Ventilation – the key for adequate indoor air quality in classrooms

Marek Begeni, Vladimír Zmrhal

CTU in Prague, Faculty of mechanical engineering, Department of environmental engineering, Technická 4, 166 07 Prague 6, Czech Republic

Abstract

The paper describes current issue, which is indoor air quality (IAQ) at schools. It is generally known that the key to keeping for adequate IAQ is ventilation. Realized experimental measurements confirm assumption that the classrooms IAQ in Czech Rep. very often doesn't meet hygienic standard. This issues have societal character, as unsatisfactory IAQ has direct impact on the health of pupils, their illness and productivity as well. Due degradation of productivity, it is possible also observe effect on learning process. The paper also describes possible solutions of classrooms ventilation with respecting operation costs of each chosen system, which are natural ventilation, natural-occasional ventilation and forced ventilation. Minimum air flowrate is presented in relation of pupil's age and their current carbon dioxide production. Within study of this issue was done questionnaire survey, whose main findings are presented in the article below.

Key words: Ventilation, school, classroom, indoor air quality, CO_2

1. Introduction

In relation to massive reducing energy consumption by school buildings (windows replacement and thermal insulation of facades) is indoor air quality at schools frequent topic recently. Most of schools has openable windows, which are very often inappropriately designed and in this case is natural ventilation not working well [3]. The biggest problem is in winter time, when is natural ventilation by windows almost suppressed. Pupils spend dominant time of day in one classrooms and poor indoor air quality (IAQ) has got impact to their attention, study results and health. This is confirmed by number of studies as for example ([2], [6], [8], [10], [11], [12], [13], [14], [16], [18]).

According to the school facilities statistics (source: ČSÚ [attended nursery, primary and secondary schools approx.1,6 mil. pupils / students (in year 2013 / 2014). From the statistics is not clear, how many school buildings has already finished steps for energy consumption reduction. But with reference to questionnaire survey [4] and focusing of government financial subvention is possible considered, that poor ventilation rates and indoor air quality problem is relating to significant number of schools. Questionnaire survey shows, that 54 % schools (from number of participating) has got energy consumption reduction steps already finished, in case of windows replacement and facade thermal insulation. Next 16 % has got these steps finished, but together with heat source replacement. Suitable solution is probably forced ventilation; however it has some need for energy consumption. The energy consumption is in terms of electricity need for air transport and heat energy for reduction of heating loses by supply air. This point is questionable, because theoretically natural ventilation should need more energy consumption for heating in comparing to forced ventilation with heat recovery exchangers.

One of the main arguments against proper ventilation of classrooms is energy demand and investment. IAQ and living conditions for child (pupils / students) are up on other side. Ventilation (natural or forced) for sure brings some operation costs like energy consumption, maintenance costs and etc. Very often is possible meet opinion like „I will save a most of costs, when I will don´t ventilate“, it may seem in association to energy consumption reduction as reasonable, mainly when government hasn´t enough money for education in present time and also when is big pressure for buildings energy consumption reduction. This issue is in fact more extensive, there is all societal impact and it is connected to other sectors such as medicine, education, industry and etc. The health care costs resulting from poor IAQ is very difficult calculate and is mostly impossible to use this argument for improving indoor environments in schools.

1.1. CO_2 as the indicator

As the indicator of IAQ is often used concentration of carbon dioxide (CO_2), which is and can be relatively well observe. The production of metabolite CO_2 depends on human activities, age and proportions (weight / height). Within low activity as is for example sitting / resting is production lower compared to heavy physical work or sports activities. It is similar to heat production, which is heat transfer from body to environment. Dependence of CO_2 production to physical proportions of human and current activity can be described by equation (modified as in [1]):

$$V_{CO2} = 1{,}742 H^{0{,}725} W^{0{,}425} M \; [l/h] \qquad (1)$$

* Author´s contact : marek.begení@fs.cvut.cz

where H is height of the body [m],
W weight of the body [kg],
M metabolic heat [met].

Children age and CO_2 dependence is shown on Fig. 1. Children physical proportions were determined from growth charts used by paediatricians (50% percentile is used).

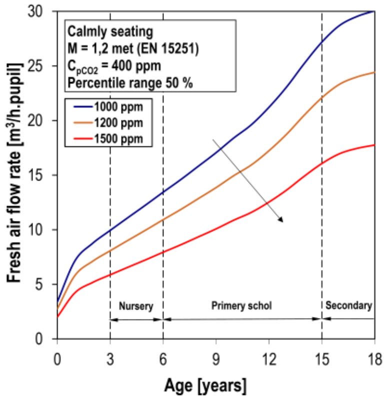

Fig. 1. *CO_2 production depending on children age*

1.2. CO_2 and others pollutants

In Tab. 1 is presented the influence of carbon dioxide in the air to human. In the schools, this influence is stronger, because of children. Children are more sensitive compared with adults. The result of unsatisfactory IAQ is especially low production, drowsiness, headache, higher illness (impaired immune system), and other symptoms of restlessness. In the extreme case and longer stay in impaired indoor environment, can lead to degradation of chronic diseases as is asthma, allergies and etc. [13], [7]. This is highlighted by fact that children spent in such unsatisfactory indoor environment to 80 % of their time.

Tab. 1. *CO_2 concentration and impact to human [10]*

CO_2 concentration [ppm]	Description of impact to human
380 – 400	Standard concertation in outdoor environment
800 – 1 000	Recommended level of indoor CO_2 concentration
1 200 – 1 500	Maximum acceptable indoor concentration
> 1 500	Occurring symptoms fatigue and low production
> 2 500	Drowsiness, lethargy, headache
< 5 000	Maximum indoor concertation without health risk
> 5 000	Increased heart rate, not recommended longer stay
> 10 000	Occurring health problems
> 40 000	Lethal

At indoor environment is however a number of other pollutants that have a significant impact to human health. Such as radon, water vapour, viruses, bacteria, volatile organic compounds VOC (often from furniture adhesive), dust and etc. In many of international studies for example [16] is stated, that placed carpet is increasing concentration dust particles.

All said pollutants may be removed from indoor environment with high efficiency by adequate ventilation. With respecting of surroundings of school is necessary select filtration of air or ventilation openings (off the street). Especially in city centers is limitation of natural or hybrid ventilation ambient noise.

1.3. Ventilation systems

For ventilation are generally used three types of systems – natural, hybrid and forced.

Natural ventilation

Natural ventilation systems are currently the most common type of ventilation in schools. This is most primitive method. Air flowrate is ensured by pressure difference between building interior and exterior. This system as is shown in next chapter is nowadays completely dysfunctional. The reason is that it is dependent on a number of boundary conditions such as the internal and external air temperature, the pressure effect caused by wind, pressure conditions in building including placement of classrooms. In past years, a similar system was widely used as leaky windows ensure sufficient air flowrate without opening. Current windows have almost no infiltration. Natural ventilation system is insufficient even when there is a short-term opening tiltable window that has a very low effective height to provide sufficient pressure differential, including a small area for air flowrate. Another problem is the incoming cold air in winter time, which can in close are to windows create thermal discomfort including significant ventilation heat loss.

Hybrid ventilation

It is a combination of natural and forced ventilation. In situation of unfavourable boundary conditions, when is impossible provide the required air flowrates by natural pressure difference, it will be created mechanically (by fan). The pressure difference may be created for example automatically via opening of the windows and set on exhaust fan, thereby creating a negative pressure in the room or open air shaft with sufficient effective height. This system is not often used, as it has very high demands on the pipe dimensions (shafts).

Forced ventilation

As the most suitable solution is offers a forced ventilation system which can be designed as balanced or negative pressure type. For balanced ventilation is usually used ventilation unit, which is able to provide air filtration, thermal air treatment including heat recovery and air flow control based on the quality of indoor air. Since it is an embedded mechanical work, which is necessary for air transport, this system requires with comparing to previous systems energy demand for fans. It requires also higher investment costs incl. maintenance costs. System design must be done with accordance to national standards and respecting noise emitted by fans. According to [4], 93% of school buildings were built before 1990, with windows providing natural air infiltration. For this reason it is often impossible to use a central ventilation system and is often need using decentralized ventilation units.

2. Classroom model

Fig. 2 shows CO_2 concentration in classroom with natural occasional ventilation during breaks by one day (in lessons is ventilation a minimum = 0,1 h^{-1}). Determination of CO_2 is done on the base of balance in ventilated room. Model allows study increase of carbon dioxide in classroom under various operation conditions including ventilation simulation during lessons and brakes with CO_2 production or without. It is seems, that during brake is possible reduce carbon dioxide concentration to level, where after following lesson is concentration slightly exceeding the limit value. Such result is possible achieved only with absence of pupils and teacher during brakes and guarantee intensive ventilation. Ventilation rate during brakes would be as high as 5 h^{-1}, and it is almost unrealistic to ensure such high flow rate only by window opening. Another problem is the expected significant reduction of the indoor air temperature in the classroom during winter and creation of discomfort.

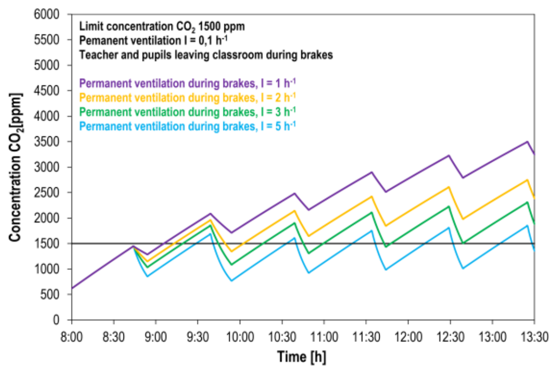

Fig. 2. Classroom model with CO_2 concentration

3. Questionnaire survey

To obtain information regarding situation and awareness of schools IAQ at Czech Rep. was implemented anonymous questionnaire survey [4] sent to the directors of elementary and secondary schools. Totally was asked for answer 5 777 educational entities and were received 1263. In terms of ventilation and windows construction, it was found that 72% of schools of the responses received, has new tight windows. In 51% of cases the windows are fully openable, 36% of the windows are tiltable with upper and lower wing. Only 8% of respondents replied that they have windows only with tiltable lower wing and 3% so-called micro-ventilation (Fig. 3)

Most respondents reported, that they are using windows for ventilation in different modes during lesson (Fig. 4). At the breaks have almost half of schools (40%) windows closed because of the safety of students or open only lower tiltable wings (18%) As is written later in the article, natural ventilation does not provide adequate indoor air quality. Despite this, 67% of respondents to subjectively answered that the IAQ as good or very good (Fig. 6). From the above it can be concluded that the majority of respondents unaware of problems.

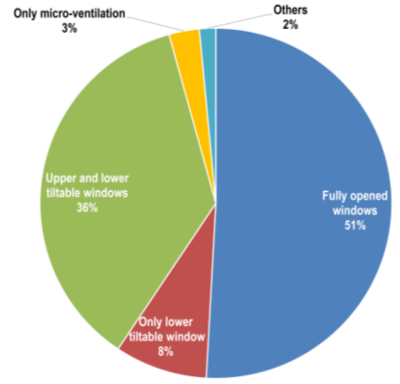

Fig. 3. Windows types used in schools from questionnaire

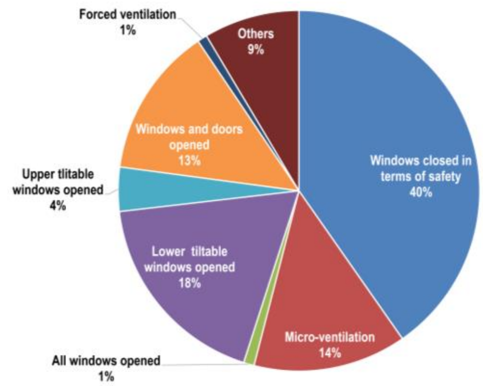

Fig. 4. Windows opening in schools during lessons

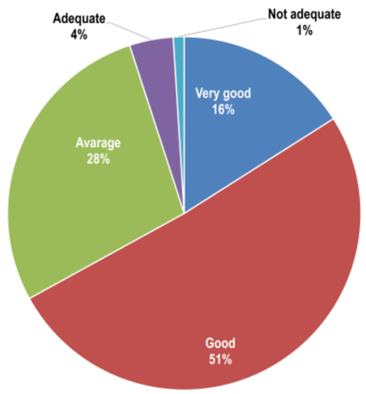

Fig. 5. Subjective evaluation by respondents

4. Experimental measurements

In this chapter is presented result of experimental measurements at several schools, which were made in winter, when the situation is the most serious.

Nursery

As the first is shown CO_2 concentration in nursery (Fig. 6). From presented concentrations may seem on the first view, that issue of IAQ is not actual. It is due several reasons. Nursery has completely different regime compared to other school types. In one day times schedule of nursery are different activities ensuring children leaving from classroom to outdoor. Children CO_2 production in this age is very low and last but not least is factor of attendance. Attendance of children and their time in nursery is irregular because it depends on possibilities of their parents who do not have place children to nursery every day.

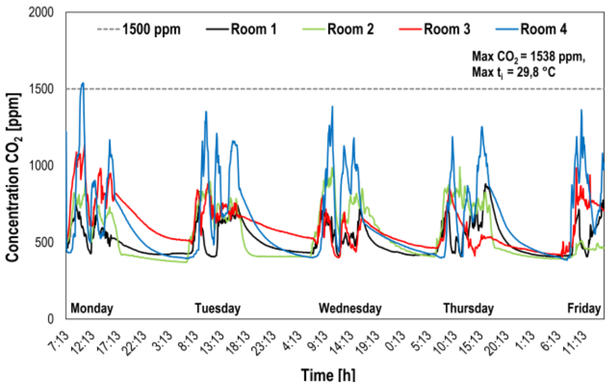

Fig. 6. *One week CO_2 concentration measurement in nursery*

Elementary school

The complete opposite of nursery is elementary school, where IAQ appears as the most serious. Time schedule is done and no. of pupils in one classroom is quite high (up to 30). Fig. 7 shows CO_2 concentration measurement.

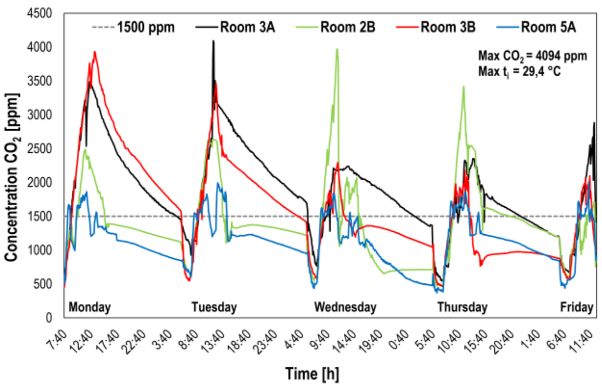

Fig. 7. *One week CO_2 concentration measurement in elementary school*

The results shown on Fig. 7 content also CO_2 concentration in classroom with ventilation unit (blue), which show significantly better results than others and with exceptions meet limit value which is 1500 ppm. The other classrooms are often significantly exceeding this value. In the studies have been measured concentrations exceeds 5000 ppm, which is according to tab. 1 with health risk. Character of the CO_2 concentration is always similar. After arrival of pupils to classroom is very rapid increase of CO_2 concentration up to very high value and this concentration remains nearly to the end of school day. Circumstances of stay in such environment were mentioned in paragraph 1.2

Secondary school

For completeness, Fig. 8 shows CO_2 concentrations in the classrooms of secondary school. Secondary school has similar operation as elementary school The difference is in the age of pupils / students, who produce large amounts of carbon dioxide (fig. 1) In terms of operation, high school classrooms is better, because students often change classrooms in the school system for individual courses.

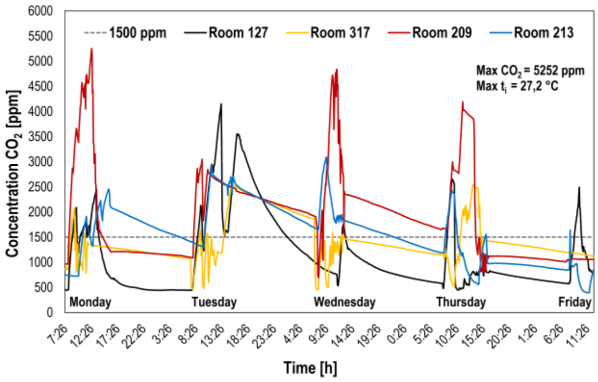

Fig. 8. *One week CO_2 concentration measurement in secondary school*

Classroom no. 209 (red line) on fig. achieves very high CO_2 concentrations exceeding 5000 ppm, but in other classrooms, it is also exceeding limit value of 1500 ppm. It means, that the issue of IAQ is present in the secondary schools as well. Like the elementary schools, by leaving the classroom is the rapid decrease of concentration and the next day, students come into the classroom with CO_2 concentrations corresponding approximately to the concentration same as outside.

4.1. The influence of IAQ knowledge

At lesson is most of windows closed, because of minimize cold air intake. Often reason is to save energy for heating. Similarly, it is during breaks, mainly for safety reasons and students are prohibited to open windows [4]. Therefore, the only one who can open the windows is always a teacher. Teachers, of course, are not able to assess for themselves the IAQ, and therefore is often very poor. For this reason, were made in normal operation measurements of carbon dioxide concentration (elementary school classrooms) with the location of the CO_2 sensor on the visible place. Teacher was learned about basic means of concentration shown on sensor and when to open windows. The result is then blue line on fig. 9, from which is evidently, that only the knowledge of CO_2 concentration can greatly contribute IAQ in classrooms.

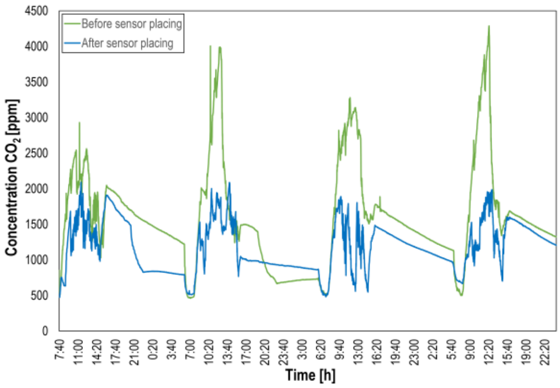

Fig. 9. *One week CO_2 concentration measurement with teacher knowledge of actual situation*

4.2. Comparison of various types of natural ventilation

To determine the real possibilities of natural ventilation by windows has been performed examining the impact of the opening to the air flowrate. In the classroom was artificially increasing CO_2 concentration and was examined different variants of natural ventilation by windows. From concentration decrease were determined air flowrates.

Totally 6 variants of natural ventilation were examined, differing in no. and type of opened windows. It was a typical classroom of elementary school from 70./80. with three pairs of windows constructed with tiltable lower wing (at the lower part) and fully openable upper part. - fig. 10.

Fig. 10. *Picture of the classroom*

The measurement results are on fig. 11, from which is evident that all variants have insufficient air flowrate (except variants with all open tiltable windows and any variant with open upper part). In tab. 2 is list of examined variants including calculated air flowrates from concentration decrease [15]. For measurement was used 5 CO_2 sensors placed on different position in classroom. From presented results is evident, that concentration is similar in each of these places in all classroom. Because of axil fans use during measurement to keep equilibrium concentration and to ensure adequate CO_2 mixing.

Under these conditions, it was found that the air flowrate by one tiltable window is in given conditions (t_e = -5,8 °C) and for this case is only 75 m^3/h. Which is on the base of current standards sufficient air flow for 3-4 pupils in age 6-10 years to keep concentration 1500 ppm.

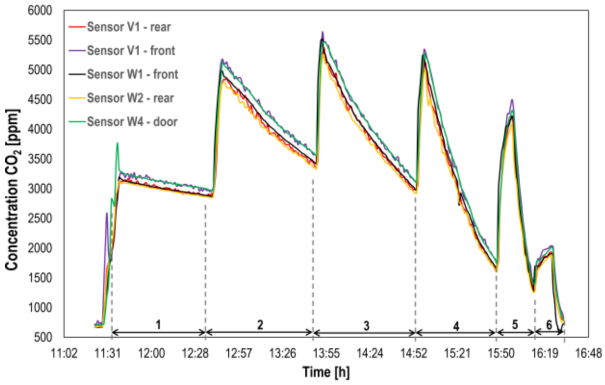

Fig. 11. *CO_2 depends on various type of natural ventilation*

Tab. 2 *Tested ventilation types including estimated flow rates*

No.	Description	Air flow rate [m^3/h]
1	Infiltration - All windows closed including doors, air flow rate only through windows and doors leakage	11
2	Opened one tiltable window, others closed	75
3	Opened two tiltable windows, others closed	131
4	Opened all tiltable windows (6), others closed	330
5	Opened one top window, others closed	1251
6	Opened two top windows, others closed	1994

5. Energy demand

The above paragraphs describe briefly the issue of IAQ in schools, including the various possible options and experimental measurements. Each ventilation system however brings certain operation costs. Natural ventilation have demand for heat energy to cover heat losses and forced ventilation have also demand for fan power of ventilation unit. For this reason, was carried out analysis [5] of total operation cost for classrooms ventilation including natural and forced ventilation (using ventilation units with heat recovery). Results of this analysis are on fig. 12.

There were analysed 17 decentralized ventilation units with heat recovery available on the Czech market (without further specification), with a nominal flowrate of 500 m^3/ h (flowrate per pupil 20 m^3/ h for 25 pupils). For the analysis were chosen units with ceiling or vertical installation. Technical data was taken from the ventilation units manufactures websites. For each unit was noted data of nominal air flowrate, power input and heat recovery ratio. From fig. 9 it is evident, that most of the units has SFP = 3000 W.s/ m^3. In analyses are not included central units, as well as units that have different nominal flow.

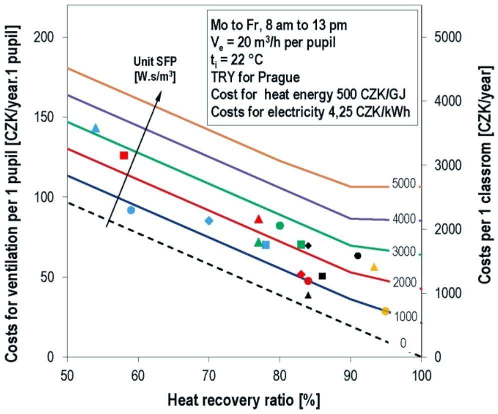

Fig. 12. *Total costs for ventilation per 1 pupil – points in graph represent specific air handling units (1 € = 27,5 CZK)*

When is used real unit, are real costs with decentral air handling unit and heat recovery in wide range **from 29 to 143 CZK/year per pupil.** It depends on type of unit and *SFP* respectively heat recovery ratio. From analyses is easy visible, that higher standard of air handling unit brings saving of operation costs.

6. Conclusion

This article presents a very broad issue of IAQ in schools, when a seemingly simple problem has quite complicated solutions. To keep adequate quality is needed to ensure an adequate air flowrate of fresh air - ventilation. Since the issue concerns mostly children in a certain stage of their development, this is a very serious issue with regard to societal and social aspect. As shown, the technical solution can be found, but with a series of limiting factors. The main limiting factor is investment cost of a forced ventilation system. Operating costs are relatively low, the analysis were estimated with average 71 CZK / year per student. Everything is a question of priorities and attitudes of schools founders, who are not following standards and laws. The main driving force is the possibility of subsidies (for example OPŽP). The current situation in the classrooms Czech schools is alarming. Students spend most of their time in inadequate environments that may affect their health. With regard to the energy savings requirements, forced ventilation solutions with heat recovery is the most appropriate and reliable solution. However, it is necessary to ensure the proper design and operation so as not counterproductive due to noise, drafts, etc.

List of symbols

M	metabolic heat (met)
H	height of the body (m)
SFP	specific fan power ($W/m^3.s^{-1}$)
V	air flow rate (m^3/h)
V_{CO2}	CO_2 production (l/h)
W	weight of the body (kg)

Abbreviations

ZZT	heat recovery (%),(-)
CO_2	carbon dioxide (-)
ppm	unit – parts per million (-)

References

[1] ASHRAE Handbook 2009 Fundamentals. 2009, Atlanta: ASHRAE. ISBN – 978-1-933742-55-7

[2] BAKÓ-BIRÓ, Zs, et al. Ventilation rates in schools and pupils' performance. Building and Environment, 2012, 48: 215-223.

[3] BEGENI, M., ZMRHAL, V. Větrání učebny základní školy. Vytápění, větrání, instalace. 2014, roč. 23, č. 4, s. 180-183. ISSN 1210-1389

[4] BEGENI, M., ZMRHAL, V. Dotazníkový průzkum stavu školských budov. In: portál TZB info. ISSN 1801-4399. 2015.

[5] BEGENI, M., ZMRHAL, V. Potřeba energie pro větrání učeben. Vytápění, větrání, instalace. 2015, roč. 24, č. 5, s. 218-222. ISSN 1210-1389

[6] Český statistický úřad. [online]. Dostupné z: http://www.czso.cz/csu/dyngrafy.nsf/graf/cr_od_roku_1989_skoly

[7] DAISEY, Joan M.; ANGELL, William J.; APTE, Michael G. Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information. Indoor air, 2003, 13.1: 53-64

[8] DE GIULI, V; DAPOS, Osvaldo; DE CARLI, Michele. Indoor environmental quality and pupil perception in Italian primary schools. Building and Environment, 2012, 56: 335-345.

[9] DE GIULI, V; DAPOS, Osvaldo; DE CARLI, Michele. Indoor environmental quality and pupil perception in Italian primary schools. Building and Environment, 2012, 56: 335-345.

[10] JINDRÁK, M. Větrání ve školách - požadavky a realita. In: Tepelná ochrana budov. 2013, roč. 16, č. 3, s. 20 - 24. ISSN 1213-0907.

[11] KAZMAROVÁ, H., et al.. Kvalita ovzduší ve školách: Projekt Sinphonie, www.szu.cz, 2011

[12] MENDELL, Mark J., et al. Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools. Indoor air, 2013, 23.6: 515 - 528.Buildings. Indoor air, 1999, 9.4: 226-252.

[13] Mi, Y.-H., Norbäck, D., Tao, J., Mi, Y.-L. and Ferm, M. (2006), Current asthma and respiratory symptoms among pupils in Shanghai, China: influence of building ventilation, nitrogen dioxide, ozone, and formaldehyde in classrooms. Indoor Air, 16: 454–464. doi:10.1111/j.1600-0668.2006.00439.x

[14] MYHRVOLD, A. N.; OLSEN, E.; LAURIDSEN, O. Indoor environment in schoolspupils health and performance in regard to CO2 concentrations. Indoor Air, 1996, 96.4: 369-371.

[15] ŠŤÁVOVÁ, P., RIV/68407700:21220/10:00175229 - Výpočet intenzity větrání při rovnovážné koncentraci CO2 - NCALC 3.0, [16] WARGOCKI, P, et al. The effects of electrostatic particle filtration and supply-air filter condition in classrooms on the performance of schoolwork by children (RP 1257). HVAC&R Research, 2008, 14.3: 327-344.

[17] WARGOCKI, P.; WYON, David P. Providing better thermal and air quality conditions in school classrooms would be cost-effective. Building and Environment, 2013, 59: 581-589.

[18] WYON, David P.; The effects of indoor air quality (IAQ) on performance, behaviour and productivity. Pollution atmosphérique, 2005, 2005: 35-41