Ventilating with room units in educational institutions

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Abstract— In current article the results of the research about indoor climate in educational institutions are presented. The study is mostly concentrated on the research of different ventilation systems and carbon dioxide (CO_2) levels. CO_2 is one of the most important indicators about air quality in buildings. The correlation between air change rate and CO_2 levels in certain rooms is already well proven fact. European Standard EN-15251 about indoor climate conditions requirements gives the basis for new and renovated buildings. The renovation process in reality can either improve or deteriorate the indoor climate. The success lays in the renovation measures used. Demand based ventilation gives better energy conservation possibilities. Therefore, room based ventilation solutions are studied. The research results show carbon dioxide levels in educational institutions with different ventilation systems.

Keywords— Carbon dioxide concentration, room unit based ventilation, CO_2 concentration analysis, air change rates, CO_2 in educational buildings, naturally ventilated buildings, mechanically ventilated buildings.

I. Introduction

The most cited literature on indoor climate available in the whole world does not indicate only the air change rates, but also describes the maximally permitted CO_2 concentrations in buildings. Currently the air change rates are mostly fixed values which do not take into consideration the parameters of the external air pollution. The European indoor climate normative EN15251:2007 [1] takes into account different allowed CO_2 levels depending on the external air CO_2 concentration. but the air change rates are still constant. Table 1 presents the CO_2 values according to the EN15251.

Table 1. CO_2 levels according to the EN15251

Category	Respective CO_2 level exceeding external air concentration in ppm for energy calculations
I	350
II	500
III	800
IV	> 800

According to regulations in Estonia enforced by the Ministry of Social Affairs the maximum allowed CO_2 concentration in schools is 1000 ppm [2]. In most cases this figure is not achievable without bigger investments and heavier life cycle costs made to ventilation systems. Medical investigations have discovered diseases, headache and lethargy in patients in case the CO_2 concentrations exceed 10 000 ppm. A visually summarizing graph [3] is presented as follows:

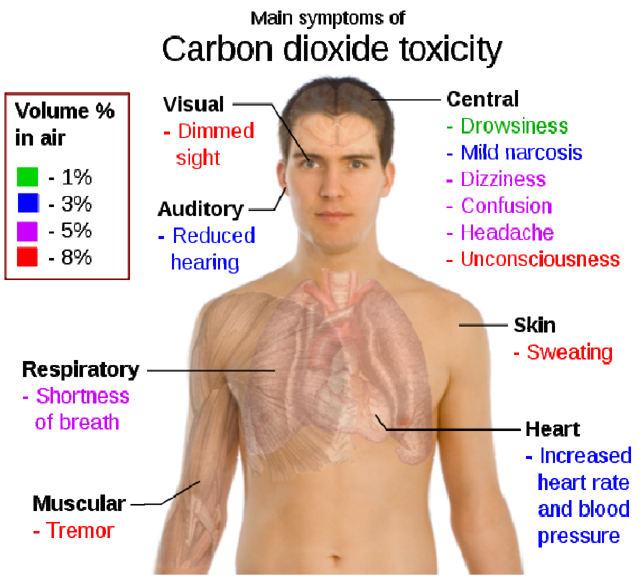

Fig.1. Symptoms of carbon dioxide.

Studies in Europe refer also to the huge problems related to CO_2 concentrations in schools. The studies carried out In Dutch schools show that in some cases the CO_2 level is more than 5000 PPM at the end of a class. 7 schools had CO_2 levels between 1500 – 3700 PPM [4]. A comprehensive study of 141 schools [5] gives the following results:

Table 2. Dutch studies: CO_2 levels.

Study	No. schools	CO_2 levels ppm	
		Average	Range
1984	11	1000	500-1500
1990	6	1290	950-1950
1995	6	1320	700-2700
1997	96	990	425-2800
2004	5	1220	480-2400
2004	11	1580	450-4700
2005	6	1355	550-3000

A study in the United Kingdom (UK) in 2 different classrooms shows the average CO_2 concentration 1638 ppm and 2086 ppm by the outdoor concentration of 593-709 ppm [6]. Table 3 presents the weekly average results of the study in the UK primary school in 2001.

Table 3. UK studies: CO_2 levels.

School	CO_2 levels PPM
	Range
1	200-1300
2	300-2000
3	300-3500
4	310-2830

In the UK studies in most cases the CO_2 range during occupation of the classrooms was above 1000 ppm.

The overall air quality in educational buildings is usually worse than the normative allow. A similar situation can also be found in Estonian schools.

In Estonia the internal climate in educational buildings has been studied and analyzed in different investigations [7, 8, 9, 10, 11, 12, 13, 14, 15].

A comprehensive theoretical analysis of the air change rate and CO_2 levels generated by occupants and level prediction possibilities with simulation calculations is given in the Building and Environment Journal [16].

An interesting study of natural ventilation possibilities in schools has been carried out in the UK [17]. The results are presented in Table 4.

Table 4. Natural ventilation: CO_2 levels during 8:40-15:00.

Weekday	CO_2 levels PPM	
	Average	Range
Monday	1504	601-2804
Tuesday	1303	489-2718
Wednesday	735	296-1770
Thursday	691	341-1940
Friday	1208	345-2608

The figures are promising but in reality they are achieved by opening the windows. There are also several other parameters of indoor climate that affect the indoor air quality and thermal comfort negatively. Therefore this solution should not be recommended for educational buildings. It is also necessary to carry out a study throughout a year. Furthermore, the Sick Building Syndrome (SBS) caused by insufficient air change is very dangerous in children's institutions [18, 19, 20].

It is commonly known that the indoor climate and the CO_2 levels depend on the type of ventilation and its functioning [21], Table 5.

Table 5. CO_2 levels for different types of ventilation

Room	CO_2 levels ppm		
No	Average	Max	Vent. type
1.1	960	1857	Natural
1.2	1054	1725	Natural
2.1	789	1047	Mechanical
2.2	733	880	Mechanical
3.1	853	1472	Hybrid
3.2	1100	1615	Mechanical
4.1	1801	4016	Natural
4.2	1255	2676	Natural
5.1	1536	3181	Natural
5.2	2636	5567	Natural
6.1	1185	2570	Natural
6.2	1391	2585	Natural
7.1	1972	2530	Natural
7.2	1778	3109	Natural
8.1	932	2578	Natural
8.2	1031	2488	Natural
9.1	1695	3359	Natural
9.2	1199	2590	Natural

II. METHODOLOGY

In theory there is a well proven formula for estimating the CO_2 concentration in indoor conditions [7, 15] with natural ventilation. Suppose that the initial carbon dioxide concentration in the air of a classroom before the beginning of the class is C_o. As the class starts, carbon dioxide begins to generate intensively. The air change in the classroom is relatively low. The distribution of temperature in classrooms is uniform (conditions are isothermal), supply and exhaust airflows are equal. The carbon dioxide concentration in the inflow air is C_v and in the outflow air C (distribution of carbon dioxide in classrooms is uniform). We can write the balance equation

$$m \cdot d\tau + L \cdot C_v \cdot d\tau - L \cdot C \cdot d\tau - V \cdot dC = 0 \qquad (1)$$

From equation (1)

$$dC = -d\left(\frac{m}{L} + C_v - C\right) \qquad (2)$$

By integration of equation (1)

$$\frac{L}{V}\cdot\tau = -\ln\frac{\frac{m}{L}+C_v-C}{\frac{m}{L}+C_v-C_o} \qquad (3)$$

where

m - carbon dioxide generation in classroom,

L - air change in classroom,
V - volume of room,

C_v - carbon dioxide concentration in external air (in supply air),
C - carbon dioxide concentration in classroom air (in exhaust air),
C_o- carbon dioxide concentration in the air of the classroom at the beginning of the class,
τ - time.

From equation (3) we can express the basic equation for carbon dioxide concentration C at the time moment τ

$$C = C_v + \frac{m}{L} - \left(C_v + \frac{m}{L} - C_o\right)\cdot\left(e^{-\frac{L}{V}\cdot\tau}\right) \qquad (4)$$

By carbon dioxide concentration (in external air, in classroom air at the beginning of a class and in classroom air at the time moment of τ), carbon dioxide generation rate in classroom and parameters of room, by formula (3 or 4) it is possible to determine the air change in a room.

Fig.2 presents a theoretical rise in carbon dioxide during a 45 minute class (outside air 400 ppm) in a normal Estonian school with classroom volume about 240 m^3) and 25 students.

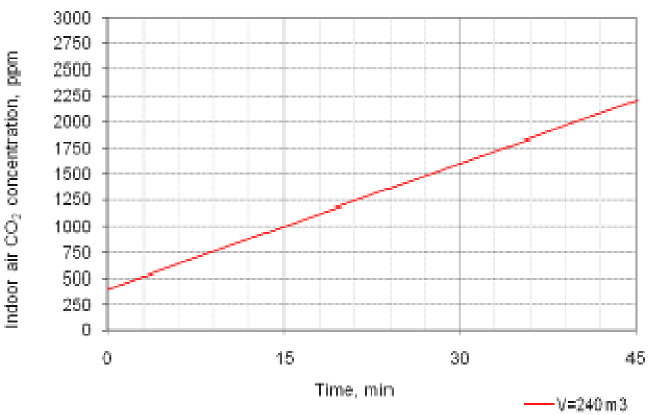

Fig.2. Calculated change in CO_2 concentration in typical Estonian classroom (natural ventilation).

The normative [2] defines 1000 ppm as a maximum level for CO_2 concentration in classrooms. Not acceptable conditions will be reached during first 15 minutes of the class.

Nevertheless, full ventilation renovation programs are not affordable for all Estonian schools. Furthermore, there are technical difficulties to build balanced centralized ventilation systems due to lack of space for air handling unit (AHU) rooms and especially for ventilation ducts. There is also a problem with energy consumption of the centralized units as not all the classrooms are used simultaneously. Therefore the current research studies the possibilities of local ventilation room units with heat recovery.

III. EXPERIMENTAL MEASUREMENTS

The case study was made in three different classrooms in a school located near Tallinn.

All classrooms had a physical volume of 240m^3.

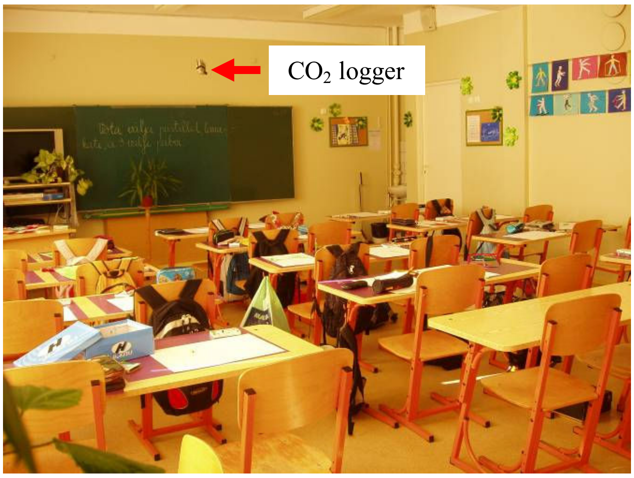

Fig.3. Logger position in classroom.

Fig.4. Room units locations.

Parameters of the natural ventilation, room units and regular ventilation are presented in Table 6.

Table 6. Air change and rise of CO_2 concentration

No	Ventilation system	CO_2 rise, ppm	Air change l/s person
1	Natural ventilation	1091	1.1
2	Room unit (M-WRG) 2nd speed	339	3.6
3	Room unit (M-WRG) 3rd speed	377	4.3
4	Room unit (M-WRG) 4th speed	500	5.7
5	Room unit (M-WRG) 5th speed	43	6.0
7	Regular supply and exhaust vent. 1st speed *	161	8.8

* 2nd and 3rd speed exceeded allowed sound levels.

M-WRG unit installation overview and technical parameters are presented as follows:

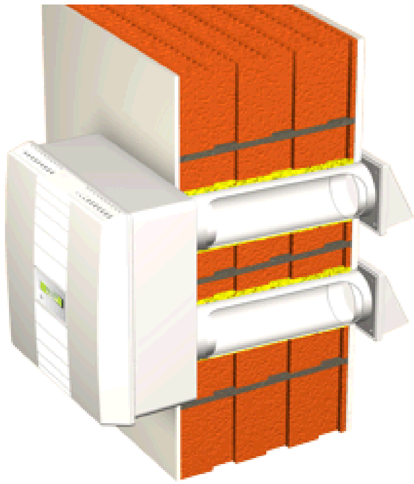

Fig.5. M-WRG installation principle.

- Air volumes 15 – 100 m^3/h per unit;
- Crossflow plate heat exchanger with heat recovery ca 75%;
- Electrical heating 3,8 – 34 W;
- Air filtering G4;
- Sound level 15,5 – 46,5 dB(A)
- EC-DC fans;
- Frost protection;
- Condensate removal to outdoor.

Fig.6. Contence of M-WRG unit.

The results of the measurements in classrooms with natural ventilation are presented in Fig.7 and Fig.8.

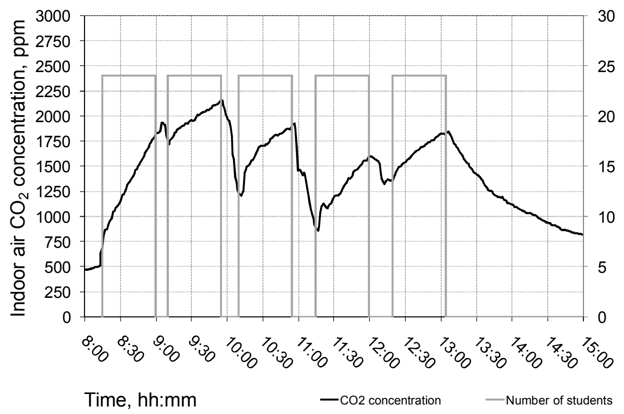

Fig.7. Measured CO_2 concentration change in classroom (natural ventilation).

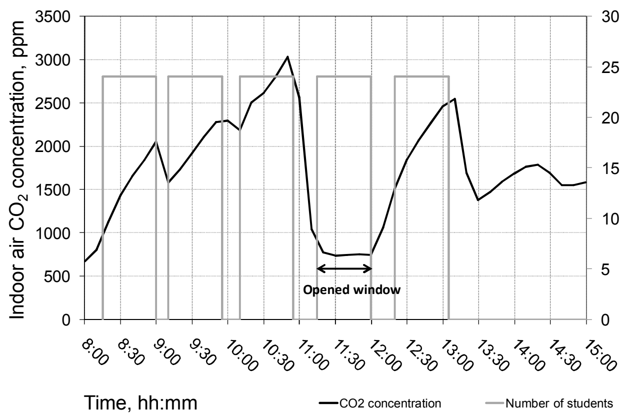

Fig.8. Measured CO_2 concentration change in classroom (natural ventilation).

Overview of Fig.7 and Fig.8 shows rapid CO_2 concentrations rising during the first class and there is a remarkable correlation with Fig.2 that presents the calculation results.

Other measurements were carried out in a classroom with mechanical supply and exhaust ventilation system. These systems usually give good air change results in case they are designed, built and balanced properly. In most cases problems appear with unbalanced systems or not properly completed balancing of ventilation system. The CO_2 measurement results can be found in figures Fig.9 and Fig.10.

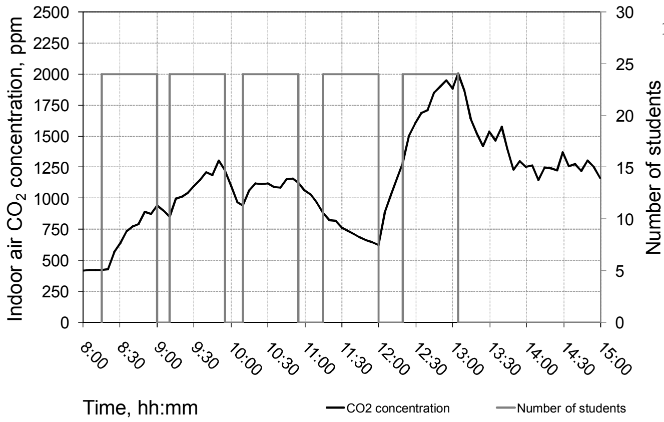

Fig.9. Measured change in CO_2 concentration in a classroom with a mechanical centralized ventilation

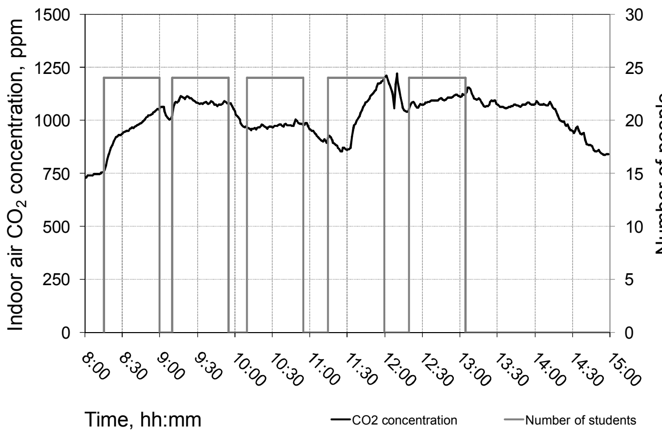

Fig.10. Measured change in CO_2 concentration in a classroom with a mechanical centralized ventilation

Carbon dioxide levels in the previous figures still exceed the normative of 1000 ppm during the school-day several times. EN15251:2007 III category can be averagely achieved.

VENTILATING WITH ROOM UNITS

Five M-WRG room units are installed below the windows in one of the classrooms.

Class start as also in previous cases at 8:00.

Children usually appear 15 minutes earlier.

Three CO_2 data loggers are spread into classroom as follows:

- in front of the board;
- next to the external wall (near the windows);
- next to the internal wall (near to corridor).

Some deviations in measurements can appear due to teachers' activity with tuning the M-WRG units' speeds to lower level during the class.

Figures 11, 12, 13, 14 and 15 present the measurement results in correlation with number of students.

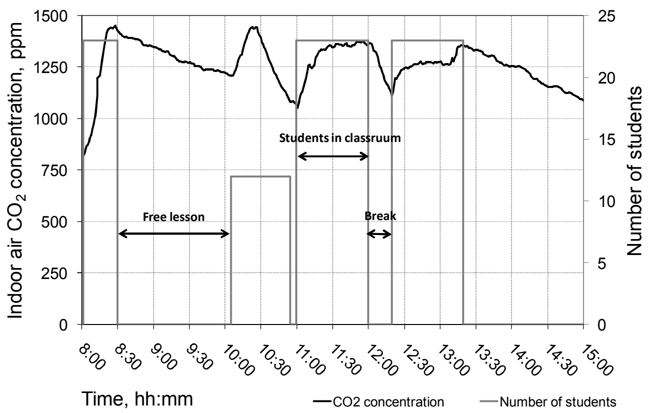

Fig.11. Measured change in CO_2 concentration in a classroom (ventilation with room units)

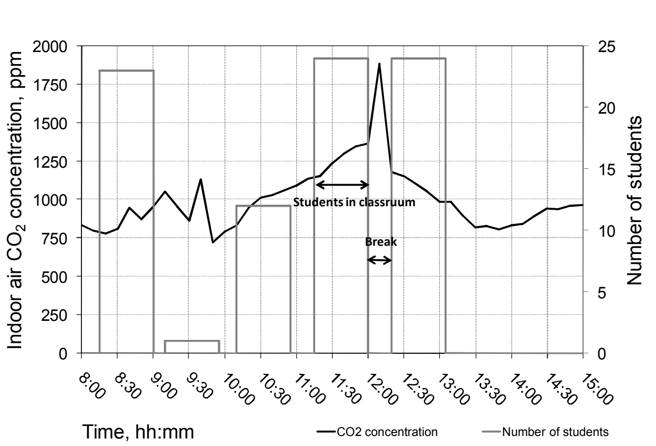

Fig.12. Measured change in CO_2 concentration in a classroom (ventilation with room units).

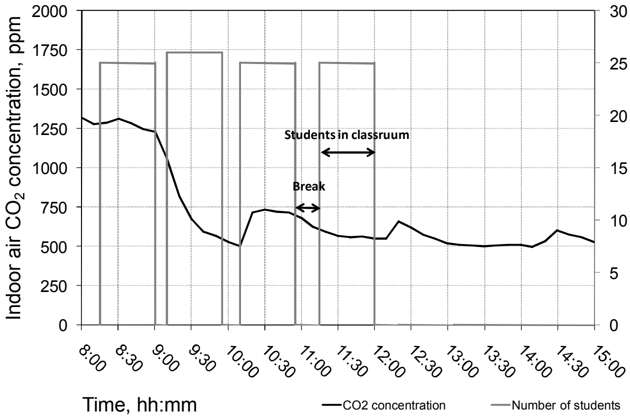

Fig.13. Measured change in CO_2 concentration in a classroom (ventilation with room units).

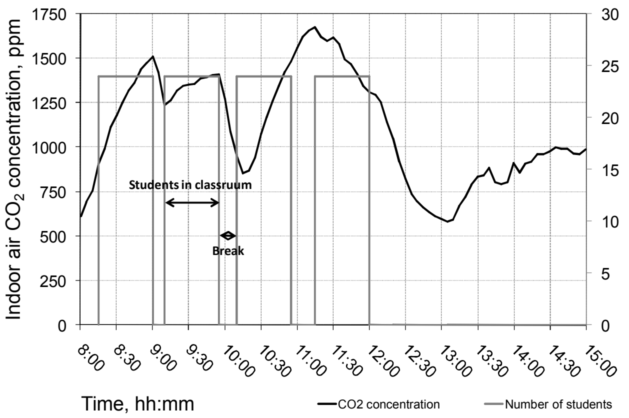

Fig.14. Measured change in CO_2 concentration in a classroom (ventilation with room units).

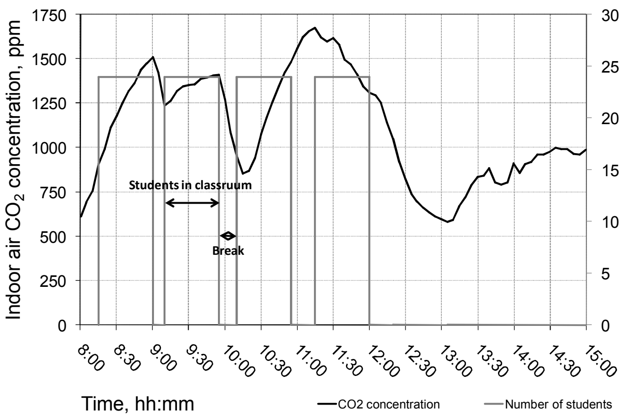

Fig.15. Measured change in the CO_2 concentration in a classroom (ventilation with room units) at the lowest speed

Fig. 16 presents a comparison of the changes in the CO_2 concentration with different ventilation systems based on the research.

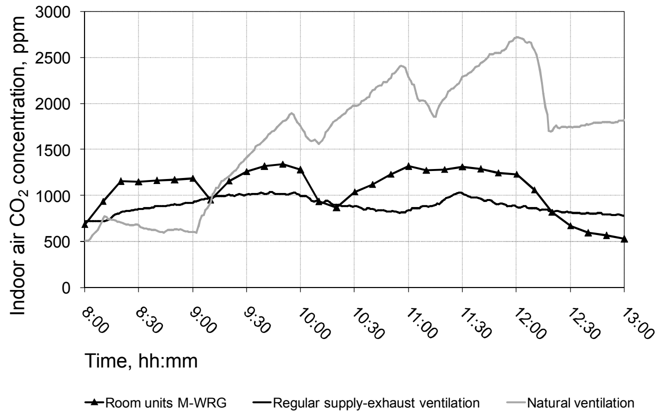

Fig.16. Indoor air CO_2 concentration in observed ventilation systems.

The cumulative duration figures present indoor carbon dioxide levels with room unit based ventilation. Different measurement periods are added.

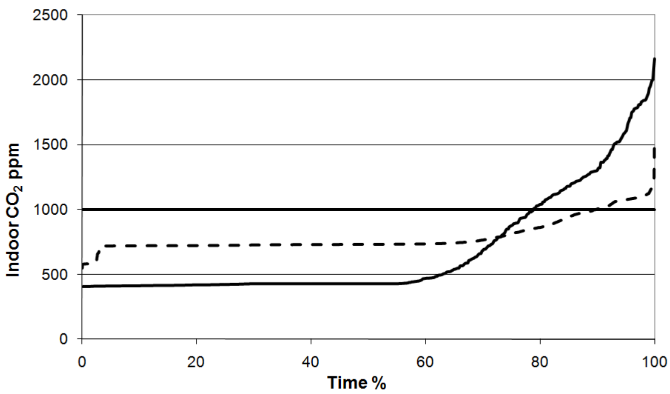

Fig.17. Indoor air CO_2 concentration duration graph in room 1.

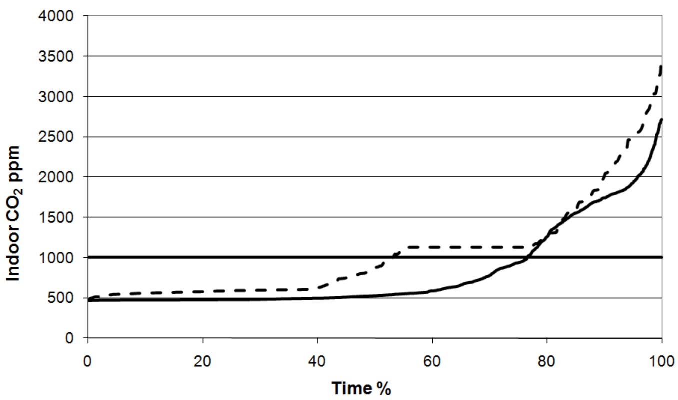

Fig.18. Indoor air CO_2 concentration duration graph in room 2.

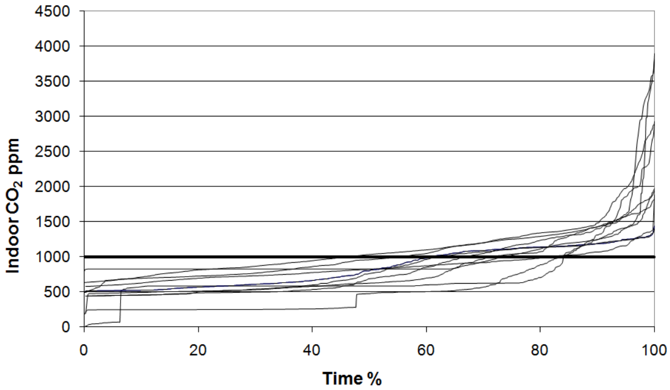

Fig.19. Indoor air CO_2 concentration duration graph in room 3.

Averagely 80% of the measured period satisfies the 1000 ppm normative. It is recommendable to add one more room based unit to one classroom to lower the carbon dioxide concentration and units sound level.

IV. CONCLUSION

Problems with indoor climate in educational institutions are well known in all countries. The carbon dioxide concentration is a problem not only in older schools, but also in new or lately renovated schools. Concentrations higher than 1500 ppm are commonly measured. In some cases 4000 – 5000 ppm has been measured.

The normatives about the carbon dioxide concentration in indoor air are quite strict - not more than 1000 ppm is generally allowed. So there is a conflict between the real situation (based on measurements) and health protection regulations. The studies show that the CO_2 concentrations higher than 10 000 ppm in room air cause various health problems. High CO_2 concentrations decrease the students' productivity. As children are more sensitive than adults the strict normatives are well justified.

The present study shows the dynamics of changes in the CO_2 concentration. The investigation includes both theoretical and practical approach. Also different ventilation solutions are compared:

- natural ventilation;
- centralized balanced ventilation;
- ventilation with room heat recovery units

Mostly is focused to the possibility to use room based ventilation units with heat recovery.

A rise in the CO_2 concentration with natural ventilation is in remarkable correlation with calculation results (Fig.1, Fig.2 and Fig.3). After 15 minutes of the normal class usage the indoor climate with natural ventilation is not acceptable. There is a slight decrease in the CO_2 concentration during the break.

The air change rate inside the classrooms can be estimated with the formula presented in methodology. Therefore separately air volumes are not presented.

Centralized mechanical ventilation gives generally good results to ensure the proper indoor climate, but there can also be problems. Energy consumption will be high if the classrooms usage profiles are not taken into consideration. Also the balancing of the centralized systems in many cases have not been done properly. It is also possible to build complicated VAV systems, but in reality these systems are noisy, expensive and hard to maintain.

Ventilation based on room units is flexible and energy efficient. The main shortcomings are higher noise levels at some speeds (must be taken into account in the design process) and human interference into the adjustment of the fan speeds. The best solutions would be control of the units with CO_2 sensors. It is necessary to add one unit to each classroom to satisfy the 1000 ppm requirement. In the city centre more attention has to be paid to outdoor carbon dioxide level, because it is an important aspect for planning the ventilation.

The price level of the small room ventilation units is getting more and more affordable to the different consumers. In addition, the installation does not need room consuming ducting installations. Therefore the solution can be recommended as a ventilation renovation measure. Further research into room-unit-based ventilation systems in educational buildings is be recommended.

REFERENCES

[1] Standard EVS-EN15251:2007.

[2] "Health-protection Ordinance for Educational Institutions", Ministry of Social Affairs in Estonia.

[3] Wikipedia

[4] Hens Hugo S.L.C., De Meulenaer, *Schools: All problem buildings?,* Proceedings of Clima 2007 WellBeing Indoors, 2007.

[5] Wim Zeiler, Gert Boxem, *Ventilation of Dutch schools; an integral approach to improve design.*, Proceedings of Clima 2007 WellBeing Indoors, 2007.

[6] Zs. Bako-Biro, N. Kochhar, D.J. Clements-Croome, H.B.Awbi and M. Williams, *Ventilation in Schools and Learning Performance.*, Proceedings of Clima 2007 WellBeing Indoors, 2007.

[7] T. A. Koiv, M. Rebane, P. Parre, *Indoor climate and improvement possibilities in educational premises.*, Proceedings of Clima 2007 WellBeing Indoors, 2007.

[8] T. A. Koiv, *Indoor climate and ventilation in Talllinn school buildings.*, Proceedings of Estonian Academy of Sciences. Engineering, 13(1), 17-25, 2007.

[9] T. A. Koiv, *Indoor climate and energy efficiency of apartment and educational buildings in Estonia.*, Proceeding of 3rd WSEAS International Conference on Engineering Mechanics, Structures, Engineering Geology, Corfu Island, Greece, July 22-24, 2010, 196-199. WSEAS.

[10] T. A. Koiv, H. Voll, M. Rebane, *Indoor climate in educational and residential buildings.*, Journal of Chonqqing University (English edition), December 08, 2009, 35-38.

[11] T. A. Koiv, H. Voll, K. Kuusk, A. Mikola, *Indoor Climate and Energy Consumption in residential buildings.*, Proceeding of 3rd International Conference on Energy and Development-Environment-Biomedicine, WSEAS Press 2009, 82-86.

[12] T. A. Koiv, H. Voll, K. Kuusk, A. Mikola, *Indoor Climate and Energy Consumption in residential buildings.*, Proceeding of 3rd

International Conference on Energy and Development-Environment-Biomedicine, WSEAS Press 2009, 82-86.

[13] A. Hani, T. Kalamees, T. A. Koiv, *Determination of energy performance requirements for apartment buildings in Estonia*, Proceeding of Healthy Buildings, Syracuse NY, 2009, Paper 409.

[14] T. A. Koiv, H. Voll, M. Rebane, *Indoor climate in educational and residential buildings.*, International Conference on Sustainable Development in Building and Environment, Chonqquing, 2009, 2.

[15] P. Tint, Ü. Kask, T.A. Koiv, T. Vinnal, K. Reinhold, *Improvement of environmental and health issues in educational institutions.*, Safety and Reliability for Managing Risks, Estoril, Portugal, 18-22 September 2006, 835-840.

[16] T. Lu, A. Knuutila, M. Viljanen, X. Lu, *A novel methodology for estimating space air change rates and occupant CO_2 generation rates from measurements in mechanically ventilated buildings.*, Journal Building and Environment 45, 2010, 1161-1172.

[17] M. Griffits, M. Eftekhari, *Control of CO_2 in naturally ventilated glassroom.*, Journal Energy and Buildings 40, 2008, 556-560

[18] K. Andersson, *Epidemiological approach to indoor air problems.*, Indoor Air , 1998/4, 32-9

[19] H. B. Awbi, AJ. Pay, *A study of the air quality in glassroom.*, Proceeding of 2^{nd} international conference on indoor air quality, ventilation and energy conservation in buildings, Montreal Canada 1995

[20] DJ. Clements-Croome, *Creating the productive workplace.*, Spon-Rouledge, 2000

[21] D. Mumovic, J. Palmer, M. Davies, M. Orme, I. Ridley, T. Oreszczyn, C. Judd, R. Critchlow, H. A. Medina, G. Pilmoor, C. Pearson, P. Way, *Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in England* Journal Building and Environment 44, 2009, 1466-1477