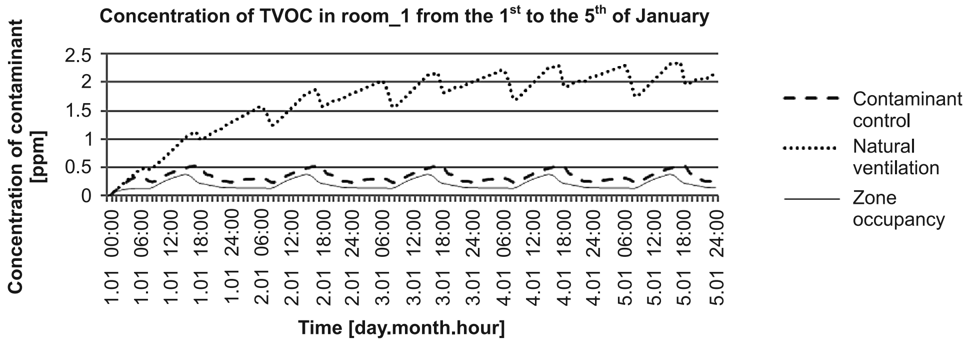

Fig. 8. Concentration of TVOC in room_1

Figures 4 to 8 show contaminant concentration in the room_1 zone. It can be concluded that the natural ventilation system does not provide proper indoor air quality for the simulated passive house. Both mechanical ventilations systems provide proper indoor air quality, but the ventilation system based on zone occupancy is more efficient when it comes to removing contaminants. The same trend was noticed in the other rooms within the house.

The concentration of the contaminants in each room is not only determined by the contaminant sources inside each room but also by the arrangement of ventilation inlets and outlets within the house. The effect of this arrangement can be observed by analysing the concentrations of carbon monoxide (CO) and nitrogen dioxide (NO_2) when using the mechanical ventilation systems. These contaminants are generated only in room_1 while cooking but because of the large openings between room_1 and hall_2 as well as the outlets in room_2 and the bathroom, contaminants migrate form room_1 throughout the house with the movement of the air. While in room_1 cooking causes the level of CO to increase over15ppm (Fig. 5) in hall_2 its concentration is also over limit ranging from 10ppm to 12ppm. The same tendency can be seen for $NO_{2,}$ the concentration of which in room_1 is around 1ppm (Fig. 6) and 0.9 in hall_2. The lowest concentration of both CO and NO_2 are in room_2 and reach range around 4ppm and 0.3ppm respectively. This simple analysis shows, how the arrangement of inlets and outlets can influence contaminant concentration throughout a building. This is why a proper spacing and location of the ventilation inlets and outlets is needed, since otherwise contaminants could accumulate in certain areas where air exchange is not sufficient.

3.6. Air flow rate through the ventilation system

The flow rate of the mechanical ventilation systems was taken under consideration, as the natural ventilation system does not provide proper air quality (the concentrations of the examined contaminants are exceeded and do not meet the established standards). Based on Fig. 9, in which the airflow rate through the air handling unit is displayed, it is quite clear that the contaminant control ventilation system is more energy efficient than the zone occupancy based one. It would also be more justifiable to use it when it is expected that several more occupants could be inside of the house (ex. during a party).

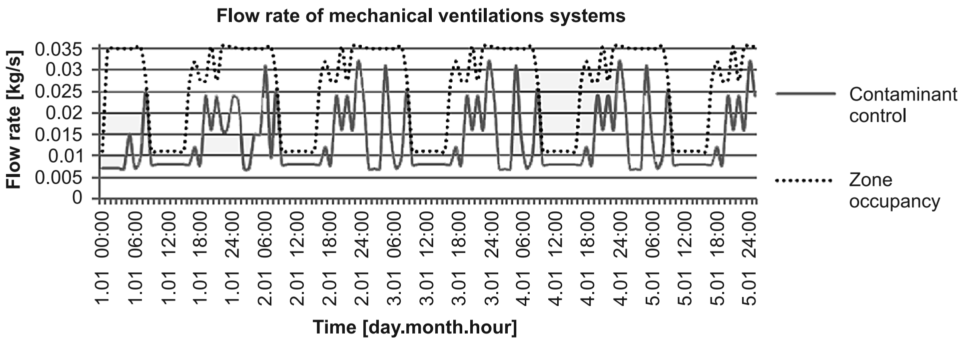

Fig. 9. Flow rate of mechanical ventilation systems

4. Conclusions

The performed simulations, which were generated using CONTAMW software, show that natural ventilation is not an adequate option in the examined passive house, as the main source of fresh air is provided through infiltration leakages through the building envelope which are not sufficient in a passive house. This fact limits possible airflows causing the highest contaminant levels among all the examined systems. The natural ventilation is also the least energy efficient as it has no heat recuperation system.

Even though the ventilation system controlled by occupant schedules is the most efficient when it comes to removing contaminates, it is also less energy efficient than the other considered mechanical ventilation system. Another problem would be with the estimation of the number of people for which the system would be designed. It is common for family members to entertain guests in a house. This is why the most optimal solution seems to be the application of the ventilation demand system based on carbon dioxide concentration. It is independent on occupant activity, which makes it the most reliable ventilation system.

To conclude, multi zone CFD simulation programs like CONTAMW can be used to determine, which ventilation system is the best to maintain indoor air quality at the lowest energy consumption. However detailed CFD calculation coupled with multi zone approach of the whole building would be required to determine which configuration of ventilation inlets and outlets are the most effective in removing contaminants.

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