Air Quality Measured in a Classroom Served by Roof Mounted Natural Ventilation Windcatchers

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ABSTRACT

This study examines air quality measured in two classrooms in a UK school, which uses two different forms of natural ventilation, over an eight month period. The first classroom is an internal room that contains a top-down natural ventilation system known as a “Windcatcher”. The room also has a separate mechanical extract fan. The second classroom is ventilated using windows and doors that open to the outside. This study focuses on measuring the performance of a Windcatcher and reviews its potential to replace ventilation provided by conventional windows. Potential benefits of Windcatchers include the ability to provide night cooling without posing a security risks, and daytime ventilation without relying upon opening windows. The study will examine Windcatcher performance in terms of air quality delivered in the first room, and then compare results with measurements obtained for a room that uses conventional opening windows. The study will also review the effectiveness of Windcatchers in meeting the regulatory standards for naturally ventilated classrooms, as set out by the UK Government.

The air quality measurements reported demonstrate that the classroom utilising a Windcatcher was able to meet the UK Government standards for carbon dioxide and temperature, while the classroom relying solely on windows failed to meet the carbon dioxide requirements. Furthermore, the study demonstrates that Windcatchers provide significant night cooling and increase air exchange rates. Windcatchers do, therefore, have a significant role to play in meeting ventilation requirements in schools.

1. INTRODUCTION

The use of natural ventilation strategies in non-domestic buildings, as a partial or direct replacement for conventional mechanical air-conditioning systems, can help to cut carbon emissions. Natural ventilation systems, such as the roof mounted Windcatcher, require minimal power use, has few moving parts, is easy to maintain, and can take advantage of night cooling to achieve further energy savings (Kolokotroni and Aronis 1999). Furthermore, natural ventilation has been shown to impact favourably on the perceived indoor air quality (IAQ) in a building (Fisk 2000), and occupants have been shown to be more tolerant of variations in carbon dioxide levels and temperatures than in mechanically ventilated buildings (Hummelgaard et al. 2007). Accordingly, this paper aims to investigate further the impact of natural ventilation on the IAQ and ventilation rates in buildings by analysing the performance of a roof mounted natural ventilation system.

Natural ventilation has the potential to play a significant role in achieving improvements in IAQ. The constituents of IAQ are wide, but key indicators include: temperature and relative humidity, which “have a strong and significant impact on the perception of IAQ” (Fang et al. 1998); and carbon dioxide, which in itself may not be a direct cause of poor IAQ, but is recognised as a surrogate indicator of IAQ and ventilation rates (Seppanen and Fisk 2002). For carbon dioxide, concentrations above 1000 ppm are generally considered unacceptable (Apte et al. 2000) but British Government guidelines suggest an average occupied concentration of

1500 ppm and a maximum level of 5000 ppm (ODPM 2006). Quantitative links between carbon dioxide, ventilation and occupant performance have been established (Seppanen et al. 2006). The effects of poor IAQ can manifest themselves within the variety of symptoms that make up Sick Building Syndrome (SBS) (Seppanen and Fisk 2002), although studies have shown that "on average, occupants of buildings with natural ventilation and openable windows report fewer SBS symptoms" (Fisk 2000).

Children are particularly susceptible to poor air quality (Mendell and Heath 2005), yet IAQ and ventilation rates in many schools are inadequate (Daisey et al. 2003). The British Government has attempted to address this through Building Bulletin 101 (ODPM 2006), and many schools in the UK are now using natural ventilation products to meet their ventilation and IAQ needs. The product referred to in this paper is the Windcatcher; an omnidirectional, wind-driven, roof-mounted terminal that is ducted to ceiling level simultaneously allowing air to flow in and out of the supplied room (Gage et al. 2001). Recent evaluations of Windcatcher performance demonstrate that Windcatchers can operate successfully in a variety of configurations (Kirk and Kolokotroni 2004) and are capable of achieving acceptable levels of carbon dioxide (Kolokotroni et al. 2002). Windcatchers have now been installed in over 800 UK schools; however, there is little data available that analyses the performance of Windcatchers in school buildings. This paper begins to address the knowledge gap in this area by measuring the performance of a Windcatcher in a UK school using IAQ indicators.

2. METHODS

2.1 Description of the Test Building

Two classrooms within a primary school were studied. The first classroom, which we shall call the Test Room, is an internal room that contains no windows, but has an 800 mm square Windcatcher in the roof. This classroom is separated from an adjacent classroom by a 10 m^2 sliding door, which was opened and closed regularly during the study. The test room also contains a mechanical extract fan that operates during working hours only. The adjacent room is of a similar size to the Test Room, but has windows on a single wall that are exposed to the outside; it is also ventilated by an 800 mm Windcatcher. The second classroom, which we shall call the Control Room, is ventilated using windows and doors that open to the outside; it has similar occupancy density to the Test Room, see Table 1. The Control Room is glazed on the southern and eastern sides and solar shading is provided by an overhanging roof. Both rooms share the same heating strategy.

Table 1 – Details of the Classrooms

Room	**Floor Area (m^2)**	**Room Volume (m^3)**	**Number of Occupants**
Test	59.1	165.5	32
Control	93.6	261.2	57

2.2 Windcatcher Control Strategy

The Windcatcher is automatically controlled and opens according to room temperature and the season. Dampers in the base of the Windcatcher control the flow of air and when a prescribed opening temperature or *set point* is reached, the dampers open 20% for every 1°C above the set point, although the minimum opening temperature is 15°C; see Table 2.

Table 2 - Control Settings

Season	**Set Point (°C)**	**Start Date**
Spring	19	April 1st
Summer	16	June 1st
Autumn	19	September 1st
Winter	22	November 1st

In the summer, the dampers open fully at midnight to provide night cooling unless the internal temperature is at or below 15°C.

2.3 Measurement Methodology

Measurements of CO$_2$, relative humidity (RH) and temperature were taken at one minute intervals in the Test and Control Rooms for a period of at least five days during the winter, spring and summer seasons. Winter measurements were taken in December 2005 and will be known as *Winter*. Spring measurements were collected in March 2006, summer measurements in May and June 2006; these measurements will be known as *Spring*, *Summer 1* and *Summer 2*, respectively. No autumn results were obtained because the spring and autumn set points are identical.

Q-Trak 8551 sensors were used to take the IAQ measurements and these were placed approximately 50 cm above floor level. The CO_2 measurements are accurate to ±3%, and ±50 ppm at 25°C, with an uncertainty of ±0.36% per °C change in temperature. The RH readings are accurate to ±3%, with a ±1% hysteresis. External temperature was measured using iButton Dataloggers that are accurate to ±1°C.

Air change rates (ACR) were measured using sulphur hexafluoride (SF_6) with an Innova 1312 dual gas analyser and a CBISS 4-Point Intelligent Sampling System. ACR was calculated using the constant decay equation (Liddament 1996) and averaged over each test.

3. RESULTS

In Tables 3 to 6, IAQ measurements are presented for the occupied hours in each room and for each season. External temperatures were acquired from the Met Office for a site 4km away at a bearing of 289° from the school.

In Tables 3 to 6, higher levels of CO_2 are observed in winter than in summer, which is consistent with another study of British school classrooms in winter (Coley and Beisteiner 2002). This is especially noticeable in the Control room, where CO_2 levels are seen to change significantly between the Summer 2 and Winter tests. This difference is thought to be caused by staff opening classroom windows, doors and corridor skylights in the summer.

Table 3 – Occupied hours, winter; maximum values

	Temperature (°C)			Relative Humidity (%)		Carbon Dioxide (ppm)	
Room	**Test**	**Control**	**External**	**Test**	**Control**	**Test**	**Control**
Average	18.93	19.74	7.11	45.51	54.22	1159.09	2550.95
Max	21.40	21.20	N/A	54.00	60.80	2286	4329
Min	16.80	17.70	N/A	38.60	44.60	575	551

Table 4 – Occupied hours, spring; maximum values

	Temperature (°C)			Relative Humidity (%)		Carbon Dioxide (ppm)	
Room	**Test**	**Control**	**External**	**Test**	**Control**	**Test**	**Control**
Average	20.03	18.47	11.21	49.75	59.86	1247.24	1798.47
Max	21.20	20.10	15.00	61.20	71.90	2715	4213
Min	19.00	16.80	6.50	38.90	45.50	487	580

Table 5 – Occupied hours, summer 1; maximum values

	Temperature (°C)			Relative Humidity (%)		Carbon Dioxide (ppm)	
Room	**Test**	**Control**	**External**	**Test**	**Control**	**Test**	**Control**
Average	19.38	20.88	16.88	52.87	49.98	839.77	1323.51
Max	21.30	23.60	26.00	65.40	67.50	1726	4171
Min	17.10	18.30	10.50	37.00	28.20	385	379

Table 6 – Occupied hours, summer 2; maximum values

	Temperature (°C)			Relative Humidity (%)		Carbon Dioxide (ppm)	
Room	**Test**	**Control**	**External**	**Test**	**Control**	**Test**	**Control**
Average	25.16	26.78	25.02	50.57	46.58	575.35	588.23
Max	27.80	28.90	30.50	62.00	61.10	821	1078
Min	22.80	24.70	19.00	38.50	36.10	410	411

Table 7 – Air Change Rate Room configurations

Configuration	Room	Fan	Windcatcher	Sliding Door	External Windows
1	Test	On	Open	Open	N/A
2	Test	Off	Open	Closed	N/A
3	Control	N/A	N/A	N/A	Closed

Table 8 - Air Change Rates of Test and Control Rooms

Room	Configuration (See Table 7)	Air Changes Per Hour (h^{-1})			Mean Flow Rate (l/s)	Temperature Difference (°C)	Average Wind Speed (m/s)	Wind Direction ( )	
		Mean	**Median**	**Standard Deviation**				**From**	**To**
Test	1	6.22	5.32	4.04	286.09	7.37	2.32	330	340
Test	2	2.10	2.13	2.17	96.47	7.76	2.57	340	340
Control	3	0.94	0.74	1.35	68.31	10.59	2.06	10	10

Results from the air change tests are presented in Table 8 and show the contribution to the overall ACR that the Windcatcher makes. Here, the background ACR was also measured in the Control Room, and the wind speeds and directions are again provided by the Met Office.

The temperature difference (δT) in Table 8 is the difference between the internal temperature (T_{int}) and the external temperature (T_{ext}) and is positive if T_{int} is greater than T_{ext}. Values of δT were high during the tests and would have contributed to a high pressure difference, while the external wind speeds were low and below the national average of 4 m/s (Gage et al. 2001).

The different configurations of the sliding door will affect ventilation rates; for example, when the door is open cross-ventilation with the adjacent classroom will be present and the Windcatcher may begin to operate as a passive stack. This is similar to the behaviour observed in a previous study of Windcatchers in summer (Kirk and Kolokotroni 2004).

4. DISCUSSION

4.1 Temperature

Temperatures in Table 3 show that the set point temperature was not reached in the Test Room during the *Winter* test and the Windcatcher remained closed. During S*pring,* the Windcatcher was 20% open for the majority of the time, although it did reach a maximum opening of 40%. During the S*ummer 1* test, the Windcatcher was, on average, 60% open, although this value did vary between 20% and 100% open. During the *Summer 2* test, the Windcatcher was 100% open at all times, and here the average Test Room temperature was 1.6 °C below that of the Control Room, although the orientation and glazing of the Control Room means that this room would have been subject to a solar gain that was not experienced by the Test Room. The effects of night cooling in the Test Room are, however, clearly evident in Figure 1. This night cooling can be explained by the difference between the temperatures gradients of the Test and Control rooms during the *Summer 2* period. The Test Room shows a greater rate of night time cooling than the Control Room and this is attributable to the Windcatcher. Moreover, by comparing maxima and minima data, the Test Room is seen to cool by an average of 2.8 °C per night while the Control Room cools an average of 1.5 °C per night.

Observation of both rooms at weekends shows how conditions in the rooms varied without occupant interference. *Summer 2* weekend temperatures show that as soon as δT becomes positive, the internal temperature of the Test Room drops immediately while there is a high degree of hysteresis in the Control Room. This shows that the Windcatcher allows air exchange between the Test Room and the outside as soon as a positive δT is reached.

Here, the fan in the Test Room only functioned during occupied hours and when the room was unoccupied the sliding door was always closed. This provides confidence in our observation that the additional night cooling can be attributed to the Windcatcher.

4.2 Carbon Dioxide

CO_2 concentrations varied seasonally and are directly related to the ACR of each room. The control strategy dictates that the Windcatcher had a greater influence on the ACR as T_{int} increases. The CO_2 levels measured for the Test Room were, on average, lower than that in the Control Room. In fact, the Control Room averaged above 1500 ppm during the *Winter* and *Spring* tests and this exceeds BB101 guidelines. Because both rooms have similar occupancy densities, CO_2 levels indicate that the Test Room is better ventilated than the Control Room throughout the year. *Summer 2* measurements show that average levels were similar in the two rooms, but that the Control Room experienced higher maximum levels. Observations of the Control Room indicate that during the summer period the windows were wide open, which explains the drop in CO_2 levels in the Control Room in the summer months. However, CO_2 levels in the Test Room are seen to be adequate in the summer months, and significantly lower than those observed in the winter months; this is believed to be a function of the Windcatcher operating effectively when the doors of the Test Room are open.

4.3 Air Change Rates

Under the conditions experienced during the gas decay tests, results indicate that the greatest ACRs are provided when the Windcatcher is fully open, the fan is on and the sliding doors are open (see Table 8). When operating autonomously, the Windcatcher provided a third of the maximum achievable ACR; however, the wind speeds for these tests were below average and so under normal conditions one may expect to see the Windcatcher contribute further to the ACR.

During *Winter*, the fan functioned autonomously, while during *Summer 2* the Windcatcher was fully open, the fan on, and the sliding doors open. A comparison of CO_2 levels in the Test Room for these two periods shows that concentrations were over 580 ppm lower, on average, during *Summer 2* than during *Winter*. Peak values were 1465 ppm lower during *Summer 2*, and the distribution of CO_2 concentration indicated by the standard deviation was 307.46 ppm during *Winter*, and only 84.26 ppm during *Summer 2*. As CO_2 is a surrogate indicator of ventilation rate, it can be said that the ventilation during *Winter* was less than during S*ummer 2*. Therefore the ACR provided by the fan during *Winter* was less than that the ACR provided by the Windcatcher, fan and the open sliding door during *Summer 2*. The CO_2 data indicates that the fan was unable to deal with high levels of occupation or prolonged occupation as effectively as when used in conjunction with the Windcatcher and/or the open sliding door.

5. CONCLUSIONS

The results presented demonstrate that the Windcatcher can function effectively as part of a system of measures designed to deliver natural ventilation. The Windcatcher has been shown to provide an effective method for providing night cooling at the school and this serves to lower the cooling load of the building in the summer months. Moreover, as the Windcatcher became increasingly active, it had a greater impact on the IAQ, decreasing average and peak carbon dioxide levels and helping to meet UK Government requirements under BB101.

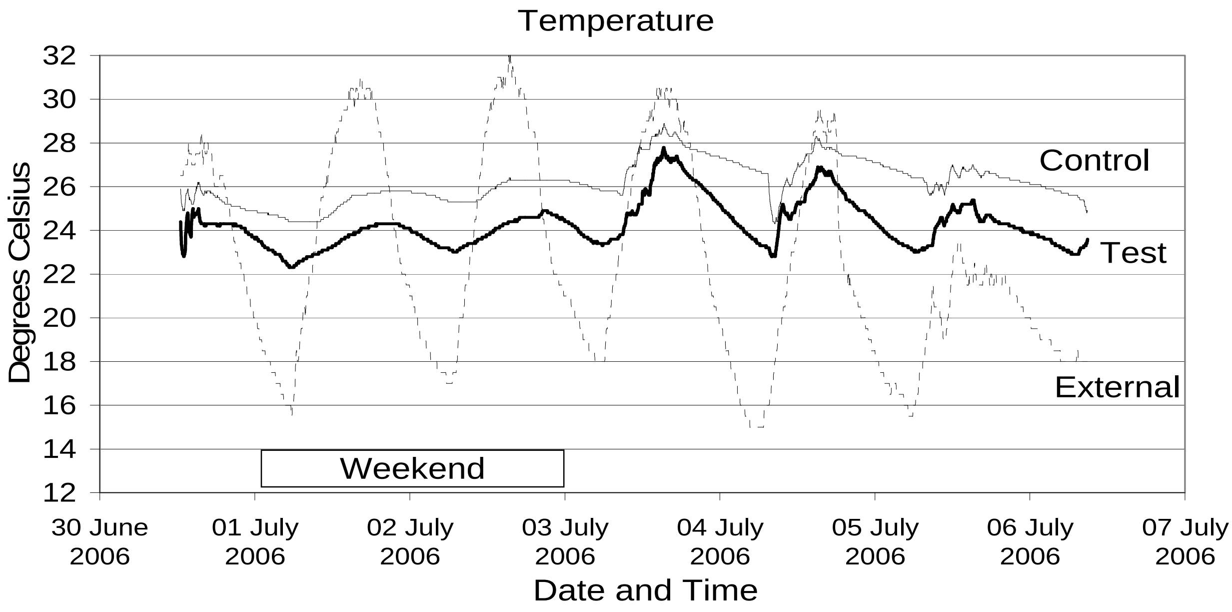

Figure 1. Temperature for *Summer 2*

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