IMPACT OF VENTILATION SYSTEMS ON INDOOR AIR QUALITY AND ANNUAL ENERGY CONSUMPTION IN SCHOOL BUILDINGS

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ABSTRACT

The paper presents the results of the analysis of the impact of various ventilation systems on indoor air quality and energy consumption, performed for a typical Polish elementary school that was built in 1970s. Simulations were made with the use of two computer codes: *CONTAM W* and *ESP-r*. A multizone model of the global capacity of 9464 m^3 was performed. The model contained 17 classrooms and 10 additional rooms typical of such buildings. The simulations were made for the whole heating season, the breaks in teaching and twenty-four-hour variability of internal heat gains were taken into account. The goal of the tests was to find a compromising solution which would provide good indoor environment and economical energy consumption. Carbon dioxide concentration was used as the air quality indicator, the seasonal energy consumption of the whole building was selected as the energy efficiency indicator.

The results clearly show that natural ventilation systems, traditionally applied in classrooms, cannot provide suitable conditions for learning. The CO_2 concentration is very often more than 3000 ppm. Indoor air quality is better when classrooms are regularly ventilated during breaks by opening the windows. However, during periods of low outdoor temperature it causes large decrease in the indoor temperature below 10 ^oC. Better quality of the indoor air can be achieved by using mechanical ventilation, which makes it possible to keep CO_2 concentration at the level of 1000 ppm.

KEYWORDS

school buildings, carbon dioxide, indoor air quality, simulation, energy consumption

INTRODUCTION

Indoor air quality is a factor which influences children's efficiency of learning. This is the reason why high level of the indoor air quality in classrooms is required in many countries. It may be obtained only by sufficient ventilation. Better quality of indoor air increases energy consumption which is opposite to the necessity of the energy saving.

It is commonly observed that ventilation rates are reduced from 7 l/s/p to even 0.5 l/s/p (Thompson[1998]). However, energy should not be saved without taking into account the occupant's comfort and health, especially in school buildings. Thus in design and analysis of ventilation systems the airflow rate cannot be reduced even it causes increase in the energy consumption.

The most popular indicator of indoor air quality is concentration of carbon dioxide generated by people. In most standards which, determine the necessary airflow rate, the value of 1000 ppm is applied as a limit of CO_2 concentration. This value was given in 1858 by German physiologist Pettenkofer[1858]. Up to now, the published analyses of air contaminations in school buildings have shown that indoor air quality in classrooms is not able to provide acceptable conditions for learning. In majority of the cases discussed carbon dioxide concentration in classrooms exceeds 1000 ppm, significantly reaching even 4000 ppm (Prill et al.[2002], Weinläder et al.[2000]).

In Poland most of the school buildings were built in 1960s and 1970s. These buildings are characterized by relatively high energy consumption. The increase in heating costs which was observed in 1990s showed how expensive the maintenance of such buildings was. For that reason, many of the buildings have been recently renovated. The purpose of such renovation is to reduce the energy consumption by means of thermal insulation, windows replacing and central heating modernising. However, modernization of ventilation systems is rarely performed.

The paper presents the results of analysis of the impact of different ventilation systems on indoor air quality and energy consumption. The analysis referred to a typical Polish elementary school, which was built in 1970s, after retrofitting (windows replacing + thermal insulation of external walls).

DESCRIPTION OF THE ANALYSIS

A four-storey elementary school building of total cubature 9464 m^3 and usable heating area of 2277 m^2 was chosen for the analysis. The building contained 17 classrooms and 10 additional rooms. Its technical data is presented in Table 1

TABLE 1
Technical equipment of the building

Building façade	external walls	brick 40 cm + polystyrene 8 cm; U=0.4 W/m^2K
	windows	double glass U=1.1W/m^2K air tightness factor a=0.2 $m^3/(mhPa^{2/3})$
	roof	rib-and-slab roof 22 cm, insulated by slag 20 cm + polystyrene 10 cm; U=0.3 W/m^2K
Heating	central heating system system with radiators, all radiators equipped with thermostats; gas boiler; all rooms except store-room are heated	
Ventilation ducts	all rooms except corridors equipped with gravitational ventilating ducts – one or two individual ventilating ducts (27×14 cm) connecting each room with the outlets on the roof	

The classrooms were occupied by 25 or 30 students and 1 teacher. The lessons were in progress from Monday to Friday according to the timetable from 8:00 am to 4:30 pm. One lesson lasts 45 min. and the brakes last 10 minutes except for the two long brakes which last 20 minutes.

The analysis was made with the use of two computer codes: *CONTAM W*, the latest version of which can simulate the control of ventilation rates based on contaminant concentrations (Dols and Walton[2002]) and *ESP-r*, the energy simulation system which is capable of modelling the energy and fluid flows (ESRU[1997]). The multizone model containing 21 zones was prepared (see Figure 1)

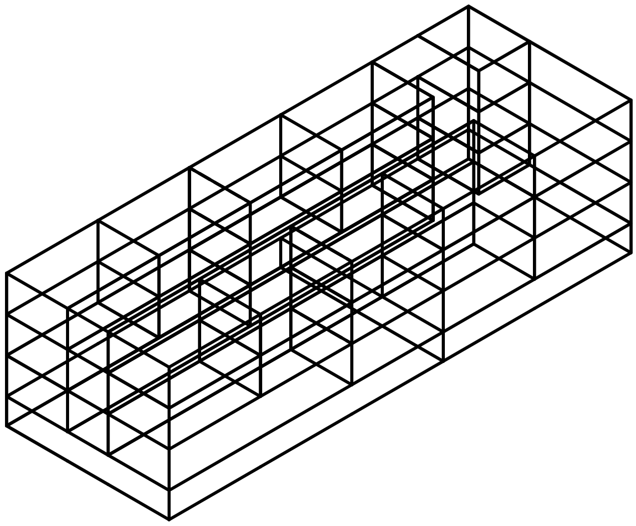

Figure 1 Multizone model

Simulations were made for the whole heating season, the breaks in teaching and twenty-four-hour variability of the internal heat gains were taken into account. It was assumed that each person in school was a source of emission of 13 l of carbon dioxide per hour as well as a source of sensible heat depending on the job: pupils during lessons 63 W, pupils during brakes 75 W, teachers 100 W and the others 95 W. The temperature in rooms was 20 ^{o}C from 6:00 am to 5:00 pm. In the evening and at weekends it was reduced to 15 ^{o}C.

Six ventilation systems were simulated. The fourth case was selected as the reference case:

A: Gravitational ventilation system, the windows in all rooms always closed.
B: Gravitational ventilation system, the classrooms additionally ventilated by opening the windows during brakes, in the other rooms the windows always closed.
C: Gravitational ventilation system, the windows in all the rooms equipped with air inlets, the classrooms additionally ventilated by opening one window during brakes, the other windows always closed; from 5:00 pm to 7:00 am and during weekends the flow through the air inlets limited to 20% of their whole capacity.
D: Mechanical, exhaust ventilation system: the windows in all the rooms equipped with air inlets operated as in case C, gravitational ventilating ducts in classrooms and in toilets equipped with roof fans of constant capacity: classrooms 470 m^3/h, toilet 360 m^3/h. The fans operating on working days from 8:00 am to 4:30 pm, afterwards gravitational ventilation system used. The other rooms as in case C, in all the rooms the windows always closed.
E: As case D but the fans in the classrooms equipped with CO_2 DCV control.
F: Mechanical, supply and exhaust demand controlled ventilation system: the classrooms equipped with individual compact air unit with rotary heat recovery unit (recovery efficiency depending on the airflow with the average from 60% to 80%), the units equipped with CO_2 DCV. The units operating on working days from 8:00 am to 4:30 pm, afterwards gravitational ventilation system used. The other rooms like as case D, in all the rooms the windows always closed.

Figure 2 presents the systems described above for one classroom (fourth storey, on the west side of the building)

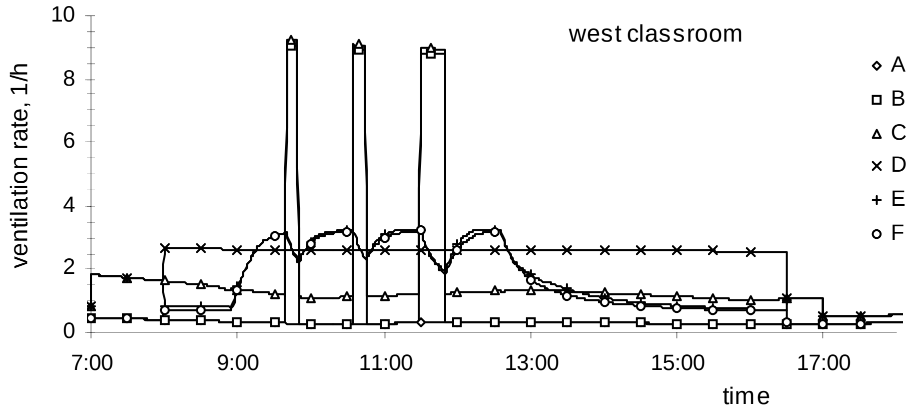

Figure 2 Airflow in six case study for one classroom during one day

Each of the cases was simulated for a period of 7 months – the whole heating season (from October to April) at 1 min time step. The energy analysis accounted for the total load of building. This load was determined for each case over an entire heating season of the weather data for Warsaw climate.

RESULTS

In result of the simulations, the text files containing the values of the ventilation airflow in each zone, distribution of carbon dioxide concentration in the classrooms, heat demand for ventilation air heating and total heat demand of the building. The calculation results are presented in Fig 3 and 4 and Table 1 and 2.

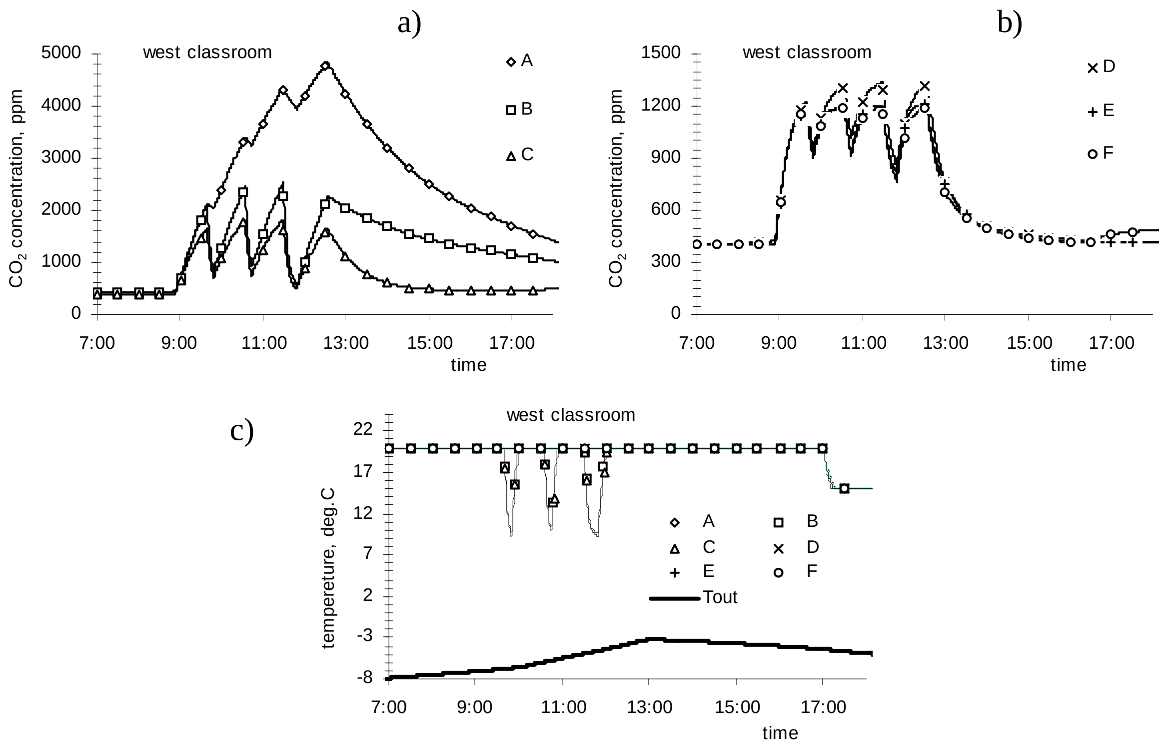

Figure 3 a), b) CO_2 concentration during one day for the classroom selected (see Fig. 2)
c) indoor temperature during one day for the classroom selected (see Fig. 2)

The variation of airflow rates for the cases considered, average in the heating season (October to April) are presented in Table 1. As an indicator of the indoor air quality CO_2 concentration in classrooms during lessons was assumed (only net time of lessons). Figure 4 presents the average distribution of CO_2 concentration in the classrooms for cumulative distribution function 50% (C50) and 90% (C90).

Case A illustrates the conditions in schools after retrofitting, where ventilation systems have not been renovated. Ventilation rates at the level of 0.3 1 per hour result in low indoor air quality, when carbon dioxide concentration reaches 5000 ppm. Additional ventilation of the classrooms by opening the windows during the brakes (case B) could improve situation, the maximum CO_2 concentration falls below 3000 ppm, but during the periods of low outdoor temperature it causes large decrease in the indoor temperature below 10^{o}C (see Fig.3c).

TABLE 1
Average ventilation airflow and carbon dioxide concentration in building

			A	B	C	D	E	F
Ventilation rate, 1/h	working days: 8:00 am÷4:30 pm	classrooms	0.3	0.8	1.6	2.6	1.7	1.7
		toilet	0.2	0.2	2.0	3.1	3.0	2.4
		the other rooms	0.3	0.3	0.5	0.6	0.5	0.5
		the whole building	**0.3**	**0.4**	**1.4**	**2.1**	**1.7**	**1.5**
	working days: 4:30 pm÷8:00 am weekends and holidays: all day long	classrooms	0.3	0.3	0.5	0.5	0.5	0.3
		toilet	0.2	0.2	0.6	0.6	0.6	0.4
		the other rooms	0.2	0.2	0.3	0.3	0.3	0.3
		the whole building	**0.2**	**0.2**	**0.5**	**0.5**	**0.5**	**0.3**

Satisfactory indoor air quality is acquired only with the use of mechanical ventilation systems (case D-F) by providing several times higher ventilation rate Then, the average CO_2 concentration in classrooms during lessons does not reach 1000 ppm (see Fig.4).

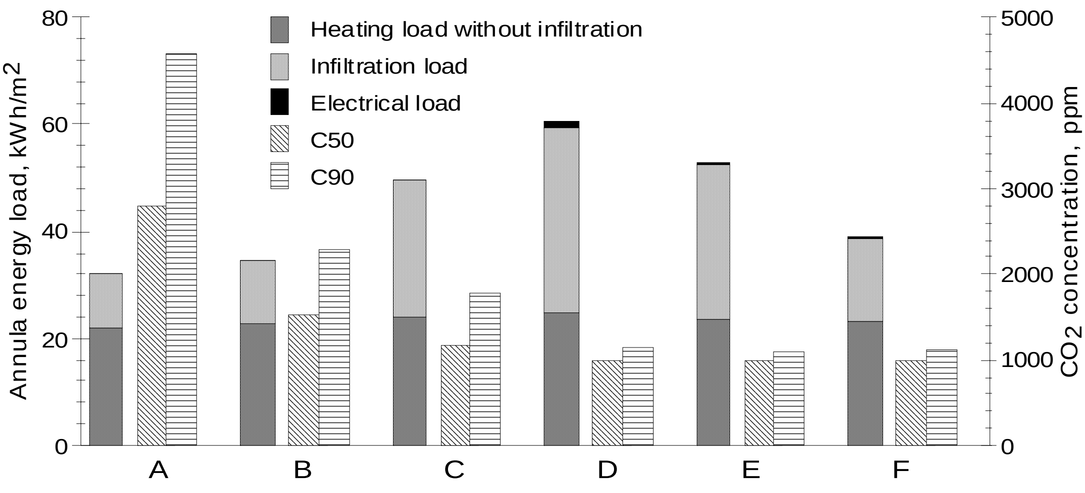

Figure 4 Annual energy consumption in the whole building and CO_2 concentration, average in all classrooms

Annual energy consumption, divided into infiltration and electrical energy for fans is presented in Figure 4 and Table 2.

TABLE 2
Annual energy consumption and average concentration of CO_2 in the building

	A	B	C	D	E	F
Infiltration, kWh/m^2	10.1	11.8	25.5	**34.6**	28.8	15.6
Electrical load, kWh/m^2	-	-	-	**1.2**	0.7	0.4
Total heating load, kWh/m^2	32.1	34.7	49.5	**59.3**	52.3	38.6
Ratio of heating loads (in comparison with case D)	54%	58%	83%	**100%**	88%	65%
Average CO_2 concentration in classrooms, ppm	2787	1539	1172	**991**	991	994
Ratio of CO_2 concentration (in comparison with case D)	281%	155%	118%	**100%**	100%	100%

Table 3 presents estimated investment costs for introduction of the analysis systems to existing school building.

TABLE 3
Investments costs for introduce discussing ventilation systems

	A	B	C	D	E	F
Investments costs, EURO	-	-	6 500	30 000	40 000	110 000

CONCLUSIONS

The results of the simulations show variability of ventilation rates and the indoor air quality related to it in the analysis of school buildings and total energy consumption for heating. It may be concluded that natural ventilation systems, commonly used in Polish schools, are not able to provide acceptable conditions for learning. Indoor air quality is improved when classrooms are regularly ventilated during breaks by opening the windows. However, during periods of low outdoor temperature it causes dramatic decrease in the indoor temperature (below 10^{o}C). The best quality of the indoor air can be achieved by using mechanical ventilation, which makes it possible to keep CO_2 concentration at the level of 1000 ppm. Maintaining such good indoor air quality in the existing school buildings is connected with the increase in the heating costs. Investments for such renovations should not be considered only from the economical point of view but as necessity in respect of the pupil's health and comfort.

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