QUANTIFYING THE PERFORMANCE OF NATURAL VENTILATION

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ABSTRACT

Increasing attention is being paid to natural solutions to building design, e.g. mixed-mode (or hybrid) ventilation, or increased use of daylight. However, the issue of quantifying performance is less clear: is an hour of no ventilation or 5 minutes of acute glare every so often acceptable? Likewise, relying on average values can also create misleading pictures of performance: the annual average irradiance could be acceptable but there is likely to be insufficient daylight for large parts of the winter; similarly an acceptable annual average air change rate may not reveal a ventilation deficit for significant periods of the year. For these cases performance should be time and magnitude based, the question is how?

This paper focuses on the issue of natural ventilation, which is more complicated than daylighting due to the capacitive properties of a volume of air. Given that pollutants build up in air over time and can be quickly flushed from a space the concentration at a particular instant or air supply rate at a particular instant does not necessarily give an indication of acceptability.

This paper explores some statistics that could be used to assess natural ventilation. A critique is given and advice provided as to the suitability of the different measures to answer design questions.

INTRODUCTION

There are several standards pertaining to ventilation of buildings. The following is a brief summary of some of the key documents.

ASHRAE

Standard 62.1 (2004a) defines three methods for achieving suitable fresh air supply: two prescriptive and one performance based. The first prescriptive method defines the operable window area that should be open (4% of net floor area) and the depth of the space that can be ventilated naturally (8 m). The second method defines the volume of air that should be supplied to the space via a mechanical system. In addition to the flow rate the system choice is taken into account via several coefficients (e.g. ventilation effectiveness). The final method allows the design team to select IAQ performance metrics and to design the system to provide control based on the declared critical contaminant levels; crucially the standard does not provide guidance on which contaminants should be monitored or what the critical levels are.

Standard 62.2 (ASHRAE 2004b) defines ventilation requirements for residential buildings based on room types. This procedure is analogous to the second of the prescriptive methods in 62.1. Again the focus is on mechanical ventilation systems.

CEN 15251

This proposed European standard (CEN 2006, Oleson 2007) takes a similar approach to the second prescriptive method of ASHRAE 62.1: the fresh air supplied to a space is calculated on the basis of the number of occupants and the floor area of the space.

UK Schools

The UK government publishes performance targets for school design in Building Bulletin 87: BB87 (DFES 2003). There are two methods to demonstrate compliance: flow rate or CO_2 concentration.

Canada

For domestic ventilation systems the only standard is in relation to mechanical systems (CSA 2005). The method is prescriptive and is based on room type or use, analogous to ASHRAE 62.2.

Clearly the majority of regulations relate to mechanical ventilation supply rates and set performance criteria for these systems. The question is then how a system with variable flow could be assessed. This has been examined for mechanical systems with a constant source of pollutant (Sherman and Wilson 1986), but raises the question of how a natural or hybrid ventilation system with varying pollution generation could likewise be assessed for performance. For a natural system the supply rates will vary based on conditions within the building and the prevailing ambient conditions. Likewise the generation of pollutants will vary: from more or less occupancy/activity in a space and from building materials as they age and as environmental conditions vary. Therefore, a mechanism to assess the performance of a natural or hybrid scheme is required.

ASSESSMENT METRICS

There are many possible measurements that can be made to assess indoor air quality, many of which would require detailed knowledge of building materials and complex simulation work, say for VOC concentration analysis. It is unlikely that this type of information would be available at the early design stage when the decisions are made regarding ventilation strategy. The designer is more likely to have information relating to flow rates than any other more detailed information (flow rate information plays a key role in estimating the energy use of the building as required in many standards/regulations (for example ASHRAE 90.1 (2004c), 90.2 (2004d), and the Energy Performance of Buildings Directive (EU 2002)).

This study has looked at aspects of supply flow coupled with CO_2 concentrations to examine the link between indoor air quality and basic flow information. The characteristics that have been examined are:

1. The mean, median and maximum supply rate.
2. The under supply volume of outdoor air as compared to that required in a mechanical design.
3. The number and duration of periods where the supply of outdoor air is less than the equivalent mechanical rate.

Figure 1. Image of classroom model

MODEL

A basic model of a classroom was created in the ESP-r system to examine ventilation performance for an annual simulation, figure 1. Three test cases were devised:

1. Naturally ventilated with an operable window area, designed to ASHRAE 62.1. This equated to an area of 2.2 m^2. The window was controlled to proportionally open at classroom temperatures above 21 ^{o}C, becoming fully open at 24 ^{o}C.
2. Mechanical ventilation based on occupancy and floor area to ASHRAE 62.1 requirements (and analogous to the CEN and BB87 methods). This resulted in a fixed volume flow rate of 0.198 m^3/s to the classroom during occupied periods.
3. IAQ based control complying with BB87 requirements (again analogous to ASHRAE 62.1). The same size of fan as in case 2 was used in this case with control based on the classroom's CO_2 concentration. The control set point was 1 g/kg (1000 ppm).

The classrooms were simulated for the typical UK climate.

Performance assessment

There are two methods to comply with the standards: prescriptive and performance. Most standards are prescriptive, setting operable areas of windows for natural ventilation or supply airflow rates for mechanical systems. This work is examining the performance of a natural ventilation design by comparing its performance to the equivalent mechanical design for the classroom. In this way climate specific issues can be taken into account by examining the performance of a naturally ventilated space.

Furthermore, if following a natural ventilation design there will be periods in the year when there is little or no supply of fresh air: calm conditions resulting in no wind driven flow and insufficient temperature difference to create a stack pressure difference. Thus if the standard used by the design team states a minimum supply rate then it could be argued that only mechanical ventilation can be used. This would clearly involve a greater use of energy in the building and would increase capital costs for what may not be an issue to the occupants.

Simulation variants of case 1

Initially two variants of case 1 (natural ventilation) were analysed: single sided ventilation (case 1a) and cross flow ventilation (case 1b). These cases provided some insight to the usefulness of the performance metrics introduced earlier in this paper. These are discussed first and lead to a further three variants which are then introduced and discussed.

RESULTS

The results for the initial two simulations are presented in tables 1, 2, 3 and 4; these results are for the occupied period only. Table 1 shows the basic statistical analysis of the flow rates. As can be seen there is, on average, sufficient flow to match the mechanical requirement of 0.198 m^3/s. However, the maximum flow and the standard deviation is much larger for the cross flow model. This would indicate that there is greater variability in the flow and that there will be periods of low flow as well as periods that the flow could be unacceptably high (approaching 20 air changes per hour). Given this information the single-sided ventilation solution would be the prefered choice.

Table 1. Basic flow statistics (m^3/s).

Case	*Single side (1a)*	*Cross flow (1b)*
Maximum	0.45	0.93
Mean	0.25	0.28
Median	0.21	0.25
Std deviation	0.09	0.14

Table 2 shows the total volume of air that the natural ventilation design does not deliver to the room compared to the mechanical system. As can be seen the single sided ventilation option is again better than the cross flow design.

Table 2. Total annual undersupply of outdoor air.

Case	*Single side (1a)*	*Cross flow (1b)*
Volume (m^3)	93,000	130,000
Volume (%)	6	9

Table 3 shows the number and duration of periods where the supply of outdoor air is less than that of the mechanical design. As can be seen the cross flow scheme has fewer periods of insufficient fresh air supply and the maximum period is less than half of the single sided scheme (note that this is occupied hours only, so the cross flow maximum duration would represent approximately a whole working week). In this case the cross flow scheme would be prefered to the single sided case.

Table 3.Ventilation deficiency periods.

Case	*Single side (1a)*	*Cross flow (1b)*
Number of periods (-)	259	238
Max duration (hrs)	87	37
Mean duration (hrs)	3.4	2.6
Median duration (hrs)	1.0	1.0

Table 4 shows the CO_2 concentration statistics. As can be seen the CO_2 levels in both cases are the same on average (both mean and median). However, the maximum concentration for the cross flow scheme is three times greater than for the single sided scheme. This would indicate that the single sided case has the better performance. Note also that the natural ventilation cases have a lower mean and median concentration of CO_2 during occupied hours, despite less air being supplied during these hours. This would indicate that when there is excess air supply (as evidenced in table 1) the classroom CO_2 levels are flushed and significantly reduced.

Table 4. CO_2 concentration statistics (g/kg).

Case	*Single side (1a)*	*Cross flow (1b)*	*Mechanical (2)*	*CO_2 control (3)*
Maximum	2.0	6.2	1.4	1.4
Mean	1.2	1.2	1.4	1.4
Median	1.2	1.1	1.4	1.4
Standard deviation	0.34	0.59	0.02	0.07

These two models would indicate that the primary focus of a natural ventilation design should be to deliver on average the same fresh air flow rate as the equivalent mechanical system – this could be either the mean or the median as there would appear to be little difference in the predictions, although the median would probably be the prefered statistic as the distribution may be more skewed in other cases. The second consideration is that the undersupply of fresh air should be minimised. It would appear that there is little use in calculating the duration of periods (table 3) when there is insufficient fresh air supply as this does not correlate with CO_2 concentrations.

To test the above statements a further three simulations were conducted with modifications to the cross flow design:

c) The operable area of the windows was halfed with the aim of reducing the maximum air flow through the classroom.

d) The initial cross flow model was adjusted to leave the windows open 20% during occupied hours (i.e. double the operable area in the above model). Again this should further increase the fresh air supply to the classroom.

e) The case c model was adjusted to leave the windows open 20% during all occupied hours, with the aim of increasing the minimum air supply to the classroom.

The results from the cross flow models are displayed in tables 5, 6, 7 and 8.

Table 5. Basic flow statistics (m^3/s).

Case	*1b*	*1c*	*1d*	*1e*
Window size	*Full*	*Half*	*Full*	*Half*
Window control (min open %)	*0*	*0*	*20*	*20*
Maximum	0.93	0.54	0.92	0.57
Mean	0.28	0.19	0.32	0.21
Median	0.25	0.16	0.31	0.19
Std deviation	0.14	0.10	0.14	0.09

Table 5 shows the effect of reducing operable window area and increasing the minimum free area for flow.

Taking these effects separately it can be seen that, as expected, the maximum flow rate is significantly reduced from cases 1b to 1c (42% reduction) and 1d to 1e (38% reduction); as are the other statistics. Comparing the effect of increasing the minimum free area (cases 1b with 1d and 1c with 1e) increases the mean and median flows and has little effect on the maximum flow rate, this is due to there being no increase in the maximum operable area, but the windows in cases 1d and 1e are at least 20% open during occupied hours. Again this is as expected. Additionally the standard deviation is reduced in cases 1c and 1e indicating that the flow rate is more constant in the room compared to cases 1b and 1d. Finally only case 1c has a median supply rate less than the mechanical requirement, and case 1d has the largest supply overall.

Table 6. Total annual undersupply of outdoor air.

Case	*1b*	*1c*	*1d*	*1e*
Window size	*Full*	*Half*	*Full*	*Half*
Window control (min open %)	*0*	*0*	*20*	*20*
Volume (m^3)	130,000	340,000	94,000	240,000
Volume (%)	9	22	6	16

Comparing the undersupply of fresh air, table 6, it can be seen that the results are again in line with expectations: the larger free area windows have increased flow and the increase in minimum free area likewise reduces the undersupply volume. Note again that case 1c is the worst performer based on this statistic and that case 1d is the best.

Table 7. Ventilation deficiency periods.

Case	*1b*	*1c*	*1d*	*1e*
Window size	*Full*	*Half*	*Full*	*Half*
Window control (minimum open %)	*0*	*0*	*20*	*20*
Number of periods (-)	238	176	202	178
Max duration (hrs)	37	384	18	244
Mean duration (hrs)	2.6	5.6	2.0	5.9
Median duration (hrs)	1.0	1.0	1.0	1.0

Examining the frequency and duration of periods when the mechanical requirement is not achieved, table 7, the message is slightly different. Again the performance is better in case 1d than 1b (fewer periods, shorter maximum and mean duration) but this is not for case 1e compared to 1c. The difference between these cases is less clear: 1c has a shorter mean duration but has a much longer maximum duration. This would indicate that the ventilation deficiency period statistics are not a reliable indicator of performance.

Table 8. CO_2 concentration statistics (g/kg).

Case	*1b*	*1c*	*1d*	*1e*
Window size	*Full*	*Half*	*Full*	*Half*
Window control (min open %)	*0*	*0*	*20*	*20*
Maximum	6.2	6.9	6.3	6.8
Mean	1.2	1.7	0.97	1.6
Median	1.1	1.6	0.84	1.5
Std deviation	0.59	0.76	0.51	0.73

Finally examining the CO_2 statistics, table 8, shows that there is little difference in maximum concentration between all the cases. This would indicate that the length of the maximum duration of undersupply does not relate to the maximum CO_2 concentration, which would appear to be independent of window size and control for this study. Comparing the standard deviation changes between cases 1b and 1d, and cases 1c and 1e it can be seen that there is a slight reduction, but the values indicate that there is still considerable variation in CO_2 levels in the classroom.

DISCUSSION

This work has set out to examine the relationship between CO_2 concentration and fresh air supply to a classroom. Figures 2 and 3 show typical relationships for CO_2 concentration against prevailing air change rate. Figure 2 shows the data from case 1a and figure 3 shows the data from case 1d. As can be seen there is a general relationship, however at low air change rates there is considerable variation in the concentration of CO_2 and the ventilation scheme has a large impact on the range. Examining periods of high CO_2 concentration and matching the fresh air supply rate, figure 4, it can be seen that the preceding conditions have an impact on the peak concentration. The impact is less when the supply rate is greater as there is greater dilution, as can be seen in figures 2 and 3.

Comparing the performance of the natural ventilation models (table 8 and table 4) to the mechanical system (table 4) it can be seen that cases 1a, 1b and 1d have lower mean and median CO_2 concentrations, or for more than 50% of occupied hours the natural ventilation design performs better than the mechanical design. Cases 1c and 1e are only slightly higher; i.e. for almost 50% of occupied hours cases 1c and 1e perform better than the mechanical system.

In terms of peak CO_2 concentrations the single sided ventilation model displays lower values than the cross flow models. However, the modelling used in this study assumes that the air is well mixed in the classroom. This is more likely with a cross flow design.

The single sided ventilation scheme has a much longer maximum undersupply period than cases 1b and 1d and only slightly higher mean and median CO_2 concentrations, but much lower peak concentration (2.0 compared to 6.2 and 6.3). Thus it appears that the performance of the natural ventilation scheme is independent of the length of the longest period where supply rates are lower than the equivalent mechanical system. Likewise the mean duration of these periods shows only a weak relationship to the average CO_2 concentration and no relationship to the peak concentration. Therefore these statistics cannot be used to assess the performance of a natural ventilation scheme.

The undersupply volume is more closely related to the performance. For all the cases with a low undersupply the corresponding mean and median CO_2 concentrations are also low. Conversly where the undersupply is large the average concentration is also large. This is of particular interest when comparing the flow statistics for cases 1a, 1c and 1e. For all of these cases the values are essentially the same, however there is a significant difference in the undersupply. Comparing the CO_2 concentration statistics (tables 4 and 8) it can be seen that case 1a has a significantly lower peak concentration. Thus to assess the performance of a natural ventilation scheme both the basic flow statistics and the undersupply volume should be calculated.

CONCLUSIONS

This work has examined whether a link between basic flow information and CO_2 levels in a classroom can be made. The classroom was selected on the basis that it is a densely occupied space and therefore effects should be more pronounced. The simulation study showed that the frequency and duration of low supply flow rates has little impact on the performance of a natural ventilation scheme in terms of CO_2 concentration. Additionally the study indicates that the basic flow statistics and the undersupply volume together are an indicator of good performance. From this study it would appear that the following conditions would provide good performance:

- Low peak air supply rate, e.g. less than twice the equivalent mechanical rate. This is an intuitive limit to avoid drafts.
- An average (median) flow rate similar, or slightly greater, than the equivalent mechanical rate. This has been demonstrated here.
- In conjunction with the median flow rate criterion the undersupply of fresh air should be minimised. Evidence from this study would indicate that an undersupply value in the region of 5-7% of the total mechanical supply volume is an indicator of good performance.

Future studies will examine these statistics computationally on a large range of buildings. However, there is a need to assess occupant responses to high pollutant levels and their interactions with operable windows.

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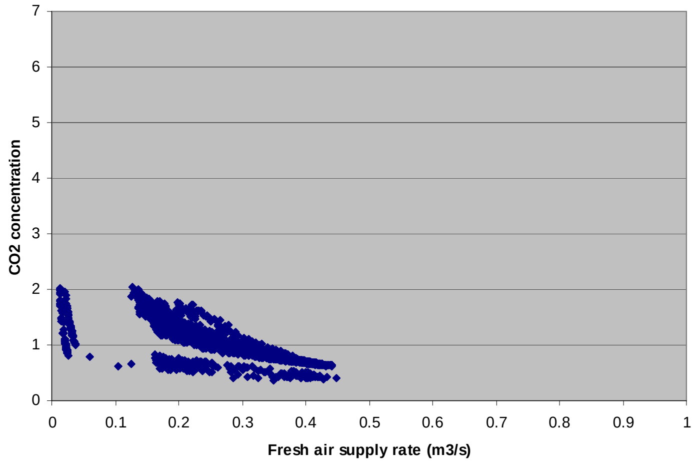

Figure 2. Concentration/flowrate for case 1a.

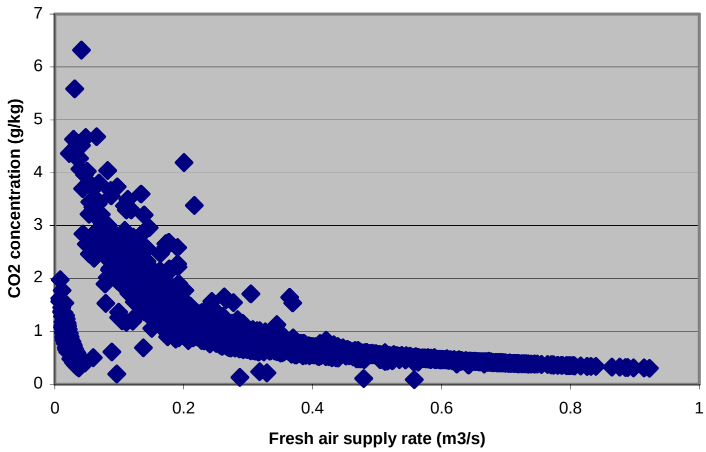

Figure 3. Concentration/flowrate for case 1d.

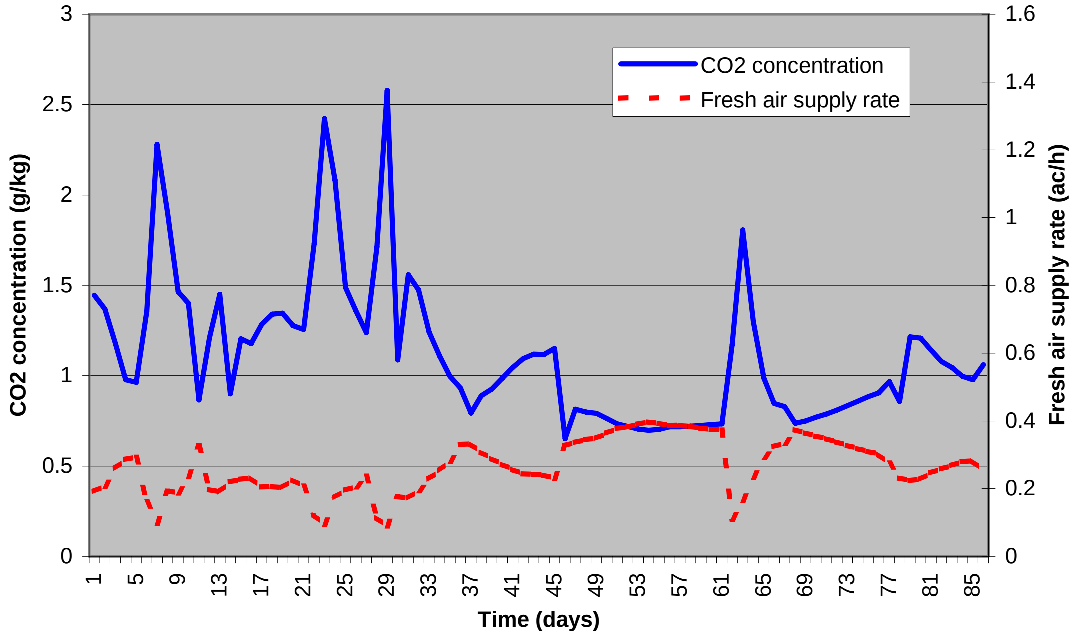

Figure 4. CO2 concentration and fresh air supply rate vs time.