A comparative analysis of the indoor air quality and thermal comfort in schools with natural, hybrid and mechanical ventilation strategies

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SUMMARY

Within the UK, the importance of providing adequate ventilation in schools has been recognised in a recently adopted document (Building Bulletin 101), which defines the set of performance criteria in relation to ventilation rates and indoor air quality in new school buildings. This paper describes a series of field measurements that investigated the ventilation rates and indoor air quality in three new secondary schools in England with respect to these new criteria. The study also analysed the overall performance of the integrated heating and ventilation systems with regards to comfort. All the schools satisfied the recommended ventilation performance standards during the week that the measurements were undertaken. However, this apparently reassuring message can be misleading unless one takes into account both the original design assumptions and then the actual occupancy of the classrooms and occupant behaviour in general. With regards to comfort, for many rooms the schools did not meet the relevant recommended levels.

INTRODUCTION

The UK Government has committed to a massive programme of rebuilding and refurbishing schools in England and Wales in the next 10 to 15 years [1]. To underpin this programme, entitled ‘Building Schools for the Future’, the Department for Education and Skills has published design guidance - Building Bulletin 101 ‘Ventilation in School Buildings’ [2]. This performance standard document is cited as a means of compliance with the new Building Regulations Part F (Ventilation) in England and Wales [3]. In this document CO_2 concentration has been chosen as the key performance indicator for the assessment of indoor air quality and ventilation performance in schools. The recommended ventilation performance standard can be summarised as follows:

1. the average concentration of CO_2 should not exceed 1500 ppm
2. the maximum concentration of CO_2 should not exceed 5000 ppm during the teaching day
3. at any occupied time the occupants should be able to lower the concentration of CO_2 to 1000 ppm
4. purpose provided ventilation in naturally ventilated buildings should provide external air supply to all teaching and learning spaces with (a) a minimum of 3 l/s per person, (b) a minimum daily average of 5 l/s per person and (c) a capability of achieving a minimum of 8 l/s per person at any time

5. purpose provided ventilation in mechanically ventilated buildings should provide external air supply to all teaching and learning spaces with a minimum of 5 l/s per person at all time, and (b) a capability of achieving a minimum of 8 l/s per person at any time

In addition to the requirements stated in Building Bulletin 101, the authors have investigated if the comfort of occupants was compromised by the ventilation strategy. A previous study has highlighted thermal comfort as an important aspect of providing winter time ventilation [4]. Taking these requirements into account, this paper focuses on a comparative analysis of indoor air quality and thermal comfort in three recently built schools in England with different ventilation strategies: natural, hybrid and mechanical.

METHODS

Measurements were carried out in three schools in England during the heating season 2005-2006. All schools were built in compliance with Building Bulletin 93 [5], which defines noise and acoustic criteria in relation to school design. The monitoring was carried out in two selected classrooms in each school over a period of five working days. Levels of CO_2 were monitored at five-minute intervals throughout the occupied day close to the occupied zone at seated head height to indicate the overall indoor air quality and provide a means of inferring the ventilation rate based on the number of occupants. Two Gascard II infra-red gas monitors ($MYCO_2$) (accuracy: 2% of the range - 0-5000 ppm) coupled with HOBO dataloggers were used for the indoor measurements. In addition, outdoor CO_2 was measured using a Telaire 7001 infra-red gas monitor (accuracy: 50 ppm or 5% of the reading, whichever is greater). Ventilation rates were also estimated over suitable intervals using Equation 1, a form of 'continuity equation' [6] [7] [8]:

$$C_{(t)} = C_{ex} + \frac{G}{Q} + \left(C_{in} - C_{ex} - \frac{G}{Q} \right) e^{-\frac{Q}{V}t} , \qquad (1)$$

where: $C_{(t)}$ - internal concentration of carbon dioxide at time t (ppm), C_{ex} - external concentration of carbon dioxide (ppm), G - generation rate of carbon dioxide in the space (cm^3/s), Q - internal-external exchange rate (m^3/s), C_{in} - initial concentration of carbon dioxide (ppm), V - room volume (m^3), and t - time (s).

In addition to CO_2 levels, the following thermal comfort parameters were measured during the occupied periods in each of the selected classrooms:

1. dry bulb temperature, measured via: a screened platinum resistance sensor to eliminate any thermal radiation effects, an air velocity compensation sensor and a relative humidity compensation sensor.
2. relative humidity was measured with a VAISALA capacitive sensor
3. globe temperature was measured with a platinum resistance sensor within a 30mm black sphere
4. air velocity was measured with a DANTEC heated thermocouple sensors

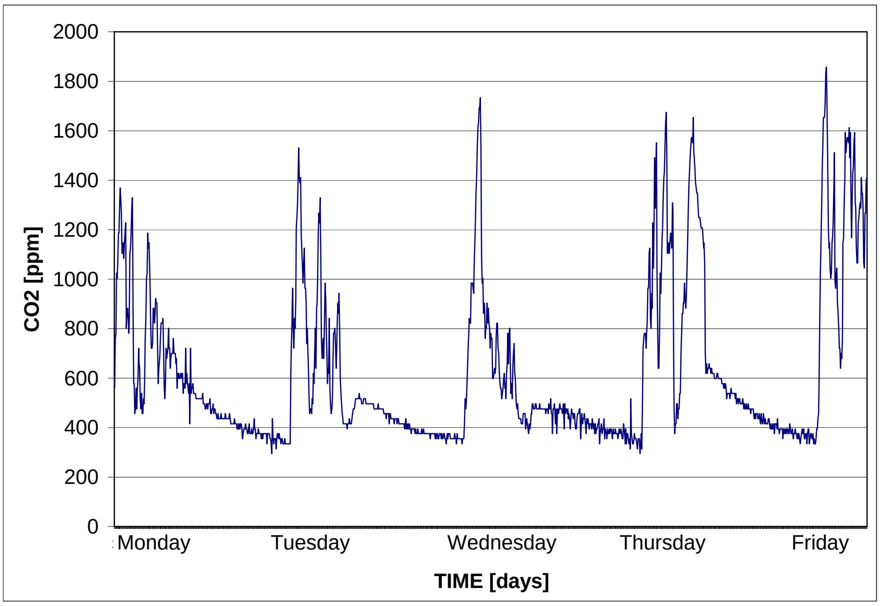
Measurements made every second were averaged over 2 minute intervals. The thermal comfort parameters were measured at two locations simultaneously, one being fixed at the normal work position of a pupil close to an openable window, while the second thermal comfort analyser was moved at different locations across the rooms. The procedure laid out in ISO Standard 7730-1995 was used to determine the PPD (percentage of people dissatisfied) and the DDR (draught dissatisfied rating) indices and specifications of the conditions for thermal comfort. A brief description of the ventilation strategy and findings for each school is given below.

RESULTS

<u>School 1 - Natural Ventilation strategy</u>: This school is located at an exposed rural site and represents a basic single sided naturally ventilated design with openable windows into deep classrooms. Each room had three top hung windows but each had a maximum opening angle of 30°. Some thought had been given to providing cross ventilation by providing a small grill into the suspended ceiling and a duct that led to the atrium space from which the classrooms were entered. No fan was found. A smoke test carried out suggested that the ducted extract contributed insignificantly to the ventilation strategy in the room. Heating was provided by low temperature hot water radiators located under the openable windows. Both classrooms (NV1 and NV2) have an identical ventilation strategy, but different use. Whilst room NV1 was used as a seminar room, room NV2 was used as a 'typical' whiteboard classroom. A number of small intervention studies were carried out in each classroom (windows opened/closed, etc.) to test the capabilities of the design to adequately ventilate the room. Note that the number of students during the 'observed' occupancy in the rooms was very low - usually 50% of the 'as designed' number of occupants. Therefore, two ventilation rates were calculated and reported. For example: in the case of the naturally ventilated room NV1 with three top hung windows opened the calculated ventilation rate for the 'observed' occupancy of 10 occupants was 11.7 l/sp. However, the ventilation rate in the case of the 'as designed' occupancy of 30 reduces to 3.9 l/sp.

Table 1: School 1 – summary of IAQ measurements

A typical CO_2 levels in a room with natural ventilation strategy (NV1)



CO_2 levels [ppm]*

Classroom	NV1	NV2
average	960	1054
STD	331	397
maximum	1857	1725

Comments:
*note that the occupants kept the door to the atrium open most of the time
** calculated for 10 occupants (calculated for 30 occupants)
*** calculated for 30 occupants

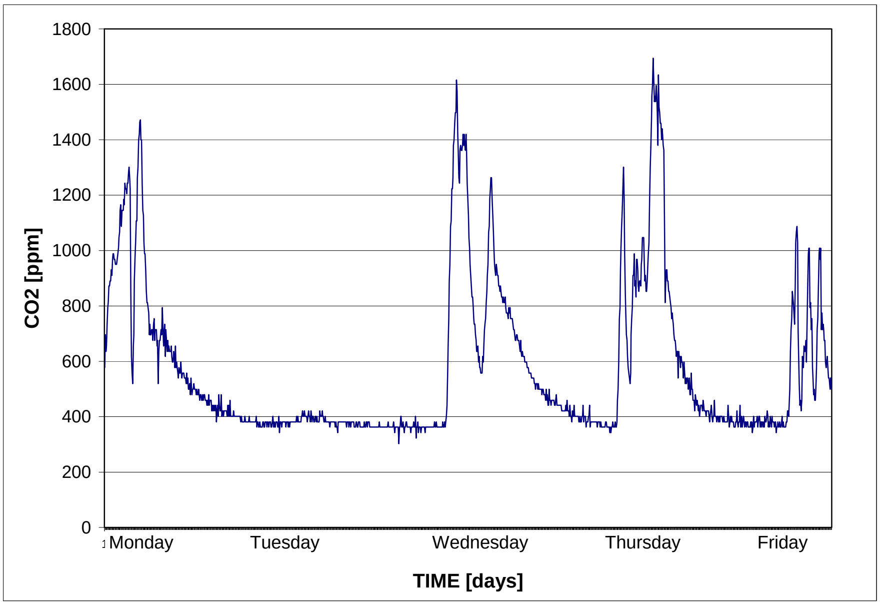
Intervention	All windows opened (l/sp)	2/3 of all windows opened (l/sp)	1/3 of all windows opened (l/sp)	All windows closed (l/sp)	Cross ventilation (l/sp)
NV1**	11.7 (3.9)	n/a	6.0 (2.0)	2.8 (0.9)	20 (6.5)
NV2***	3.9	3.4	1.7	n/a	n/a

Table 2. School 1 – summary of thermal comfort measurements

Room	TC analyser	PPD [%]	DDR [%]	T [°C]
NV1	moving	11.4	15.8	22.4
NV1	stationary	16.9	30.4	25.8
NV2	stationary	12.6	13.4	21.5
NV2	moving	5.5	3	21.4

<u>School 2 - Mixed Mode and Mechanical Ventilation strategy</u>: This school has a combination of mixed mode ventilation and full mechanical ventilation systems. General ventilation is provided to the classrooms mostly by means of a packaged air handling unit (AHU) system. 100% fresh air is fed into the air handling unit where it is conditioned (tempered) - the system being controlled by a BMS. The tempered air from the AHU is conveyed to each classroom through externally buried concrete pipes (any mould growth in the pipes was not an issue that was investigated). Heating is by a combination of underfloor and trench heating. Suspended ceilings were not generally fitted so that the exposed thermal mass could provide some passive cooling. In the mixed mode classroom (HMV1) the designed ventilation strategy relies on both mechanical (variable speed fan) and natural ventilation (automatic windows). In the mechanically ventilated room the designed ventilation strategy relies on variable speed fan only.

Table 3. School 2 – summary of IAQ measurements

<table>
<tr><td colspan="2">A typical CO_2 levels in a room with a mixed mode vent. strategy (HMV1)</td><td colspan="3">CO_2 levels [ppm]*,**</td></tr>
<tr><td colspan="2" rowspan="5">
</td><td>Classroom</td><td>HMV1</td><td>HMV2</td></tr>
<tr><td>average</td><td>853</td><td>975 (1100)</td></tr>
<tr><td>STD</td><td>268</td><td>309 (320)</td></tr>
<tr><td>maximum</td><td>1472</td><td>1615 (1615)</td></tr>
<tr><td colspan="3">Comments:
* attendance was low, usually 50% of the ‘as designed’ number of occupants;
** values in the brackets have been obtained for occupant numbers close to the ‘as designed’ number of occupants</td></tr>
</table>

Intervention	MV ON all windows opened (l/sp)	MV ON automatic windows opened (l/sp)	MV OFF all windows opened (l/sp)	MV OFF automatic windows opened (l/sp)
HMV1	10.6 (5.3)	6.7 (3.4)	n/a	3.0 (1.5)
HMV2	10.5	n/a	7.6	n/a

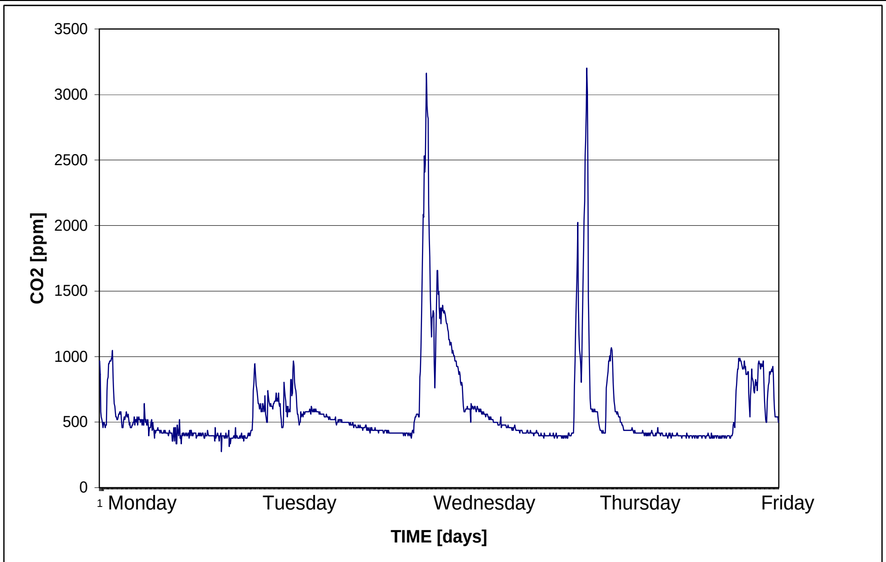
Table 4. School 2 – summary of thermal comfort measurements

Room	TC analyser	PPD [%]	DDR [%]	T [°C]
HMV1	moving	12.6	13.4	21.5
HMV1	stationary	5.5	3	21.4
HMV2	moving	17.4	9.8	20.3
HMV2	stationary	9.1	4.5	20.0

School 3 - Mechanical Ventilation strategy: The school is serviced by mechanical ventilation with under floor heating and manual windows. The teaching rooms (MV1 and MV2 are considered here) have full mechanical ventilation from a ceiling based supply and extract. The fresh air is tempered and conveyed to the room via a simple duct system mounted in a void above the suspended ceiling. There are two air inlets and only one extract within the classroom. The extract, which leads to the large void space above the suspended ceiling is not separately ducted but a small transfer hole connects this plenum void to the corridor. The corridors have additional extract fans located on the roof. This would suggest that mechanical ventilation provides positive pressure within the room. In addition to the mechanical ventilation system, the ventilation strategy in the room is underpinned by two smaller manually operated windows.

Table 5. School 3 – summary of IAQ measurements

A typical CO_2 levels in a room with a mechanical vent. strategy (MV1)



CO_2 levels [ppm]

Classroom	MV1	MV2
average	789	733
STD	171	142
maximum	1047*	880

Comments:
* note that during this period the number of occupants exceeded the maximum designed number of occupants (30+2)
** manually operated windows were used occasionally

Intervention	MV ON all windows closed (l/sp)	MV OFF all windows opened (l/sp)	MV OFF all windows closed (l/sp)
MV1	8.4	n/a	0.5
MV2	9.4	3.8	n/a

Table 6. School 3 – summary of thermal comfort measurements

Room	TC analyser	PPD [%]	DDR [%]	T [°C]
MV1	stationary	5.4	27.1	23.6
MV1	moving	5.9	18.5	24.1
MV2	stationary	5.8	9.9	22.2
MV2	moving	5.9	18.5	24.1

DISCUSSION

A. CO_2 levels

School 1: A typical diagram of CO_2 levels based on the recorded five minutes values is shown in Table 1 for the naturally ventilated room NV1. Generally, on each day, the levels of CO_2 increased from the start of the day reaching a peak at the end of the morning session and decreasing during the lunch time when the classrooms are generally unoccupied. The CO_2 levels start increasing again after the lunch break reaching the afternoon peak at the end of the last period. This is due to the following: a) the breaks between two classes are short (usually 5 minutes) not allowing the CO_2 concentration to equilibrate to the external level, b) in some cases pupils are allowed to stay in classrooms during the breaks contributing to an even more rapid build up of CO_2 levels, c) the lack of an effective ventilation strategy. Note that the standard deviations of CO_2 levels (STD) for the natural ventilation strategy applied here are very high (Table 1). In the case of these naturally ventilated rooms, the average CO_2 levels exceeded 1,000 ppm in room NV2 only. The lower values in room NV1 were partially due to low occupancy levels in the room. Despite low occupancy, the maximum levels recorded were still high.

School 2: A typical diagram of CO_2 levels for the mechanically ventilated rooms is shown in Table 5. The value of 1000 ppm was exceeded only once for a very short period of time. Note that during that short period, the number of the occupants in the room exceeded the designed number of occupants by 2. As expected, fluctuations of CO_2 levels are less significant than for School 1. The fluctuations in these rooms with constant flow rate fans were related either to occasional use of manual windows or to change in number of pupils in attendance. It should be noted that the use of fans with constant flow rate may result in over-ventilation and unnecessary energy consumption in schools with low attendance.

School 3: In the mixed mode classroom HMV1 the designed ventilation strategy relies on both mechanical and natural ventilation (automatic windows). During programmed occupancy periods the windows are set to remain open until the measured room space temperature falls below the set point by more than 2°C. However, due to security reasons (the classroom was located on the ground floor in a less secure area of city) the automatic control was overridden and the windows were kept shut. As a consequence, the role of the mechanical ventilation supply has shifted from a supplementary one to being the main ventilation provider. In order to test the ventilation strategy as it was supposed to be operated, the research team also opened the automatic windows manually (Table 3). Note that the standard deviation in this case of the room HMV1 was lower than in the case of naturally ventilated room. In this room the number of students during the ‘observed’ occupancy was very low, usually 50% of the ‘as designed’ number of occupants. Prior to this study, the volume of the flow entering the room HMV2 (fully mechanically ventilated) through the heater battery was too high causing discomfort to the students sitting near the trench. By reducing the air flow through the battery the problem of discomfort was addressed, but as a consequence of the reduced air flow the operational performance of the mechanical ventilation system was degraded. In this case it was not possible to change the furniture layout without incurring excessive costs (i.e. the furniture was fixed).

B. Estimated ventilation rates

The estimated ventilation rates have shown that the naturally ventilated classrooms were the least well ventilated in the normal style of usage but did not exceed any threshold values because of low occupancy levels under those conditions (Table 1, 3 and 5). The mechanical and mixed mode schools could exceed 8l/s per person but the greatest ventilation rate observed was in the naturally ventilated classroom when the door was opened to provide cross ventilation to the atrium. This mode was frequently used by the school when there were higher levels of occupancy in the classrooms.

C. Temperatures and comfort

With regard to the internal temperatures, CIBSE Guide A1 [9] suggests design criteria for educational buildings. For teaching spaces the specified winter temperature is 19-21°C. The average temperatures found in the schools varied depending on the school and room with NV1 and NV2 being the warmest between 24°C and 26°C and the rooms HMV1 and HMV2 being the coolest between 20°C and 22°C. For many rooms the schools did not meet CIBSE recommended levels for winter conditions and sometimes barely falling within the summer upper limit, indicating that there could be some discomfort among students due to the thermal environment. Note that the average external temperatures were app. 5°C with maximum temperatures exceeding 10°C for a few hours only.

Dissatisfaction due to air movement does not have a simple relationship with air speed; the draught index takes into account fluctuations in local air speeds and local temperatures in order to determine the percentage of people dissatisfied due to draughts. Note that the draught risk exceeded the generally accepted level of 15% a number of times. It should be noted that in mechanically ventilated rooms (Table 4) problems were experienced with draughts from the ventilation systems. In the rooms MV1 and MV2 the incoming ventilation air was 'dumped' from the air inlets causing discomfort to occupants. However, the highest DDR was related to a naturally ventilated room NV1 when all three top hung windows were fully opened (Table 1).

D. General

In this study all the schools satisfied the recommended performance ventilation standards leading to the conclusion that the implemented ventilation strategy was providing adequate ventilation. However, this is misleading unless one takes into account three important factors: a) the occupancy schedule for classrooms (i.e. the classrooms were not fully utilised during the 'normal' occupied hours, preventing CO_2 building up during the day), b) the occupancy level during classes (i.e. number of students attending classes) and c) occupant behaviour. As shown previously, these factors have had a significant effect on the performance of some classrooms.

The mechanical and mixed mode systems generally performed adequately but it was clear that these systems can provide a different set of difficulties for the occupants and operators. They tended to lack the flexibility of operation (for example: zonal control of underfloor heating system) offered by the natural ventilation system and also the reliance on control by a BMS required the school facilities staff to be familiar with the system and its use. The automatic windows used as part of the hybrid ventilation strategy had to be locked shut because of security concerns and this compromised the hybrid mode of operation.

ACKNOWLEDGEMENTS

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