CARBON DIOXIDE: PROBLEMS OF STANDARD SETTING, CONTENT CONTROL AND PREVENTION OF ADVERSE EFFECTS IN EDUCATIONAL INSTITUTIONS

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This article is a review of data published in Russian and foreign studies that reflect current problems concerning content of carbon dioxide in spaces of residential and public buildings, including children's educational organizations. We consider: mechanisms of action of high concentrations of carbon dioxide on the human body, which manifests as acute and delayed disruptions of metabolic processes in circulatory, central and respiratory systems; existing carbon dioxide content measurement methods used for indoor spaces; principles of setting microclimate and air quality standards for temporarily and constantly occupied indoor spaces and the respective parameter control principles. This analytical review revealed the need for standard-setting efforts, development and approval of a methodology enabling measurement of the actual carbon dioxide concentration in children's educational institutions, since routine measures adopted for the purpose lack in effectiveness or realization, which prevents normalization and stabilization of all qualitative and quantitative air parameters at the levels making the environment of a classroom safe and optimal for education-related activities given high occupancy of the space.

Keywords: carbon dioxide, educational organizations, health effects, high concentrations, standard setting problems, prevention

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УГЛЕКИСЛЫЙ ГАЗ: ПРОБЛЕМЫ НОРМИРОВАНИЯ, КОНТРОЛЯ И ПРОФИЛАКТИКИ НЕБЛАГОПРИЯТНОГО ВОЗДЕЙСТВИЯ В ОБРАЗОВАТЕЛЬНЫХ ОРГАНИЗАЦИЯХ

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В статье представлен обзор литературных данных по российским и зарубежным исследованиям, отражающих современные проблемы, касающиеся содержания углекислого газа в помещениях жилых и общественных зданий, в том числе детских образовательных организаций. Рассмотрены механизмы влияния высоких концентраций двуокиси углерода на организм человека, проявляющиеся острыми и отсроченными негативными эффектами в виде нарушения обменных процессов кровеносной, центральной и дыхательной систем, существующие методы оценки содержания двуокиси углерода в воздухе помещений, а также принципы нормирования и контроля оптимальных параметров микроклимата и качества воздуха в помещениях, предназначенных для временного и постоянного пребывания людей. По результатам аналитического обзора установлена необходимость нормирования, а также разработки и утверждения методики оценки фактических показателей концентрации углекислого газа в детских образовательных организациях в силу неэффективности или невозможности обеспечения достаточного объема режимных мероприятий до нормализации и стабилизации всех качественных и количественных показателей воздушной среды, обеспечивающих оптимальные и безопасные условия воспитания и обучения при высокой ежечасной наполняемости учебных кабинетов.

Ключевые слова: углекислый газ, диоксид углерода, образовательные организации, влияние на здоровье, высокие концентрации, проблемы нормирования, профилактика

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Carbon dioxide (CO_2) is a metabolic product necessary for human survival. When there is an excessive amount of CO_2 in the air, it can have an adverse effect on the body, and high concentrations are toxic. The actual content of CO_2 in enclosed spaces is an important hygienic indicator of air quality that should be thoroughly studied in the context of development of preventive measures aimed at minimization of health risks. This compound is the key air contamination factor in residential and public spaces, therefore, its action is an actively researched subject, since concentration of CO_2 most often leads to deterioration of a person's wellbeing, as well as acute and delayed adverse effects. Such research efforts are especially important for educational organizations for children, where large number of them stay for a long time, since children and adolescents are most susceptible to adverse environmental influences. It should also be noted that there are no regulations setting standards for CO_2 concentration in Russia, neither for residential nor for public spaces. However, considered from the perspective of prevention of negative effects on students, the matter of setting CO_2 concentration standards for educational institutions, as well as development of a methodology to assess the actual content of CO_2 in rooms intended for children (daycare, educational purposes), requires careful attention.

This study aimed to examine Russian and foreign scientific publications covering problems of exposure to carbon dioxide, principles of setting respective standards, feasibility of indoor air quality monitoring, measures designed to ensure conformity to hygienic requirements in terms of air.

We searched various electronic databases (E-library, PubMed, Cyberleninka) for scientific publications covering problems of CO_2 content in residential and public spaces, principles of setting CO_2 content standards, respective effects on health and prevention methods. Over 100 works by foreign and domestic authors, most of them published from 2004 to 2023, and regulatory materials were analyzed. The key research method utilized for the study was analytical.

For a long time, CO_2 was believed to be the final product of metabolism that has negative effect on the body, but from the 2nd half of the 19th century, it is considered a metabolic product necessary for vital activity [1, 2]. The optimal composition of breathing air for human beings is 21.5% oxygen and 0.03–0.04% CO_2, with the remaining volume filled by nitrogen, the most common element on Earth. Such composition underpins normal metabolism [3, 4]. Authors of the monograph [2] cite the study [5] pointing out that both gas molecules (CO_2, reactive oxygen species (ROS) and nitric oxide) and their derivatives of radical and non-radical nature, which model all neuroendocrine and metabolic processes in the body, participate in the unified physico-chemical regulation of biological processes. Carbon dioxide, unlike nitric oxide (NO) and ROS, does not produce a pathological and cytotoxic effect. Relying on the experimental data, the authors hypothesized that CO_2 plays a protective part, inhibiting ROS and regulating free radical homeostasis in the body.

Studies of the recent decades confirm that human body needs CO_2. Partial pressure of carbon dioxide (pCO_2) is an indicator that reflects the effect on cerebral cortex, respiratory and vasomotor centers; it is used to assess the content of CO_2 in the body. The compound regulates the tone of blood vessels, bronchi, metabolism, hormone secretion and blood electrolytes. Indirectly, it affects enzymatic activity and the rate of biochemical reactions in the body. Oxygen concentration fluctuations, e.g., drop to 15.0% or growth to 80%, do not have a significant effect on the body, while a 0.1% change in CO_2 concentration causes considerable adverse changes, which indicates the greater importance of CO_2 for the body [3].

However, inhaling too much CO_2 leads to pathological changes [6]. In the international classification, CO_2 is an asphyxiating gas (hazard class IV), same as with ammonia. Concentration of CO_2 in the atmospheric air started increasing as industrial revolution developed: it boosted anthropogenic nitrogen dioxide emissions and disrupted the carbon cycle, which is undoubtedly one of the most important factors affecting people's lives and health, and the situation is gradually deteriorating, since the problems of carbon dioxide level regulation remaining unsolved [7]. CO_2 is a greenhouse gas, and reduction of its emissions to atmosphere is an environmental policy priority for a country that signed the Kyoto Protocol. In a human body, this gas affects cardiovascular and respiratory systems, causing drowsiness, nausea, weakness, loss of consciousness when accumulated to a high concentration. Therefore, it is important to understand the trends of industrial atmospheric emissions, because CO_2 is the main component thereof in many regions [8]. Studies investigating the greenhouse effect of CO_2 have uncovered its effect on human genetic activity, which means it affects health in general. The respective mechanism relies on the "greenhouse effect" with involvement of membranes of certain skin cells [9].

Arterial blood CO_2 concentration is an important indicator reflecting the state of blood supply to body tissues, which means it is connected to the human body's adaptive potential [10], and, controlled, can help improve bodily functions in general [11]. In the body, CO_2 is part of chemical compounds (carbonic acid, carbonates, bicarbonates) and carbohemoglobin. The content of CO_2 in the blood depends on its partial pressure, which reflects the balance between the amount of carbon dioxide formed and the amount of CO_2 released by the lungs. The normal level (normocapnia) of CO_2 in the blood is pCO_2 40 mm Hg for arterial blood and 47 mm Hg for venous blood. High pCO_2 causes hypercapnia (gas acidosis), excessive release of CO_2 and low pCO_2 in arterial blood — hypocapnia (gas alkalosis) [12]. It is the increased CO_2 content in the atmospheric air (more than 7.6 mm Hg) that can up the amount of CO_2 in the lung alveoli and arterial blood above physiological thresholds (over 40 mm Hg and over 46-49 mm Hg, respectively), turning the vital gas toxic to the body [13].

Clinical signs of CO_2 toxicity in a hypercapnia case are shortness of breath at rest, nausea, vomiting, headache, dizziness, mucous membranes and facial skin cyanosis, severe sweating, visual impairment [2]. When CO_2 concentration goes up by no more than 2%, the body reacts on the part of cardiovascular (first tachycardia, then bradycardia) and central nervous systems, with nerve endings excitability growing up and then down. If CO_2 concentration increases to 5–6%, brain suffers inhibition of electrical activity [14]. Carbon dioxide concentration above 10–12% leads to rapid loss of consciousness and death [15].

CO_2 is acknowledged as the indicator of quality of air (content of harmful substances therein) in office spaces, catering facilities, banquet halls and auditoriums, medical institutions, classrooms, preschool spaces, transport, etc. The established optimal carbon dioxide level for such spaces is that which is closest to CO_2 concentration in the atmospheric air [16]. Until recently, this indicator was the only one used to assess quality of air in non-industrial enclosed environments, since it was assumed that there is a direct correlation between CO_2 content in an occupied room and the level of chemical and bacterial contamination [17, 18].

Numerous studies confirm that CO_2 is the most important indicator of air quality, since it is the main pollutant indoors, even given many other contaminating elements and compounds [19–25]. When a large number of people occupy a room for a long time, the concentration of carbon dioxide in that room grows rapidly, and if ventilation there is inefficient or impossible, the environment acquires qualities harmful for well-being and health. It was also found that the quality of air in a space deteriorates proportionally to the number of persons and the time of their stay therein [26].

The matter of hygienic assessment of CO_2 content and its impact on health has attracted attention both in Russia and abroad, where the interest towards the subject is further advanced because of the growing number of so-called "sick buildings" (Sick Building Syndrome) [27].

The concentration of CO_2 is measured in ppm, parts per million or *pro pro mille*. Essentially, it is a cubic centimeter of carbon dioxide per cubic meter of air (cm^3/m^3). However, some Russian and foreign studies, as well as regulatory documentation, provide CO_2 content in mg/m^3 or percentages. The relationship between these units of measurement should be clarified on the example of normal conditional concentration of CO_2 in atmospheric air. Thus, 400 ppm (or 400 $million^{-1}$) means that 1 m^3 of air contains 400 cm^3 of CO_2, or 0.04%, since 1 ppm = 0.0001%. At the same time, conversion from mg/m^3 requires a more complex formula that factors in molecular weight of the gas, gas mixture pressure and temperature. Conventionally, the content of CO_2 in 1 mg/m^3 equals approximately 0.510725 cm^3/m^3.

Russian studies have shown that well-being begins to deteriorate at the concentration of 1000 ppm: people start complaining of stuffiness, general discomfort, weakness, headache, poor attention capacity. Additionally, the frequency and depth of breathing grow up, bronchi narrow, and at concentrations above 15% glottis spasms. A long stay in a room with excessive amount of CO_2 alters condition of the circulatory, central nervous, respiratory systems, perception, operative memory, and attention distribution [3, 20, 22].

The content of carbon dioxide in bedroom air affects how well people sleep therein, and some researchers believe the quality of air is more important for a good sleep than the quantitative indicators [28]. Studies show that increased CO_2 content in a room's air translates into more complaints of rapid fatigue, which manifests as hindered attention concentration ability, drowsiness, headache [29, 30]. The key effect of carbon dioxide on a body is the arrest of blood's ability to absorb oxygen. The degree of poisoning with this compound depends on the time of exposure and its concentration in the atmospheric air [31].

According to the research done by the domestic scientist, concentration of CO_2 in a room should not exceed 1000 ppm, regardless of the source of the compound (for example, plants emit CO_2 at night). Using a special research methodology, the author concluded that short-term inhalation of CO_2 by healthy people at concentrations of 500 and 1000 ppm causes certain shifts in external respiration function, blood circulation and electrical activity of the brain [32]. Studies have shown that air in a residential or public space may be considered safe when the level of CO_2 therein is 1000 ppm (0.1%) [20]. This is the concentration recommended for indoor air in most foreign countries.

Another research has shown that when the content of CO_2 in the air is at 2–2.5%, people in the respective space suffer no noticeable alterations of well-being and ability to work [33]. Concentration of 4–5% causes shortness of breath, boosted cardiac activity; there is a direct link between CO_2 content and ability of a person to work. CO_2 at 6% impairs mental activity significantly, triggers headaches and temporary insanity. When the concentration of CO_2 grows up to 7%, people become physically unable to control their actions, faint, in some — die. If carbon dioxide content reaches 10%, death is the outcome that occurs quickly, and at 15% — instantly, because of respiratory paralysis.

Increasing partial pressure of CO_2 in human alveoli causes functional disruptions. Carbon dioxide becomes more soluble in the blood, which yields a weak carbonic acid ($CO_2 + H_2O = H_2CO_3$) that subsequently decomposes into H^+ and HCO_3^-. The first sign of acidosis is a poor perception of new information. The higher the concentration of CO_2 in the air breathed by a person, the lower his/her blood pH and the more acidic it is. People who spend a lot of time in spaces with high CO_2 levels are 3.5 times more likely to have dry cough and twice as likely to have rhinitis [33]. This is consistent with earlier studies reporting that if the concentration of carbon dioxide in a room exceeds 500 ppm, pH of the blood of people therein may decrease [34], and prolonged exposure to CO_2 concentrations of 0.5–1% can lead to increased calcium deposition in body tissues, including kidneys [35].

Studies conducted by Belarusian scientists point to a correlation between poor ability to work and increased CO_2content in the air. When it approaches 1%, a person's motor reaction time goes up, and the accuracy of tracking reaction deteriorates; at 1.5–2%, there appear qualitative changes in mental activity, disruptions of functions of differentiation, perception, operative memory, and attention distribution. Longer periods of work while exposed to air with 3% CO_2 content translate into pronounced disorders of thinking ability, memory, fine motor coordination, hearing, vision, and the number of typos and errors goes up sharply [14].

Investigation of effect of conditionally permissible concentrations of CO_2 in the air yielded quite interesting data. According to foreign studies, carbon dioxide content above 600–800 ppm causes 30% deterioration of attention, above 1500 ppm — fatigue (reported by 79% of participants of the respective study), above 1000 ppm — headaches in 97% of people suffering migraines [36]. Prolonged exposure air with high concentration of carbon dioxide can be considered a risk factor leading to development of chronic fatigue syndrome, more frequent upper airway disorder cases [20, 37]. Finnish researchers staged an experiment in an office space and learned that symptoms like eye inflammation, nasal congestion, inflammation of the nasopharynx, problems with respiratory system, headache, fatigue, and impaired ability to concentrate, all of which are associated with high CO_2 levels, ceased to manifest acutely when the concentration of carbon dioxide dropped below 800 ppm (0.08% vol.) [38].

Exposure to air with CO_2 at 2000 or 4000 ppm induced inflammatory reactions in neutrophils *ex vivo* (human and mice) and *in vivo* (mice), caused vascular damage in muscle tissues, brain and distal colon, which persisted for 13 hours after two hours of exposure. Exposure to a concentration of 1000 ppm caused inflammatory reactions *ex vivo*, but not *in vivo*. In addition, mice exposed to air with CO_2 at 5000 ppm could exhibit increased inflammation in the bronchial epithelium [39], and people exposed to air with 3000 ppm of carbon dioxide — mild inflammation in the nasal cavity [40]. A randomized double-blind controlled experimental study showed that 8-hour (working day) exposure to air with increased content of CO_2 adversely affects cognitive performance of people. The experiment considered three concentrations, 550, 945 and 1400 ppm, in an office environment; compared to 550 ppm, 945 ppm slowed cognitive performance by 15%, 1400 ppm — by 50%. On average, the participants' indicators decreased by 21% as concentration of carbon dioxide increased by 400 ppm [41].

Recently, researchers started investigating the effects of stay in spaces of educational organizations occupied by many students simultaneously and, therefore, presenting certain risk factors. The problem is urgent because elements and compounds from indoor air shape the hazard index more actively than those found in atmospheric air. This necessitates reinforcement of measures aimed at supervision and control of the sources of chemical toxicants, as well as at ensuring conformity with the standardized aeration patterns and room occupancy limits [42].

For spaces of educational organizations, the level of CO_2 considered optimal is 800–1000 ppm. The threshold is set at 1400 ppm. If there is more carbon dioxide in the air, its quality is considered to be low, because more CO_2 means deterioration of the ability to concentrate and process the study-related workload. However, several studies exploring the subject point that the said threshold should be moved down to 1000 ppm. The data reported therein indicate that at that concentration, over half of the participants feel the effects of poor microclimate: their pulse speeds up, they suffer headache, fatigue, and they complain of having "nothing to breathe" [14].

Another study models carbon dioxide concentration fluctuations depending on the number of students in the room, its volume and ventilation capacities. It was established that by the end of classes, the content of CO_2 in the respective space reaches 2500 ppm, which is unacceptable. If the room is small (up to 200 m^3, for 25–30 people), growing CO_2 concentration also brings up the air temperature to 27 °C and alters air humidity to 30.0–40.0% [43].

One experiment set up in an educational establishment has shown for more than half of school hours, the amount of CO_2 in the air exceeds 1300 ppm, and sometimes approaches 2500 ppm. It is impossible to concentrate in such environment; a person's ability to perceive information is disrupted critically. Other symptoms likely to manifest when the content of CO_2 in the air is excessive are hyperventilation, sweating, eye inflammation, nasal congestion, and difficult breathing [44].

Another group of researchers investigated carbon dioxide concentrations in standard and non-standard gyms under different hygienic conditions. They analyzed changes in the general well-being of students before, during and after physical activity in spaces with normal and elevated concentrations of CO_2. Results: increase of content of carbon dioxide adversely affects students' abilities, their concentration, coordination abilities and general well-being. There is a clear correlation between CO_2 concentration and well-being, performance and effectiveness of students during physical activity [45]. A study [46] uncovered that by the end of classes, carbon dioxide content in gyms grows up by 1.5–3, which indicates unsatisfactory operation of their ventilation systems.

The available studies demonstrate the importance of regulation of CO_2 content and the tasks of indoor air quality assessment and monitoring. This is especially relevant for organization providing educational services, where children stay for a long time, exposed to various chemicals contained in the air, with CO_2 being the main among them. In Russian Federation, there is an Interstate Standard [47] that sets out general requirements for optimal and acceptable conditions of microclimate in occupied portions of residential, preschool, public, administrative and household buildings. This Standard regulates indoor air quality, which depends on the CO_2 percentage. The Standard prescribes air of quality class 1 for children's institutions, hospitals and polyclinics, and for residential and public spaces, air quality indicators may be accepted as per the design assignment that factors in pollution of outdoor air, which is the source of contamination of indoor air.

In addition to the Interstate Standard, regulations for residential and public spaces are contained in the National Standard [48] based on the 2004 European indoor air quality standard for occupied spaces [49]. Under the National Standard [48], air quality depends on the level of ventilation (air exchange rate), which ensures acceptable CO_2 values. European Standard [49] allows indoor air quality to differ from that of outdoor air by 350 ppm CO_2 only, but the overall CO_2 content therein should not exceed 1000 ppm. In Russia, the level of CO_2 is not measured, therefore, there are no baseline values to calculate the volumes of air that a room needs from this point of view.

Hygienic regulations covering microclimate in educational establishments prescribe values for three quantitative indicators only: temperature, relative humidity and air velocity. The respective documents are 2020 Sanitary Rules [50] and 2021 Sanitary Rules and Regulations [51]. As for the quality of air in educational establishments, the Rules state that "concentration of contaminants in excess of the thresholds stipulated by the regulations is forbidden" [50]. The list of atmospheric pollutants set out in the hygienic standards [51] does not include CO_2. However, there are threshold values limiting concentration of CO_2 in the air of working spaces. Carbon dioxide, a gaseous chemical, is on the list of contaminants (№ 2124), and international hazard classification puts CO_2 in the same hazard class IV as ammonia (asphyxiating gas) [51]. At the same time, the maximum permissible concentration (MPC) of CO_2 in the working space air is 27000 mg/m^3 (13,790 ppm or cm^3/m^3), and the average daily (per-shift) MPC of CO_2 is 9000 mg/m^3 (4597 ppm or cm^3/m^3) [51]. For comparison, excerpt from the US Occupational Safety and Health Standards [52]: "...toxic and dangerous substances, air pollutant limit values: carbon dioxide permissible exposure limit (PEL, baseline 8-hour time weighted average (TWA)) is 5000 ppm; short-term exposure limit (STEL) — 30,000 ppm..." In other units of measurement, 30,000 ppm is 58,740 mg/m^3, which is a STEL twice as big as required in the Russian regulations, and 5000 ppm is 9790 mg/m^3, which is a TWA almost equivalent to the Russian per-shift concentration of CO_2.

In Russia, such concentrations were first established by Hygienic Standards in 2006 [53]. In the USSR, the first scientific justification of CO_2 MPC was study [54], which investigated the effect of concentrations of 1000 ppm (0.1%) and 5000 ppm (0.5%) in residential and public spaces.

However, in the world, the important problem is that of ensuring high quality of the environment in school buildings, since there are no legally binding limit values setting thresholds for most indoor air pollutants [55]. In Finland, the CO_2 MPC in an occupied space under normal weather conditions is 1200 ppm. The Norwegian and Swedish standards covering residential buildings, schools and offices set the maximum for CO_2 concentration at 1000 ppm. Japan, Portugal, Korea, France, Denmark have also taken 1000 ppm as upper limit for specified spaces, including schools and office buildings. Standards and guidelines regulating CO_2 content in residential, school and office buildings were summarized in a single document as part of the air carbon dioxide content assessment by the ANSES, French National Health and Safety Agency [56, 57]. In Germany, the accepted CO_2 concentration is 0.15%, or 1500 ppm, which is a hygienic guideline value. Such values were also published by the Indoor Air Hygiene Commission of the Federal Ministry of Environment and the State Health Agency [58].

The various methods and guidelines for design and evaluation of indoor air quality and thermal comfort in school buildings are outlined in the European Standard [59], the British Building Bulletin [60] and the ANSI Standard [61]. European Standard gives input parameters for indoor environment to be factored in the design and assessment of energy efficiency of buildings; these parameters account for various indoor environment quality aspects. In this document, the calculated CO_2 concentrations are grouped in four categories by the expected percentage of those dissatisfied with air quality (the lower the category, the lower the expected share of dissatisfied people, with the minimum at 15% and maximum at 40%). Thus, the upper threshold for the 1st category is 550 ppm, 2nd category — 800 ppm, 4th category — 1350 ppm. The normal level is that of category 2. A lower level may be chosen for students with special needs. A higher level does not pose a health hazard, but may make the space less comfortable.

The British Building Bulletin [60] sets rules, standards and recommendations concerning ventilation, thermal comfort and indoor air quality for school buildings. In case of classrooms, the bulletin sets different indoor air quality requirements for different ventilation strategies. Mechanical systems and hybrid systems used in mechanical mode should let in sufficient amount of outdoor air to have the average daily CO_2 concentration less than 1000 ppm during the working period. In addition, maximum concentration should also not exceed 1500 ppm for more than 20 minutes running, every day during the working period. Natural ventilation and mixed systems incorporating natural ventilation should ensure the average daily CO_2 concentration of 1500 ppm when the space is occupied, and the maximum concentration should not exceed 2000 ppm for more than 20 minutes running in a day.

The limit CO_2 content value was removed from the ANSI standard [61] in 1989, a deliberate omission (previously used value — 1000 ppm) allowing to downplay the importance of this indicator in the overall indoor air quality assessment, while this concentration is at best an indicator of the outdoor air intake rate per person. Comparison of ANSI standard [61] and European Standard [59] shows that the current minimum ventilation rate for classrooms as per the ANSI regulations is half the threshold value of the European Standard (5 instead of 10 l/s per person). On the other hand, the no longer used value of 1000 ppm will be approximately equivalent to the 1st category of the European Standard (950 ppm, with outdoor CO_2 concentration of 400 ppm).

A comparative assessment of air quality in schools of South Tyrol (Italy), which referenced different standards, showed comparable, but not identical results. The study revealed that when a class is not aerated throughout the lesson, CO_2 levels can exceed 2000 ppm or even 3000 ppm. The threshold of 1000 ppm is reached after 13–18 minutes without active ventilation, and the value of 1500 ppm may be exceeded after 23–35 minutes if there is no aeration. Carbon dioxide concentrations measured in classrooms were below 1000 ppm most of the time; the threshold of 2000 ppm was exceeded rarely (0–2%), which indicates that these spaces were aerated at least once per lesson [62].

Currently, there are several methods of determining the level of CO_2 in the air practiced in Russia. The M. Pettenkofer's method, suggested in the 19th century, is an indirect integral sanitary indicator of air purity, which is mentioned in the National Standard of the Russian Federation [63]. For several decades now, the value has been used as a baseline of satisfactory air quality in an enclosed space, and in the context of designing air conditioning and ventilation systems, as per the current edition of the European [64] and National Standards [65], which establish technical requirements for ventilation and air conditioning systems.

Volumetric methods used to measure CO_2 content: Holden, Kudryavtsev, Kalmykov gas analyzers; Subbotin-Nagorsky and Hess titrometric methods; the comparative Prokhorov method [66]. For express assessment, the methods are: a) D.V. Prokhorov's method that involves comparative assessment of indoor air and outdoor air that has CO_2 at 0.03–0.04% (300–400 ppm or cm^3/m^3); b) reaction of carbon dioxide with a soda and phenolphthalein solution, which is applicable even in school laboratories. The main current approved methods have been developed in accordance with the National Standard [63], which is identical to the International Standard [67]. These standards outline the key provisions regulating measurements of carbon dioxide content in the air of enclosed spaces.

GANK-4 gas analyzers, used as prescribed in the operating manual [68], enable direct measurements of concentration of chemicals and deduction of quantitative values from their content in the atmospheric air, working area air, enclosed and residential spaces, industrial emissions, vented emissions and technological processes. The data acquired are used in the context of environment protection, occupational safety, technological processes optimization measures. GANK-4FEx stationary gas analyzer is used to measure concentration of carbon dioxide under the certain current certified measurement methods and operational documentation of the unit. As per Federal Law of the Russian Federation № 102 of 26.06.2020 "On ensuring uniformity of measurements" [69], all measurement methods used in situations regulated by the state should be applied in accordance with the procedure established in the respective certification documentation.

The need for standards regulating carbon dioxide concentrations in educational establishments arises from inefficiency of ventilation or impossibility to aerate duly in order to normalize and stabilize all microclimate parameters to their optimal values in enclosed classrooms with high hourly occupancy (for example, when the break between lessons is not enough for this purpose, and aerating a room when there are children in it is prohibited [50]). Another factor contributing to the urgency of CO_2 concentration problem is the widespread replacement of wooden window frames with plastic windows, which turn classrooms into sealed chambers that, with an imperfect air exchange system, promote growth of concentration of CO_2 [70, 71].

Carbon dioxide content measurement and control in enclosed spaces will minimize the risks of its adverse effects on the body. In this connection, much attention has been paid recently to the development of systems enabling automated registration and analysis of carbon dioxide indicators in indoor air with their further centralized processing [72]. This is especially important for educational organizations, as allows timely detection of CO_2 level and subsequent appropriate remedial measures. Installing temperature, relative humidity and CO_2 concentration measurement systems in spaces with forced ventilation ensures conformity of the gas-air environment therein with sanitary standards and rules. This goal is achieved through upgrading forced ventilation systems with automatic start-up devices that launch them when the concentration of CO_2 exceeds the optimal level (1200 ppm (0.12%)) [73].

An important prevention measure is installation of plenum ventilation, which can steadily reduce the level of CO_2 and thus mitigate its harmful effects on health, and installation of sensors to monitor the concentration of CO_2. It should be noted here that ventilation systems designs are driven by the air exchange standards. In Russia, the standard minimum air exchange rate is 30 m^3/h (in Europe — 72 m^3/h); it does not depend on the area and volume of the room, only on the "breathing rate" and the volume of ventilation. Thus, when the occupants of the room are a state of calm wakefulness, the concentration of CO_2 will increase to 1000 ppm, and when they practice physical activity, it will exceed the threshold. Thus, the air exchange rate of 30 m^3/h, adopted through the Russian regulations, does not ensure comfortable indoor environment. Moreover, as suggested in the CO_2 control recommendations, its optimal concentration in a room requires increase of the air exchange rate: to have carbon dioxide at 1000 ppm, the rate should be 33 m^3/h, at 500 ppm — 200 m^3/h [3].

With the constant growth of CO_2 content in the atmosphere of cities, maintaining a safe and comfortable level of this compound in an enclosed space using ventilation systems is more energy-consuming if there are no systems removing it therefrom. Currently, it becomes widely recognized that the most effective way is to purify the air in occupied rooms with the help of devices absorbing indoor air pollutants. The right combination of such purifiers and a reasonable ventilation system can give a very good result along with better energy efficiency, as provided by developments described in the scientific publications of recent years [74–80].

CONCLUSION

The analysis of studies published both in Russia and abroad confirms that there is a significant interest in the problem of CO_2 content, substantiated by the rapid increase of its concentration in indoor air. Numerous authors focus on investigation of the influence of various concentrations of indoor air CO_2 on the people's functional state and health, and the results of this investigation indicate that even small deviations from the recommended (in particular, for educational and preschool establishments) permissible concentrations cause adverse changes in individual body systems, with acute and delayed negative effect on the general well-being of students, as well as deterioration of their performance and mental activity, increased fatigue and low resistance to infectious and non-infectious agents, and more frequent upper airways diseases. The analytical review emphasizes the need to study the issue of setting standards for the actual CO_2 content while perceiving the compound as one of the risk factors peculiar to school and preschool environments. Another highlighted problem is that of development and approval of a methodological framework enabling monitoring and control over this indicator with the ultimate goal of preventing the negative effects.

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