Проведено порівняльний аналіз нормативних документів, які стосуються вентиляції шкільних приміщень, що діють сьогодні європейських країнах. Показано суттєву відмінність рекомендованих значень повітрообміну. Оцінка санітарно-гігієнічних умов, які формуються у класних приміщеннях при різній продуктивності системи вентиляції, проводилась як шляхом аналітичних розрахунків, так і шляхом суб'єктивного моніторингу мікроклімату експериментальних вимірювань, що проводились у шкільних кабінетах та класах, під час якого кожен учень-учасник здійснив оцінку внутрішнього середовища у формі анкети. Було проведено заміри вмісту вуглекислого газу, що виділявся в приміщенні, і визначено необхідну інтенсивність вентиляції в оцінюваних шкільних приміщеннях. Визначена таким чином кратність повітрообміну системи вентиляції порівнювалася з величинами, отриманими шляхом аналітичних розрахунків, що проводилися відповідно до чинного законодавства та стандартів, що діють в країнах Європи. Розрахунки, проведені на підставі відомих аналітичних залежностей, при яких продуктивність системи вентиляції класних приміщень визначалася на підставі концентрацій CO_2 у внутрішньому та припливному повітрі при різних значеннях кратності повітрообміну дозволяють стверджувати, що оптимальні параметри мікроклімату досягаються при повітрообміні в розмірі 30 м^3/год на особу. Результати натурних досліджень та аналітичних розрахунків представлено у вигляді таблиць і наочних графічних залежностей. Запропонована методика досліджень дозволяє підвищити точність та достовірність контролю якості повітря в класних кімнатах за рахунок прямого вимірювання концентрації CO_2 в обслуговуваній зоні приміщення. Результати досліджень дають можливість вдосконалення систем вентиляції шкільних будівель. Це створює передумови для отримання соціального ефекту при підвищенні продуктивності праці та навчання

Ключові слова: кратність вентиляції, енергоощадність, концентрація двоокису вуглецю, продуктивність вентиляції, моніторінг мікроклімату

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ENSURING COMFORT MICROCLIMATE IN THE CLASSROOMS UNDER CONDITION OF THE REQUIRED AIR EXCHANGE

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1. Introduction

Research into the process of ensuring comfortable microclimate is very relevant, since about 20 % of the total population spends a significant part of their day at preschool and school facilities. Papers [1, 2] show that the deterioration of microclimate conditions in classrooms, in particular due to an increase in CO_2 concentration, leads to deterioration of the state of health and disability of pupils, as well as insufficient learning of their educational material. This is especially important, since CO_2 concentration often exceeds permissible values in the outdoor air of large cities. Thus, room ventilation systems require significant air exchange for CO_2 assimilation.

Ecologists, doctors, diagnosticians, engineers and designers of ventilation and air conditioning systems pay special attention to the issue of an influence of air quality in premises of buildings on the state of people health. A physical condition of a person depends on a content of pollutants in air. If the air quality is poor, people experience fatigue, loss of concentration, development of diseases, etc.

Carbon dioxide, along with nitrogen oxides, carbon monoxide, sulfur dioxide and volatile organic compounds, are typical pollutants. Thus, we should take this into consideration at evaluation of the quality of air when designing ventilation and air conditioning systems. The European standard EN 13779 "Ventilation for-residential buildings – Performance requirements for ventilation and room-conditioning systems" [3] suggests accepting the concentration of carbon dioxide of 350 ppm in outdoor air in countryside, of 400 ppm – in small cities and of 450 ppm – in centers of large cities as a general base reference value. In fact, it can be substantially higher.

The problems outlined emerged a long time ago, therefore the USA accepted ASA A53.1: Light and Ventilation standard in 1946. The first version of ASHRAE 62 replaced this standard in 1973. It included minimum and recommended air exchange norms for more than 250 types of building structures. Such requirements were a significant achievement at that time, but they did not take into consideration health of people, an impact on indoor comfort and energy efficiency.

In 1981, there was a revise of ASHRAE 62. In the standard as of 1981, a concentration of pollution determined air exchange and other design parameters. In ASHRAE 62 norms of the year 1989, there was an increase in minimum intensity and it related to other norms. Minimum intensity was increased and related to other norms since of 1973 in ASHRAE norm from 62–1989. This step admitted that limited energy consumption caused an inappropriate reduction in efficiency of a ventilation system. The ASHRAE 62.1-2004a edition marked the first change in requirements for air exchange since the 1989 standard.

The indirect definition approach was accepted in 2000 in ASHRAE 62-2001. Existing and future CEN standards use the specific quantitative determination of individual sources of pollutants in premises.

2. Literature review and problem statement

Currently, researchers pay great attention to the issues of energy saving in construction of new school buildings and significant renovation of existing ones. Therefore, increasing of thermal stability and tightness of perimeter structures is of prime importance in reconstruction and construction of new buildings. To achieve this objective, it is necessary to minimize uncontrolled air exchange due to air leakage through building constructions (infiltration). There are recuperators in mechanical ventilation of such systems. Recuperators reduce energy consumption of buildings [4, 5].

To determine values of air exchange in classrooms, which would provide optimal parameters of a microclimate, it is necessary to investigate how these parameters were formed in the normative documents of the leading western countries [6].

The European Committee for Standardization (CEN) developed a set of 31 standards to support implementation of the Energy Performance of Buildings Directive (2002/91/EC) accepted on 04.01.2003. There was a revision of the Directive to EU Directive 2010/31 and it was issued by the European Commission in December 2010 [7]. Table 1 shows the value of the normative air exchange regulated by this Directive.

Table 1

Normative air exchange n (1/h) [7]

Type of a premise	N (1/h)	Type of a premise	N (1/h)
all classes as a whole	4	computer classrooms	15–20
lecture room	8–15	library	4
classroom	4–12	clubs	20–30

Table 2 shows the values of minimum air exchange in premises with different length of stay recommended by the Danish Engineering Association DS 447.

Table 2

Minimum amount of air exchange in a premise (Bygningsreglement)

Premise	Minimum air exchange
For children at 24 hours stay	3 l/(s for a person) or 0.4 l/m^2
For adults at 24-hour stay	5 l/(s for a person) or 0.4 l/m^2
Classroom	5 l/(s for a person) or 0.4 l/m^2

Researchers of some European countries (the Netherlands, UK and France) use EN 15780 – Ventilation of buildings, cleanliness of ventilation systems from October 2011 to calculate intensity of ventilation. Table 3 provides an overview of the requirements to efficiency of school and office ventilation systems around the world [8].

EN 13779 and EN 15251: 2007 standards determine the amount of inflow air in the European Union.

Table 3

Requirements to efficiency of school ventilation systems in foreign standards

Country	Standards	Requirements to ventilation	
		Offices	Schools
Australia	Australian standard 1668.2 – 1991	15 l/(s per person)	younger than 16 years: 12 l/(s per person) older than 16 years: 10 l/(s per person)
Belgium	Nbn d 50 – 001		
Denmark	Danish building regulations 1995, 447 Code of practice for ventilation installations	with smokers: 10 l/(s per person) Smoking is forbidden: 4–10 l/(s per person)	5 l/(s per person) + 0.4 l/(s per m^2)
Finland	National building code, part D2, 1987	in general: min. n=0.5 1/h n=0.2 1/h in rest hours	
	Classification of Indoor Climate, 2000	3.6 m^3/(h per m^2)	11 m^3/(h per m^2)
Germany	DIN 1946	independent office: 40 m^3/(h per person) or 4 м^3/(h per m^2) more offices: 60 m^3/(h per person) or 4 m^3/(h per m^2)	30 m^3/h per person or 15 m^3/(h per m^2)
Netherlands	Dutch building regulation + NEN 1087	1.3 dm^3/(s per m^2)	on consumption: 0.5–8.8 dm^3/(s per m^2)
Norway	Ren veiledning + sbe 1999 + Guide to Norwegian Building Regulations	7 l/(s per person) + + 0.7...2.0 l/(s per m^2) in dependence on materials emissions	
Sweden	Sweden Building Regulations BBR 94 BBR+ AFS2000:42	7 l/(s for a person)	
Slovakia	Order 527/2007 [9]	20 m^3/h per 1 person	20–30 m^3/h per 1 person
Ukraine	SNIP II-L.4-62	20 m^3/h per 1 person	20 m^3/h per 1 person
Ukraine	DBN V.2.2-3-97 [10]	20 m^3/h per 1 person	16–20 m^3/h per 1 person in dependence on a type of educational establishment

After analysis of the data presented in the Tables 1–3, we can state that there is no generally accepted approach to determination of a value of standard air exchange in classrooms. The recommended values vary in a significant range: the minimum value is 10.8 m^3/h per person in accordance with the Bygningsreglement, and the maximum value is 30 m^3/h per person according to the Order 527/2007 [9]. Some documents calculate the amount of ventilation air not per person, but in dependence on an area of a classroom. The analyzed data from documents of certain countries of the European Union indicate specific numerical values of recommended air exchange. But they do not indicate methods of calculation or results of studies used to accept these values.

SNIP II-L.4-62 Comprehensive school and boarding schools, Design standards, 1964 regulated the requirements for ventilation of school premises before the national building standards came into force on the territory of Ukraine. Thus, there is a significant number of schools in Ukraine built in accordance with these standards. According to this document, it is necessary to calculate ventilation of educational premises by determination of an amount of air for assimilation of excess of heat emissions, wet releases and CO_2 emissions in order to maintain temperature of internal air within 16–22 °C, humidity – from 30 to 60 % and CO_2 content – up to 1 l/m^3.

Since 1998, DBN V.2.2-3-97 "Buildings and facilities of educational institutions", 1997 [10] has been in force in Ukraine. Table 3 presents the requirements for efficiency of ventilation systems. They differ from the above-mentioned European ones.

The State sanitary rules and regulations on establishment and maintenance of general educational institutions and organization of educational process state necessity for laboratory studies. It is necessary to measure air temperature, relative humidity, air velocity, radiation temperature, CO_2 concentration, CO concentration, formaldehyde concentration and concentrations of other substances in premises during the studies. It is necessary to perform laboratory studies and instrumental measurements in dynamics of a school day, namely – before the first lesson and at the end of the last lesson. However, the State sanitary rules and regulations do not provide specific values of permissible concentrations of CO_2 and CO.

Some modern publications apply to formation of microclimate in premises of educational institutions [11, 12], but the emphasis is on energy efficiency of ventilation systems in most cases [12], they determine air exchange based on already existing normative documents. They also consider natural ventilation systems, but such systems can not always provide calculated air exchange during a cold season [13]. Also, researchers studied natural ventilation potential for maintenance of an acceptable air quality in premises of US educational institutions during periodic operation of mechanical ventilation systems [14]. There are similar studies carried out for educational and sports facilities, in particular for water sports [15]. There researchers investigated the situation by simulation analysis and they established that forced ventilation is required to ensure adequate ventilation in a water center.

Authors of paper [1] noted that ventilation of classrooms goes through windows in almost all schools in Germany. In this regard, parameters of microclimate, especially in winter, are unsatisfactory. In addition, there are results of field studies of microclimate in a classroom (internal air temperature and CO_2 concentration) presented at various geometric characteristics of open windows and different wind speeds. Paper [2] presents results of studies on microclimate parameters in classroom premises of the gymnasium in the city of Misbach (Germany) conducted throughout a year. It shows the dependence of a change in CO_2 concentration during the entire educational period at different areas of open windows, but there is no amount of inflow ventilating air.

Since the methods of theoretical determination of air exchange do not take into consideration a subjective evaluation of microclimate, it is necessary to conduct experimental research. It will make it possible to substantiate objectively and clearly an amount of air exchange for formation of optimal parameters of microclimate in classrooms.

Oxygen enters a body, and a body emits carbon dioxide when breathing. Table 4 shows components of air inhaled and exhaled by healthy people measured in health facilities [16].

Table 4

Composition of air inhaled and exhaled by a healthy person

Substance	Air inhaled (%)	Air exhaled (%)
oxygen	20.96	15.4
carbon dioxide	0.04	5.6
nitrogen	78.0	78.0
other gases	1.0	1.0

A healthy person inhales about 250 ml of oxygen and releases about 200 ml of carbon dioxide per minute in a state of rest. The inhaled air composition differs from the composition of exhaled air, which in turn contains less oxygen, but more carbon dioxide and water vapor. During breathing, a body releases also energy, so temperature of exhaled air is higher.

Literary sources [4, 6, 17] do not indicate an amount of CO_2 released. Most often, the proportion of carbon dioxide in exhaled air is 4 %. The volume of air in human lungs when inhaling and exhaling in a state of rest is about 0.5 liters of air. It is possible to inhale about 2.5 liters of air more at quiet breathing. Due to the fact that there is a reserve in lungs, about 4 liters of air can be released from lungs after maximum breathing. About 0.5 l of air remains in lungs and bronchi after maximal exhalation. A healthy adult inhales and exhales from 7.5 to 8 l/min of air approximately at a frequency of about 15 inhales/exhales per minute.

There are difficulties in design of school ventilation systems due to the lack of data on emission of CO_2 by pupils, that would take into consideration such additional factors as age (for junior pupils and senior pupils), a ratio of girls and boys and intensity of physical activity.

3. The aim and objectives of the study

The objective of the study is to determine a value of a multiplication factor of air exchange in classrooms, which would provide optimal sanitary and hygienic conditions in premises.

It is necessary to solve the following tasks to achieve the objective:

– determination of actual values of CO_2 emissions from pupils in classrooms under different parameters of internal air by conduction of field studies in classrooms;

– microclimate monitoring in a class by the method of subjective assessment of air quality;

– obtaining of graphical and analytical dependences of CO_2 concentrations in classrooms on a value of air exchange and parameters of internal air;

– determination of an amount of air exchange for formation of optimal microclimate parameters in classrooms.

4. Experimental measurements of carbon dioxide concentration in school premises

4. 1. Measurement of CO_2 in indoor and outdoor air

It is interesting to compare results of field studies of air conducted at existing schools in Slovakia and Ukraine. In both cases, researchers performed experimental carbon dioxide concentration measurements to study air in classrooms. They also recorded temperature of indoor air and relative humidity of indoor air simultaneously with measurement of carbon dioxide concentration. They recorded a concentration of carbon dioxide, temperature and relative humidity of air during measurement of outdoor air parameters.

Measurements took place in the heating period: January, February and March. During the measurement, researchers carried out also a subjective assessment in the form of questionnaires. Pupils assessed the air quality in a premise in the questionnaires.

The results of experimental studies determined the selection of a method for determination of ventilation efficiency in school buildings.

Experimental studies in Slovakia took place in selected lecture rooms located in the city of Kosice in the Street Vysokoshkilskaya in a five-story building on the fifth floor, and in Ukraine – in Lviv in the Street Khotinskaya in a four-storey building on the fourth floor. Researchers recorded a concentration of carbon dioxide, air temperature, air velocity and relative humidity in a premise during experimental measurements.

During tests on Testo 435-4 device (Germany), they measured the following parameters of air in the selected premises: indoor air temperature, relative humidity and a carbon dioxide concentration.

Parameters of the device were as follows: measurement of CO_2 concentration in the range from 0 to 10000 ppm, accuracy of measurement of CO_2 concentration was ±3 ppm [18–21].

CO_2 concentration depends on human activity and differs in different areas in the external environment. Fig. 1 illustrates documented carbon dioxide concentration measurements made in Kosice this year, at an altitude of 20 meters above the ground approximately. Researchers measured also the concentration of carbon dioxide in the external environment during experimental measurements of the concentration of carbon dioxide in the premises under consideration.

As we can see on the graph presented in Fig. 1, the average concentration of carbon dioxide in the air of Kosice was between 420 and 430 ppm, which was consistent with the standard [3], although peak values exceeded 500 ppm.

Experimental measurements in classes of Lviv and Koshitsky schools also took place at fixed time. 5 measurements took place at the same time. Beginning of stay in a classroom was always from 8.00 in the morning. From 8.00 to 9.00 (until 9.38) a written part of the experiment lasted, when pupils responded to the questions asked in writing. All pupils left the premise after the written test. The room remained empty with closed windows to carry out further calculations to determine the efficiency of ventilation through infiltration and exfiltration. The concentration of carbon dioxide dropped indoors due to air leakage through building constructions. All people who participated in the written part of the test entered the room after 1 hour. Oral part of the test took place in the room. Duration of the oral part of the test was different. Fig. 2 shows the results on the changes in the concentration of carbon dioxide recorded.

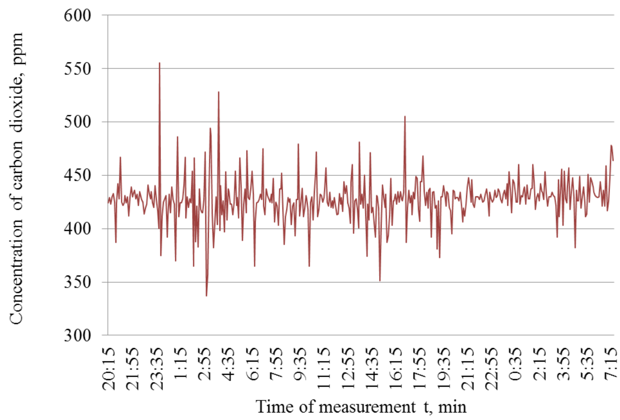

Fig. 1. Concentration of carbon dioxide measured in outside air in the central part of the city of Kosice (Slovakia)

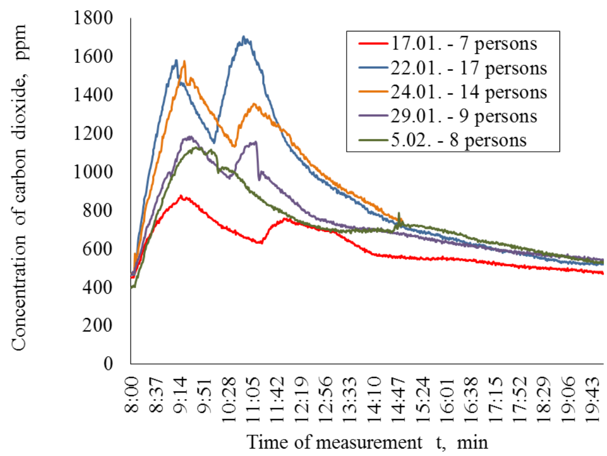

Fig. 2. Change in CO_2 concentration in the classroom during daytime

After the oral test, all people left the room, which remained empty, and windows and doors were closed. With a decrease in CO_2 concentration, room ventilation may occur through infiltration, which differs for each measurement day.

The results of the experimental measurements in the class showed that CO_2 concentration ranged from 876 to 1,582 ppm at staying in the room from 7 to 17 persons and the time of stay from 76 to 98 minutes.

4. 2. Subjective assessment of the indoor environment in the classroom

Individual participants in the measurement documented the subjective perception of the internal environment in the class during the experimental measurement. At the end of their stay in the class, pupils completed a questionnaire for subjective assessment of the indoor environment parameters, which included an assessment of thermal comfort and intensity of odors.

Table 5 shows the results of the measurements given in dependence on the number of persons in the class during the measurement. Subjective assessment by individuals in the classroom during the measurement determined air quality values.

Table 5

Assessment of air quality in the class

Date of measurements	Quantity of persons (–)	Duration of stay (min)	Indoor temperature (°C)	Final CO_2 concentration (ppm)	Perceived air quality (%)		
					Definitely acceptable	Indifferent	Almost unacceptable
17.01	7	76	18.40	876	100	0	0
22.01	17	69	20.05	1582	56	44	0
24.01	14	81	20.85	1575	43	57	0
29.01	9	88	18.95	1182	44	56	0
05.02	8	98	20.05	1128	25	63	12

From a subjective point of view, we can note that the presence of high concentration of carbon dioxide in the room also increased a number of people who were dissatisfied with the air quality in the classroom. With the largest number of pupils and the highest concentration of carbon dioxide, one can assume that the subjective perception of respondents does not correspond to the objective definition of the observed factors of the internal environment. We should note that 12 % of respondents described the state of microclimate almost unacceptable at CO_2 concentration lower than the maximum according to the results of measurements conducted on 05.02. This is due to the longest duration of stay in the premise.

4. 3. Calculation of the efficiency of a ventilation system based on measured CO_2 concentrations

We used the methodology, which determines air exchange in dependence on an amount of carbonic acid gas for determination of the required ventilation efficiency. We determined the mass flow rate of CO_2 from the concentration of carbonic acid gas obtained by experimental measurements of the carbon dioxide concentration. Experimental measurements took place in winter in several selected premises. We determined the required air flow, which meets hygiene requirements, based on the measured data on carbon dioxide.

It was very important to provide the most stable boundary conditions of measurement to be able to determine a change in carbonic acid gas concentration quantitatively according to the measured data. In addition to the measured indoor air parameters, we also fixed hourly information on outdoor air temperature and wind speed. These data influence intensity of ventilation through infiltration.

Fig. 3 shows the measured parameters of external air. It is evident from the measured values that the relative humidity of air also increases as the concentration of carbon dioxide increases.

It is necessary to divide the graph into two main parts (Fig. 3) in the analysis of the process, namely:

– an increase in the concentration of carbon dioxide, when a source of pollutants is indoors – A–B part;

– ventilation of the premise through infiltration, when there is no source of pollutants in the premise – B–C part.

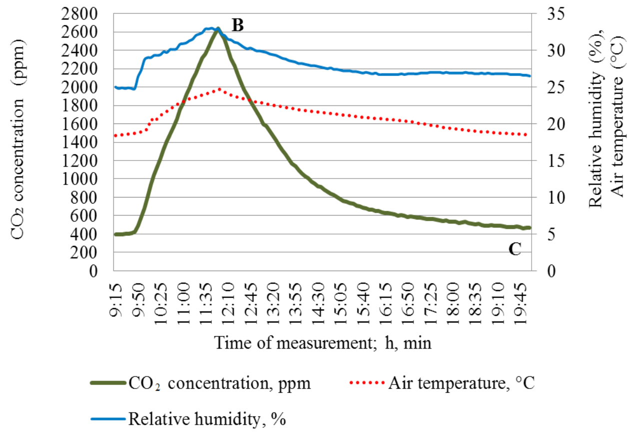

Fig. 3. CO_2 concentration, air temperature and relative humidity

There is an increase in the concentration of carbonic acid gas in A-B part, where the main source of pollutants is a person. We can express the change in the concentration of carbon dioxide mathematically by the relations [22, 23]:

$$C_{IDA}=C_{SUP}+\frac{q_{ms}}{q_V}\cdot\left\{1-\exp\left[\left(\frac{-q_V}{V_M}\right)\cdot t\right]\right\},\ (\text{mg/m}^3), \quad (1)$$

where C_{IDA} is the CO_2 concentration in air at t time (mg/m^3); C_{SUP} is the CO_2 concentration in inflow air at t time (mg/m^3); q_{ms} is the mass flow of CO_2 in a premise from a source of a pollutant (mg/s); q_V is the volume flow of air required for premise ventilation (m^3/s); V_M is the room volume (m^3); t is time (s).

The known variables were a volume of premises, CO_2 concentration and time of its change. Unknown values were – mass flow of CO_2 and of outdoor air, which penetrates into a premise due to infiltration.

We obtained the concentration of carbon dioxide in ppm by multiplication of the concentration of carbon dioxide in mg/m^3 by k=0.556.

We used the method of indirect chemical mixing to determine the intensity of air exchange by means of air infiltration in the premise. This method controlled reduction of CO_2 concentration. The method implied monitoring of time of reducing of CO_2 concentration during its emission. And measurement stopped when its indoor concentration decreased to the concentration in the outside air. For this case, we used the following differential equation [24]:

$$n=\frac{1}{t}\cdot\ln\frac{C_{IDA,Z}}{C_{IDA,K}}n=\frac{1}{t}\cdot\ln\frac{C_{IDA,Z}}{C_{IDA,K}},\ (1/\text{s}), \quad (2)$$

where n is the multiplication factor of ventilation through infiltration (1/s); $C_{IDA,Z}$ and $C_{IDA,K}$ are the CO_2 concentrations in a premise at the beginning of a concentration decrease (mg/m^3) and at the end of its reduction (mg/m^3); t is the time of reduction of CO_2 concentration (s).

The increase in CO_2 concentration occurred due to the presence of people (A–B part). Ventilation in the room occurred due to infiltration.

There are no people in B–C part, so there is no CO_2 either. In B–C part, there is a gradual decrease in CO_2 concentration through infiltration (uncontrolled ventilation). Since CO_2 concentration at the end of the measurement differed from its concentration in the exhaust air, we determined the intensity of ventilation through infiltration in a premise by time of reduction of carbon dioxide concentration.

$$\frac{C_{IDA,B}-C_{SUP}}{C_{IDA,C}-C_{SUP}}=e^{-n.t}, \quad (3)$$

where n is the multiplication factor of ventilation through infiltration (1/s); $C_{IDA,B}$ and $C_{IDA,C}$ are the indoor CO_2 concentrations at the beginning and at the end of concentration reduction, respectively (mg/m^3); C_{SUP} is the CO_2 concentration in inflow air (mg/m^3); t is the time of reduction of CO_2 concentration (s).

We compared the equations and the multiplication factor of ventilation through infiltration:

$$n=\frac{1}{t}\cdot\ln\frac{C_{IDA,B}-C_{SUP}}{C_{IDA,C}-C_{SUP}}=e^{-n.t}, \ (1/s). \quad (4)$$

Since the boundary conditions (external air temperature and wind speed) influenced a change in the amount of infiltration, we determined a multiplication factor of ventilation by CO_2 assimilation at different values of air exchange [21].

We used the calculation volume of air flow supplied into a premise with uncontrolled infiltration of fresh air in the expression (1) for determination of the concentration of carbon dioxide.

4. 4. Calculation of theoretical emission of carbonic acid gas by a person

When calculating the efficiency of ventilation systems, it is necessary to know an amount of CO_2, which gets into a room from people. We can determine a volume and mass flow of CO_2 from humans based on previously reported values of lung volume, inhalation/exhalation volume and CO_2 percentage content as components of a gaseous mixture.

When calculating volume and mass flow of CO_2, we assumed that the average value of one inhalation/exhalation was 0.5 liters. We took the intensity of respiration, which depends on a physical activity and temperature of air indoors, within 12–20 times per minute. In this case, the volume inhalation/exhalation flow will vary within the range of 0.10–0.17 l/s or 0.36–0.60 m^3/h. In order to determine the mass flow of CO_2, which accompanies the process of breathing, it was necessary to multiply CO_2 volume flow by its density. Accordingly, CO_2 density at room temperature was ρ_{CO2}=1.82 kg/m^3. Taking into consideration CO_2 percentage content in the air, we determined CO_2 mass (by hours and seconds) flow. Table 6 shows the results of the calculation.

5. Determination of efficiency of ventilation based on coefficients of concentration of carbon monoxide obtained experimentally

5. 1. Determination of the actual mass flow of carbonic acid gas

The direct measurement of CO_2 mass flow, which goes from pupils to a classroom, is a technically challenging task. This value depends on a number of factors such as a physiological state of pupils, room temperature, age and gender of pupils. Therefore, we used the indirect measurement method to determine CO_2 mass flow from pupils. We measured CO_2 concentration at the known number of pupils in a premise (20 people) and the known initial CO_2 concentration in a premise with an interval of 15 minutes in indoor air. Fig. 4 presents the obtained results as the graphical dependence of changes in CO_2 concentration during 95 minutes of measurements. The same graph also shows the curves of the dependence of the change in CO_2 concentration in a room during a specified time at different values of CO_2 mass flow in the range from 6.55 to 9.8 mg/s obtained on based on the dependence (1). The curve constructed based on experimental data coincides with the calculated curve corresponding to CO_2 mass flow – 7.86 mg/s.

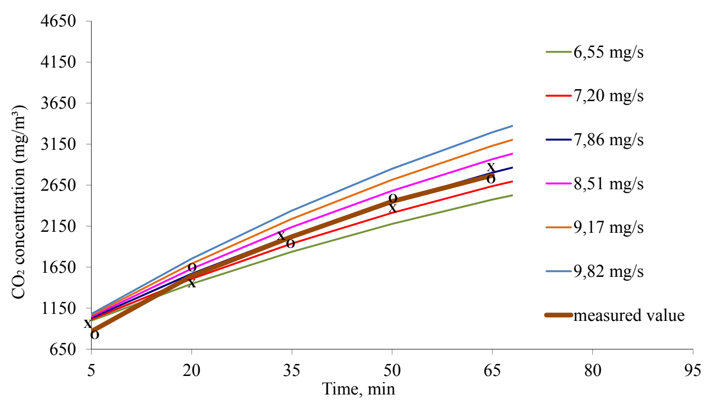

Fig. 4. Dependence of CO_2 concentration on CO_2 mass flow and time of measurements ("x" and "o" are the results of experimental measurements in Kosice and Lviv respectively)

Table 6

Calculated values of mass flow of carbon dioxide from one adult person

Volume of one inhale/exhale	Intensity of breathing	Volume of inhale/exhale		CO_2 mass flow	
l	1/min	l/s	m^3/h	kg/h	mg/s
0.5	12	0.10	0.36	0.028	7.86
0.5	13	0.11	0.39	0.031	8.51
0.5	14	0.12	0.42	0.033	9.17
0.5	15	0.13	0.45	0.035	9.82
0.5	16	0.13	0.48	0.038	10.47
0.5	17	0.14	0.51	0.040	11.13
0.5	18	0.15	0.54	0.042	11.78
0.5	19	0.16	0.57	0.045	12.44
0.5	20	0.17	0.60	0.047	13.09

We compared the curves, which reflect actual and theoretical changes in the concentration of carbonic acid gas, and we can state that the actual averaged value of CO_2 emissions by pupils in a class corresponded to the calculated value of 7.86 mg/s per person.

5. 2. Determination of a multiplication factor of air exchange

We determined a multiplication factor of air exchange in dependence on CO_2 concentration. We used the formulas (1)–(4) for determination of its concentration taking into consideration CO_2 mass flow (7.86 mg/s per person), a volume of a room and a measured initial concentration of carbon dioxide. We made calculations for various multiplication factors of air exchange (from 0.3 1/h to 1.4 1/h). Fig. 5 shows the results of calculations.

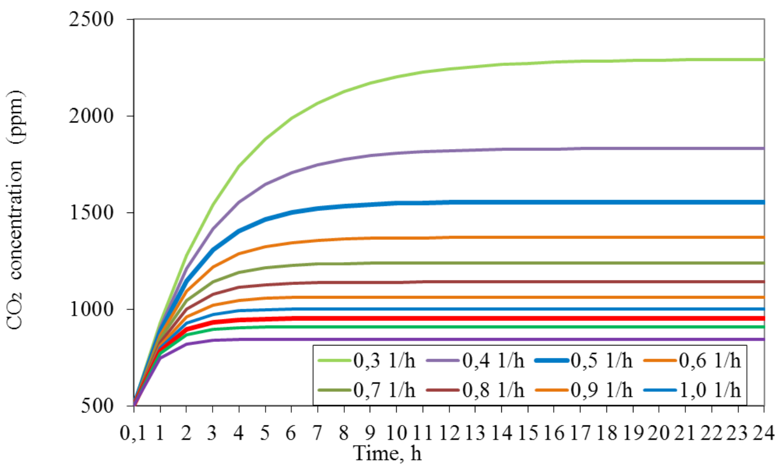

Fig. 5. Dependence of CO_2 concentration on time for various multiplication factors of air exchange

We can see on Fig. 5 that there is an increase in CO_2 concentration at different multiplication factors of air exchange. We observe the highest CO_2 concentration of 3,360 ppm at closed windows, when ventilation in a classroom occurs only through infiltration and exfiltration through building constructions.

It is necessary to change air in a classroom three times in one hour to achieve the maximum acceptable concentration of carbonic acid gas of 1,000 ppm.

The method of finding of the required multiplication factor of air exchange is quite accurate, but very labor-intensive. We compared the defined multiplication factor with the multiplication factor obtained from other sources: norms and standards active in Slovakia and Ukraine.

5. 3. Theoretical determination of a multiplication factor of air exchange

We compared the determined multiplication factor of indoor air exchange, which base is the experimentally measured CO_2 concentration of 3.0 l/h, with the calculated values of the multiplication factor of air exchange in accordance with standards and legislation active in Slovakia and Ukraine.

We compared the multiplication factor of air exchange, which is based on the experimentally measured concentration of carbon dioxide:

– in accordance with pressure caused by the simultaneous action of temperature and wind;

– measured reduction of carbonic acid gas concentration.

We determined the multiplication factors of air exchange listed in Table 7 by infiltration, which, in turn, was determined by measurement of reduction of CO_2 concentration. We obtained the data on a concentration drop during the measurement after a\the written test, when no one was in a closed premise, and the CO_2 concentration decreased due to leakage through structures. We should note that in a class where there was 7 people and the multiplicity factor of air exchange through infiltration through building structures was 0.54 1/h, the CO_2 concentration increased to 1,500 ppm over 8 hours of stay.

We determined CO_2 mass flow based on the data on CO_2 concentrations measured during the stay of persons in a premise during the written part of the test and the calculation value of the multiplication factor of air exchange through infiltration.

We determined the amount of CO_2 using the measured CO_2 concentration, and then we determined the multiplication factor of air exchange in the selected lecture room. We also calculated the required multiplication factor of air exchange for this lecture room in accordance with the Order of the Ministry of Health of the Slovak Republic No. 527/2007 [9] and according to EN 13779 [3]. Table 8 shows the values obtained.

Comparing different methods for calculation of efficiency of ventilation systems, the classroom examined in accordance with STN EN 15251: 2007 belonged to category II. According to EN 13779 [3] the classroom belonged to IDA 2 category, which required an average air quality in a premise.

We calculated air flow by the established multiplication factor of air exchange, taking into consideration the infiltration and the volume of the premise. Table 9 shows the values obtained.

Table 7

Multiplication factor of air exchange due to leakage through building constructions

Order of measurements	Quantity, (pers)	Outdoor temperature, (°C)	Wind speed, (m/s)	Multiplication factor of air exchange through infiltration, (1/h)	
				Under influence of temperature and wind	From a drop of CO_2 concentration
1	7	+0.5	8.2	0.88	0.54
2	17	+1.0	3.6	0.68	0.55
3	14	–3.3	2.8	0.35	0.45
4	9	–3.3	3.9	0.24	0.42
5	8	+3.0	6.7	0.31	0.49

We compared the obtained results with the current European standards presented in Table 3 and analyzed them in the form of the diagram (Fig. 6). We presented the received volume air flow (m^3/h for 1 person) in the form of the multiplication factor of air exchange for the particular selected lecture room where measurements and calculations took place.

Table 8

Required multiplication factor of ventilation in a classroom

Order of measurements	Quantity of persons	Area per person (m^2/person)	Emission of CO_2 mass flow in the premise (mg/s)	Emission of CO_2 mass flow per person (mg/s)	Required multiplicity factor of ventilation (1/h)			
					STN EN 13 779	Extraction from 527/2007	Ukraine	Calculation value based on measurements
17.01	7	9	46.35	6.62	1.00	1.06	1.1	1.1
22.01	17	4	131.33	7.7	2.51	2.56	2.46	2.6
24.01	14	5	109.83	7.8	2.08	2.11	2.18	2.1
29.01	9	7	68.16	7.6	1.33	1.36	1.4	1.4

Table 9

Mandatory volume flow of inflow air in a class

Order of measurements	Quantity of persons (–)	Area per person, (m^3/person)	Volume air flow per person, m^3/(h person)			
			STN EN 13779	Extraction from 527/2007	Ukraine	Calculation value based on measurements
1	7	28.43	28.43	30.13	31.2	31.27
2	17	11.71	29.38	29.97	30.4	30.44
3	14	14.21	29.57	29.99	29.82	29.85
4	9	22.11	29.41	30.07	29.91	30.96
5	8	24.88	28.36	30.10	30.14	29.85

Consequently, we should perform calculation of the multiplication factor of air exchange in accordance with Order 527/2007 [9], which considers the required volume of inflow air of 30 m^3/h per person, for the best result. We can state this in accordance with the measured data on CO_2 concentration in the chosen room and the calculated multiplication factor of air exchange according to different calculation methods.

6. Discussion of results of studying the optimal air exchange in classrooms

CO_2 concentration is not only an indicator of cleanliness of indoor air. Carbon dioxide is a toxic substance even at relatively low concentrations, and therefore we should consider its concentration as an initial value for calculation of efficiency of ventilation systems for long-term stay of people.

The proposed methodology makes it possible to increase accuracy and reliability of air quality control in classrooms due to the direct measurement of CO_2 concentration in a service area of a premise.

Nowadays, high-precision tools for measurement of CO_2 concentration for scientific purposes and household appliances, which make possible continuous monitoring of CO_2 concentrations in classrooms, are available. Deterioration of the environmental situation, especially in large cities, which causes an increase in CO_2 concentration in outdoor air, leads to a significant increase in efficiency of ventilation systems.

The above research results make possible to design ventilation systems for classrooms with efficiency, which will provide optimal sanitary and hygienic conditions. The advantage of the study is that the results obtained experimentally are in good agreement with the results obtained by the analytical method. This suggests that we can use the dependences (1) to (4) for determination of CO_2 concentration of at an arbitrary time in premises of different purposes with a long stay of people. In addition, in comparison with researches of other authors, it proposes a combination of the analytical method with experimental research in the field conditions. The disadvantage of the study is that it is not universal, since it concerns only classrooms. Therefore, there is a need for further similar studies for other school premises – specialized offices, gymnasium, assembly hall, etc. In particular, we performed the study with pupils of senior classes. It would be advisable to conduct similar studies with stay of pupils of 1–4 grades in premises and to compare results. The total air exchange of a classroom determined by the estimated volume of inflow air of 30 m^3/h per person can reach significant values. Therefore, in view of this, school premises require equipment with energy-efficient ventilation systems with the maximum degree of utilization of heat of exhaust ventilation air.

In this case, it is necessary to pay special attention to the method of provision of inflow air to a classroom to provide a normalized difference between temperature of internal air and inflow air. We can realize this with a use of modern air distributors, for example [25–27], and when creating dynamic microclimate [28].

7. Conclusions

1. Comparison of the results of experimental studies and estimated values make us state that the actual mass flow of CO_2 in a classroom corresponds to the estimated value of 7.86 mg/s per person.

2. According to the results of field studies, we established that if the multiplication factor of air exchange is 1.0 1/h, CO_2 concentration is less than 1,000 ppm. Further increase in the multiplication factor of air exchange results in a slight decrease in CO_2 concentration.

3. Subjective monitoring of microclimate in classrooms made possible to assess a state of air environment at different air parameters and different duration of stay in a classroom.

4. We established that air exchange in the amount of 30 m^3/h per person provides parameters of the microclimate close to the optimal ones in a classroom. The calculation methodology and the required volume of inflow air in the amount of 30 m^3/h per person can serve as the basis for improvement of ventilation systems of school buildings. It will also be a prerequisite for obtaining a social effect in improvement of efficiency of learning for future generations.

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