

## Review

# Review of IAQ in Premises Equipped with Façade–Ventilation Systems

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**Abstract:** Poor indoor air quality affects the health of the occupants of a given structure or building. It reduces the effectiveness of learning and work efficiency. Among many pollutants, PM 2.5 and 10 dusts are extremely important. They can be eliminated using mechanical ventilation equipped with filters. Façade ventilation devices are used as a way to improve indoor air quality (IAQ) in existing buildings. For their analysis, researchers used carbon dioxide as a tracer gas. They have shown that façade ventilation devices are an effective way to improve IAQ, but require further analysis due to the sensitivity of façade ventilation devices to the effects of wind and outdoor temperature. In addition, legal regulations in some countries require verification in order to enable the use of this type of solution as a way to improve IAQ in an era characterised by the effort to transform buildings into passive houses (standard for energy efficiency in a building).

**Keywords:** IAQ; façade ventilation devices; thermal comfort; CO<sub>2</sub> concentration



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## 1. Introduction

The condition of indoor air is primarily its composition. Indoor air is a mixture of dry air and water vapour. Acceptable indoor air quality, in accordance with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard [1], is defined as air in which there are no known pollutants in concentrations considered by the regulations to be harmful, and in which the vast majority of occupants (80% and more) express no dissatisfaction with thermal comfort, noise and vibrations, or with lighting.

The importance of air quality for health varies drastically depending on the level of development of a country. In developing countries, air pollution contributes to 3.7% of the disease burden, while in developed countries, the same factor is not listed among the top 10 pathogens [2,3]. According to the report of the World Health Organization (WHO) [4], 3.8 million deaths worldwide in 2016 were the result of air pollution. In low- and middle-income countries, it is responsible for 10% of all deaths, and for 0.2% of the death in low-income countries. In China alone, the number of deaths as a result of poor air condition was 111,000, and the number of emergency room visits was 4.3 million [5]. Among the threats necessitating the immediate hospitalisation of 37.9–52.2% of the population in China are: Lung diseases, cardiovascular diseases, cancer, or asthma resulting from the accumulation of toxic pollutants, harmful gases, metals, hydrocarbons, etc. [6]. The main sources of pollution are those in the outside air, coming from the industry, power plants, and motor vehicles, but also resulting from the poor quality of the fuels burned (wood, coal, kerosene, etc.) [7]. The increase in mortality is also indicated by the other authors [8], who cite gases produced by cars as the cause of a large number of deaths. How building occupants experience air quality depends on their physical condition and age [9], as well as their gender. It is women who more often than men assess the air quality as bad [10,11].

Poor air quality affects not only health [12], but also work efficiency, reducing it, and increasing the frequency of absenteeism [13–20]. In the case of schools, it lowers learning efficiency, as described in the literature [21,22]. The obvious issue is the investment costs

that must be borne to improve the indoor air quality. However, the costs to the employer of the absence of the employee are about 4 to 40 times higher than the costs of installing a ventilation system. In the article [23], Sowa states that simple payback time (SBPT) for ventilation devices used to improve air quality is 1–3 years, which is really not much.

Indoor air is a mixture which is subject to dynamic qualitative and quantitative changes. According to the literature [24], in order to correctly assess the IAQ, it is first necessary to know and characterise the sources of pollutant emissions by determining the total content of pollutants (e.g., volatile organic compounds) in the material which is a potential source of emissions—then to specify the size of the pollutant emission stream from this source and to determine the chemical and physical interaction of air pollutants. When assessing the indoor microclimate, it is important to define the air exchange conditions, i.e., the amount of air and the manner in which it flows (infiltration/mechanical ventilation), as well as the condition of the air supplied from outside (potential sources of pollution in the nearest surroundings of the building). For the assessment of IAQ, the tightness of the building envelope and its permeability to pollutants are also important. Only after the IAQ has been correctly determined should a solution be sought to change its condition.

Many scientists have conducted IAQ analyses. The article collects the results of their research and prepares recommendations for further research. Those recommendations have not yet been defined in detail in the literature. The research gap in the field of IAQ improvement was searched. The aim of the article was to find the direction for further research on façade ventilation, which has not been sufficiently researched so far, while it is a solution that can be used on a very large scale in the future.

## 2. Contaminants

### 2.1. House Hold Dust Mites

The house dust mites are a threat mainly in residential premises, but is also present in the work environment [25]. For example, in agriculture, in granaries where workers come into contact with grain and thus with grain weevil, dust mites can cause asthma and skin diseases. In the workplace, it is possible to protect the body by using protective clothing and special equipment, but doing so is impossible in residential buildings. The indoor environment encourages the multiplication of mites. At a temperature of 25 °C and humidity associated with the occurrence of mould, i.e., between 74% and 80%, an increase in house dust mite colonies is observed. The best way to fight mites is by means of a ventilation system for the supply and the exhaust of air.

### 2.2. Fungi and Moulds

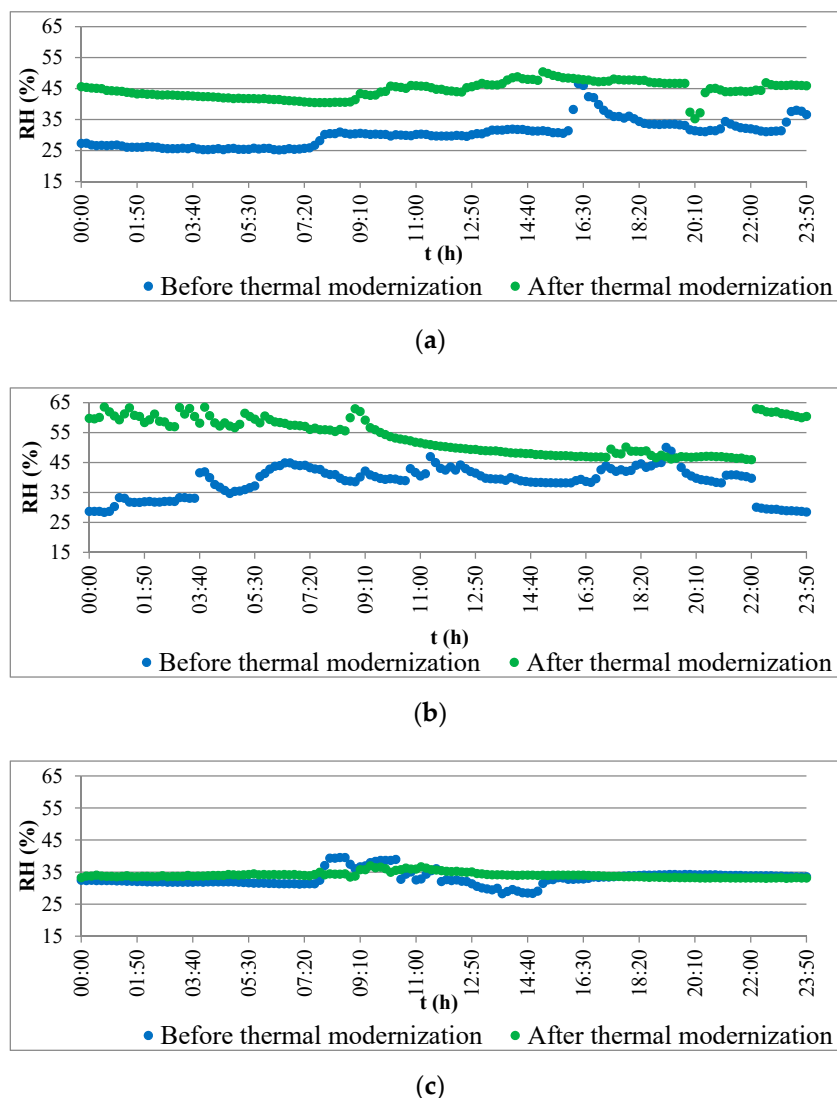
In the interior environment, the fragments of fungi and moulds released from the surfaces on which they have developed cannot be ignored. According to the analysis carried out by Górný [26], they are biologically significantly harmful due to immunological reactivity, cytotoxicity, and mycotoxin transport.

### 2.3. Humidity

In the current effort to seal the building envelope, it is necessary to control the humidity of the air. According to the literature [27], the weekly amount of water vapour in a room approaches 100 kg. The relative humidity of air influences on the abundance of allergens, pathogens, and noxious chemicals [28], therefore it is very important to control this parameter. Maintaining the air humidity in the premises at a more or less constant level requires intensive removal of water vapour to the outside [29]. At the same time, the share in the moisture balance of the amount of water vapour contained in the air, permeating through partitions by diffusion, determined on the basis of EN 13788 [30], is within 1–3% of the total emission of water vapour [31].

The analyses carried out so far have shown an increase in indoor air humidity in buildings subject to thermal modernisation (Figure 1). This means that investors, while focusing on improving one parameter, take actions affecting other conditions of the internal

environment. This clearly indicates the need for a global view of the building as a whole, which is to say, of the structure of the building itself together with its technical equipment, in the event of any changes to the building [32].



**Figure 1.** Course of indoor air humidity in the time before and after thermal modernisation: (a) Premises with heat-insulated walls; (b) premises with a heat-insulated roof; (c) premises with heat-insulated walls and ventilation gaps [32]; RH: Relative humidity, (%); t: Time (h).

Indoor air humidity increased in the premises with insulated partitions without additional ventilation openings, which confirms insufficient air exchange. The analysis showed that higher values of the parameter were achieved in the premises where the only source of moisture was human bodies. Hence, it can be concluded that the increase in humidity is not the result of using the premises equipment (e.g., of cooking). This conclusion is also confirmed by mould fungi that did not occur in the kitchen, bathroom, or social rooms. In buildings where, apart from building insulation, a change in the method of air supply to the building was introduced, the air humidity remained at the same level.

#### 2.4. Carbon Monoxide

A very important source of carbon monoxide (CO) is the burning of natural gas in other than optimal conditions. Not present in natural gas, carbon monoxide is a deadly poisonous by-product of the burning of natural gas in an environment where the fuel

to oxygen ratio is imbalanced, for example, in inadequately ventilated spaces. Another significant potential source of carbon monoxide is garages adjoined to apartments.

Carbon monoxide builds up gradually in the body. Its molecule binds with haemoglobin to form a carboxyhaemoglobin called HbCO. HbCO decay occurs as a half-life disintegration, similarly to radioactive isotopes. The half-life of carbon monoxide is about 4 h. If exposure to carbon monoxide occurs during the day, peak blood levels will be observed at bedtime. During an 8-h sleep, the concentration would drop to about a quarter of the maximum concentration. In case of no further exposure to the source, the concentration would have fallen to 1% of the maximum value after one day. Regular exposure to even small levels of the carbon monoxide will cause it to build up significantly in the body. The long-term exposure to sub-lethal concentrations may cause influenza-like symptoms [33]. When using devices with an open gas flow, e.g., a gas heater for heating water, gas cooker, etc., it is most important to ensure an adequate air supply. Contemporary thermal modernisation programs devote considerable attention to the assessment of the carbon monoxide risk. However, according to [34], increases in CO concentrations are episodic and short-lived, and the values before and after modernisation are comparable. The most appropriate change that should be introduced in buildings is to change the heating sources and the cookers for the preparation of meals. The values of the carbon monoxide concentration measured by scientists [35] in classrooms ranged from 0.2 to 0.9 ppm. However, in flats equipped with cookers that burn kerosene and solid materials such as coal and wood, the carbon monoxide concentration ranged from 4.32 to 4.82 ppm [36].

### 2.5. Carbon Dioxide

The combustion of a natural gas produces carbon dioxide ( $\text{CO}_2$ ) and water vapour in addition to carbon monoxide. Moreover, carbon dioxide is a product of the respiration process. It occurs naturally in the outside air in a concentration of approximately 0.03%. It is worth noting that there are also other natural sources of carbon dioxide, for example, when acidic groundwater flows through layers of limestone. It is also a component of landfill gas. It is a toxic gas and exposure to concentrations above 6% is lethal. In commercial and industrial buildings, the short-term concentration of carbon dioxide (20 min) should be a maximum of 1.5% and the exposure limit in the workplace set as an 8-h average is 0.5% [25]. Such concentrations are rarely observed in residential and public buildings. Generally, the limit is 700 ppm (0.07%) above the external  $\text{CO}_2$  concentration [1]. If the apartments are well-ventilated, the concentration of carbon dioxide will not be exceeded, although it will change significantly with time due to the fact that it is influenced by a number of changing factors [37]. These include internal factors, e.g., metabolism, combustion, and ventilation systems and external factors. The latter, in turn, depend on the environmental conditions and the interaction of the building and the external environment. In most cases, carbon dioxide is correlated with other air pollutants, therefore it is often used to regulate the efficiency of ventilation systems [38]. However, it cannot be regarded as an irrefutable indicator of air quality [39,40] since its relationship to some pollutants is too weak. Moreover, the condition of the internal environment is also determined by thermal, acoustic, and illumination comfort. Nevertheless, too high a concentration of  $\text{CO}_2$  can have a negative impact on health (headache, dizziness, nausea, fatigue). Therefore, its dilution is an important element to improve IAQ, and it is possible when using efficient ventilation [41–44].

### 2.6. Nitrogen Oxides

Nitrogen oxides ( $\text{NO}_x$ ) are another pollutant that may appear in the air during combustion. Studies on the presence of nitrogen oxides in rooms have shown the dependence of the distance between buildings and the road and of the traffic intensity [45,46]. However, the main source of  $\text{NO}_x$  is combustion of fuels inside buildings, and smoking. Their formation is not related to an insufficient amount of oxygen for combustion, but results from a secondary chemical reaction in which oxygen combines with nitrogen to form a product

mixture consisting primarily of dioxide nitrogen and trioxide nitrogen ( $\text{NO}_2$  and  $\text{NO}_3$ ). The combustion is a majority source of nitrogen oxides, which is confirmed by the discrepancy in the concentration of pollutants between summer and winter [47–50]. During the heating season, a higher content of  $\text{NO}_x$  was observed. The release of nitrogen oxides during heating or food preparation may cause co-pollution, e.g., a secondary reaction of nitric acid formation. Since nitric acid is formed during the reaction of  $\text{NO}_2$  with water, this means that if it is inhaled, the reaction will take place in the respiratory system. The reaction of producing  $\text{NO}_x$  is endothermic and depends on the actual combustion conditions, which in practice translates into the design of the burner. It does not depend on the nitrogen content in the combustion gas, but on the content in the ambient air. The role of such co-pollutants is unknown. However, the reduction of  $\text{NO}_x$ , e.g., by improving the air exchange, will also have a positive effect on reducing the correlation. According to WHO [51], candles and mosquito lamps can also be sources of nitrogen dioxide.

### 2.7. Volatile Organic Compounds

Volatile organic compounds (VOCs), as defined by WHO, are a group of compounds with a vapour pressure at 25 °C greater than  $10^{-1} \text{ Tr}^{-1}$ . The melting point of VOCs is lower than room temperature, and the boiling point is in the range of  $50 \div 260 \text{ }^\circ\text{C}$  (Table 1). In indoor air, they come from emissions, from building and finishing materials, including carpets, paints, adhesives, wall coverings such as wallpaper, floor coverings, and interior fittings such as photocopiers; from emissions from external sources (especially from motor vehicles); from burning fuel and tobacco smoke; they can be metabolic by-products (from humans, plants, animals, and fungi); and they can also come from the vital activity of a human, i.e., cooking, cleaning, and hobbies [52]. Sometimes they can emanate from landfills. In general, both the concentrations and the variability of exposure time to VOCs are higher indoors than outdoors [53].

**Table 1.** The classification of organic pollutants of indoor air [54].

A Group of Compounds	Boiling Point (°C)
VOC—Volatile Organic Compounds	50–100 ÷ 240–260
SVOC—Semi Volatile Organic Compounds	240–260 ÷ 380–400
POM—Particulate Organic Matter	>380

It should be noted that VOC emission is not constant over all periods of time. For example, construction materials reach their peak emissions immediately after construction, after which time the emissions gradually diminish. The intensity of ventilation also affects the rate of emission decay. Low ventilation flows will cause the emission to persist for a longer period of time.

In addition to the emission itself, the possibility of VOC absorption and desorption (similar to water vapour) in materials such as wallpaper, soft furniture, etc. should be taken into account. The rate of sorption and desorption depends on the finishing material, the compound in question and environmental parameters such as temperature and relative humidity, as well as ventilation efficiency.

Some VOCs can be present in concentrations that cause unpleasant odours. At high concentrations, unpleasant odours may be responsible for breathing disorders and vomiting. The intensity of the fragrance mixture will be lower than the sum of the individual fragrance intensities of the individual components.

In industrial premises, it is easy to determine whether VOCs will have a negative effect on health as their concentrations are high. In residential buildings, the concentrations will be much lower than the limit values, at which negative health effects are noticeable. However, health effects may be seen due to the combination of VOCs present at low concentrations. Sneezing, coughing, and conjunctivitis may occur, and in extreme cases, skin swelling, rash, and breathing problems are observed. Table 2 shows the degree of

harmfulness and the total concentration of total volatile organic compounds (TVOC) in indoor air.

**Table 2.** Total volatile organic compounds (TVOC) concentration in indoor air and their health harmfulness [55].

The Concentration of TVOC $\mu\text{g}\cdot\text{m}^{-3}$	The Degree of Harmfulness
<100	Potentially harmless
200–300	Potentially harmful
300–5000	Harmful to health

### 2.8. Formaldehyde

Formaldehyde is the simplest aldehyde and is treated separately from VOC due to some differences. It is colourless, highly chemically reactive, and highly flammable. It has an extremely pungent smell. In the industry, it has many uses, e.g., as a preservative and as a sterilising agent.

Airborne formaldehyde breaks down into carbon monoxide and formic acid. The level of formaldehyde concentration depends on the geographical location, e.g., in villages it is only 0.2 ppb, and in cities with high traffic it is as high as 20 ppb. It can not only be inhaled, but also absorbed through the skin. Once absorbed by the body, it is easily broken down into format (which is removed in the urine) or carbon dioxide (which is removed by breathing). Some by-products are used in building tissues.

Direct contact with formaldehyde causes symptoms including eye, nose, and throat irritation. The skin is irritated by contact with a strong formaldehyde solution. Animal studies indicate that the prolonged exposure to formaldehyde concentrations in the air above 6 ppm causes cancer of the epithelium of the nose (or, the nose). Humans cannot tolerate these concentrations due to the intense irritation. The US Environmental Protection Agency (EPA) has stated, on the available evidence, that formaldehyde is likely to be a human carcinogen substance.

### 2.9. Radon

All soils and rocks contain the radioactive elements of uranium and radium. The by-product of their decay is radon, another air pollutant. Typically, the uranium content in soils and rocks is around 3 ppm. However, in some locations, especially where the soil is on granite or shale, concentrations as high as 10 ppm can be observed. Sometimes sandstone and limestone deposits can also be of a similar condition.

Radon is odourless and colourless. The gas penetrates through porous soil layers and is then emitted at the earth's surface. Radon concentration in the external environment is not a threat, a fairly common level of radioactivity is 20 Bq/m<sup>3</sup> [25]. However, when it penetrates into a closed space, e.g., a building, where it cannot be dispersed, the concentration constantly increases.

In a building, a so-called draft that sucks radon up through floors and, for example, through pipe penetrations may exist. Typically, the building envelope is a barrier to prevent radon from entering the room, but some building materials contain radioactive isotopes. Hence, radon will be released into the interior (unless the interior surfaces are cleaned). For example, in Hong Kong, where there is no access to large amounts of limestone-based materials (for the production of concrete and cement), a major problem with high radon concentrations is observed. If the facilities are tight and the ventilation is insufficient, radon poses a threat to the life of residents, especially when the users are smokers [56]. Research conducted in schools [57] confirmed that radon migrates through soil and porous materials by diffusion into the interior of buildings. The radon concentration values showed a dependence on the level of the storey.

Radon is a gas and can be inhaled as such, but there is another way it enters the human body. Since it is radioactive, it decays into a wide range of radioactive decay products, including polonium. The decay products are more often solid than gaseous and attach to



airborne dust particles. If such dust particles are inhaled, they accumulate in the upper respiratory tract during normal breathing. Radioactive decay continues in the body and the lung tissue is irradiated. The consequence of exposure to radioactive material is the increased risk of cancer. In the case of radon, it is an increased risk of lung cancer [58].

Tobacco smoking and the effects of radon enhance each other's effects on the risk of cancer. Their combined risk is greater than the sum of both effects. For heavy smokers, the risk of developing cancer from radon exposure may be up to six times greater than that of non-smokers [25].

#### 2.10. Landfill Gas

The next air pollutant is landfill gas, which is a mixture of gases emitted from landfills as a result of the decomposition of organic waste. The biodegradation process is complex, and the rate of gas production and its quantity depend on the age of the landfill, the nature of the waste deposited, and the moisture content. The waste decomposition consists of two stages. The earlier is aerobic decomposition, where the microbes in the landfill use the oxygen trapped in the deposited waste. After all the oxygen has been used, biodegradation goes to the second stage, the anaerobic, which produces methane.

Methane is a colourless and odourless gas. It has suffocating properties since it displaces oxygen from its admixture with air. At a volume concentration of 5–15%, it forms an explosive mixture with air. Below 5%, there is not enough methane to support combustion, above 15%, there is not enough oxygen to support combustion. Hence, the values of 5 and 15% are defined as the lower and upper explosive limits.

#### 2.11. Particulate Matter

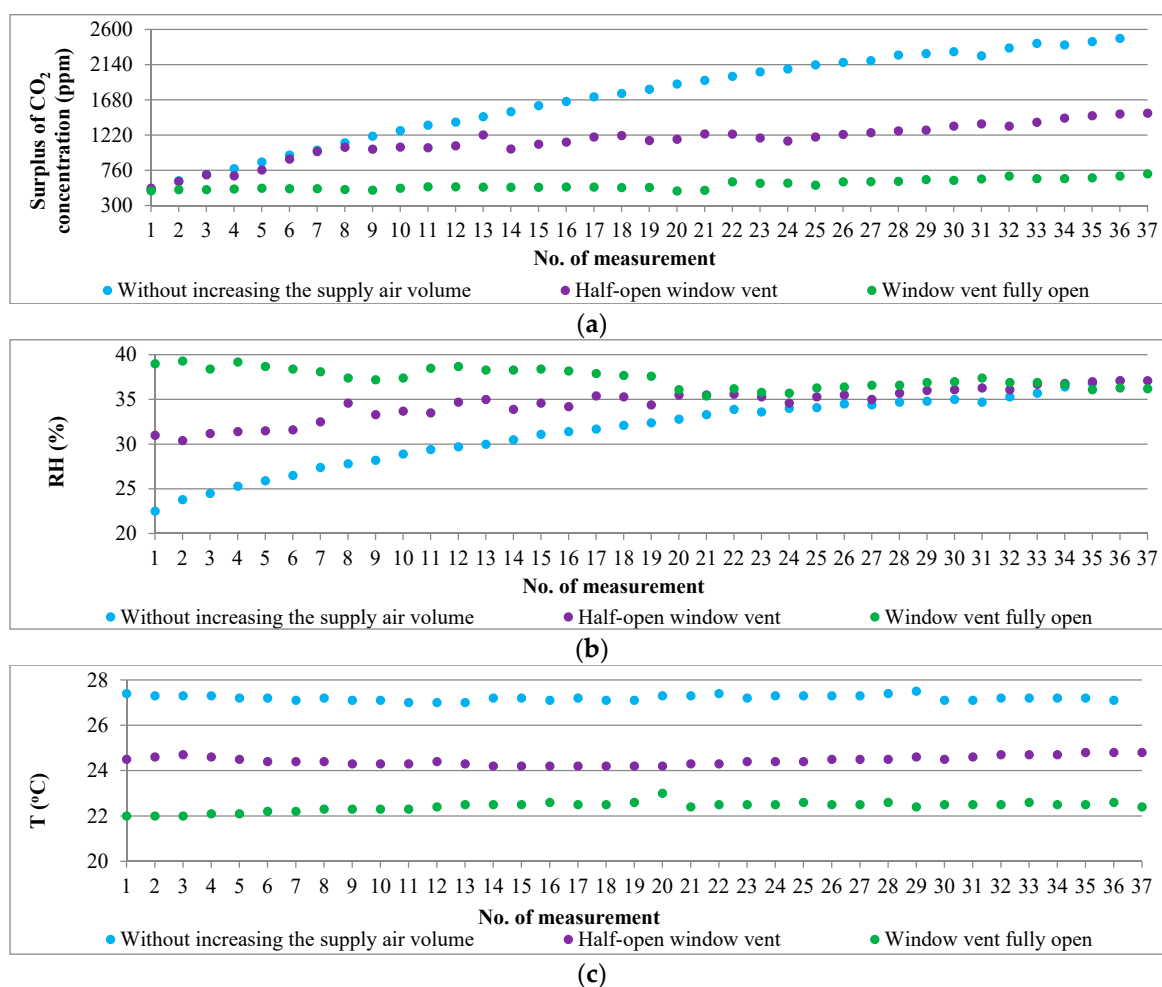
Apart from gaseous pollutants in the air, PM 2.5 and 10 dusts are also observed, the main source of which is the air flowing in from outside [59,60]. Their concentrations in indoor air often exceed the permissible values [61]. The PM 2.5 pollutants from the air surrounding a building vary depending on the location of the building. In less industrialised areas, the risk they present to health is much lower [62]. The research carried out by scientists [63] in 179 locations showed an inflow of particulate matters along with the outside air. In this case, the quality of the window joinery is important. When the window joinery is sealed, the amount of particulate matters incoming is reduced.

Particulate matters show seasonal variability [63,64]. The concentrations of PM 2.5 and 10 are higher in winter than in summer. According to the research results [a], the percentage of values higher than the established norm occurred during autumn (68%) and winter (72%), while in summer 99% of the measurements were within the standards. The source of these pollutants is the combustion process. Short-term exposure to high concentrations of dust in the inhaled air increases the risk of morbidity [65]. Due to the observed high concentration of particulate matter in the air, the monitoring of PM 2.5, which is currently implemented in 15 European countries [66], is extremely important.

### 3. Improving the Indoor Air Quality

A too low exchange of air causes an increase in both the air humidity and the carbon dioxide concentration [67]. However, increasing the amount of air in naturally-ventilated facilities is not an ideal solution, as it carries the risk of lowering the internal temperature [68].

Figure 2 presents the course of changes in the relative humidity, temperature, and concentration of carbon dioxide of the indoor air from the moment students enter the classroom until they leave it. You can clearly see the improvement in air quality and the lowering of the air temperature at the same time. Students in the classroom, sitting in desks near the window, assessed the microenvironment as too cool.



**Figure 2.** Changes in indoor air parameters during class [68]: (a) Surplus concentration of carbon dioxide above the external air concentration (ppm); (b) relative humidity—RH (%); (c) indoor air temperature—T (°C).

Some people use plants as a way to improve air quality to reduce pollution. Potted plants can be a means of removing chemical fumes from indoor air. The results of research and analyses [69,70] suggest that their greatest effectiveness is manifested in the removal of VOCs in energy-saving and non-ventilated facilities. Scientists document the ability of plants to remove benzene, toluene, octane, and trichlorethylene in particular [71], as well as formaldehyde [72]. However, it should be noted that plants can also be a source of pollution. Placed in plastic pots, they can be a potential source of contamination. Soil with microbes and pesticides can also pose a threat to air quality. According to an analysis conducted by scientists [73], the impact of plants on controlling air quality is actually small. The author states that the required area for green cultivation would be several square meters per person, if we were to balance the work of ventilation. In addition, plants are characterised by a high sensitivity to diseases and pests. Plants, apart from lowering the temperature, increase the humidity in the air, and moulds often appear in potting soil.

The technical equipment for the dilution of pollutants is the ventilation system. Observations presented in the literature [74] showed that the correlation between air leakage through leaks and the pressure difference is the key to understanding the interaction between the building envelope and HVAC systems (heating, ventilation, and air conditioning). Structures that are designed and built safely ensure that the pressure field is controlled, which in turn ensures that the finished buildings are healthy, durable, comfortable, and economical.



It is purposeful to reduce the energy consumption for air exchange in the premises. The solution that combines energy efficiency with an appropriate IAQ and thermal comfort is hybrid ventilation. When it is equipped with automatic regulation with soft-sensors [75], successfully this fulfils its task. In the literature [76], an analysis of indoor air quality was carried out using natural and mechanical ventilation, taking into account energy consumption. The conducted analysis showed that the presence of gaseous pollutants CO<sub>2</sub>, HCHO, O<sub>3</sub>, and NO<sub>3</sub> does not depend on the ventilation system used. The amount of energy used to heat the air was lower with natural ventilation. In terms of the PM 2.5 dust pollution, the influence of both the type of ventilation system used and the location was observed. Moreover, the higher filtration efficiency significantly reduced the PM 2.5 concentration. The outside air pollution in months with moderate temperatures was higher than in periods of hot and cold temperatures. In the analysed climate model, there was often a need to use a hybrid air recirculation system in combination with natural ventilation in order to maintain comfortable conditions. However, in this case, the effect of filtration was never sufficient compared to mechanical ventilation. The final conclusion from the above-mentioned study is the legitimacy of using natural ventilation from the point of view of energy consumption of systems for air heating and sufficient filtration of gaseous pollutants. However, natural ventilation is insufficient with respect to PM 2.5 dust. Due to the significance of the exposure of the body to the impact of dust on health, it is extremely important to have good filtration of the incoming air, which can be obtained using mechanical ventilation. The confirmation of this thesis was obtained by means of a scientific analysis conducted in urban and rural kindergartens in the area of Silesia [77]. The authors observed an influx of atmospheric pollutants. Only those buildings featuring gas and/or coal stoves had an internal source of pollution. Due to the long stay of children in such facilities, scientists recommend implementing an air quality control strategy. On the other hand, in newly established facilities, they recommend the use of mechanical ventilation equipped with air purification systems.

Research on the harmfulness of air pollutants is of interest to many scientists. C. Arden Pope et al. [78] described the risk of respiratory diseases and cardio-pulmonary mortality due to inhalation of polluted air. In addition to describing the relationship between external pollution and diseases of people staying indoors, Badyda et al. [79,80] described the relationship between road traffic and the amount and type of harmful substances contained in indoor air, such as NO<sub>2</sub>, PM 10, or CO. They showed that in cities with heavy traffic, and thus with more gases from internal combustion engines in the outside air, the percentage of people with lung and bronchial diseases is higher.

An analysis conducted by scientists [81] showed the enormous health costs of people exposed to ozone and particulate matter. The study involved office buildings with natural ventilation to eliminate the sick building syndrome (SBS). The estimated costs of fighting the symptoms of the syndrome turned out to be lower than the costs of improving the health of people exposed to ozone and particulate matter in naturally-ventilated facilities. Scientists have noticed that the effects of the above-mentioned pollutants in naturally ventilated facilities can be reduced by closing the windows during periods when pollution levels exceed the permissible exposure limits by 10% or more. However, this would require mechanical ventilation to maintain comfort.

Scientists [82] analysed natural ventilation in office buildings as a solution to reduce energy consumption. The conclusion from their analysis is, sufficient air exchange in buildings equals  $1 \div 6 \text{ h}^{-1}$ , provided that the buildings have high heat gains and these are buildings whose architecture has been designed with the awareness of the relationship between the type of building, its shape and location, with the efficiency of its natural ventilation.

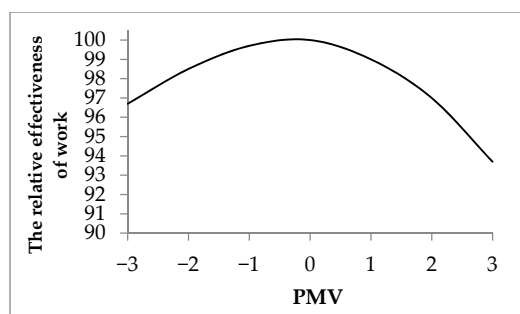
The vast majority of facilities in the world are naturally-ventilated. At the same time, newly erected buildings are airtight and therefore require mechanical ventilation. Actions leading to the improvement of indoor air quality are to ensure minimisation of energy costs. This means that the air exchange in buildings cannot be too low or too high. For

this reason, it is important for indoor air quality to take into account infiltration and its impact on both ventilation efficiency and energy consumption. The calculation of the infiltration efficiency largely depends on the airtightness of the building. In specific cases, the tightness of the structure is known, but in general terms, the default value should be assumed. The value that was considered reasonable is 0.3 [83,84]. Such an assumption leads to the underestimation of the ventilation efficiency for very leaky buildings, which is, however, acceptable due to erring on the safe side, i.e., the understatement of the share of infiltration in the dilution of pollutants. Similarly, for very tight objects, adopting such a value will overestimate the influence of infiltration, but here also the error is not very important, since infiltration contributes little to the total air exchange.

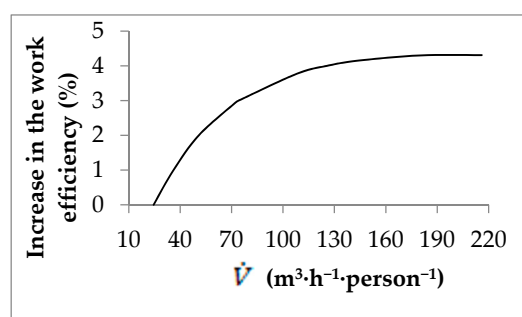
The distribution of pollutants in the indoor air is also influenced by the fact that movement occurs, e.g., people move about the premises or doors are opened and closed. The analysis in the hospital building was performed by Mazumdar S. et al. [85] comparing mixing and displacement ventilation. Scientists noticed variations of 10 to 90 s in the distribution of pollutants as people moved around and the pollutants following them. The average change in the concentration of pollutants resulting from the movement of the objects was within 25% for all the tested cases and was greater the closer the moving object was to the source of pollution. The authors showed that in premises with objects in motion, the use of displacement ventilation with an air exchange of 4/h will allow the same conditions to be obtained in the room as obtained with the use of a mixing ventilation system featuring an air exchange of 6/h. At the same time, the distribution of pollutant concentration using the displacement ventilation was not homogeneous. The concentration was higher near the source of the pollutants, therefore the risk of pollutant transfer in this case was greater than for the mixing ventilation.

Poor indoor air quality causes symptoms of SBS. In the literature [86], the authors analysed the influence of the ventilation system efficiency on the symptoms of the sick building syndrome. The average frequency of symptoms increased by 23% with a decrease in ventilation efficiency from 36 to 18 m<sup>3</sup>/h·person and decreased by approximately 29% with an increase in the air stream from 36 to 90 m<sup>3</sup>/h·person. Moreover, scientists [87,88] showed a relationship between the incidence of the sick building syndrome and gender. Regardless of the type of work performed and environmental factors, women were more likely to report ailments.

Poor indoor air quality translates into disease frequency and the efficiency of work and learning [89–91]. Scientists are interested in analysing the relationship between the efficiency of ventilation systems and the efficiency of learning. An example is Johnson et al. [92], whose research showed the air quality disturbances in primary schools. In many facilities, the amount of fresh air was insufficient. The dependence of work efficiency on the assessment of thermal comfort in premises and the amount of fresh air per person is shown in Figures 3 and 4.



**Figure 3.** The relationship between thermal discomfort and the efficiency of office work (based on [93]); PMV: Predicted mean vote.



**Figure 4.** The dependence of the efficiency of office work on the amount of fresh air per person (based on [93]);  $\dot{V}$ : Fresh air stream per person, ( $\text{m}^3 \cdot \text{h}^{-1} \cdot \text{person}$ ).

Other scientists also wrote about poor air quality in educational facilities [94]. They showed insufficient dilution of carbon dioxide and carbon monoxide, and in the conducted survey, they noticed symptoms of disease in students. Vimalanathan and Babu [95] showed that the temperature is the main factor affecting work efficiency, with 21 °C considered optimal. The authors also pay attention to illumination as an important element of the internal environment.

A way to improve the air quality in premises may be opening the windows, provided that the building is not located in an area with high external air pollution (e.g., an industrial area or roads with heavy traffic). Opening windows to exchange air, a method used by residents in dormitories, does not uncomfortably chill the crowded premises even when the outside air temperature is −9 °C, and it significantly reduces the concentration of carbon dioxide. However, in the case of a cubature of 6.5 m<sup>3</sup> per student, it is not possible to provide thermal comfort by opening the windows [1].

Indoor air quality also means acoustic comfort. Acoustic waves are airborne vibrations. They are characterised by a frequency expressed in Hz and sound intensity in dB. Noise sources can be related to human behaviour, noise from motor engines, noise from buildings, construction noise, operating noise, and noise generated by social gatherings. Among these sources, in a residential environment, traffic has the largest share. It was found [96,97] that noise induces stressful reactions in exposed persons and may lead to serious physical, psychological, and social damage (it can be harmful both to the hearing organ and the whole human body). With natural ventilation, noise may be generated when air flows through leaks at high wind speeds. In mechanical ventilation and air-conditioning systems, it is related to the flow of air in the ducts and end elements of the installation. Most often it results from design or installation errors. The literature [98] presents an analysis of the impact of HVAC installations and air flow on the noise level in premises. Tests carried out in classrooms showed that in the event that the amount of ventilation air was sufficient, the permissible noise level in the rooms was exceeded. On the other hand, in premises where the sound level was appropriate, the air flow rates were too low. The main sources of noise were excessive turbulence at the inlet to the supply air elements, incorrect settings of the diffusers, and too-high air flow velocity. In the United States, 9 million people are exposed to sounds above 85 dB, and 10 million people have a hearing loss of 25 dB or more due to noise. In Europe, more than 28% of all workers are exposed to noise levels of 85–90 dB. An estimated 120 to 250 million people worldwide suffer from some degree of hearing loss, and noise in the workplace is an important risk factor for hearing loss among workers (16% on average) worldwide [99].

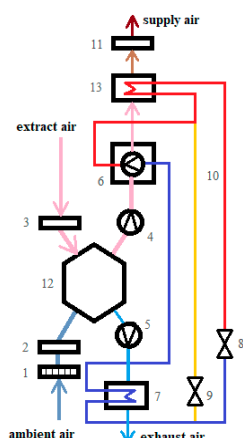
In his study, Połednik [100] described the influence of electromagnetic radiation on the well-being and health of room users. The electromagnetic radiation's source can be found both in the internal and external environment. One of the sources of electromagnetic radiation is electric underfloor heating, where the recorded values were as high as 800 mG, with the permissible value of 2 mG [101]. Electromagnetic radiation can produce a thermal effect due to the absorption of radiation energy and its conversion into thermal energy, as

well as disturbing the basic functions of cells, changing their membrane and functional potential, and disturbing the bioelectric processes between neurons. While electric fields are easily confined by trees, walls, or even human skin, magnetic fields are difficult to shield and their impact diminishes with distance from the source. Scientists are looking for a way to suppress internal electromagnetic fields [102,103] that will reduce the impact of radiation on people in the room.

#### 4. Façade, Decentralised Ventilation

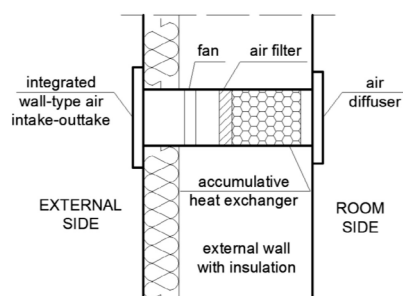
An important issue is the fact that energy consumption by the construction sector will continue to grow. They are already the main energy-consuming sector [104–108]. Heating, ventilation, and air conditioning (HVAC) systems alone account for 40–60% of a building's energy needs [109–112], and the ventilation systems themselves account for 20–30% [113]. With this in mind, in order to globally reduce energy consumption and CO<sub>2</sub> emissions, old buildings should be modernised [114–117], and also take reduction energy and CO<sub>2</sub> emissions into account in the risk assessment of project management [118,119]. Building managers reduce the heat demand of existing buildings by insulating them and sealing the building envelope. However, such actions have consequences in the form of reduced air exchange and the deterioration of indoor air quality (IAQ). This, in turn, has a negative impact on the performance and health of people in the premises [120,121]. Likewise, the way the air is distributed in the room is important. In the process of designing an installation, it is assumed that fresh air and indoor air are ideally mixed if the flows specified in the regulations are adopted. In fact, with different locations for air inlets and outlets, the air may not be renewed, and this results in an increase in the amount of air to achieve a minimum IAQ. In order to combine the appropriate IAQ in the premises and energy savings, various methods are used to control centralized systems, for example, based on the relative humidity level [122] or the concentration of carbon dioxide in the internal air [123]. In many existing buildings, it may not be possible to install centralised ventilation systems [124–128]. For this purpose, hybrid ventilation systems or decentralised façade ventilation can be used [129–132]. The latter make it possible to adjust the capacity to the need for a given amount of fresh air. Due to the lack of ventilation ducts, such systems are equipped with small fans, which translates into low pressure losses [133].

The decentralised façade ventilation units can be configured as mini-air handling units (AHU) (Figure 5) equipped with two fans and a heat recovery exchanger, or as façade-mounted units with one fan and with or without a heat recovery exchanger.

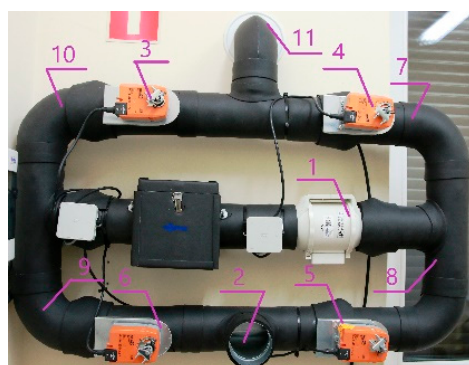


**Figure 5.** Scheme of the micro-HP (Heat Pump) and HRV (Heating Recovery Ventilation) 1-frost protection, 2-ambient air filter, 3-extract air filter, 4-fan of supply air, 5-fan of exhaust air, 6-compressor, 7-evaporator, 8-expansion valve, 9-valve, 10-hot gas defrost bypass, 11-post-heater, 12-heat exchanger, 13-condenser [107].

In the second case, we have systems with a reversible fan, that alternately in one cycle supplies the air, and in the next cycle exhausts the air to the outside [134] (Figure 6). Another solution are devices with which the cyclical supply and exhaust are affected by changing the dampers system [110,135] (Figure 7). The authors, examining solutions without a heat recovery exchanger [136], indicated the need to heat the air due to the risk of drafts. The risk of drafts was also indicated by Merckx et al. [137], who in their research showed that only airflow directed upward vertically does not cause the phenomenon of drafts.



**Figure 6.** Scheme of the experimental façade ventilation unit with a reverse fan [138].



**Figure 7.** Decentralised façade ventilation unit with dampers [110]; (1) fan flowing the air constantly in one direction; (2) inflow/outflow grate; (3–6) dampers; (7–10) ducts; (11) intake/outtake.

Typically, air heating in decentralised façade devices is limited to the use of an aluminium or ceramic accumulation exchanger [139,140], which heats the supply air from the exhaust air stream. Choi et al. [141], investigating decentralised façade units, found that in the case of changing the bidirectional mode, the demand for heating and cooling energy is lower by approximately 20% compared to the simulation of the simultaneous supply and exhaust mode. At the same time, it should be noted that the systems mounted in the façade have lower pressure losses, are easily installed, and require no maintenance. However, they generate a higher noise level [134,137] and are more sensitive to wind pressure and to the stack effect [134]. Merzkirch et al. [111] have shown that a large imbalance of the supply and exhaust flows in decentralised units leads to a reduced heat exchange efficiency. Moreover, due to the change in the direction of rotation, decentralised wall units have a time-varying efficiency of heat exchange resulting from the heat charging and removal process [136]. Smith and Svendsen [139], in turn, analysing decentralised façade units, showed that the use of rotary heat exchangers shows a low or moderate risk of mould when ventilating single premises in dry conditions and are not suitable for ventilating damp premises.

The researchers used carbon dioxide as an indicator of air quality when analysing façade ventilation units for single premises. In the case of devices with a reversible fan, at various air flow velocities, a sufficient reduction of CO<sub>2</sub> concentration was observed (Figure 8) to ensure an appropriate IAQ [138].

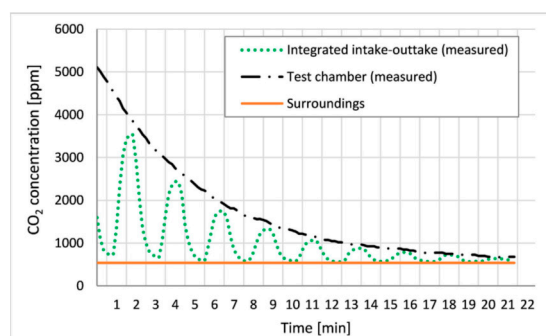


Figure 8. Change of CO<sub>2</sub> concentration in the unit in a time [138].

The analysis of the air exchanges achieved by the unit with a dampers system [135] showed that, for both the 2-min supply/exhaust time and the 10-min time, the air exchange was sufficient for an office premise. In addition, the analysis of changes in the mean value of carbon dioxide concentration over a 30-min period showed reductions in the analysed parameter (Figure 9). The reduction of CO<sub>2</sub> concentration was also confirmed by others in their studies [142].

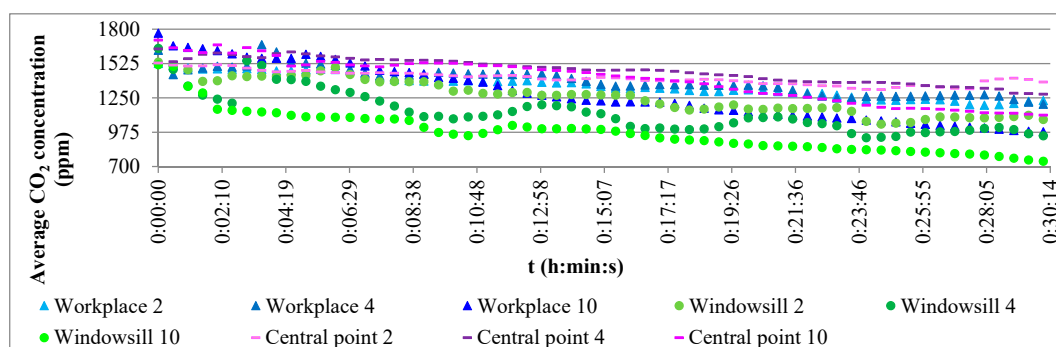


Figure 9. The trajectories of changes in the average value of CO<sub>2</sub> concentration in time [130]; t: Time, (h:min:s).

On the other hand, the analysis [110] of the influence of the supply/exhaust cycle length on the CO<sub>2</sub> concentration showed that for each cycle length, throughout the entire measurement period the carbon dioxide concentration did not exceed the value of 800 ppm, which means that the premises met the requirements of ASHRAE [1] regarding air quality in offices (Figure 10). There is a visible increase in the concentration of carbon dioxide upon entering the user's room. At the same time, with a longer supply/exhaust time (10 min), the maximum value of the carbon dioxide concentration is lower than for the short cycle (2 min).

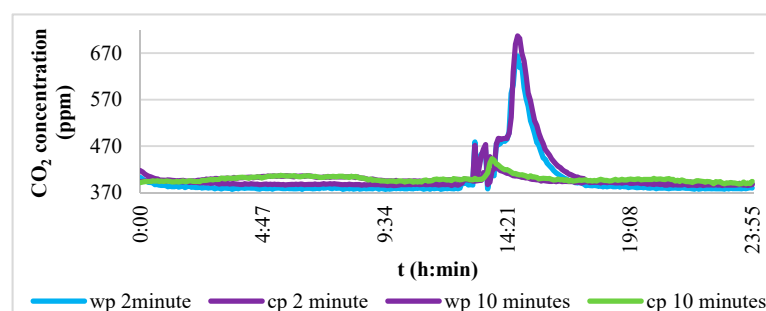


Figure 10. The course of changes in the concentration of carbon dioxide. Blue and purple colours are the 2-min cycle; yellow and green colours are the 10-min cycle; wp: Workplace; cp: Central; t: Time, (h:min) [110].



Despite studies proving that façade ventilation units effectively reduce the concentration of pollutants and improve IAQ in premises in many countries, e.g., in Poland, regulations prohibit the use of units where an integrated intake and outtake are installed in the wall [143]. The researchers [144,145] proved, however, that there was no recycling of the exhaust air stream in these types of units, which indicates the need to change national regulations. At the same time, decentralised façade units require further research into noise reduction and elimination of the influence of wind on their operation.

## 5. What Should Be Done in the Field of IAQ?

Indoor air quality is an extremely important aspect of human life, therefore scientists should not stop the research in this field. Façade ventilation has not been sufficiently researched. The test results described in the literature concern the concentration of carbon dioxide. Future work should take into account the ability of façade devices to reduce allergens and analyse the dependence of particulate matters outside the building and in a building ventilated by façade devices. Moreover, experiments on the use of HEPA filters or products such as Molekule are lacking. In addition, long-term analyses of indoor airborne particulate matters levels should be performed.

## 6. Conclusions

Indoor air quality affects the health of occupants, as well as work efficiency and learning effectiveness. At the present time, we are striving to reduce energy consumption. In existing buildings, modernisation works are carried out, consisting of insulating the building envelope and replacing the window and door frames with tight ones. These works lead to a reduction in air exchange, which results in deterioration of the indoor air quality. To improve the situation, mechanical ventilation is introduced. Due to the limited space in existing facilities, it is usually not possible to introduce central systems. Façade ventilation systems for single premises ventilation are becoming increasingly popular. In the literature are studies on the effective removal of pollutants by these types of units as well as an analysis of the thermal comfort of rooms equipped with façade ventilation units. Based on the literature review, it can be concluded that:

- these solutions are sufficient to maintain IAQ;
- they do not recycle the exhaust air stream;
- they require further research, especially in the field of: Noise reduction; elimination of the impact of wind and outside air temperature on the operation of such units (especially the impact on the amount of heat recovery); capacity of particulate matters removal and ways of filtration;
- the legal regulations of some countries require verification (integrated air intake and outtake are allowed to be mounted only on the roof, not on the façade).

Since the global goal is to make all buildings, including existing ones, passive buildings, the research in field IAQ in the premises with façade ventilation units is important and urgent.

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