MONITORING OF THE CARBON DIOXIDE CONCENTRATION AND TEMPERATURE OF THE INDOOR ATMOSPHERE IN A LECTURE HALL WITH NATURAL VENTILATION

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ABSTRACT. One of the main indoor air pollutants and a key parameter in assessing indoor air quality is carbon dioxide (CO_e). Increasing its concentration over time causes discomfort and worsens the quality of the occupants' work. In the particular case of school premises - classrooms and lecture halls, the increased CO_2 content, which is two and sometimes more times than the accepted norm (400 ppm - 1200 ppm), adversely affects the concentration (sharpness) of the attention and mental work of the students and the teacher (lecturer). This, in turn, affects the degree of perception of the content taught and the extent of learning at the moment.
To provide and maintain an acceptable level of CO_2 concentration in the indoor air of the classrooms, it is necessary to ensure continuous or periodical air ventilation.
In our previous research the results of the study of spatial distribution of carbon dioxide concentration and temperature in a lecture hall with a volume of about 300 m^3 with natural ventilation were analyzed and the evolution of the two parameters in dependence on the occupancy of the hall and the intensity of natural ventilation was traced. The experiment was held in late spring (May - June).
The present paper repors the results of the study of the distribution of the air temperature and CO_2 concentration in the same lecture hall but in the heating season(January), when central heating is used.

Keywords: Carbon dioxide, indoor air quality, natural ventilation

МОНИТОРИНГ НА КОНЦЕНТРАЦИЯТА НА ВЪГЛЕРОДНИЯ ДИОКСИД И ТЕМПЕРАТУРАТА В АТМОСФЕРАТА НА ЛЕКЦИОННА ЗАЛА С ЕСТЕСТВЕНА ВЕНТИЛАЦИЯ

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РЕЗЮМЕ. Един от главните замърсители на въздуха в помещение и основен параметър при оценяване на качеството на въздуха е въглеродният диоксид (CO_2). Увеличаването на концентрацията му във времето причинява дискомфорт и влошава качеството на работа на обитателите. В частния случай на учебни помещения - класни стаи и лекционни зали, повишеното съдържание на CO_2 два, а понякога и повече пъти над приетата норма (400 ppm - 1200 ppm), влияе неблагоприятно върху концентрацията (остротата) на вниманието и умствената работа на обучаваните и преподавателя. Това, от своя страна, рефлектира върху степента на възприемане на преподавания материал и дълбочината на усвояването му в момента.
За да се осигури и поддържа приемливо ниво на концентрацията на CO_2 във вътрешния въздух на учебните зали, е необходимо да бъде осъществявана постоянно или периодично вентилация на въздуха.
В предишна наша работа бяха анализирани резултатите от изследването на пространственото разпределение на концентрацията на въглеродния диоксид и температурата в учебна зала с обем около 300 m3 с естествена вентилация. Бе проследена еволюцията на тези параметри в зависимост от заетостта на залата и интензивността на естественото проветряване. Експериментът беше проведен в късна пролет (май - юни).
В настоящата работа са докладвани резултатите от измерването на разпределението на температурата на въздуха и концентрация на CO_2 в същата лекционна зала, но в зимния сезон (месец януари), като за отоплението й се използва парно.

Ключови думи: Въглероден диоксид, качество на въздуха във вътрешна среда, естествена вентилация

Introduction

The main purpose of educational institutions - schools and universities - is the learners to acquire a certain amount of theoretical content to master skills and gain experience to analyze practical problems, make decisions on how to apply their theoretical knowledge and successfully solve them. The prolonged stay in the premises leads to enrichment of the indoor air with carbon dioxide (CO_2). The main reason for the increase in CO_2 is the breathing of the inhabitants themselves (students and people in the hall) during the class hours. CO_2 content in the air exhaled from a human is about 4-5.6%, which is about 100-140 times more than that in the environment – 0.04% (Kapalo et al., 2014).

Indoor air quality is defined as required per person fresh and pleasant air that is not harmful to their health and has a positive impact, stimulates their work and increases their performance and productivity (Fanger, 2006). A number of studies devoted to the indoor air quality on human health have shown a clear connection between polluted air and the quality of activities that workers perform in this environment (Clements-Croome, 2004; Demianiuk et. al., 2010; Satish et al., 2012).

Requirements for energy efficient buildings with a view to reduce energy consumption and associated costs minimize the natural airflow through infiltration. In order to regulate the temperature and cleanliness of the air in the rooms, there should be a possibility for their additional controlled ventilation. In most educational institutions, this is done by natural ventilation, as the occupants themselves regulate the thermal conditions by periodically opening the windows of the room.

Velichkova et al. (2016) investigated the quality of the indoor atmosphere, predominantly the CO_2 concentration, of a lecture hall at the University of Mining and Geology during the spring-summer season (May, June), where it was found that natural ventilation can provide the necessary conditions for the learning process, as long as the occupant density of the hall does not exceed 0.15 m^{-3}. However, the intensity and duration of natural ventilation under winter conditions, are rather limited due to the need of creation of thermal comfort for the occupants. The question arises whether natural ventilation is a good enough way to ensure the right conditions - temperature and air purity - in the lecture halls during this season.

The aim of this study is to analyze the air quality in a lecture hall during the winter season and to assess the effectiveness of natural ventilation (by means of window operation) in controlling hall thermal conditions and indoor air quality.

Experiment

Lecturer hall

The experiments were carried out in the 346 lecture hall at the Department of Geological Prospecting at the University of Mining and Geology "St. Ivan Rilski". The location of the hall is shown on Fig. 1.

Fig. 1. A view to 346 lecture hall at the department of Geological Prospecting at the University of Mining and Geology "St. Ivan Rilski"

The hall is located on the third floor, it is oriented to the northeast, with its windows facing the courtyard of the University, with forest vegetation.

Its dimensions are: width of 8.20 m, length of 13.50 m, height at the place of the lecturer desk of 3.40 m and height at the opposite edge of the hall of 2.10 m. The floor has a displacement of 1.30 m. The room space is 304 m^3. There are 8 windows, each with an openable area of 1.2x1.2 m^2. The diagram of the room with the points for measuring the temperature (points from 1 to 6) and the concentration of carbon dioxide (point 4 and point 6) is shown in Fig.2.

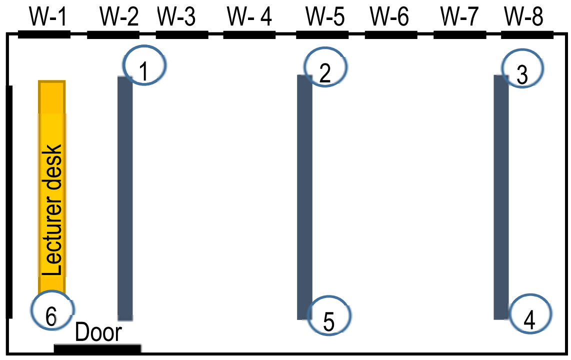

Fig. 2. A scheme of 346 lecture hall: W-1 – W-8 are the windows, 1, 2, 3, 4, 5, 6 are the measurement points. For visibility only the first, medium (the ninth) and the last school decks are shown

Used appliances

The dynamic (time dependence) characteristics of the CO_2 concentration and temperature were determined at p.4 and p.6 (Fig. 2) by a portable air-logger analyzer TROTEC BZ30. The device simultaneously measures and records the CO_2 concentration (0 ÷ 9999 ppm, with accuracy of ± 5 %), the temperature T (-5 ÷+50°C, with accuracy of ±0.1°C) and the relative humidity RH (0.1÷99.9 %, ±0.1%). The concentration of carbon dioxide was obtained by averaging over the measurements, recorded in 1 minute time interval.

The temperature and its behavior over time was also measured in points 1, 2, 3, 5 by Thermo-data logger.

Only in point 6 and when the hall was empty the temperature was measured at three different heights (levels): 0 m - floor level, 1 m and 2 m.

Conditions of the experiments

The measurements were made at a height of 85 cm above the floor of the room (the level of the exhaled air of the present - respiratory zone). The reasons for this choice were described in Velichkova et al. (2016).

The experiments were conducted during the same time interval 14-16:30 h on three dates: on January 26, 2017, during an exam, with 15 occupants in the hall; on January 30, 2017, during a lecture, with 26 occupants and on February 1, 2017 during a lecture, with 13 students in the room. The ambient air temperature was T=-3 ÷1°C.

The experiments were conducted as follows: the hall was ventilated after the previous class, when empty, by opening the eighth window, then the window was closed and the class (lecture or exam) started. The hall was not ventilated for a while. After that, the room was aired again by reopening the eighth window for the experiments on 26th and 30th January and also the door for the experiment on 1st February. For that time interval the dynamic characteristics (i.e. the time dependent changes of these quantities) of the CO_2 concentration and temperature T were recorded in p.4 and p.6.

Students' activity is as follow: on 26th January, an exam (presentations), on 30th January – lecture, and on 1st February - lecture. In all cases, students were unevenly seated in the room (and took their places) mainly in the front half of the hall, near and slightly below the average desk where were the points of measurements 2 and 5 (Fig. 2). Briefly, the conditions (regimes) of the experiment are as follows:

- Regime M0, the hall was empty and it had been ventilated by opening the last (W-8) window;
- Regime M1, the hall was empty and it had not been ventilated;
- Regime M2, the hall was occupied and it had not been ventilated;
- Regime M3, the hall was occupied and it had been ventilated by opening W-8;
- Regime M4, the hall was occupied and it had been ventilated by opening W-8 and the door;
- Regime M5, the hall was occupied and it had been ventilated by opening W-1 and the door.

Processing the data

To analyze the experimental data, we have accepted that the air in the halls is homogeneous. The equation for the mass balance is

$$V\mathrm{d}C = G\mathrm{d}t + QC_{\mathrm{V}}\mathrm{d}t - QC\,\mathrm{d}t\ , \qquad (1)$$

where G is the rate of CO_2 generation which is a result of the respiration of the occupants, Q - volumetric airflow rate into (and out of) the space, i.e. it is the airflow exchanged with the outside environment for one second, V – hall space, C_V - the CO_2 concentration in inflow air, and C - the indoor air CO_2 concentration and respectively, CO_2 concentration in the outflow air.

When the hall was occupied and had not been ventilated (Q=0) and if accepted that the generation rate of CO_2 did not change with time depending factors, CO_2 concentration is a linear function of time –

$$C = C_0 + \frac{G}{V}t\ . \qquad (2)$$

C_0 in Eq. (2) is the room CO_2 concentration in the beginning of the experiment.

When the hall has been ventilated ($Q \neq 0$), the carbon dioxide concentration will change exponentially over time

$$C = C_V + \frac{G}{Q} - \left(C_V + \frac{G}{Q} - C_0\right)e^{-\frac{Q}{V}t}\ . \qquad (3)$$

Approximating experimental data in regime M2 with Eq. (2), the rate of CO_2 generation G could be estimated, and in regimes M0, M3, M4 and M5 with Eq. (3) - the airflow rate Q.

Results and discussion

The temperature profile in height (Fig. 3) when a lecture hall is empty (regime M1) indicates that it is stably stratified.

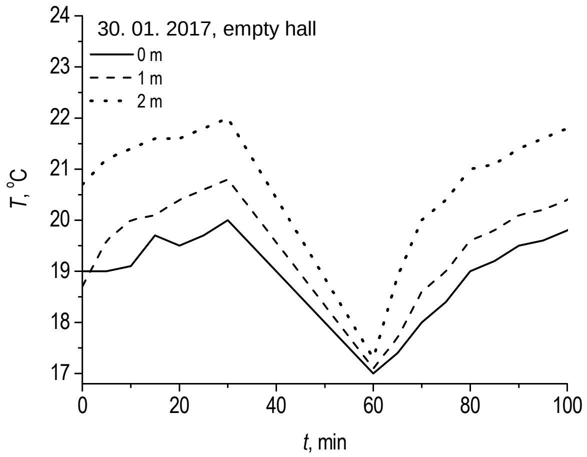

Fig. 3. Stratification of temperature

It can be seen on the figure that in regime M1 the temperature increases with 2.3°C with the increase of the height . Its gradient also grows up with 0.3 K/m. Natural ventilation for 30 minutes by opening W-8 (regime M0) results in a drop of the temperature from about 3°C at the level of the floor to 5°C at 2 m height. At the end of the regime M0 the temperature at the three levels reaches about 17°C, while maintaining its stratification. After shutting down the ventilation (regime M1), the temperature rises twice as fast and 5 minutes later it reaches 2/3 of its maximum value. Then it increases slowly (during 35 minutes) to its previous values still maintaining the stratification

The measurements of the temperature and CO_2 concentration for the three dates show that after the initial ventilation (regime M0), the temperature in the upper inner part of the room (p.4) was higher in comparison with the temperature at the lecturer desk - the lowest inner part of the room (p.6). The difference might range from 0,5–1,5°C depending on the way and the duration of ventilation. When the room was occupied by students located in its front half (as was the case on 26th Jan and 1st Feb), the temperature increase is the same for both points and it is not dependent on the room displacement. On these days the number of students was 13-15 and the respective occupant density of the hall was 0,043 - 0,050 m^{-3}. When the density of occupancy was almost 2 times higher (0,086 m^{-3}, with 26 people on 30th Jan), the temperature in the upper part of the room (p.4) increased by about 1°C, while at its bottom (p.6) it remained almost unchanged.

As expected, the number of students affected the change in CO_2 concentration in the hall as the rate at which it grew was proportional to the number of occupants. Carbon dioxide concentration reached its highest value (1250 ppm) when the number of students in the hall was the biggest (26 students). This fact confirms the result obtained in (Velichkova et al., 2016) that the only source of indoor air pollution with carbon dioxide is the human presence.

The dynamic characteristics of the temperature and CO_2 concentration in p.4 and p.6 were illustrated in Fig. 4 for 30th Jan and in Fig. 5 for 1st Feb. The experimental data for increase and decrease of CO_2 were approximated by Eq.(2) in regime M2 and Eq.(3) in regimes M0, M3 - M5. The resulting values of CO_2 generation rate *G* and the airflow rate *Q*, are shown in Table 1. In the same table the values of *G* and *Q* obtained from the experiments during the spring-summer season in 2016 are also shown.

The dynamic characteristic of temperature (Fig. 4, left) shows that the changes in temperature in both measuring points in regime M0 are with the same speed, but the magnitude of this change is 1°C greater in the upper inner part of the room. After closing the window (regime M2) the temperature increases relatively slower in p.6 and 50 min later its value is about 1°C lower than the one in p.4. After subsequent ventilation by opening W-8 and the door (regime M4), the temperature decreases, but the rate of its reduction in p.4 now is more than twice as high as the one in p.6. The observed behavior of the temperature could be explained by taking into account the circulation due to the higher temperature of the air exhaled by the students in the respiratory area (around the middle of the room) and the additional circulation that appeared at opening the door, because of the temperature difference between the room and the corridor - about 2 - 3°C.

The described temperature behavior reflects on the dynamic behavior of the CO_2 concentration (Fig. 4, right). It can be seen that the concentration grows up at a higher speed in the upper inner part of the hall p.4, reaching a value of 150 ppm higher than the one in p.6. The air circulation caused by its additional heating in the respiratory area where the CO_2 content is greater might explain such behavior of the dynamic characteristics and respectively the higher value of the generation rate in p.4, although there were no students in this part of the hall.

The fact that the door was also opened at next ventilation resulted in a slightly higher flow rate (see Table 1) and better ventilation, respectively, so that the CO_2 concentration reached the external level - about 400 ppm, (Fig. 4, right).

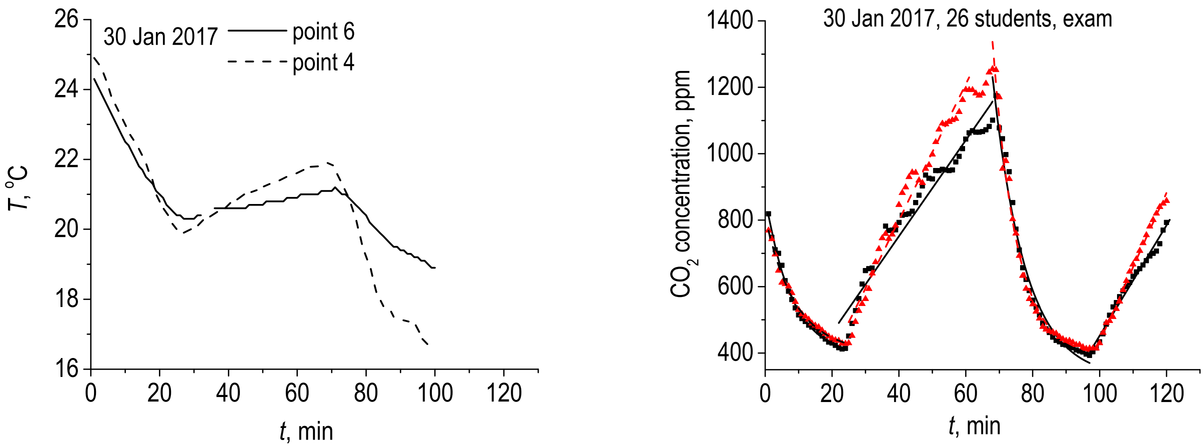

Fig.4.Dynamic characteristics of the temperature (left-hand) and the concentration of CO_2 (right hand), measured at p.4 (▲) and p.6 (■). The lines were obtained by approximation of the experimental data for p.6 (solid line) and p.4 (dashed line) with Eq.(2) for regime M2 and Eq.(3) for regimes M0 and M4

The experiments on 26th Jan and 1st Feb, when the occupants' density of the room is half (0,043-0,050 m^{-3}) compared to 30th Jan (0.086 m^{-3}), show an adequate change in the growth of CO_2 concentration. In both cases, the increase of the temperature in regime M2 (without ventilation) is at approximately the same rate for the two measuring points, and the values of the CO_2 concentration recorded in the upper internal part of the room (p.4) and in the lower internal part of the hall p.6 are practically the same. This fact indicates that as a result of the air circulation when the number of people was smaller, the air temperature and the CO_2 content were uniformly distributed in the hall volume. The temperature in the upper inner part remains higher than in the lower though with only 0.5°C. . This temperature difference observed in all experiments caused the greater amount of fresh air to move around the windows where the temperature gradient is higher.

The lower value of the generation rate derived from the approximation of the data from 26th Jan experiment might be due to the fact that part of the students were leaving the room and there was practically an unpredicted growth of the ventilation when the door was opening. The situation on the 1st Feb experiment was similar, when a little after the beginning of the classes, CO_2 started to increase rapidly, leading to *G* = 173 ml/(min.p) in p.4 and G = 242 ml/ (min.p) in p.6. These values are similar to the ones obtained from the experiments on the other two dates. Shortly after the start of the classes, the door could not be well closed, which reflected the rate of the CO_2 concentration increase. Since we do not have enough data to correctly account for the air flowing through the door (perhaps not very large due to the slight difference between the room and corridor temperatures), we could not calculate correctly the values of *G.* But this could create additional ventilation that might explain the change observed in the increase of CO_2 concentration.

Unlike the initial room airing by W-8 (regime M0, 1st Feb), when the class ends additional ventilation is going through W-1 and the door (regime M5). Then the temperature in p.6, located closest to the source of ventilation, drops by 3°C, while in p.4 - only by 1.2°C. What is interesting is that when the ventilation is done through the W-8 and the door (regime M4), the airflow rate at p.4 (with a higher temperature) was 45 % lower than that in p.6. In regime M5 (airing via W-1 and the door) - the airflow rate in p.4 is 67 % higher than the one in p.6. This difference is only 11-13% for the experiments of 26th and 30th Jan.

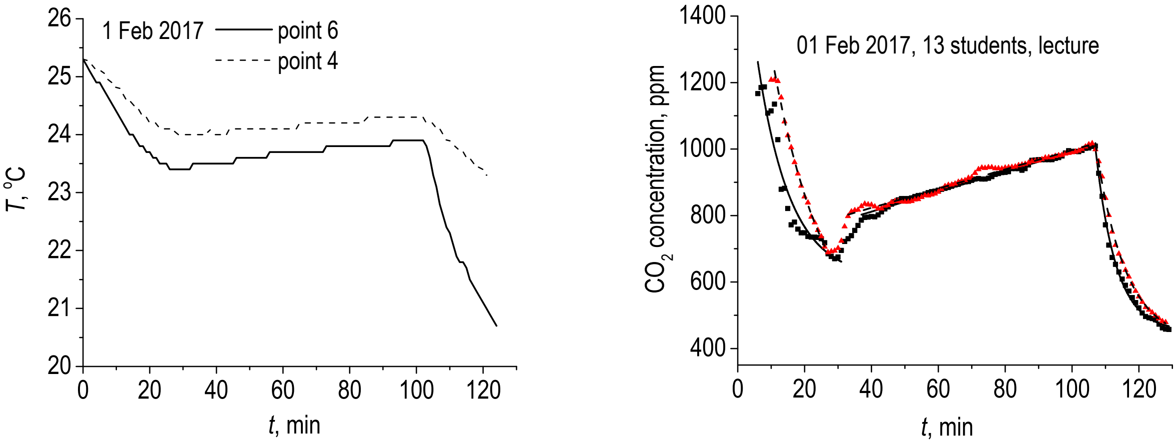

Fig. 5. Dynamic characteristics of the temperature (left-hand) and the concentration of CO_2 (right hand), measured at p.4 (▲) and p.6 (■). The lines were obtained by approximation of the experimental data for p.6 (solid line) and p.4 (dashed line) with Eq. (2) for regime M2 and Eq.(3) for regimes M0 and M5

Table 1

Experimental conditions and calculated by the graph parameters: rate of CO_2 generation G, airflow rate Q and specific airflow rate n, obtained during the summer season experiments 2016 and winter season experiments in 2017

Data		2016 r.		2017 g.					
		18 March	1 June	26 January		30 January		1 February	
activity		lecture	exam	exam		lecture		lecture	
Number of students		16	31	15→3		26		13	
Distribution		Irregular, more students were sitting in the front half of the hall	regular	Irregular, more students were sitting in the front half of the hall					
Occupant density, m^{-3}		0.053	0.103	0.050		0.086		0.043	
G, ml/(min.p), regime M2	point 4	-	-	240	204	232	227	242	
	point 6	153	188	229	78	167	199	173	
Q, ℓ/s	point 4	-	-	646		564	704	312	569
	point 6	417	847	750		626	624	606	340
$n = \frac{Q}{V}$, $\frac{(m^3/\min)}{m^3}$	point 4	-	-	0.129		0.113	0.141	0.062	0.114
	point 6	0.083	0.169	0.152		0.125	0.125	0.121	0.165
$\Delta C = C_{in} - C_{out}$,ppm		260	380	550		700		600	
				380		890		600	

In all cases it could be clearly seen, that the reduction of carbon dioxide is stronger at the location close to the opening at the lower temperature. This shows that the airflows which are refreshing the air in the process of ventilation depend mainly on the difference between outdoor and indoor temperatures which is almost the same for the three experiments and does not depend on the number of occupants and the CO_2 concentration in the room atmosphere.

Comparing data for 1st Feb and 26th Jan shows that change in CO_2 concentration for the experiments on 1st Feb is less than the one on 26th Jan (Table 1), although the number of students is almost the same (13-15 students). According to Lazović et al., 2015, the speed at which a person generates CO_2 depends on the duration and intensity of physical and mental activities as well as on the stress. In our previous experiment in case of a uniform distribution of the students in the lecture hall, with a high enough density, we received that *G*= 188 mℓ/(min.p). This value is very close to the value given by Dubrovskii, 2002). The *G* values received at data approximation in present experiments exceed those obtained by us in 2016 and also cited for normal mental activity. This is possible, taking in account the fact that during classes, each student presented their own project and after a discussion of their work, the lecturer assessed their knowledge - the way they defended their project and their activity in the discussion of their colleagues' projects. That increases the participants' stress (more possibly its duration).

This situation, similar to an exam, leads to increase of mental activity and undoubtedly causes some degree of stress. Higher *G* values in comparison with experiments in 2016 might also be interpreted as an indicator of more intense mental activity during the winter season than in spring - summer. Underestimation because of the though small ventilation by the opened door could explain the smaller *G* values.

The results from the experiments on all dates show that at given room occupancy and used ventilation regimes each student receives fresh air, much more (2.5-4.5 times) than the required one of 7÷10 ℓ/(s.p), according to the Bulgarian State Standard (BDS/EN 15251, 2007).

Conclusion

A necessary condition for a pleasant and effective work of the students during the learning process is to provide an indoor atmosphere of good quality in educational institutions. Our study shows that the natural ventilation in the considered lecture hall at usual occupancy density is perfectly suitable for this purpose even in winter conditions, as well. For that occupancy of the room and the ventilation regimes employed, each student has received a sufficient amount of fresh air which ensured good conditions for working and training.

It has been found that the way in which ventilation takes place depends on the location of the ventilation source and on the difference between outside and inside temperatures. Therefore, to determine which source of natural ventilation should be used without compromising students' thermal comfort, it should be taken in account which are the preferred seats in the hall.

The existence of a stable temperature stratification in the hall is established.

Having in mind the students' activities during the experiments, the higher values of the generation rate of carbon dioxide might be associated with activating their mental activity and the state of stress.

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