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Integrated Approaches to Determination of CO_2 Concentration and Air Rate Exchange in Educational Institution

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1. Introduction

The effective use of energy resources occupies one of basic places of sustainable development. Having regard to the increase of standard of living, urbanization, part of buildings energy consumption grows. This range of problems touches public and housing building. Taking into account sourcing for coverage of building services, especially sharply the question of the effective use of power resources appeared in Ukrainian public sphere, that is related to wearing out of building stock and shortage of financing (Deshko et al. 2013). Providing of the prudent use of energy without the loss of terms of comfort is basic directions nowadays. IEA EBC Annex 53 (Yoshinoa et al. 2017) employed an interdisciplinary approach including physical and human-related factors to analyze and evaluate the real energy use in buildings. Building operation and maintenance, occupants' activities and behavior, and indoor environmental quality can have a significant influence (Yoshinoa et al. 2017).

In most cases, energy efficiency improvement starts with thermo- readjustment measures in the building (Dumała & Skwarczyński 2011, Siuta-Olcha et al. 2016). Reducing energy consumption and ensuring comfort conditions (Deshko et al. 2020) are important synergy effects in implementing energy saving measures.

At state and regional level one of the most guided segments there are public building, among them the special attention is paid to establishments of education.

Lately large consideration is spared to a vent constituent (to determination of air exchange rate) that can present 30-50% of general energy consumption (Younes et al. 2012, Jokisalo et al. 2008, Frączek et al. 2018). For providing of the proper terms of labour from the point of view of ventilation in a standard (EN 12831: 2003) regulated normative air exchange rate. In building the ventilation air exchange rate is provided in two ways: natural and mechanical. In most old Ukrainian educational building mechanical ventilation is not envisaged or not works. Thus through wearing out of main building stock the ventilation comes through air-channels, airing and leaks in windows, doors etc.

Features of energy-saving measures implementation in Ukraine follow the general trends in Central and Western Europe, where after the implementation of measures associated with improvement of building envelope thermophysical properties, the CO_2 concentration in premises with natural ventilation has increased significantly (Földváry et al. 2017). Reducing this component is the second step in implementing energy-saving measures in Ukraine. Therefore, in the context of widespread implementation of programs aimed at increasing the thermal protective properties of the building envelope, greater attention should be paid to factors influencing natural ventilation (free convection). Air exchange is affected by a large number of parameters which can be conventionally divided into internal and external (Fig. 1).

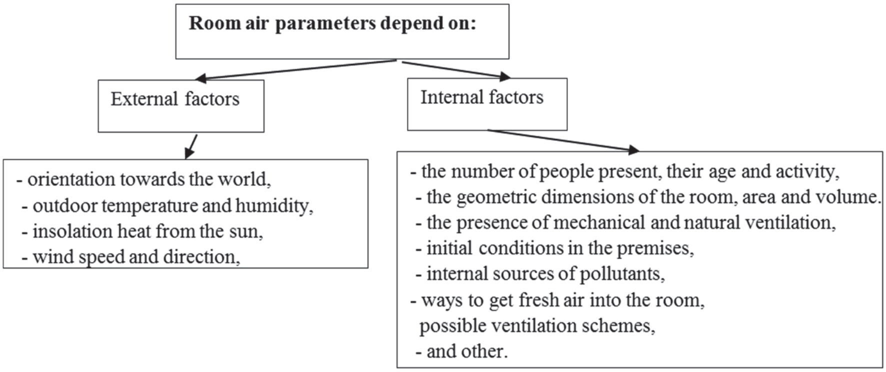


Fig. 1. Parameters affecting indoor air quality

The intensive use of educational buildings brings to the substantial increase of CO_2 concentration indoors, which needs an additional study. Carbon dioxide (CO_2) is one of the indicators of the human bioeffluents emission. There is a classification that is generally accepted and used in standards for premises occupied by people, where the main contamination is caused by human metabolism (DBN V.2.2-3:2018, DBN V.2.5-67:2013, EN 15603:2008, DSTU B A.2.2-12:2015). At the same time, determining the carbon dioxide content by means of modern portable devices is a simple and convenient method to determine asthma and to carry out ventilation in school classrooms on the basis of these measurements.

Permissible values for the CO_2 content in classrooms compared to the requirements of standards of other countries and Ukraine are given in Table 1 (Kapalo 2018, DIN EN 15251), which are slightly different.

Considerable attention is paid by scientists to the determination of actual air exchange and the indoor CO_2 concentration (Földváry et al. 2017, Konig et al. 2018, Johnson et al. 2004, You et al. 2012, Stabile et al. 2017). There are various methods to measure air exchange rates, for example SF6 tests (Johnson et al. 2004), but usually they are quite complex and expensive. A number of studies have been carried out based on a field experiment to determine the natural air exchange for buildings in South China and Europe (Yongming et al. 2017, Almeida et al. 2017); the studies require special equipment and provide an average view on air exchange taking into account the variability of internal and external parameters affecting air exchange over time. Convenient air exchange rate monitoring method using continuous CO_2 sensors was developed through both laboratory experiments and field studies in classrooms in China (You et al. 2012). Similar approaches have been used in articles (Shi et al. 20015, Leivo et al. 2017, Salthammer 2019). The results obtained by such methods should be supplemented and analyzed by mathematical modeling. Similar approaches for determining the natural air exchange were used on animal farms in Germany (Konig et al. 2018); the peculiarity being that the buildings, where the animals were located, were single-storey, long-shaped and had large doorways.

The article (Földváry et al. 2017) notes that residential buildings in Central and Eastern Europe do not comply with modern energy efficiency requirements. In addition, indoor air quality is not given due attention. The authors (Földváry et al. 2017) conducted a study of the CO_2 concentrations in a residential building in Slovakia before and after renovation. It was found that after renovation the air exchange is significantly reduced and the indoor CO_2 level is increased, that is, the implementation of measures to improve the thermal protection properties of the building envelope should go together with measures for mechanical ventilation.

For schools in Central Spain with natural air exchange (Stabile et al. 2017) occurring through opening of windows, a study was conducted regarding the CO_2 concentration in classrooms for the heating and air conditioning period having the recommendations for airing the classrooms established, which can vary from 5 to 20 minutes, depending on a number of internal and external factors. Similar problems with high levels of CO_2 are typical for schools in Ukraine.

Table 1. Comparison of standards for the CO_2 content requirements in classrooms

	Country	Standard	CO_2 Level
1.	Finland	Ministry of Health and Social Development Standard, 2003	Air quality: high – 700 ppm; medium – 900 ppm; satisfactory – 1200 ppm.
2.	USA	US Department of Health Reference Guide on Indoor Air Quality in Schools	Limit: 1000 ppm
3.	USA	ASHRAE 62-1989 Standards “Ventilation for Acceptable Indoor Air Quality”	1000 ppm
4.	USA	The Occupational Safety and Health Administration (OSHA) Recommendations, 1994	800 ppm
5.	Poland	PL-EN 15251:2012	500 ppm+CO_2 concentration in the intake air
6.	Russia	GOST 30494-2011	Optimal values: 500-800 ppm. Acceptable limit: 1400 ppm.
7.	Great Britain	"Ventilation in School Buildings. Standards and Design Manual", 2006.	1500 ppm – limit value for a school day from 9.00 to 15.30
8.	Nether lands	"Overview of Indoor Air Quality Standards for Kindergartens in the Netherlands" Hygiene Standards	1000 ppm – hygienic standard for kindergartens; 1200 ppm – hygienic standard for schools;
9.	Estonia	Standards of the Ministry of Social Affairs	1000 ppm – hygienic standard for schools
10.	Germany	DIN EN 15251, Input parameters for indoor climate for design and energy performance evaluation of buildings - indoor air quality. Temperature, light and acoustics. 2007	Absolute concentration for energy efficiency calculations 750…1200 ppm
11.	Ukraine	DBN B.2.2-3:2018 with reference to DSTU B EN 15251:2011	750…1200 ppm

Simulation modeling based on physical and empirical calculation methods is widely used for the analysis of natural air exchange. Physical models for determining natural air exchange are quite complex and require a large number of output parameters, which significantly complicates the calculation for buildings with many zones. These approaches use algebraic equations that relate features of the building, such as height, orientation, air permeability of building envelope, and weather conditions. One of the first approaches was developed by Shaw and Tamura (Ng et al. 2015), which was based on a single equation that combined the stack and wind effect to calculate the natural air exchange rate.

An alternative variant is the use of empiric methods of determination of ventilation exchange rate on the basis of standards of ASHRAE and BLAST. Methods of the ASHRAE standards can be applied to low-rise buildings (Jokisalo et al. 2009, Chen et al. 2012, Nielsen & Drivsholm 2010). Ventilation is created on the basis of three mechanisms: the stack effect, wind effect and mechanical ventilation, first two touch the natural constituent of ventilation. Among these mechanisms a wind effect has the most difficult nature (Bilous et al. 2018) and depends on number of storeys, orientations of apartment speed and direction of wind et all. Empirical approaches have been reflected in software for calculating the energy performance of buildings. Among the most widely used software complexes for energy modeling of buildings are: eQuest, EnergyPlus, TRNSYS, DOE2, DesignBuilder, and Ecotect Analysis. More recently proposed a method of estimating infiltration in commercial buildings using EnergyPlus, which considers wind, not just temperature effects, but does not take into account the wind direction (Ng et al. 2013, Bilous et al. 2020).

One of the software used for the analysis of air flows in buildings is CONTAM (Ng et al. 2014, Ferdyn-Grygierek & Baranowski 2015). CONTAM is a multi-zone computer program for air quality and ventilation analysis that allows determining infiltration, exfiltration and airflows into rooms from controlled mechanical ventilation systems, wind pressures acting on the exterior surfaces of a building, the stack effect caused by the difference in indoor and outdoor air temperatures, concentrations of pollutants and their effects on humans. It should be noted that this software product is used at the design stage and has not found its application in the energy management of existing buildings.

It follows from the inspection that the study of the indoor air quality and air exchange parameters requires considerable attention both in low-efficiency buildings and in efficient buildings. A number of approaches are being used based on experimental, physical or empirical methods. The combination of methods will allow achieving best results that can be used in energy management, in implementing energy saving measures and ensuring adequate working/staying conditions in buildings.

The aim of the work is to apply integration of approaches for the determination of the CO_2 concentration and the air exchange rate in educational institutions of Ukraine on the basis of field and simulation modeling.

Tasks:

1) to investigate the factors that affect the change in the concentration of CO_2 in the premises of schools,
2) to explore the use of CO_2 concentration data to determine air exchange rates,
3) to create simulation models for determining natural air exchange based on empirical methods,
4) to compare of air exchange rates data from experiment and simulation.

2. Materials and methods

In this work, field and simulation modeling were conducted to determine changes in the indoor CO_2 concentration and natural air exchange in educational institutions, on the example of objects located in the city of Kyiv; the research scheme is presented in Fig. 2.

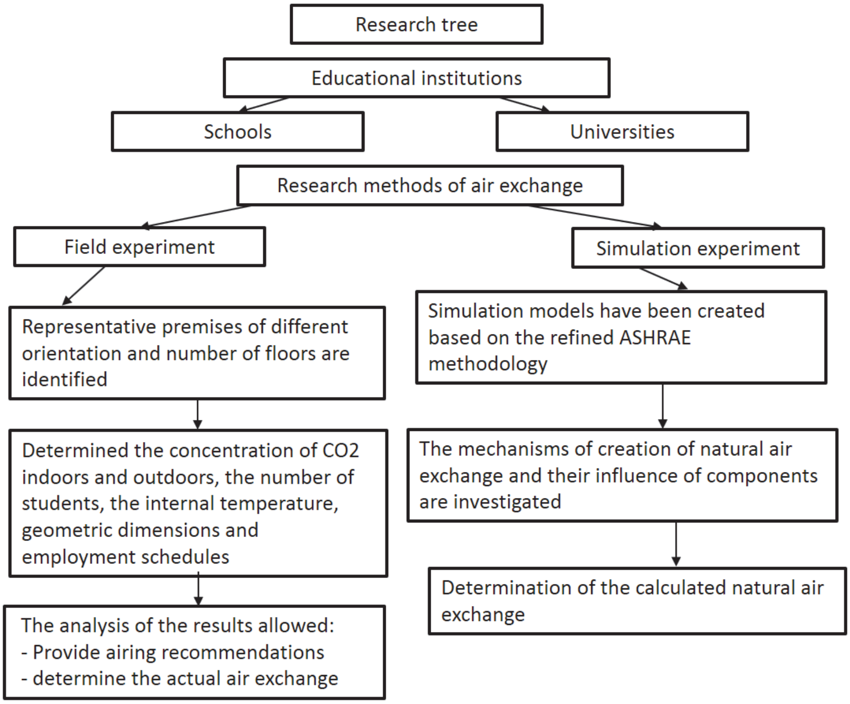


Fig. 2. Research scheme

2.1. Field experiment

The research was conducted consistently and developed in three schools and university. All schools are of typical H-shape, built in the years of mass development. On the basis of school 1 the substantiation of the representative rooms' definition was carried out, the local place of the sensors installation in premises for determination of the CO_2 concentration and other input parameters for calculation of the natural rate of air exchange were investigated. In school 2, the CO_2 concentrations in representative rooms were measured at the beginning and at the end of classes. In school 3, the CO_2 concentrations were measured for two options: 1) measurements of the CO_2 concentration in representative rooms at the beginning and at the end of classes; 2) recording of the dynamics of changes in the CO_2 concentration in representative rooms with 10 min. steps, taking into account changes in the number of students, physical activity and the schedule of the classroom occupancy. Experimental measurements of the concentration changes in representative rooms were carried out in the training building of Igor Sikorsky KPI. A local study of the background outdoor concentration of CO_2 was conducted near the examined objects during the day with different distances from them. Measured: outdoor temperature and relative humidity and in classes; speed and direction of wind on the street; CO_2 concentration on the street / background; schedule of stay of people and their number in classes; type of physical activity of people.

For the measurements were used:

- Complex device CO_2 logger TR-75Ui with CO_2 measurement range: 0…9999 ppm, temperature: 0… 55°C, relative humidity: 10… 95% RH.
- Thermistor electronic complex LM8000 device with temperature measurement range 20°C… + 65°C and relative humidity 10…95% RH was used for duplication of air temperatures and relative humidity.
- GM320 pyrometer with measurement range 50°C… + 380°C for wall surface temperatures measurements.
- The Eco Dist Plys laser rangefinder with the ability to measure up to 30 m and 1mm accuracy was used to measure the area and volume of the classes, as well as the built-in area and volume calculation function.

2.2. Methodology for analyzing the correlation between the CO_2 concentration data and air exchange, as well as methodology for processing experimental data

On the basis of balances of air flows and the indoor CO_2 concentrations (marking at Fig. 3) the following ratios were obtained.

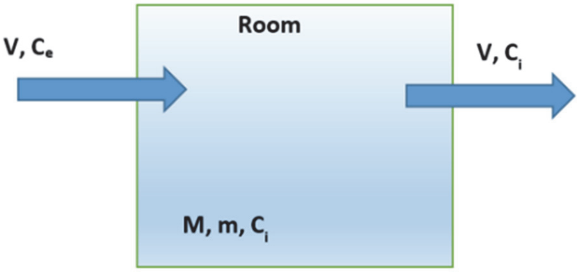


Fig. 3. Schematic representation of marking to CO_2 and air exchange values in the room V_r - rooms, m^3; V – air exchange, м^3/hour; m – indoor CO_2 emission, g/hour; M – indoor CO_2 mass, g; M_o – indoor CO_2 initial mass, g; C_e, C_i, C_{i0} – CO_2 concentration in the intake air, in the room at a given time and initial concentration, g/m^3

Indoor CO_2 concentration is determined as follows:

$$C_i = \frac{M}{V_r}, \tag{1}$$

Change in CO_2 amount over time:

$$\frac{dM}{d\tau} = m + V \cdot C_e - \frac{V}{V_r} M, \tag{2}$$

Amount of CO_2 in a time interval $\Delta\tau_j$:

$$M_j = M_{j-1} + \overline{m_j} \bigtriangleup \tau_j + \overline{V_j} \cdot \overline{C_{e.j}} \bigtriangleup \tau_j - \frac{\overline{V_j}}{V_r} \cdot \frac{M_{j-1} + M_j}{2} \bigtriangleup \tau_j, \tag{3}$$

In n time intervals $\Delta\tau_j$ formula (3) becomes as follows:

$$j = 1 \ldots n, \quad M_n = M_0 + \sum_{j=1}^{n} m_j \bigtriangleup \tau_j + \sum_{j=1}^{n} V_j \cdot C_{e.j} \bigtriangleup \tau_j - \sum_{j=1}^{n} \frac{V}{V_r} \cdot M_j, \tag{4}$$

Formula (4) can be used to determine the mass of CO_2 in the internal air through the values of C, V and *m* for each time interval $\Delta\tau_j$.

Integration of formula (2) at constant values C_e, V and *m* gives an expression for the mass of CO_2 in internal air at any point of time τ:

$$M = \frac{V_r}{V} \left\{ m + V \cdot C_e + \left[\frac{V}{V_r} \cdot M_0 - \left(m + V \cdot C_e \right) \right] \cdot e^{-\frac{V}{V_r}\tau} \right\}, \tag{5}$$

It follows from formula (5) that the internal concentration of CO_2 at constant values C_e, V and *m* is determined as follows:

$$C_i = \frac{m}{V} + C_e + \left[C_{i0} - \left(\frac{m}{V} + C_e \right) \right] \cdot e^{-\frac{V}{V_r}\tau}, \tag{6}$$

For boundary cases, formula (6) becomes as follows (7-8):

$$If\ \ m \to 0, C_i = C_e \left(1 - e^{-\frac{V}{V_r}\tau} \right) + C_{i0} \cdot e^{-\frac{V}{V_r}}, \tag{7}$$

$$If\ \ m \to 0\ \ i\ \ C_i >> C_e, C_i = C_{i0} \cdot e^{-\frac{V}{V_r}\tau}. \tag{8}$$

Experimental data on changes in the indoor CO_2 concentration over time were processed by formula (6).

2.3. Simulation experiment

Air exchange is difficult to determine experimentally. Even with the same window designs in terms of air permeability, different amounts of air enter the room. Room air exchange depends on a number of factors, both external and internal ones. Simulation models were created for the representative rooms of the training building of Igor Sikorsky KPI to determine the natural air exchange of rooms based on the ASHRAE generalizing methodology. The use of simulation modeling allows to compare results and to verify the proposed methods of determining actual air exchange rate based on experimental data.

Methods

The methodological basis of the scientific research includes methods of mathematical modeling, systematic approach considering climatic and operational factors.

The generalization of the methods for air exchange rate determination based on the calculation of pressure differences given in the studies of Berge A. and others (Biler et al. 2018, Berge 2011) and according to the ASHRAE approaches (Jokisalo et al. 2009) is used in the paper, which allows to use the given technique for multi-story buildings. The pressure difference that determines the air exchange rate in a building is created by two different mechanisms: stack effect, wind pressure effect (Fig. 4) and is calculated as their sum (formula 9):

$$\Delta P_{tot} = \Delta P_s + \Delta P_w = \Delta P_{int}, \tag{9}$$

where:

ΔP_{tot} – total pressure difference, Pa,

ΔP_s – pressure difference from stack effect, Pa,

ΔP_w – the wind pressure difference, Pa,

ΔP_{inf} – infiltration pressure difference, Pa.

The stack effect is also called the buoyancy effect created by the difference in density between warm and cold air. Reduction of air pressure with the height determined by the formula (10):

$$\Delta P_s = z(\rho_e - \rho_i)\cdot g, \tag{10}$$

where:
z – height from the reference point, m
ρ_e, ρ_i – density of exterior and interior air, kg/m^3,
g – acceleration of gravity, m s^2.

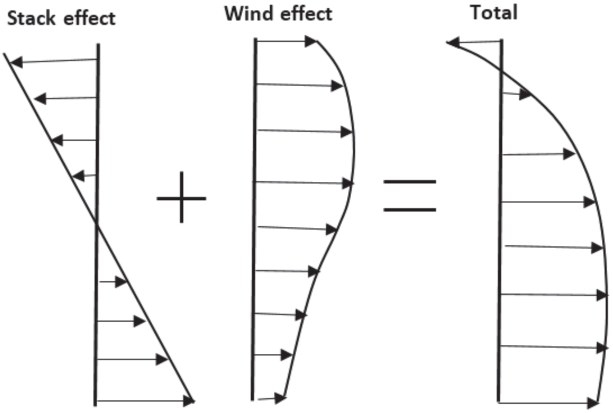


Fig. 4. Example of building height distribution and sum of pressure difference profiles

From the neutral pressure level towards the first floor, the pressure difference is positive, towards the last floor it is negative. Assuming that air is the perfect gas, formula (10) looks like:

$$\Delta P_S = 3456 \cdot z(\frac{1}{T_e} - \frac{1}{T_i}), \tag{11}$$

where:
T_e, T_i – exterior and interior air temperature, respectively, K.

Wind pressure is created when airflow hits an obstacle. The magnitude of the wind pressure depends on the wind speed and direction (windward, leeward side, etc.).

Most software products for modeling wind pressure, use the following formula (Biler et al. 2018, Berge 2011):

$$\Delta P_w = \frac{\rho U_{met}^2}{2} C_h C_p(\theta) \tag{12}$$

where:

ρ – density of the environment, kg/m^3,

U_{met} - wind speed according to the nearest weather station, m/s,

$C_p(\theta)$ – wind pressure factor considering wind direction through the angle of incidence θ,

θ – the magnitude of the wind angle relative to the normal drawn to the considered surface, degree,

C_h – wind pressure factor that considers the height.

The amount of air entering the room due to leakage under the specified conditions (without mechanical ventilation) is determined by the following formuls:

$$G_{\inf} = C(\Delta P_{\inf})^p \quad \text{or} \quad G_{\inf} = \frac{\Delta P_{\inf}{}^p}{R_b} F_w \tag{13}$$

where:

G_{inf} – the amount of air entering the room due to leakage, kg/h,

C, p – this coefficient and the degree index depend on the purpose of the building,

R_b – window air permeability resistance, (m^2·h·Pa$^{2/3}$)/kg
(DSTU B V.2.2-19:2007),

F_w – window area, m^2.

The space air exchange rate as a characteristic of the ventilation node in mathematical models is determined by the following formula (DSTU B V.2.2-19:2007):

$$n = \frac{G_{\inf}}{\rho V} \tag{14}$$

where:

V – volume of the space, m^3,

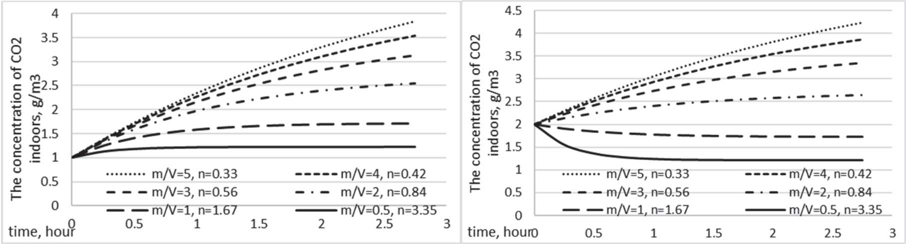
n – air exchange rate, h^{-1}.

Determining the natural rate of air exchange based on ASHRAE advanced methodology does not take into account room-to-room airflows through ventilation ducts/extractors, but it does take into account wind speed and direction, but it takes into account number of storeys, orientation, and so on. Determining the air exchange rate based on experimental methods does not give a clear idea of the infiltration or exfiltration component, and may be established during processing, and physical representations of the natural air exchange in buildings.

3. Results and discussion

On the basis of formula (6) a calculated study of the influence of air exchange, initial concentration and indoor CO_2 emissions, air flow by way of infiltration and exfiltration on the indoor CO_2 concentration was conducted.

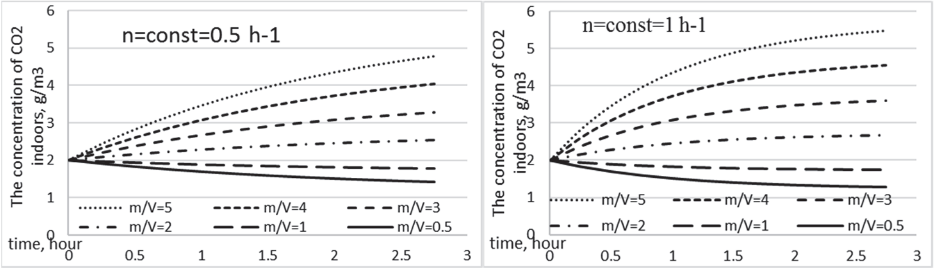
Decreasing (Fig. 5, b) / increasing (Fig. 5, a) exponential curve at the same m/V ratio is due to different initial concentrations of CO_2 and indicates the time of airing / lack of airing respectively.



a) b)

Fig. 5. Change in the indoor CO_2 concentration over time provided that the number of present persons and different initial indoor CO_2 concentrations is constant

Fig. 6 shows the influence of the number of present persons on the indoor CO_2 concentration at a constant air exchange: 0.5 h^{-1} (Fig. 6, a) and 1 h^{-1} (Fig. 6, b) at the initial concentration: $C_{i0} = 2$ g/m^3.



a) b)

Fig. 6. Change in the indoor CO_2 concentration over time under the condition of constant air exchange and different amount of present persons (indoor CO_2 emissions, *m*)

Reduction of the air exchange rate results in smaller degree of bend of the exponential dependence of CO_2 concentration over time. The number of present persons has a more significant impact on the indoor CO_2 concentration (Fig. 6) than on the air exchange rate (Fig. 5).

3.1. Experimental part

Experimental determination of the background concentration of CO_2 during the day locally next to the considered objects showed that the background concentration of CO_2 is in the range of 400-420 ppm. On the example of school 1 an experimental study was conducted to determine the local measurements of the indoor CO_2 concentration during and after classes. Measurements of the CO_2 concentration distribution were carried out after classes throughout the classroom area, and the difference between the values at the desks level was 30...180 ppm. Studies have shown that it is acceptable to use an integral characteristic of the CO_2 concentration in a representative room in the center of the room at an altitude of about one meter (the working area).

Measurements of the internal concentration of CO_2 results in school 2 during the vacation period were quite close to the background concentration, with the exception of classes where the project groups worked. Control measurements of the indoor CO_2 concentration were made at the beginning of classes, after classes and after a break.

It has been established that the CO_2 concentration is changed during the class to 700-1100 ppm and significantly exceeds the standard. During a break, the CO_2 concentration is reduced to 500-1000 ppm, depending on the type of ventilation.

At school 3, 10-minute measurements of the CO_2 concentration were made in representative rooms. Fig. 7 shows the determination of the air exchange rate on the example of high school students during three classes and two breaks.

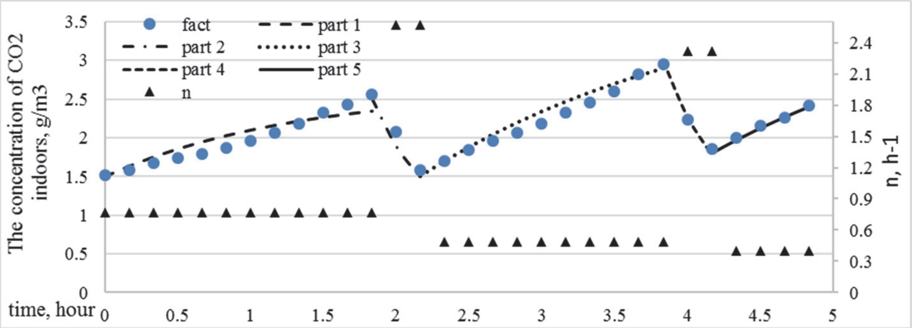
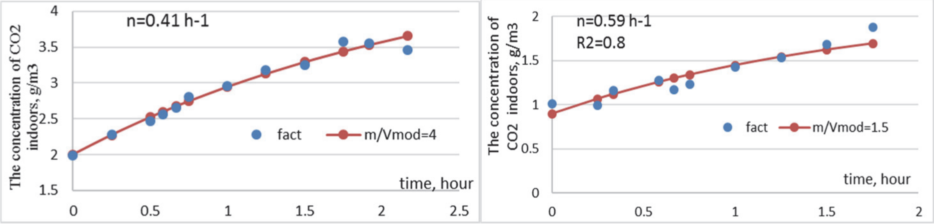


Fig. 7. Change in the indoor CO_2 concentration and air exchange rate in a classroom of school 3

The air exchange rate during classes (parts 1, 3, 5) is in the range of 0.4...0.75 h^{-1} (windows and doors are closed). During breaks, students leave the premises and the classrooms are ventilated through the opening of windows and doors. During this period (parts 2, 4), the air exchange rate is increased to 2.9-3.5 h^{-1}. For the range considered, the weighted average air exchange rate is 0.8 h^{-1} and even with forced airing, the air exchange rate is insufficient to ensure an adequate level of air exchange and the acceptable CO_2 concentration.

Similar studies of changes in the CO_2 concentration were conducted for the training building of Igor Sikorsky KPI. The building is long, 7-storey, with a technical floor, the main part of training classrooms and laboratories has one external S or N oriented envelope. Ventilation of the classrooms in the building is carried out by opening of doors to the corridors, mechanical ventilation is out of order. On the example of processing the experimental data on the change in the CO_2 concentration in classrooms, the calculation of natural rate of air exchange was performed (Fig. 8).

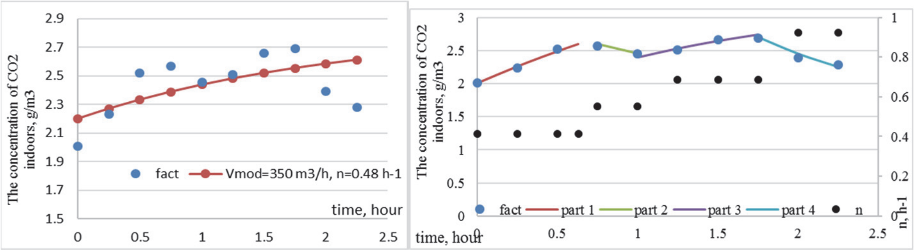
Decrease of the air exchange rate on the 3rd floor is explained by the reduction of the stack effect (according to the components of the air exchange mechanism Fig. 4).



a) b)

Fig. 8. Air exchange in S oriented rooms on 3rd floor (a) and 1st floor (b)

Similar studies were conducted for large lecture halls, where the effect of ventilation during the break was more significant. Figure 9 provides determinations of air exchange rates based on the average air exchange (a) separating the periods where doors were opened (parts 2, 4) and closed (parts 1, 3) (b).



a) b)

Fig. 9. Changes in CO_2 concentration in the lecture hall (Igor Sikorsky KPI)

It follows from the analysis that the value of the average air exchange is 0.48 h^{-1} (processing of the graph with average values of V), after separate processing of parts 2, 4 and parts 1, 3 it is established that the air exchange rate during periods of the closed doors is 0.4-0.6 h^{-1}, and if the doors are open, it can reach 0.95 h^{-1}. The weighted average air exchange rate for the considered time period during partial analysis is 0.43 h^{-1}, as opposed to 0.48 h^{-1} for the average formula.

3.2. Simulation modeling

Simulation modeling of natural air exchange of N and S oriented rooms was carried out for the training building of Igor Sikorsky KPI.

Fig. 10 shows the change in climatic conditions during three days when experimental studies were conducted.

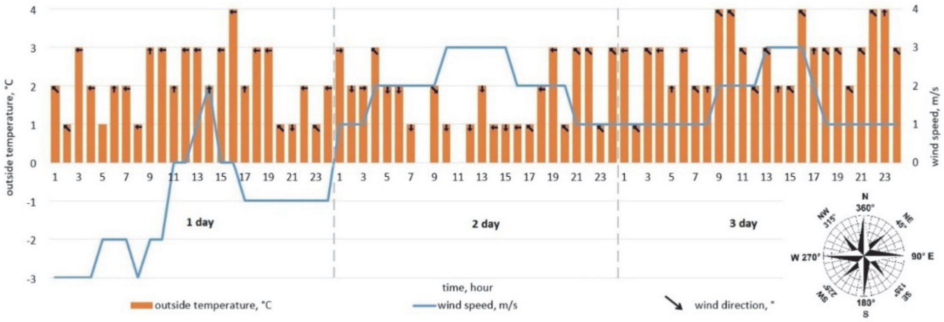
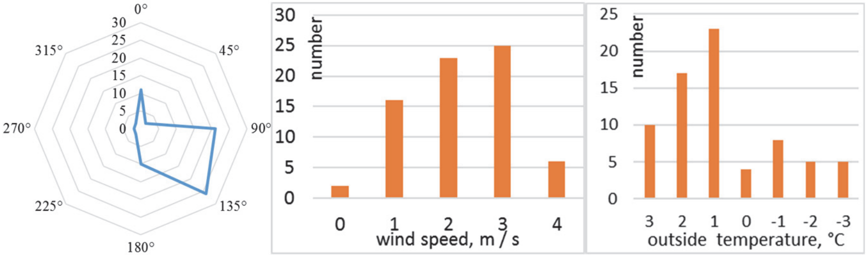


Fig. 10. Climatic conditions change

It follows from the meteorological data analysis (Fig. 11) that the dominant wind direction is SE (135°) (Fig. 11, a), wind speed is 3 m/s (Fig. 11, b), outside temperature is +1°C (Fig. 11, c).



a) b) c)

Fig. 11. Dominant parameters of the external weather conditions

A study of pressure changes under the influence of stacks and wind effect for dominant weather conditions was conducted. Fig. 12 shows the change in pressure difference of stack effect depending on the floor and outside temperature at a constant internal air temperature of 18°C.

Change in pressure due to the stack effect is directly proportional to the indoor and outdoor temperature difference. The negative value of ΔP_s is due to the starting point of the pressure difference from neutral pressure (NPL), which is on the middle floor of the building. The NPL level is the level at which the internal and external pressures are the same. The pressure difference is positive from the NPL level towards the ground floor; the pressure difference is negative from the NPL level towards the last floor.

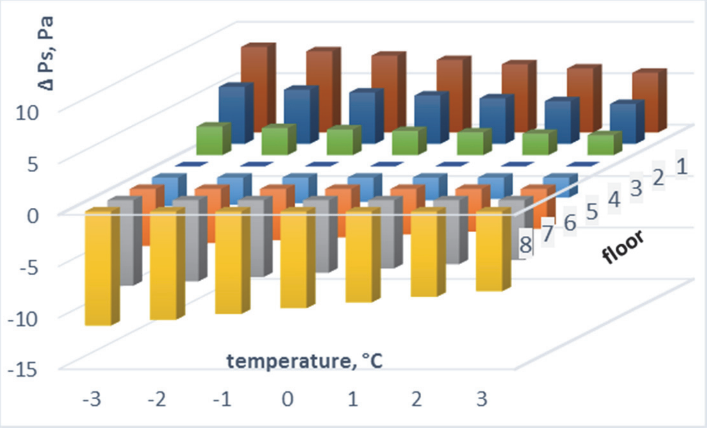


Fig. 12. Change in stack effect pressure depending on the outside temperature and floor number

Change in pressure due to the stack effect is directly proportional to the indoor and outdoor temperature difference. The negative value of ΔP_s is due to the starting point of the pressure difference from neutral pressure (NPL), which is on the middle floor of the building. The NPL level is the level at which the internal and external pressures are the same. The pressure difference is positive from the NPL level towards the ground floor; the pressure difference is negative from the NPL level towards the last floor.

Fig. 13 shows the profiles of the wind effect pressure changes for northern and southern orientation of the building for dominant wind direction and speed. For the southern orientation of premises, the wind pressure change profile has a positive sign, which is explained by the positive value of the $C_p(\theta)$ coefficient, which depends on the wind speed. At SE wind direction $C_p(\theta)$ is positive for premises of southern orientation, but it is negative for premises of northern orientation.

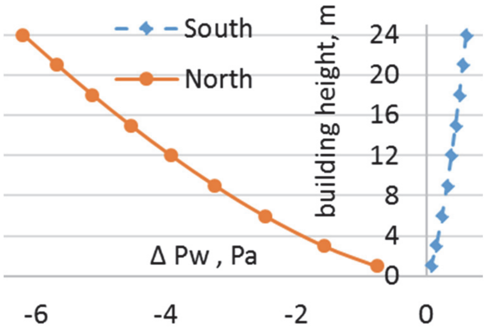


Fig. 13. Wind effect pressure change

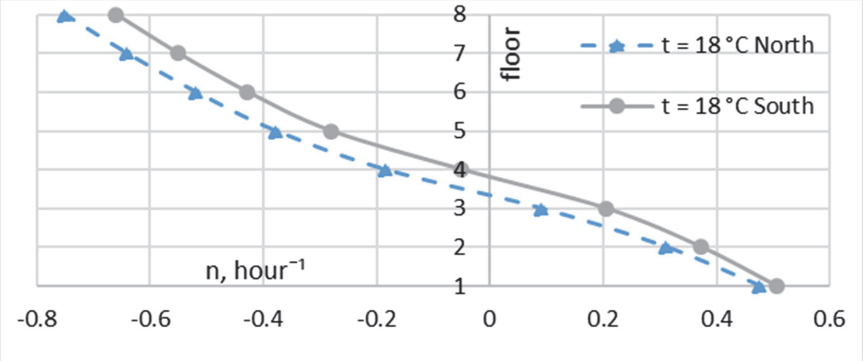


Fig. 14. Average change in the air exchange rate by height of a building for S and N oriented rooms

It follows from Figs. 12, 13 that the air exchange rate is more significantly affected by the difference in pressure caused by the stack effect rather than the wind effect. Fig. 14 shows the average change in the air exchange rate by height for N or S oriented premises. The difference of profiles of air exchange rate change by height for N or S oriented premises is explained by the predominant SE wind direction.

Figure 15 shows the hourly change in the air exchange rate for N or S oriented representative rooms. For the considered input parameters, the air exchange rate varied during three days in the range of 0.53-0.73 h^{-1}. Experimental determination of the air exchange rate (Fig. 8, b) showed that the air exchange rate for premises on the 1st floor is at the level of 0.6 h^{-1}. Simulation modeling with sufficient accuracy fits the experimental results.

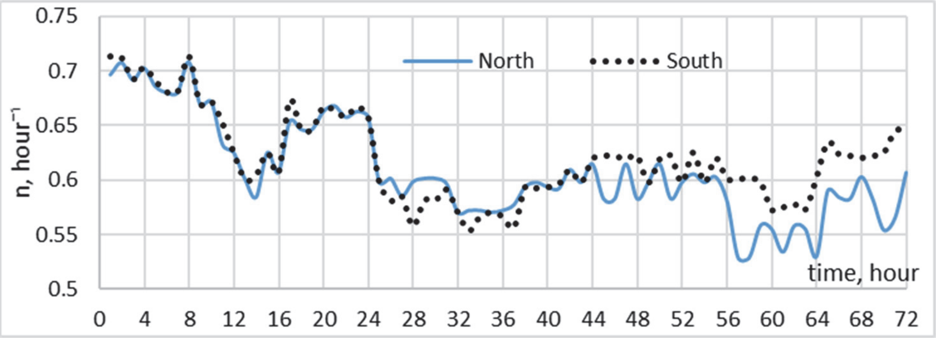


Fig. 15. Hourly change in the air exchange rate for S or N oriented rooms on the 1st floor

4. Conclusions

Studies of the air quality and air exchange were conducted in educational institutions of the city of Kyiv (Ukraine) based on field and simulation experiments. The work shows that CO_2 measurements are important not only for controlling the provision and regulation of the comfort conditions, but can also serve to determine the actual values of the air exchange rate in certain rooms.

On the example of the study in three schools in Kyiv it was found that:

1) Experimental study of the local background CO_2 concentration in the studied buildings is almost constant in time and is about 450 ppm.
2) The concentration of CO_2 in classrooms during classes increases almost twice and exceeds the norm by 700-1100 ppm. During the vacation period, the concentration of CO_2 in classrooms is close to the background concentration.
3) The model calculation showed that a decrease in the air exchange rate leads to a smaller degree of bend of the exponential dependence of the CO_2

concentration in time. The number of present persons has a more significant effect on the indoor CO_2 concentration than the air exchange rate.

4) The experiment has shown that the indoor CO_2 concentration increases significantly during classes, so it is necessary to do airing, but its available level is not always sufficient. The air exchange rate during the classes is in the range of 0.4...0.75 h^{-1} (windows and doors are closed); during airing of classes through the opening of windows and doors, the air exchange rate increases to 2.9-3.5 h^{-1}, the weighted average air exchange rate is 0.8 h^{-1}, and even with forced airing of classes the air exchange rate is not enough from the point of view of ensuring the proper level of air exchange and the permissible concentration of CO_2.

Similar studies were conducted for the training building of Igor Sikorsky KPI. The following was established:

1) Based on experimental data, the air exchange rate for the training building of the educational institution is in the range of 0.35-0.7 h^{-1} depending on the location of the classrooms. During the periods of airing (opening of doors to the corridor), the air exchange can increase by 0.45 h^{-1}, but this does not allow to reach the standard value.
2) In this work, a simulation model was created to determine the natural air exchange of the training building of the educational institution, based on the improved ASHRAE methodology and allows determining the air exchange rate under the conditions of variability of the environment, floor and orientation of premises.
3) It was found that air exchange is more sensitive to changes in pressure caused by the stack effect rather than wind effect.
4) The value of the natural air exchange based on a simulation experiment is in the range of -0.8...0.5 h^{-1}. Negative values are explained by exfiltration.
5) In the total energy balance of the building losses, the ventilation component is 30-60%. Not only comfort conditions depend on the actual level of the air exchange rate, but also the total energy consumption of the building that significantly affects the level of energy efficiency, and monitoring of the actual level of the air exchange rate should be taken into account during the complex modernization or implementation of the ventilation systems with heat recovery.

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Abstract

Many old public buildings in Central and Eastern Europe are characterized by low energy efficiency and often lack of mechanical ventilation. The general trends are aimed to improve the energy efficiency of the building sector and to provide comfort conditions. The indoor air quality can be determined based on the CO_2 concentrations.

In the article, a complex approach to the definition and analysis of data on the indoor CO_2 concentration and the air exchange rate in educational institutions at natural air exchange and in the absence of mechanical air circulation was implemented. Educational institutions in Kyiv have been considered. The study of the CO_2 concentration of indoor and outdoor air of three typical schools of mass development in the 80 s, as well as the training building of Igor Sikorsky KPI, was carried out. Experimental determination of the background CO_2 concentration during the day next to the considered objects showed that the background concentration of CO_2 is in the range of 400-420 ppm. Measurements of the CO_2 concentration distribution were carried out after classes throughout the classroom area, according to which the difference between the values at the level of the working area was 30...180 ppm. It was found that the concentration of CO_2 varies during classes between 700-1100 ppm. During the break, the CO_2 concentration decreases to 500-1000 ppm, depending on the type of ventilation.

Experimental data on the dynamics of changes in the indoor CO_2 concentration are used to determine the air exchange rate based on balances of air flows and CO_2. It is shown that the number of present persons influences the indoor CO_2 concentration more significantly than the air exchange rate. On the example of an experimental study of the CO_2 concentration in the classrooms for high school students it was found that the air exchange rate during the classes is in the range of 0.4...0.75 h^{-1}. During breaks the air exchange rate increases to 2.9-3.5 h^{-1}. For the range considered, the weighted average air exchange rate is 0.8 h^{-1}, and even with forced airing, the air exchange rate is insufficient to ensure acceptable CO_2 concentration.

For the training building of Igor Sikorsky KPI a field experiment was carried out to determine the dynamics of changes in CO_2 concentration in time and on the basis of it the air exchange rates for representative classrooms were determined. The concentration of CO_2 ranged from 500 to 2000 ppm and increases by 350-850 ppm depending on the use and location of classrooms. Based on experimental data, the air exchange rate for the training building of the education institution is in the range of 0.35-0.7 h^{-1}. During the periods of airing the air exchange may increase by 0.45 h^{-1}, but this does not allow reaching the standard value. When analyzing the obtained results, simulation models of natural air exchange of the examined classrooms were used on the basis of the improved ASHRAE method. The natural air exchange rate based on simulations is in the -0.8…0.5 h^{-1} range. Negative values are explained by exfiltration, which is typical for the upper floors.

Not only the comfort and condition of the building envelope, but also the total energy consumption of the building depend on the actual level of air exchange rate. In the total energy balance the ventilation component is 30-60%. Further use of the obtained results can be connected with monitoring of the actual level of air exchange rate and its consideration during complex modernization or implementation of the ventilation systems with heat recovery in the premises of educational institutions.

Keywords:
educational institutions, air quality, CO_2 concentration, air exchange,
simulation modeling, field experiment, comfort conditions