Indoor Air Quality and Thermal Environment in Classrooms with Different Ventilation Systems

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This article presents the measurements of indoor climate in classrooms in the same school in Denmark. The classrooms had different ventilation systems: Ventilation was achieved either by manually operable windows, or by automatically operable windows with and without an exhaust fan in operation, or by a balanced mechanical ventilation system. Indoor air temperature and carbon dioxide (CO_2) concentration, as well as opening of windows were continuously monitored for one month in the non-heating and heating seasons; measured CO_2 concentration was used to estimate average classroom ventilation rates. The results show that mechanical ventilation and natural ventilation with automatically operable windows with exhaust fan performed notably better than the other systems. They indicate also that opening of windows was largely affected by customs and habits. Present results can be used as the basis for rational selection of systems that ensure adequate classroom ventilation.

Keywords: school, classroom, ventilation system type, indoor temperature, carbon dioxide.

Introduction

The main purpose of classroom ventilation is to create indoor environmental conditions that reduce the risk of health problems among pupils and minimise their discomfort to avoid negative effects on learning [1-5].

Classroom ventilation is still provided in many schools in Europe by expecting that teachers and pupils will open the windows [6-7]. An increasing number of school classrooms are being now fitted with other methods for achieving classroom ventilation. These include among others automatically operable windows, extract ventilation using exhaust fans or mechanical ventilation systems with balanced supply and exhaust from a central or local air-handling unit. There are yet no systematic data on the performance of these various types of ventilation in schools, especially as regards their impact on the indoor climate in classrooms, on the health of pupils and teachers or on learning; some data exist on their energy performance [8-9]. Interestingly, there are also very little data on the window opening behaviour of pupils and its effect on classroom ventilation and indoor climate; some data on window opening behaviour is available for other types of buildings especially dwellings [10].

The main objective of the present work was to provide data on long-term performance of different methods for achieving classroom ventilation and their influence on the indoor climate in classrooms [11].

Figure 1. Classrooms, where the measurements took place: (a) classroom with automatically operable windows and exhaust fan; (b) mechanically ventilated classroom.

Methodology

The study was performed in an elementary school in Denmark located in rural area north of Copenhagen. Three classrooms were selected where ventilation is normally achieved by automatically operated windows and exhaust fan (**Figure 1a**). Two of these classrooms were adapted for the purpose of the present experiments to create two different modes of ventilation with either manually or automatically operable windows; the control in the third classroom remained unchanged. Additionally one classroom was selected where ventilation is achieved by a balanced mechanical ventilation system at a rate of 120 L/s per class (**Figure 1b**). All classrooms could be additionally ventilated (aired) by windows/garden doors that could be opened manually by pupils and/or teachers. None of the classrooms had mechanical cooling installed. The typology of all classrooms is presented in **Table 1**.

The measurements were performed for one month both in the non-heating season (May) and the heating season (November-December). They included the measurements of CO_2 concentration using a VAISALA GM20D sensor (accuracy: ±30 ppm +2% of the

Table 1. Typology of classrooms, in which the measurements were performed.

Classroom	Acronym	Description of ventilation systems	Average occupancy		Space volume	Floor area
			Non-heating season	Heating season	(m^3)	(m^2)
1	MW	Classroom ventilated (aired) by manually operable windows	22	19	123.5	49.4
2	AW	Classroom ventilated primarily by automatically operable windows	24	22	123.5	49.4
3	AW/EF	Classroom ventilated primarily by automatically operable windows and exhaust fan	25	24	123.5	49.4
4	MV	Classroom ventilated primarily by the mechanical ventilation system	20	16	180	72

reading) connected to a HOBO U12 logger. The logger recorded additionally the classroom temperature (accuracy: ±0.7°C) and relative humidity (RH) (accuracy: ±5% RH). Opening of windows (both manually and automatically operable) and garden doors was registered using HOBO State loggers, which were attached to the frame of each window/door in every classroom where the measurements took place. Mass balance model was used to estimate ventilation rates assuming the CO_2 generation rate per pupil to be 0.004 L/s and per teacher 0.0054 L/s; average peak CO_2 concentration was used to approximate the minimum outdoor air supply rates [12]. The outdoor CO_2 was assumed to be 350 ppm.

Results and discussion

Measured classroom temperatures in the non-heating season were systematically higher than those in the heating season (**Figure 2**). Measured temperatures in different classrooms in the non-heating season were between 22°C and 26°C and were not alike: The highest temperature was measured in the classroom, where ventilation could only be achieved by opening the manually operable windows/garden door, and the lowest temperature was measured in the mechanically ventilated classroom. Still, the classrooms can be generally classified as spaces, where high expectations of thermal conditions are met independently of the type of ventilation system installed [13]. In the heating season, the mean weighted classroom temperatures were between 19°C to 25°C the temperatures. The temperatures in classrooms without mechanical ventilation were similar; in classroom with mechanical ventilation, the temperatures in the morning were slightly lower. Consequently, the classrooms, which did not have mechanical ventilation system, could be classified as spaces fulfilling a high level of expectation, while the classroom with the mechanical ventilation system met only a moderate level of expectation [13]. The classrooms were heated by water-filled radiators placed under the windows. The radiators were equipped with thermostatic valves but their set points were not recorded during the measurements. The difference in temperatures in the classrooms could therefore have occurred due to different set points of these valves, which could be operated by the teachers and pupils according to their needs.

Measured CO_2 concentrations in the classrooms were systematically lower in the non-heating season than in the heating season (**Figure 3**). Average CO_2 concentration was below 1,000 ppm in the non-heating season in all classrooms and only in the classroom where windows had to be opened manually to achieve ventilation was the peak concentration higher than 1,000 ppm. There were clear differences in the average CO_2 concentration in classrooms during the heating season: CO_2 concentrations were close to or higher than 1,000 ppm in all classrooms and the highest concentration was measured in the classroom where windows had to be opened manually to achieve proper ventilation (airing), while the second highest CO_2 concentration was observed in the classroom with automatically operable windows where no exhaust fan was in operation.

Danish Building Regulations stipulate that the ventilation rates in classrooms should be about 6 L/s per person [14]. The estimated outdoor air supply rates met the requirements of the Danish Building Regulations only in the classroom with a mechanical ventilation system and were close to these requirements in the classroom with automatically operated windows with an exhaust fan. During the heating season, the estimated ventilation rates were lower than in the non-heating season and only the classroom with the mechanical system fulfilled the requirements of the Danish Building Regulation (**Table 2**). The lower ventilation rates are most likely the consequence of the less frequently opened windows, both manually and automatically (**Figure 4**). Especially lower outdoor temperature cause cold drafts indoors and reduce window opening. Consequently, there is a need for installing an alternate system that can provide the ventilation when windows have to remain closed due to unfavourable weather conditions, or to inform the pupils and teachers when they ned to be opened [15].

Table 2. Peak CO_2 concentration and the estimated ventilation rates in classrooms with different ventilation systems [mean (s.d.)] (for acronyms see ***Table 1***).

	Non-heating season				Heating season			
	MW	AW	AW/EF	MV	MW	AW	AW/EF	MV
Peak CO_2 concentration (ppm)	1463 (273)	1319 (154)	1093 (147)	887 (149)	2200 (436)	1447 (248)	1303 (185)	954 (147)
Estimated ventilation rates (L/s per person)	3.8 (0.9)	4.3 (0.8)	5.6 (1.0)	7.8 (1.2)	2.3 (0.6)	4.2 (0.9)	4.5 (1.3)	7.3 (1.8)

Based on the number of opened windows and the duration of the windows opening registered by the loggers, the average time during which windows were open per day in different classrooms was calculated separately for the non-heating and heating season (**Figure 4**). The results show that manually operable windows/garden doors were opened less often in the heating season, and generally much longer in the classroom where the windows/garden door had to be open manually to achieve ventilation (airing) of the classroom.

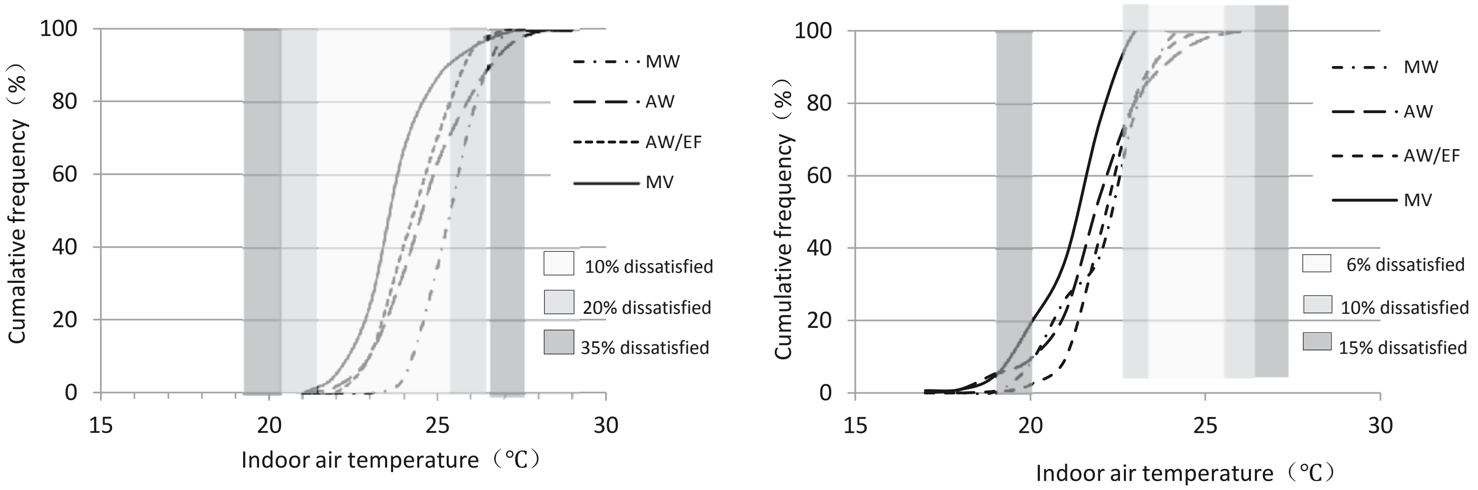

Figure 2. Temperatures during school hours in classrooms with different ventilation systems in the non-heating season (left) and the heating season (right); bands indicate ranges of indoor temperatures with different level of expectation concerning thermal environment according to EN15251 [13] (for acronyms, see ***Table 1***).

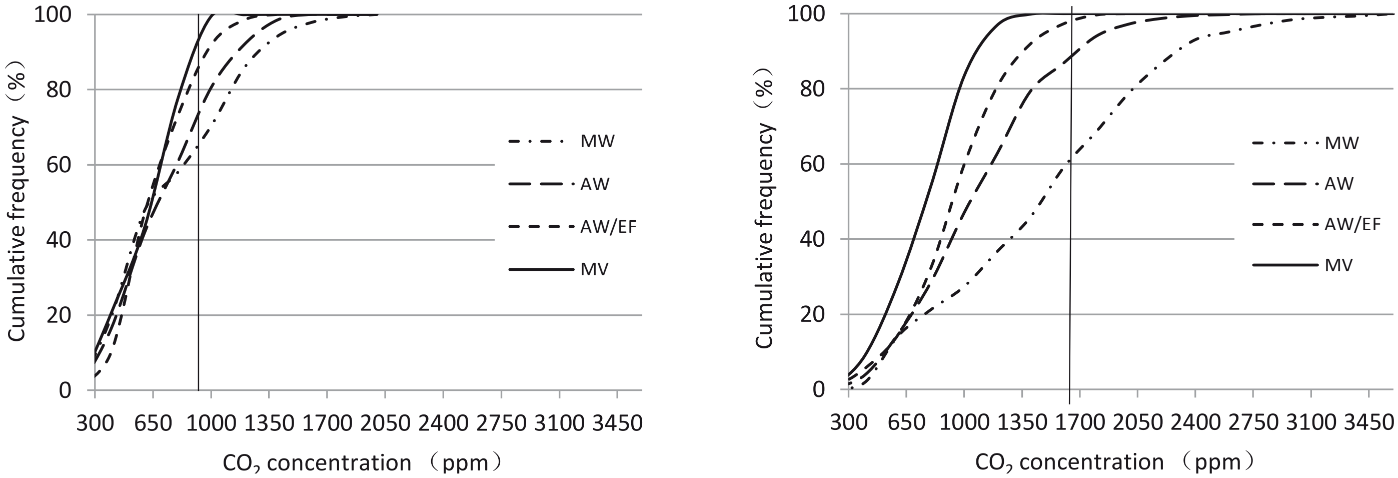

Figure 3. CO_2 concentration during school hours in classrooms with different ventilation systems in the non-heating season (left) and the heating season (right); the line shows CO_2 at concentration of 1,000 ppm, the level which should not be exceeded in classrooms [14](for acronyms see ***Table 1***).

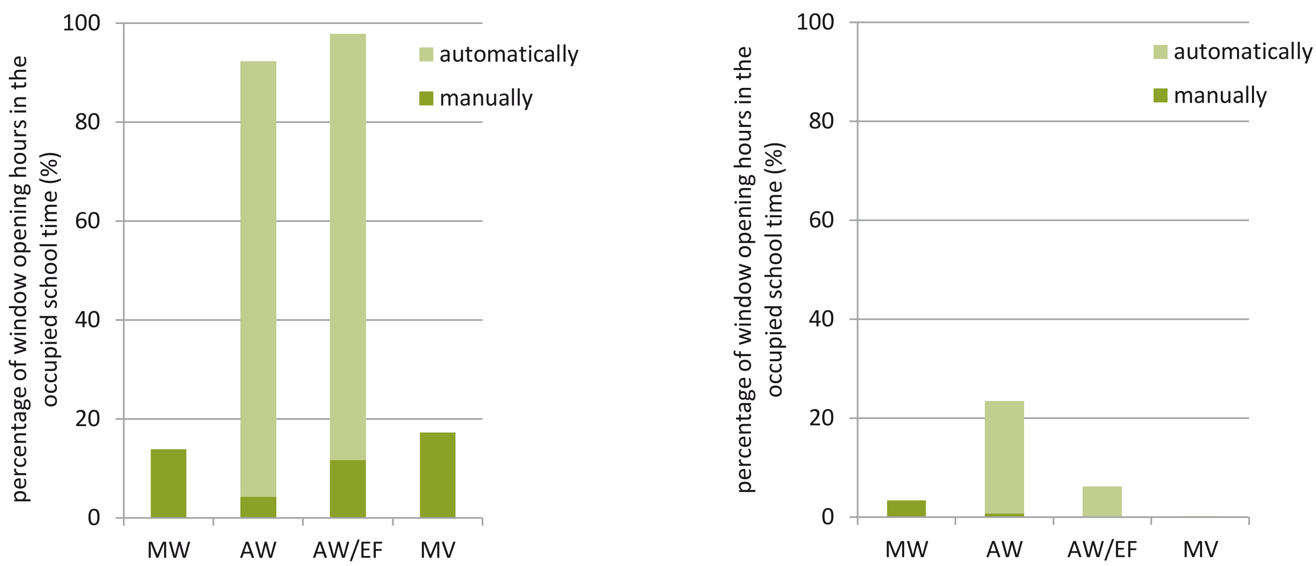

Figure 4. Proportion of time with windows open during school hours in classrooms with different ventilation systems in the non-heating season (left) and the heating season (right) (for acronyms see ***Table 1***).

The total period, during which all windows/garden doors (manually and automatically operable) were opened in different classrooms was much longer in the classrooms with automatically operable windows. This was especially the case in the non-heating season, when they were opened nearly for the entire school day, i.e. on average 6 to 7 hours per day. The windows were opened even in the classroom with a mechanical ventilation system, which suggests that window opening is largely affected by the habits and customs of the occupants.

Conclusions and implications

The measurements show that the performance of mechanical ventilation and natural ventilation with automatically operable windows in which adequate ventilation is assured was notably better than in the classrooms where windows had to be opened manually for achieving ventilation or where windows were opened automatically but with no means of ensuring that this would provide adequate ventilation (exhaust fan idled). The present results have not clearly determined which of the two preferred systems is better. The two most important selection criteria are energy use and the need for conditions that do not have a negative effect on learning. Neither of them was determined. School location and climate conditions are also among factors that can be considered when selecting the ventilation system. In the present case, the ambient pollution levels did not place any restriction on the use of natural ventilation systems with manually or automatically operated windows: The school was located in suburban area. In places where the ambient pollution does not meet the levels recommended by the WHO [16], some means of filtration and air cleaning must be applied before the air can be admitted indoors.

The strength of the present measurements is that they were performed for a relatively long time (1 month) in two different seasons, so the results are applicable to the entire school year. The limitation is that the classroom where exhaust fan was idled was not especially designed for one-sided natural ventilation to promote cross-ventilation. Furthermore, the teachers and pupils were accustomed to having automatically operable windows even in the classroom where they were idled. This could to some extent influence and reduce the number of windows that were opened manually. Despite these limitations, present results represent the approach and basis for a rational selection of systems that ensure adequate classroom ventilation and acceptable indoor environmental quality throughout the entire school year. ■

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