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OPTIMIZATION OF CARBON DIOXIDE CONCENTRATION IN THE DIDACTIC ROOMS BY THE REGULATION OF VENTILATION

OPTYMALIZACJA STĘŻENIA DITLENKU WĘGLA W SALACH DYDAKTYCZNYCH POPRZEZ REGULACJĘ WENTYLACJI

Abstract: Poor ventilation of didactic rooms can interfere with students' ability to concentrate and even cause them to suffer headaches. This is a significant issue as the ventilation systems of most lecture buildings in Poland do not provide proper air exchange. This paper presents findings of research on air parameters research in the didactic rooms of various sizes. Rooms for classes should ensure climatic comfort i.e. proper humidity and air temperature, physical and biological air quality, and low concentration of carbon dioxide. The research suggested that natural ventilation should not be used, and further research was done after the upgrading of ventilation systems and installation of exhaust fans. The coefficients of carbon dioxide emissions by one student depend on the number of people and size of the room were calculated. Designated coefficients will be used in the algorithm for determining the parameters of the fans in the ventilation system of the classrooms and lecture halls.

Keywords: carbon dioxide concentration, didactic rooms, optimization, regulation, ventilation

Introduction

Educational buildings are a specific kind of public utility facilities. What is characteristic of them is the fact that large numbers of people are present in individual rooms at the same time. A situation of this kind makes it particularly important to ensure that the people who study can do so in proper conditions while staying in this type of rooms [1]. Each person teaching classes to large groups of students can notice that after a few hours of lectures the level of concentration of participants significantly drops. However, this is not brought about by the fact of being bored by the class, but mainly by worse air quality in the rooms where these classes are held [2]. The issue of internal conditions quality in classrooms in school buildings has been raised in multiple

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scientific studies, yet they concerned the relation between air quality, energy efficiency and costs of heating these buildings only to a slight degree [3].

The quality of internal conditions in educational buildings means, first of all, suitable interior comfort in the rooms where classes are held for large groups of students [4, 5]. In Poland, the conditions concerning interior comfort in educational buildings have been specified by the requirements of the PN-EN 13779, 2008 Standard: Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems [6]. Pursuant to the above mentioned standard, interior comfort is influenced mainly by the following:

– air temperature,
– air humidity,
– physical and biological quality of air,
– CO_2 concentration [6].

Until the present moment, most administrators of educational facilities (at the level of primary, secondary and higher education) have only paid attention to the temperature inside the classrooms being compliant with the standards, and they have not been aware of the significance of the remaining parameters ensuring proper interior comfort [7]. While analyzing operating costs of classrooms, the owners use calculations made by numerous experts showing that heating costs constitute about 70% of costs connected with maintaining public utility facilities, including buildings of higher education centers. Taking into consideration the fact that in Poland about 60% of residential buildings and public utility facilities are heated with the use of centralized sources, it is difficult to optimize heating costs by changing the source of heat or fuel used. Therefore a significant majority of thermal upgrading work, aiming at the reduction of operating costs of educational buildings, comes down solely to improving insulation properties of building envelope, that is exchanging the existing windows for energy efficient ones and extending the layer of insulation of external walls [8]. Increasing the airtightness of rooms makes the operation of ventilation system much worse, it reduces heat losses through ventilation and reduces heating costs, however, it causes far too low air exchange and brings about significant worsening of air quality in classrooms as a result [9, 10]. The parameters of building ventilation should be selected in such a manner that heating cost reduction is not achieved as a result of worsening room air quality.

While drawing up the algorithm for the optimization of ventilation systems in educational facilities, what was assumed as a basic optimization criterion was maintaining in rooms where large groups of people spend time such air parameters that comply with the requirements pursuant to the PN-EN 13779, 2008 Standard [6]. This shall be implemented on the basis of the analysis of three basic air parameters inside rooms, that is:

1. Concentration of carbon dioxide, which can be easily measured although as an odourless substance it is not perceptible by the people being present inside the room. In the course of research carried out in classrooms, the concentration given in 1858 by a German physiologist Pettenkofer amounting to 1000 ppm [11] was assumed as the limit value of concentration in rooms where people spend time. This value is, at the same time, recommended by the European division of World Health Organization (WHO) [12].

2. Air temperature is the second air parameter being analysed. Maintaining temperature complaint with the Standard in a winter season is connected with heating rooms. However, taking into consideration the fact that over 40% of heat lost in buildings is discharged to the atmosphere through the ventilation system along with the used air, this air discharged from buildings together with the used air was assumed as an important optimization criterion of working parameters of ventilation systems.

3. Air humidity inside rooms is the third parameter to be taken into consideration while optimizing work parameters of ventilation systems. Excessive humidity holding inside rooms for a prolonged time can lead to mildew appearing on the inside wall surfaces and this can possibly be a result of poor thermal insulation or its entire lack, as well as improper ventilation and insufficient heating, which in practice denotes improper operation and maintenance of the facility [13].

The analysed parameters might be differentiated depending on the activity level of students who spend time in given classrooms, as well as on possible disruptive factors. One should also remember that air temperature and humidity that guarantee thermal comfort inside rooms where people spend time, assume different recommended values during and outside the heating season [14]. In the summer, the recommended values amount to: inside temperature 20–22^{o}C, relative air humidity 30–50%, whereas in the winter they should be: inside temperature 24–26^{o}C, relative air humidity 45–60%.

On the basis of the above assumptions, research was carried out aiming at the determination of the optimum ventilation parameters of classrooms for the climate zone in which Poland is located.

Materials and methods

In Poland, most buildings in which classes are held for students are equipped with natural ventilation systems. Therefore, while preparing the studies of ventilation systems of classrooms, two facilities were selected, that is classrooms of different sizes, however both located in a building equipped with gravity ventilation systems. The building in which these two classrooms are located is an old educational facility where no thermal upgrading work has been done and where old windows have not been exchanged for new ones. Fresh air enters the rooms through leakages in window and door framing.

A lecture hall (shown in Fig. 1) with the area of 51.5 m^2, in which there are two ventilation ducts VD1 and VD2, is the first facility.

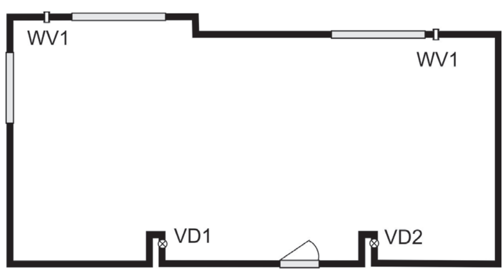

Fig. 1. Didactic room 1 with the area of 51.5 m^2

A seminar room (shown in Fig. 2) with the area of 29 m^2 and a single ventilation duct VD1, is the second facility.

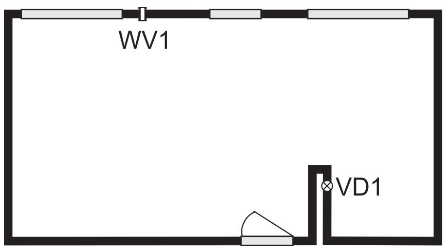

Fig. 2. Didactic room 2 with the area of 29 m^2

Measurements of air parameters inside the test facilities were taken during classes with different numbers of students and various activities. In the primary series of tests, there was only natural ventilation working in the rooms. The following were recorded in the course of research: carbon dioxide concentration, air temperature and humidity inside the rooms, air temperature outside the building, as well as the speed of air flow in the ventilation ducts. All tests of the interior air quality were done at the head level of people inside the room. The measurements were taken during the entire day with air parameters being recorded every 15 minutes, also during break times between classes. The measurements in the rooms vented solely with the use of gravitation ventilation were carried out in the period from October until April, that is both during the heating season and at the time were classrooms were not heated.

With natural ventilation working, it was necessary to open the windows to air the rooms during break times. In situations when the temperatures outside were low, the flow of air entering from the outside while airing the rooms, reaching the average values corresponding to the air exchange rate in the room of about 8 h^{-1}, significantly reduced the inside temperature, even to below 12°C. Such a situation was noncompliant with the minimum allowable temperature for classrooms amounting to 18°C, and at the same time it created a significant discomfort for people entering the room. Due to the above reason, a decision was made to carry out modernization work consisting in the following: mounting exhaust fans in ventilation ducts (marked in Figs. 1 and 2 with VD symbols), as well as installing wall ventilators (marked in Figs. 1 and 2 with WV symbols). Because of the fact that classrooms are characterized by changing occupancy during the day, the use of mechanical ventilation allows to control the flow of air discharged from them. After the modernization was carried out in both facilities, the next series of measurements was performed with measurements taken within the period from May to June and from September to December. The performance period for the second series of tests was selected so that it comprised both the heating season and the time outside the heating season, which allows to compare the results obtained in the test series before the modernization with the results reached after the ventilation was changed from natural to forced one.

Results and discussion

The carried out research of inside air parameters in both test facilities with natural ventilation showed that after students had spent several dozen minutes in the classrooms the concentration of carbon dioxide, air temperature and humidity exceeded the limit values pursuant to the PN-EN 13779 Standard [6].

The outside air parameters recorded during the tests corresponded to the average parameters in the climate zone I of Poland although, according to the PN-EN 12831:2006 Standard – Heating systems in buildings. Method for calculation of the design heat load, the building is in fact located in the climate zone III [15]. On the basis of the carried out measurements, the background of CO_2 in the outside air was determined at the level of 400 ppm.

As it is generally known, anyone who spends time inside a closed room is a source of carbon dioxide emission. Depending on the activity during various forms of classes, as well as individual students' metabolism, particular emissions of carbon dioxide by any given student can assume different values. After the analysis of the obtained results, it was assumed, for calculations for the sake of ventilation system optimization, that each person spending time in a classroom is a source of emission of 12 dm^3 of carbon dioxide per hour. After the analysis of the obtained results was performed, it was determined that relative air humidity in a classroom increases on average by 3% within one hour. This value, of course, depends to a large degree on the number of students and the type of physical activity they perform.

Sample sequences of changes in the carbon dioxide concentration, air temperature and relative humidity in the tested classrooms were presented in Fig. 3.

While checking the effectiveness of natural ventilation in the classrooms, an attempt was made to check to what degree the air tightness of a building in which classes are held is responsible for so low efficiency of room ventilation by a gravitation method. In order to increase the inflow of fresh air to the rooms, tests were carried out in which the rooms were untightened by opening windows and doors. However, this was quite burdensome for the teaching process due to the noise from the outside. For this reason, a decision was taken to air the classroom solely during break times. A sample comparison of natural ventilation of a lecture room without opening windows with airing the room three times during breaks between classes was presented in Fig. 4.

As it can be seen in the diagram presented in Fig. 4, even if we air a classroom a few times during a day, it is impossible to keep the level of carbon dioxide concentration below 1000 ppm in a room only aired by means of gravitation ventilation. Airing rooms by opening windows at intervals brings about temperature drops of the air inside below the values recommended by the PN-EN 13779 Standard [6]. It should thus be expressly stated that natural ventilation, which does not provide a possibility to adjust the ventilation air flow in a room, should not be used in such rooms in which classes with students are held. It is only mechanical ventilation that can assure proper adjustment of ventilation airflow and that is why further tests were carried out only after modernization work consisting in the following: mounting exhaust fans in ventilation ducts, as well as installing wall ventilators, had been carried out in both test facilities. In order to adjust working parameters of ventilators precisely, controllers were installed which

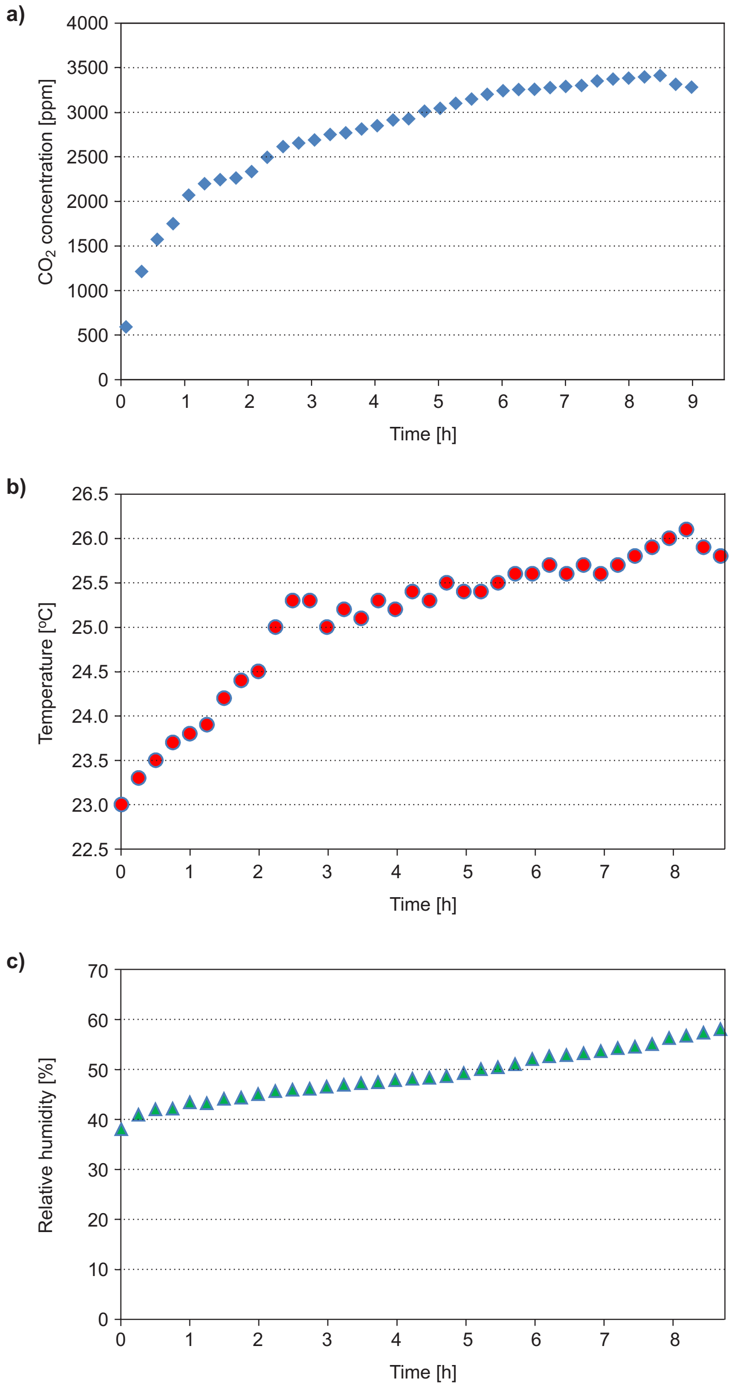

Fig. 3. CO_2 concentration (a), temperature (b) and relative humidity (c) variation in classroom

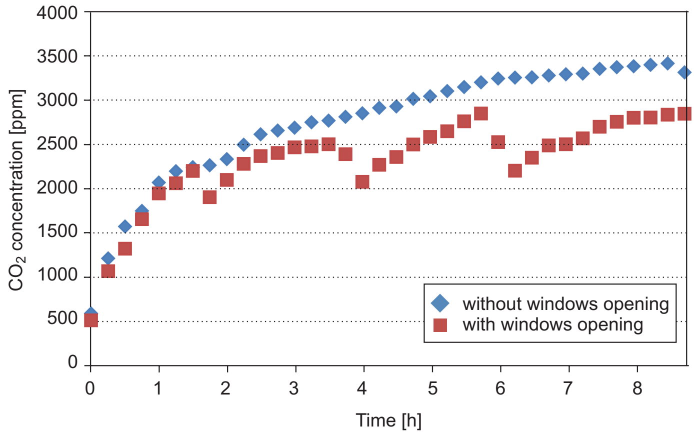

Fig. 4. The variation of CO_2 concentration variation in classroom with and without windows opening

made it possible to determine the number of work cycles per hour and their duration. Thus modified mechanical ventilation system allows to adjust the flow of air discharged from the tested rooms, which is indispensable in order to obtain the air exchange rate in a classroom which is assumed for a given series of measurements.

Tests recording air parameters inside the rooms and outside the building were carried out in both classrooms following the modernization of their ventilation systems. The tests conducted both in the smaller seminar room and in the bigger lecture hall showed similar change trends in air parameters when calculated per a single student. A sample course of changes of the most important parameter, that is carbon dioxide concentration in a lecture hall, was presented in Fig. 5. As it can be observed the use of exhaust fans allows to reduce the level of carbon dioxide concentration in the course of classes. With no precise adjustment of the ventilation system, connected with continuous monitoring

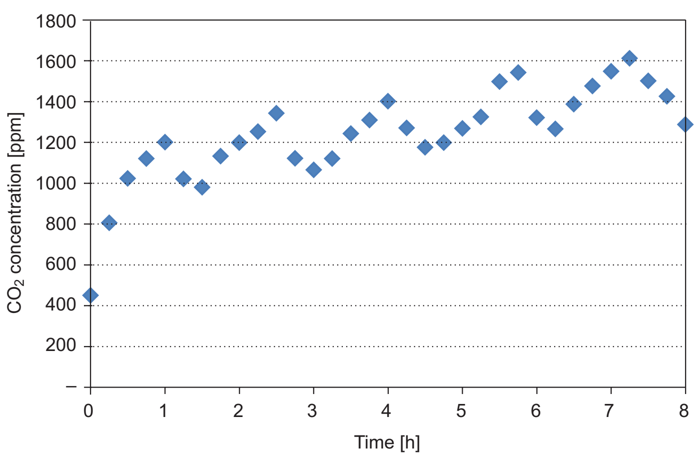

Fig. 5. CO_2 concentration variation in classroom after modernization

of air parameters, it was impossible to maintain carbon dioxide concentration at the level below 1000 ppm.

To select such parameters for the adjustment of mechanical ventilation system that guarantee maintaining air quality as recommended by the standards, and the recommended value of carbon dioxide concentration amounting to 1000 ppm in particular, classroom ventilation parameters should be optimized. In order to optimize quality parameters of air inside classrooms, assumptions had to be adapted which would allow to select adjustments of the ventilation system that would be most favourable with respect to carbon dioxide concentration, air humidity and internal air temperature, which is, during the heating season, inseparably connected also with the heating costs of these rooms. Due to the fact that over 40% of heat from a building is lost along with the used air discharged through its ventilation system, each change of ventilation airflow brings about the change of energy requirement for heating the tested rooms. Calculations of heat requirement for heating the building with the central heating system for each series of measurements were determined with the use of algorithms contained in the Regulation of the Minister of Infrastructure and Development on methodology of determining the energy performance of buildings [16].

Selection of the optimum work parameters of the ventilation system of classrooms is best represented by the sample diagram shown in Fig. 6.

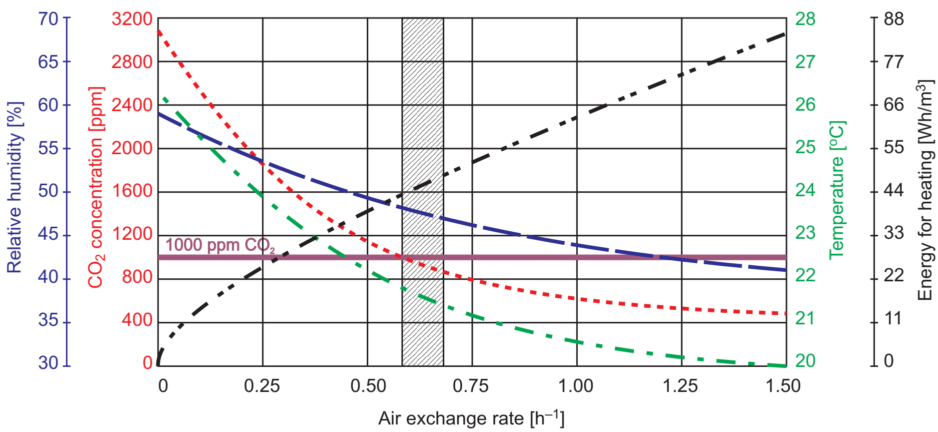

Fig. 6. Selection diagram of the didactic room ventilation parameters for air exchange rate optimization

As it can be seen in the sample diagram, the optimum parameters of air quality with the lowest possible energy consumption for heating 1 m^3 of air are achieved when the air exchange rate in a classroom at the level of 0.6–0.7 exchange per hour is selected (the optimum range of values of air exchange has been crosshatched in the diagram). Concentration of carbon dioxide and energy consumption for heating 1 m^3 of air discharged through the ventilation system are the most important parameters deciding about which adjustments of the ventilation system to select.

By using the factors of carbon dioxide emission determined in the course of research and the optimum range of the air exchange rate in the rooms, as well as on the basis of the recommended parameters of air quality as described in the standards, a mathematical model was prepared which allows to determine the optimum flow of used air discharged through the ventilation ducts, dependent on cubic capacity of rooms, the number of students present and the external air parameters (carbon dioxide concentration, temperature, relative humidity).

With the use of the developed model, when one knows the efficiency of exhaust ventilators and the cubic capacity of rooms, they might select such periods of ventilator work and cross sections of wall ventilators that ensure optimum value of the air exchange rate, which further guarantees air quality in a classroom complaint with the PN-EN 13779 Standard [6]. The selection of optimum work parameters of the mechanical ventilation system with the use of the determined model allows, at the same time, to reduce the operation costs of an educational building.

Conclusions

It was shown in the tested classrooms equipped with natural ventilation that the limits stated in the standards concerning carbon dioxide concentration and relative air humidity were exceeded, which in practice excludes the use of gravitational ventilation in classrooms.

Modernization of the ventilation systems in the tested rooms, which was suggested in the course of research and implemented by way of mounting exhaust fans in ventilation ducts, as well as installing wall ventilators, allows to guarantee interior comfort pursuant to the PN-EN 13779 Standard [6] in educational buildings where there is no technical possibility to install intake and exhaust ventilation with heat recovery.

Factors of CO_2 emission by students, depending on the cubic capacity of rooms and the number of people inside, were determined from the results of the carried out research. The averaged value of carbon dioxide emission by a single student within one hour, applied to determine the work parameters of the ventilation system, was assumed at the level of 12 dm^3/h. Also, the average value of a relative air humidity increase in classrooms was determined and it amounted to 3%.

In case of mechanical ventilation of classrooms, the optimum value of the air exchange rate by the system was determined within the range 0.6 to 0.7 of the entire exchange in the room within one hour. This exchange rate meets the air quality requirement of the PN-EN 13779 [6]. Standard for classrooms, and at the same time it allows to reduce heat losses through the ventilation system.

With the use of the developed mathematical model of ventilation system control, one can determine optimum work parameters for a ventilation system allowing at the same time to minimize costs relating to heating a building.

References

[1] Santamouris M, Synnefa A, Asssimakopoulos M, Livada I, Pavlou K, Papaglastra M, et al. Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation. Energy Buildings. 2008;40:1833-1843. DOI:10.1016/j.enbuild.2008.04.002.

[2] Połednik B. Variations in Particle Concentrations and Indoor Air Parameters in Classrooms in the Heating and Summer Seasons. Archives Environ Protect. 2013;39(4):15-28. DOI: 10.2478/aep-2013-0037.

[3] Shaughnessy RJ, Haverinen-Shaughnessy U, Nevalainen A, Moschandreas D. A preliminary study on the association between ventilation rates in classrooms and student performance. Indoor Air. 2016;16(6):465-468. DOI: 10.1111/j.1600-0668.2006.00440.x.
[4] Al Horr Y, Arif M, Katafygiotou M, Mazroei A, Kaushik A, Elsarrag E. Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. Int J Sust Built Environ. 2016;5:1-11. DOI: 10.1016/j.ijsbe.2016.03.006.
[5] Frontczak M, Wargocki P. Literature survey on how different factors influence human comfort in indoor environments. Build Environ. 2011;46(4):922-937. DOI:10.1016/j.buildenv.2010.10.021.
[6] PN-EN 13779: Wentylacja budynków niemieszkalnych. Wymagania dotyczące właściwości instalacji wentylacji i klimatyzacji. 2008. (PN-EN 13779, 2008 Standard: Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems). http://sklep.pkn.pl/pn-en-13779-2008p.html.
[7] Almeida R, Peixoto de Freitas V, Delgado J. School buildings rehabilitation: Indoor environmental quality and enclosure optimization. Springer Briefs in Applied Sciences and Technology. 2015:31-57. DOI:10.1007/978-3-319-15359-9.
[8] Semprini G, Marinosci C, Ferrante A, Predari G, Mochi G, Garai M, et al. Energy management in public institutional and educational buildings: The case of the school of engineering and architecture in Bologna. Energy Buildings. 2016;126:365-374. DOI:10.1016/j.enbuild.2016.05.009.
[9] Kapalo P, Voznyak O. Experimental measurements of a carbon dioxide concentration for determining of a ventilation intensity in a room at pulsing mode. J Civil Eng Environ Architect. 2015;62(4/15):201-210. DOI: 10.7862/rb.2015.189.
[10] Cichowicz R, Sabiniak H, Wielgosiński G. The influence of a ventilation on the level of carbon dioxide in a classroom at a higher university. Ecol Chem Eng S. 2015;22(1):61-71. DOI: 10.1515/eces-2015-0003.
[11] Mitteilungen der Ad-hoc-Arbeitsgruppe Innenraumrichtwerte der Innenraumlufthygiene-Kommission des Umweltbundesamtes und der Obersten Landesgesundheitsbehörden Gesundheitliche Bewertung von Kohlendioxid in der Innenraumluft. (Health evaluation of carbon dioxide in indoor air) Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz. 2008;51(11):1358-1369. DOI: 10.1007/s00103-008-0707-2.
[12] Krawczyk D, Rodero A, Gładyszewska-Fiedoruk K, Gajewski A. CO_2 concentration in naturally ventilated classrooms located in different climates – measurements and simulations. Energy Buildings. 2016;129:491-498. DOI: 10.1016/j.enbuild.2016.08.003.
[13] Szmolke N. Audytorskie spojrzenie na wentylację szkół (An auditor's look on ventilation in schools). J Civil Eng Environ Architect. 2015;32(62):459-467. DOI: 10.7862/rb.2015/75.
[14] Gaczoł T. Wentylacja grawitacyjna w budynkach mieszkalnych – wybrane zagadnienia (Gravitational ventilation in residential premises – chosen questions). J Civil Eng Environ Architect. 2015;32(62):81-88. DOI: 10.7862/rb.2015.38.
[15] PN-EN 12831: Instalacje ogrzewcze w budynkach – Metoda obliczania projektowego obciążenia cieplnego. 2006. (PN-EN 12831:2006 Standard – Heating systems in buildings. Method for calculation of the design heat load). http://sklep.pkn.pl/pn-en-12831-2006p.html.
[16] Rozporządzenie Ministra Infrastruktury i Rozwoju w sprawie metodologii wyznaczania charakterystyki energetycznej budynku lub części budynku oraz świadectw charakterystyki energetycznej z dnia 27 lutego 2015 r. Dz.U. 2015, poz. 376. (Regulation of the Minister of Infrastructure and Development on methodology of determining the energy performance of buildings). http://isap.sejm.gov.pl/DetailsServlet?id=WDU20150000376.

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Samodzielna Katedra Inżynierii Procesowej
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Abstrakt: W artykule zamieszczono wyniki badań parametrów powietrza w pomieszczeniach dydaktycznych różnej wielkości. W pomieszczeniach, w których realizowany jest proces dydaktyczny z udziałem dużych grup studentów, powinien być zapewniony odpowiedni komfort klimatyczny, na który mają wpływ przede wszystkim: temperatura oraz wilgotność powietrza, jakość fizyczna i biologiczna powietrza, koncentracja

CO_2. W wyniku przeprowadzonych analiz wykazano, iż w pomieszczeniach dydaktycznych wentylacja grawitacyjna nie powinna być wykorzystywana. Po modernizacji pomieszczeń i zainstalowaniu w systemach wentylacji wentylatorów wyciągowych dokonano pomiarów, na podstawie których wyznaczono współczynniki empiryczne emisji CO_2 przez studentów, uzależnione od kubatury pomieszczeń i liczby osób. Współczynniki te uwzględniono w algorytmie wyznaczającym parametry pracy wentylatorów w systemie wentylacji.

Słowa kluczowe: stężenie CO_2, sale dydaktyczne, regulacja, wentylacja