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CAN INDOOR AIR QUALITY IN VICTORIAN CLASSROOMS SATISFY GOVERNMENT STIPULATED REQUIREMENTS?

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Abstract

Research indicates that high carbon dioxide (CO_2) levels in classrooms adversely affect the health and productivity of students. To address this, the government stipulates indoor air quality (IAQ) requirements in Building Bulletin 101 (BB101) as maximum CO_2 concentrations and minimum ventilation rates for classrooms. Due to recent budget cuts, school refurbishments are attracting more attention than new-build. This research, involving a naturally ventilated Victorian classroom, uses Computational Fluid Dynamics (CFD) simulations to predict the IAQ performance of six refurbishment interventions in order to investigate compliance with BB101 requirements. Furthermore, the impact of BB101 compliant interventions on thermal comfort parameters is explored, while combining output from a parallel dynamic thermal study determines their energy impact. Three interventions (parallel windows, plenum, roof-window) satisfy BB101 IAQ requirements. Of these, the parallel window emerges as the intervention achieving the greatest energy savings and causing thermal discomfort to the least number of occupants.

Keywords: CFD simulation, IAQ, schools, refurbishment, energy

1.0 Introduction

School buildings have an important role in the effort to meet the UK government's emissions targets. The overall building stock accounts for 47% of total UK CO_2 emissions (DTI, 2005), while at the Local Authority level, schools contribute around 40-60% of total carbon emissions (Prodromou et al., 2009). The recent abolition of the Building Schools for the Future (BSF) government investment programme puts the emphasis on retrofitting existing schools in order to improve energy efficiency, rather than building new ones. Clements-Croome et al. (2008) recognise there is a 'trend to save energy by reducing ventilation rates'. On the effects of this Bakó-Biró et al. (2012) presented evidence that 'low ventilation rates in classrooms significantly reduce pupils' attention and vigilance, and negatively affect memory and concentration'. To ensure IAQ in schools the government's BB101 Ventilation for School Buildings (DfE, 2006a), concentrating on maximum CO_2 concentrations and minimum ventilation rates, provides the regulatory framework.

This study forms the third part of an investigation on the relationship of IAQ levels, energy demand and thermal comfort in a naturally ventilated Victorian classroom in a rural location in the UK. Simpson (2011) quantified the IAQ and energy consumption of the space and developed a retro-fit proposal that meets BB101 ventilation requirements. Hallin (2012) concentrated on one classroom and used dynamic thermal simulation to explore the relationship between minimum energy cost, temperature and

adequate IAQ for eight interventions. Research reported here employs CFD for the simulation of six of these interventions. CFD is a detailed modelling technique increasingly applied in recent years to the investigation of indoor airflows (Chen, 2009). The software used was the FLAIR component of the PHOENICS package.

The aim of this work is to determine the most appropriate intervention, with respect to heating energy consumption and thermal comfort parameters (draught and vertical temperature difference), in order for BB101 requirements to be met throughout the year. The IAQ requirements and thermal comfort recommendations used in this study for the appraisal of the CFD predictions are tabulated in Table 1.

Table 1. IAQ requirements and thermal comfort recommendations

CO_2 concentration BB101 (DfE, 2006b)	**Ventilation Rates** BB101 (DfE, 2006b)	**Draught** (ASHRAE, 2009)	**Vertical Temp Difference** (CIBSE, 2006a)	**Temperature Limits** BB101(DfE, 2006c) & (DfE, 2013)
mean value ≤ 1500ppm at any occupied time	minimum value ≥3 l/s/person	air velocity ≤0.25m/s	head height and ankle ΔT≤3K	T≤32°C
capacity to lower it to 1000ppm (measured at seated head height)	capability for purge ventilation ≥8 l/s/ person			T≥16°C

2.0 Methodology

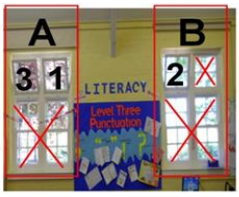
Qualitative and quantitative data used for setting up the CFD simulations was collected through walkthroughs, monitoring, interviewing occupants and maintenance staff, conducting a focus group with students, as well as completing a two-day covert window opening observation period. The 31 person classroom dimensions are 6.5x6.5m and the volume approximately 169m^3. The windows are bottom hung, single pane and wood cased. Figure 1 shows the window opening pattern and with a red ''X'' those that are sealed. The teaching period was taken as 9am to 3pm. The internal heat gains (Fig.1) amount to a total of 4415.66W during the heating period (October 1-March 30) and 2995W during the non-heating. Direct sunlight through windows does not affect the space and solar radiation is considered negligible.

Monitoring (February 2 - May 25, 2012) involved:
• Outdoor temperature in °C (HOBO Pendant® Temperature/Alarm Data Loggers)
• Class CO_2 concentration in ppm (Telaire 7001 Carbon Dioxide Monitor)
• Indoor temperature in °C (HOBO Temperature/Relative humidity/Light External Channel Data Loggers)

Based on an empirical and intuitive evaluation concerning safety and acoustics issues, as well as maintenance and ease of use, six interventions were selected for their practical suitability for the specific school:
• Intervention 1: Low level openings
• Intervention 2: Top openings with low level fully open vents
• Intervention 3: Mixed openings (low on frames A&B, high on frame C)
• Intervention 4: Parallel windows
• Intervention 5: 0.6m high plenum addition
• Intervention 6: 1.0x0.28m roof-window addition

The base case for simulating the existing window configuration in FLAIR was modelled with the window opening pattern observed in order to check the resulting CO_2 concentration and temperature against the monitored values. The geometry of the base case involved a 6.5x6.5x7.16m domain. The dimensions of the heat emitting equipment were altered to avoid complexity of the computational grid. A grid of

Openings	Dimensions
Small Windows	1.20 x 1.60m
Large Window	2.30 x 2.55m
Corridor Door	1.96 x 1.25m



INTERNAL HEATGAINS				
SOURCE	BREAKDOWN	HEAT (Watts)	SUMM (Watts)	NOTES
Occupants	30 students & a teacher	31 x 70	2170	from CIBSE Guide A Table A6.3, assumed as "seated, very light work"
Heating	Radiator	1345.66	1420.66	data from parallel study
	Convector Fan Motor	75W		data from heating engineer
Equipment	Computer	55	225	from CIBSE Guide A Table A6.7
	Monitor	70		from CIBSE Guide A Table A6.8
	Projector	100		from CIBSE Guide A Table A6.12
Lighting	8 Fluorescent F75W/35 lamps	8 x 75	600	wattage from lamp code
TOTAL: 4415.66 W				

Figure 1. Data on orientation, window measurements, opening pattern, and internal heat gains

70x60x50 (210000cells) was selected, as a grid independence test showed temperature being independent of grid density in this cell range. The domain material was specified as standard air and the buoyancy model used was Boussinesq. Considering that the k-ε model and its variations dominate CFD studies for IAQ, the Kato-Launder variation was used as the turbulence model.

The boundary conditions were:

• at external walls: specified as adiabatic zero thickness obstacles to flow

• at internal walls and ceiling: assigned a total surface heat flux on the internal surface, computed by summing the radiant heat, assumed as 45% of a person's sensible heat taken as 70W, from 31 occupants and dividing it by each wall.

• at all heat emitting fixtures and people: modelled as volume objects that don't allow air to flow through them, heat was modelled as the summation of surface heat flux of each exposed side. Occupants were individually modelled with dimensions 0.3 x 0.2 x 1.0m, emitting the remaining 55% of sensible heat as convective heat

• at windows, vents and the internal door opening: unspecified flow direction, with a loss coefficient of 2.69 and assumed medium turbulence flow with turbulence intensity at 5%, with window temperature taken as the average of the monitored external (heating season: 10.20°C, non-heating: 13.88°C) and door temperature as 21°C (heating system installer set point) and CO_2 concentration assumed as 394.01ppm (5.986x10-4 kg/kg)

• at the 31 two dimensional 0.1x0.1m mouths acting as momentum sources: CO_2 mass flux equal to 5.7 x10-4 kg/s/m^2, based on an assumed density of 1.2kg/m^3 and a volume flow rate of 4.75x10-6 m^3/s with the assumption that there are 15 0.5l breaths in 1minute, and speed of respiration CO_2 equal to 0.0125m/s.

In assuring the quality of the simulation outputs, all CFD simulations were checked for convergence of their solution results by means of:

• errors in the balance of mass flow being less than 1% of each flow (in/out)

• errors in the balance of heat flow being less than 1% of the total heat gains

• constant spot values representing the erroneous values between neighbouring cells

• decreased spot values representing the residual errors between each iteration

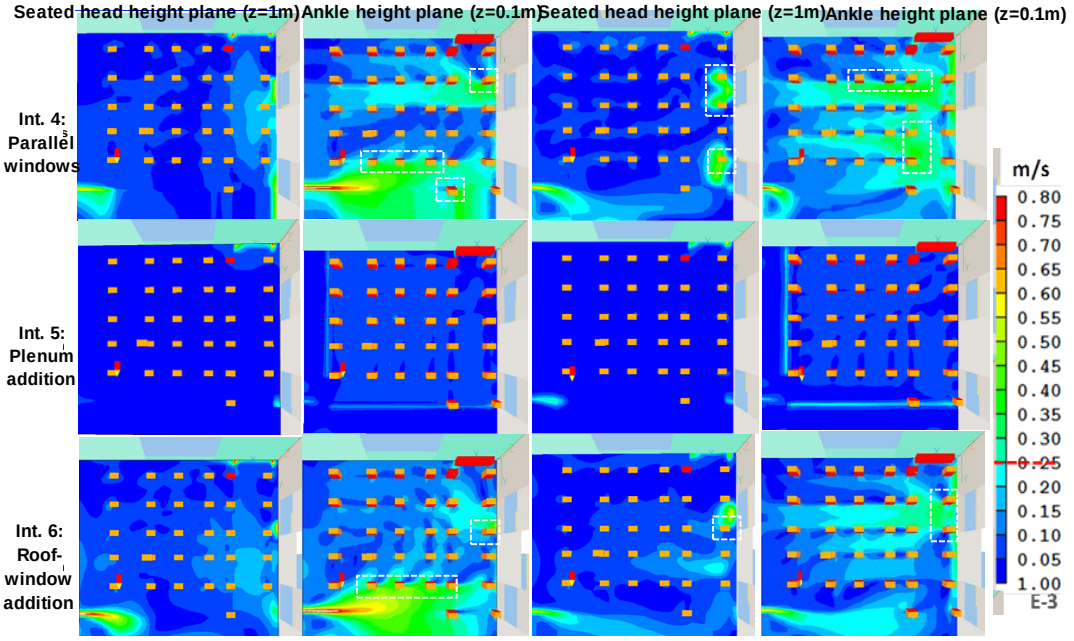
3.0 CFD simulation results

All interventions apart from low level openable windows improve the current CO_2 performance. However, four interventions − mixed level openings, parallel windows, the plenum and the roof-window− meet the BB101 requirements, for both heating and non-heating seasons. Best results for uniformity of CO_2 distribution are produced for the parallel windows and the roof-window interventions, the latter also resulting to the lowest CO_2 concentration values.

In terms of ventilation rates, the last three interventions meet the BB101 criterion of 3l/s/p, with 8l/s/p purge capacity, the whole year round. The plenum intervention is predicted to provide the highest ventilation rate.

In terms of average draught, all cases satisfy the ASHRAE requirement of being less than 0.25m/s. However, the CFD parametric studies show that due to uneven distribution of draught, there are locations in the classroom where levels are above those acceptable. Table 2 shows the plenum intervention producing evenly distributed low value draughts at the level of the ankles and the head, while in the parallel window and roof-window cases up to 16.13% of the occupants (5 persons, enclosed in white doted boxes) is affected by discomfort due to draught.

Table 2. Top view velocity variation at the ankle and head height during the heating season



The CIBSE recommendation for vertical temperature gradient to be less than 3 degrees is not met by any of the interventions analysed. The closest achieved is by the roof-window intervention at 3.35°C in the non-heating season. Composing a table similar to Table 2 but for temperature, allows checking for discomfort due to extreme temperatures. The plenum intervention generates temperatures below 16°C at both levels during the heating season. The addition of a roof-window creates temperatures within the comfort limits at all times, while the parallel windows cause discomfort due to cold at ankle level to 12.90% of occupants (4 persons) when all windows are open during the heating period

4.0 Discussion

Three interventions satisfy the BB101 IAQ requirements (Table 3), the parallel windows, the plenum and the roof-window. Taking into consideration their thermal

comfort performance (second column group) it initially appears that the roof-window performs best against the relevant standards. Although none of the three interventions is predicted to meet the CIBSE vertical temperature standard for the minimum opening areas, the roof-window causes discomfort to the least number of occupants, affecting a maximum of 16% with draught.

Table 3. Comparison of BB101 compliant interventions with respect to thermal comfort recommendations and predicted reductions in CO_2 concentration and heating energy

		IAQ REQUIREMENTS		THERMAL COMFORT PARAMETER RECOMMENDATIONS			CO_2 & ENERGY DECREASE FROM BASE CASE VALUES		
		BB101: on CO_2 conc.	BB101: on Ventilation rate	ASHRAE: Draught	CIBSE: Vertical temperature difference	BB101 & DOE: Temperature limits	CFD STUDY (PHOENICS): Plane Av. CO_2 conc. @ z=1m	DYNAMIC STUDY (IES): Room Av. CO_2 conc.	DYNAMIC STUDY (IES): Energy savings
Intervention 4: Parallel windows	W_{min}	COMPLIES	COMPLIES	NO agreement (16% of occupants in discomfort)	NO agreement	NO agreement (13% of occupants in discomfort)	14.85%	55%	21%
	W_{max}						43.64%		
Intervention 5: Plenum addition	W_{min}	COMPLIES	COMPLIES	AGREES	NO agreement	NO agreement	8.60%	42%	5%
	W_{max}						35.42%		
Intervention 6: Roof-window addition	W_{min}	COMPLIES	COMPLIES	NO agreement (16% of occupants in discomfort)	NO agreement	AGREES	33.55%	59%	8%
	W_{max}						46.53%		

Adding the factor of potentially improving the energy efficiency of the classroom alters this early conclusion. The third group of columns takes into consideration the parallel dynamic simulation study by Hallin (Hallin, 2012). Although Hallin uses room average CO_2 concentrations, the trend concerning the per cent CO_2 level reduction from the base case levels, is the same as that of the CFD study results for the plane of seated head height. For both minimum and maximum window opening areas the CFD simulation predicts the roof-window intervention to lead to the largest CO_2 reductions (33.55% and 46.53% respectively), followed by the parallel windows (14.85% and 43.64%). Hallin's findings follow the same trend (from 59% to 55%). The similarity between CO_2 results sourced from different simulation methods strengthens the confidence in using Hallin's energy savings findings as the predicted energy efficiency improvement. The roof-window only results to an 8% energy saving from the 279kW/m^2/yr of the base case. On the other hand, the parallel windows reduces heating energy demand by 21%.

This study was compromised by the electricity that supplies one of the CO_2 sensors being inadvertently switched off by cleaning personnel, although a note was placed on the switch by the research team. Also, the Telair instruments are capable of registering up to 2499ppm, missing all values above this. Determining a specific pattern of window opening behaviour to use as simulation input was difficult, because the preferred pattern was often superimposed by technical difficulties involving the operability of makeshift opening devices. Moreover, depending on the subject being taught, furniture was moved and blinds were use. Radiator heat gains were based on an erratic heating system the operation of which is not understood by the maintenance personnel due to lack of training. Lastly, modelling furniture was omitted as it would complicate the grid composition.

5.0 Conclusions

The parallel windows intervention results to the largest energy savings and causes thermal discomfort to the least number of people while meeting BB101 requirements for IAQ. Compared to the modelled base case it is predicted to:

• reduce CO_2 concentration at seated head height by up to 21.0%
• increase ventilation rate per person up to 43.3% and purge capacity up to 47.1%
• reduce heating energy consumption by 21%
• cause discomfort due to vertical temperature difference, between the levels of the ankles and seated head height only for the minimum openable window area,
• cause discomfort due to draught during the heating season to a maximum of 16% of occupants when all windows are open, and discomfort due to temperatures less than 16°C to a maximum of 13% of occupants.

Mapping localised discomfort depending on the time of year could be useful to the teacher when deciding the seating arrangement. Alternatively, these locations could provide comfort to students whose tolerance to heat is lower than that of the average. In terms of CFD modelling, it would be useful to run additional simulations for peak recorded external temperatures. This would result in the determination of a range in values of IAQ and thermal comfort parameters for each intervention.

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