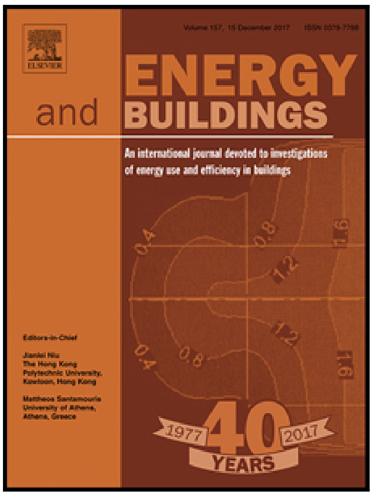

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# Performance of a natural ventilation system with heat recovery in UK classrooms: An experimental study

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## Abstract

This paper presents the ventilation performance of a Passive Ventilation System with Heat Recovery (PVHR) based on *in-situ* monitoring in a primary school in London. The study involves long-term (15-month) monitoring of temperature, relative humidity and Carbon dioxide ($CO_2$) concentrations in both the classrooms and the outdoor environment. In addition, short term (1&2 week) observational monitoring was performed in two classrooms at ventilation system level and classroom level, during both the heating and non-heating seasons. Temperatures and air velocities were measured within the PVHR system while instances of window opening and the number of students were noted in daily diaries. Air permeability and infiltration measurements were performed to characterise the spaces. Time-varying ventilation rates were estimated through a form of continuity equation considering $CO_2$ generation rates by occupants. Preliminary results show that the operation of the ventilation system is more sensitive to changes in wind speed and direction than to buoyancy. When negative pressure was observed on the classrooms' facades the ventilation system was supplying two to three times more air in comparison to instances when positive pressures were observed. The assessment of the ventilation performance of such natural ventilation systems depending solely on wind and buoyancy is complicated as they are dynamic systems that constantly balancing with the surrounding conditions, and the operation is highly correlated to the airtightness of the building's envelope.

**Keywords:** Natural ventilation; Indoor Air Quality (IAQ); Air tightness; Schools

**Highlights:**

- $CO_2$ concentrations in classrooms with passive ventilation systems (PVHR) were satisfactory
- Airtightness significantly affects the performance of the passive ventilation system
- Passive ventilation system appears more sensitive to wind changes than to buoyancy

- Human behaviour such as window opening can significantly boost the ventilation rate of the PVHR system

## 1 Introduction

According to the Climate Change Act (2008), the UK government is committed to tackling climate change by reducing greenhouse gas emissions for the year 2050 by at least 80% from the 1990 baseline (DECC 2008). Space Heating, Ventilation and Air-Conditioning (HVAC) account about two thirds of the total non-industrial energy use (Deuble and de Dear 2012, Lomabrd et al., 2008, Khan et al., 2008) from which 30-50% is related to ventilation and infiltration and about 40% accounts for heating. A reduction in the energy required to heat and ventilate buildings will contribute to a significant reduction of greenhouse gas emissions.

Natural ventilation strategies consume negligible amount of energy by utilizing natural driving forces of wind and buoyancy (temperature differences between the indoor and outdoor environment- stack effect) can provide a viable alternative to energy consumption for mechanical air-conditioning systems and a fundamental method towards energy efficient design of buildings (Calautit and Hughes 2014, Khan et al., 2008). Several studies have been published on the evaluation of the performance of wind driven ventilation techniques such as the wind towers.

Wind towers are a traditional technology used for many centuries in Middle East to naturally ventilate buildings (Montazeri et al., 2008, Elmualim and Awbi 2002). This concept is commercially applied in the UK for over 30 years working on the principles of natural ventilation utilizing both stack effect and wind driven ventilation (Jones and Kirby 2009). The major driving forces of natural ventilation such as Windcathcer are combined in a design around a stack that is divided in four quadrants with the divisions running across the full length of the stack. In these installations the system terminates at ceiling level and the four quadrants act as supply and extract airflow paths (Elmualim 2006a). The evaluation of the performance of such systems is critical for climates such as the UK.

Across the international literature, the performance of wind tower/catcher natural ventilation systems has been analysed using several methods: analytical methods (Hedayat et al., 2015) such as envelope flow models, numerical methods (Montazeri 2011) such as computational fluid dynamic (CFD) models (Ghadiri et al., 2013) and experimental methods such as ventilation tracers gas measurements and wind tunnel tests (Calautit et al., 2015).

The theoretical approach has been used in several studies. In particular, Jones and Kirby 2009 used an alternative semi-empirical approach in which an analytical model takes into account buoyancy effects, the effect of changes in wind speed and direction also considering sealed and unsealed rooms. Their results showed that the semi-empirical predictions compared well with the measured results and CFD predictions, while buoyancy was significant at low flow velocities (Jones and Kirby 2009). Calautit and Hughes (2014) claimed that although the semi-empirical model performed well against the monitored data and CFD models, there were certain assumptions required regarding the wind direction. Whilst Jones and Kirby (2009) conclude that the developed model is the only practical approach to evaluate wind towers' performance, Calautit and Hughes (2014) argue that the accuracy of the model will depend on the quality of the experimental data, as any error within the experimental measurements will also be present in the semi-empirical model.

Elmualim 2006b, used an explicit model described in BS5925:1991 and implicit AIDA model (Liddament 1996) for the performance analysis of a wind tower ventilation system. The results predicted by the models were compared to the experimental ventilation results in a seminar room in the building of the School of Construction Management and Engineering at the University of Reading in the UK (Elmualim 2006b). The results showed that the mathematical approach consistently overestimated the measured ventilation rate.

The major indicator of the performance of a Windcatcher is the rate at which fresh air is supplied and extracted through the system and the room (Jones and Kirby 2009), however, the measurement of performance has been restricted to laboratory conditions, wind tunnel tests and theoretical modelling and with only a few cases having been examined *in situ* (Elmualim 2006c). Kirk and Kolokotroni (2004) examined the performance of windcatchers installed in 3 operational buildings by using the tracer gas decay method. Their method involved tracer gas measurements for 4 different configurations of Windcatcher and window opening, showing that the air change rates delivered were related to wind speed and in low wind speeds the system became sensitive to buoyancy forces. Whilst useful, this tracer gas method provides 'snap shots' of performance under a restricted range of conditions. The performance of such ventilation systems are known to vary during both short and long term periods, influenced by varying temperature gradients, wind speeds and directions, system operating modes and the operation of the internal space (e.g. window opening). Longer term monitoring may therefore provide key insights to seasonal performance and the robustness of natural or passive ventilation system over a wider range of conditions.

Jones and Kirby 2012 studied the indoor air quality in 5 schools and 16 UK classrooms ventilated by a single top-down split duct natural ventilation system. Carbon dioxide ($CO_2$), temperature, relative humidity and ventilation rates were measured during summer and winter. The results indicate that during summer the ventilation system was capable of reducing $CO_2$ levels as the ventilation rate improved improved when the ventilation system was combined with open windows. During winter the observed ventilation rates were not sufficient, thus $CO_2$ levels raised above recommended limit values (Jones and Kirby 2012). This last point further demonstrates the need to fully understand the in situ performance of natural ventilation systems and the air quality they deliver to internal spaces.

According to Shao et al, 1998 passive stack systems that are designed without heat recovery may lead to wasteful heat loss thus, passive ventilation systems combined with the application of heat recovery techniques which utilize internal dissipated heat, can lead to further reductions in the overall energy consumption. Currently, Passive Ventilation Systems with Heat Recovery (PVHR) constitute an area of research which is expanding however little has been published so far on systems' actual performance in situ (Dorizas et al. 2017, Lipinski et al., 2014).

### 1.1 Aims and objectives

The aims of the present study are to evaluate the indoor environmental quality in typical UK classrooms ventilated by Passive Ventilation Systems with Heat Recovery (PHVR) and to provide evidence and review the *in-situ* performance of such systems installed in classrooms based on short and long term monitoring during heating and non-heating periods. The study examines the ventilation effectiveness at two levels: (a) ventilation system level and (b) classroom level. The key objectives of the study are:

(1) to determine how the internal and external conditions influence the PHVR modes of operation (supply, extract, bypass and purge)

(2) to estimate the distribution of ventilation rates provided under these conditions and different modes of operation.

## 2 Monitoring methodology

### 2.1 Sampling site description

The study took place in a primary school located in Forest Hill, South East London within the London Borough of Lewisham. The school was built in 1971 and is located in a suburban residential area with low to moderate traffic on the adjoining streets. The monitoring took place in two adjacent naturally ventilated classrooms (classroom #1: Figure 1 & #2: Figure 2), both with PVHR systems installed (Figure 3). The component of the PVHR system inside the classrooms is indicated in yellow circles in Figure 1 and Figure 2 while the component of the system that sits on the roof is shown in Figure 3. Table 1 summarises the main characteristics of the classrooms.

**Table 1: Main characteristics of the classrooms**

| | Floor area ($m^2$) | Volume ($m^3$) | Window area/ openable area($m^2$) | Orientation of openings | Window opening types & glazing | Number of students/ teachers | Age of children |
|---|---|---|---|---|---|---|---|
| **Classroom #1** | 60 | 180 | 12.6/ 1.1 | North-West | Top-hung/ double glazing/ aluminium frame | 29/1 | 8-9 |
| **Classroom #2** | 60 | 180 | 12.6/ 0.5 | | | 30/1 | 10-11 |

Figure 1: Classroom #1

Figure 2: Classroom #2

**Figure 3: School's external North-West façade showing the classrooms in which monitoring took place (left), Roof cowls of the PVHR systems of the 2 classrooms (right)**

## 2.2 Monitoring period and Data Collection

The performance of PVHR systems can vary both on a short term and seasonal basis. Wind and stack components of ventilation will vary across any given day and seasonally, affecting both the modes of operation of the PVHR system and the room ventilation rates provided by both the PVHR system and the openable windows. Both components will then vary with the operation of the room - the use of window openings, heating patterns and the associated internal temperatures. To capture this range in performance and operation, this study incorporates both long term monitoring and two in depth short term monitoring periods in both the heating and non-heating seasons (Figure 4).

Long-term measurements have been carried out from February 2016 until June 2017 and took place in a single classroom (classroom #1). During this period, internal temperatures, relative humidity and carbon dioxide levels were recorded at 3 locations within classroom 1. External weather conditions including temperature and relative humidity were simultaneously measured through a weather station installed at 1.6m above the school's roof right above the two classrooms, near the cowl of the PVHR systems of the classrooms (Figure 4, Figure 8).

Short-term monitoring took place in both classrooms (classroom #1 & #2) for two weeks during the heating season from the 19th of January until the 2nd of February 2017 and for one week during the non-heating season, 12th to the 16th June 2017. During the short-term monitoring period the same parameters of temperature, relative humidity and $CO_2$ were monitored in both classrooms 1 and 2. In addition to the long term monitored variables, short term monitoring included recording of both supply and exhaust velocities within the PVHR system. External weather conditions in addition to temperature and relative humidity, further included wind speed and direction (Figure 4, Figure 8). Short-term monitoring further involved observational studies, capturing in daily diaries the number of people along with activities performed inside the classrooms and parameters affecting the Indoor

Environmental Quality (IEQ) such as window opening (this was logged using sensors). This approach allows the estimation of ventilation rates via mass balance equations.

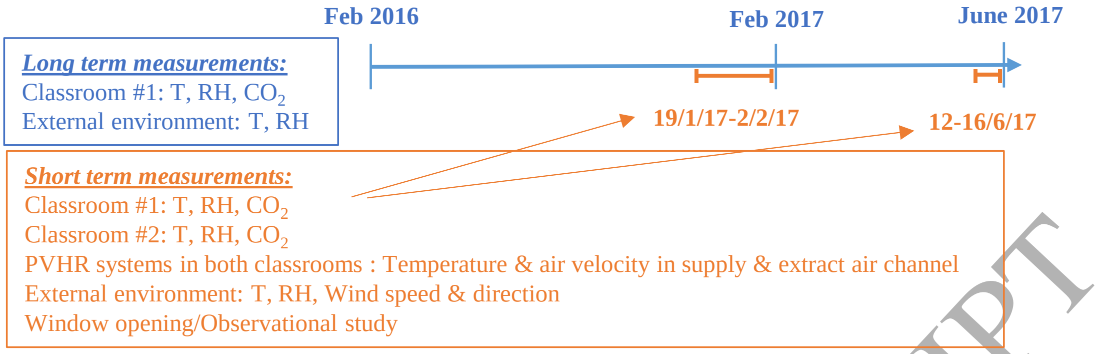

**Figure 4: Schematic representation of the short and long term monitoring periods & monitored parameters**

The general aspects of the sampling strategy of the thermal environment considered during the design of the monitoring methodology, follow ISO7726:2001. Monitoring equipment was chosen on the basis of accuracy, detection range, size and noise levels, and has been calibrated before installation. The logging interval for all of the monitored parameters was 90 seconds and the measured variables covered occupied periods only (8:50 AM to 15:30 PM).

### 2.3 Passive Ventilation with Heat Recovery: System's description

The PVHR system consists of three key components: the roof cowl (Figure 3, right), the coaxial heat exchanger and the flow splitter (Figure 5). The coaxial heat exchanger is designed to be directly connected to the cowl assembly and the flow splitter/ceiling diffuser below. Its structure is designed to channel both air flows to pass through Heat Exchanger fins without contamination caused by air mixing. The fins enable the transfer of heat from the warmer outgoing airflow to the cooler incoming airflow, principally through convection (Lipinski et al., 2014 & 2017).

**Figure 5: Key components of the PVHR system**

The system has three modes of operation: (i) heat recovery mode, (ii) by-pass mode and (iii) purge mode normally activated by the $CO_2$ levels or the window opening (Figure 6). The Heat Exchanger unit is 750mm high and consists of three channels in total – one for supply, one for extract and one for bypass airflow. When operating in heat recovery mode the cold outdoor air is pre-warmed before entering the building. The system has two further modes of operation – Bypass (automatically activated when indoor $CO_2$ levels exceed 1500ppm) and Purge (which can be either manual or automated). In an air-tight building (0-3m$^3$/m$^2$.h@50Pa) the system is operating in the heat recovery mode (Figure 6i). In a medium-airtightness building (4-6m$^3$/m$^2$.h@50Pa) the system is working on the bypass mode, in which less air is supplied from the system (Figure 6ii). In a low-airtightness building (>7 m$^3$/m$^2$.h@50Pa) or in cases in which windows at room level are open, the system is likely to be working in purge mode (Figure 6 (iii)).

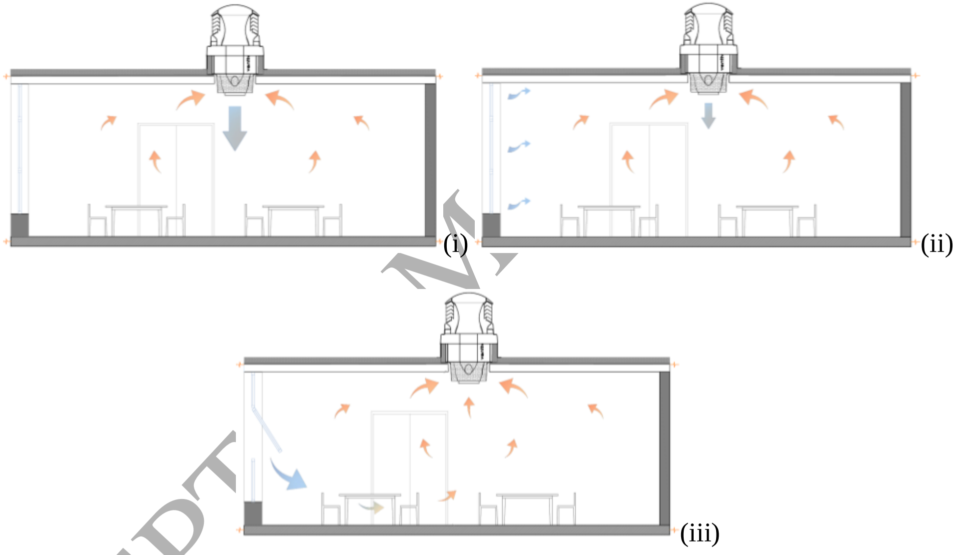

**Figure 6: PVHR system's operational modes under different levels of air-tightness (i) Heat recovery mode (ii) By-pass mode (iii) Purge mode**

### 2.4 System's in detail monitoring

In order to understand the system's performance in detail, temperatures and bi-directional air velocities were measured in both the supply and extract routes, both before and after the heat exchanger, in each of the two classrooms (Table 2). From the bi-directional air velocity sensors, the air velocities can be categorized into either "positive supply" (supply) and "negative supply" (extract through the supply channel) at classroom level and positive extract (extract) and negative extract (supply) at roof level (Figure 7).

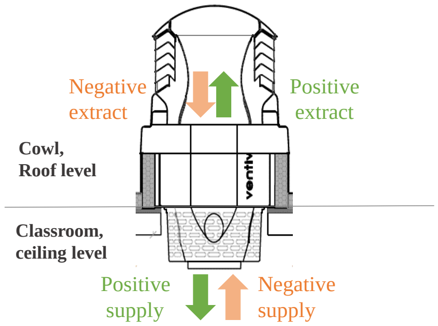

**Figure 7: Schematic representation of air flows in relation to the PVHR system**

The air velocity sensors were located at a position which, according to the profile of the distribution of air flows within a ductwork, was considered to represent the average duct velocity. The readings were converted to volume flow rate by multiplying by the cross-sectional area ($0.13m^2$) of the ductwork in which they were fitted. The location of the temperature and air velocity sensors within the system are shown in Figure 8.

## 2.5 Indoor Air Quality

Continuous measurements of $CO_2$ concentrations within each of the classrooms were collected at three different locations (Figure 8, green points). Two of the $CO_2$ transmitters were located at breathing level (one in the middle of classroom & one next to the window) according to the relevant standard ISO7726:2001 for seated persons (1.1m) and the third sensor was located near the extract point (2.7m from the floor). Temperature and relative humidity were measured at seated breathing level using the same transmitter. The characteristics of the sensors are summarised in Table 2.

**Table 2: Technical specification of monitoring equipment**

| Parameter Measured | Sensor Type/ Supplier/ Principle of operation | Range/ Resolution | Accuracy |
|---|---|---|---|
| 1xbuilt-in Relative humidity<br>1x built in Temperature<br>1xbuilt-in $CO_2$ | GD47/ Eltek Ltd/ NDIR infrared sensors<br>Compliant to:<br>EN300-220-1<br>EN16000-26 | 0-100%/ 0.1%<br>-20-60°C/0.1 °C<br>0-5000ppm/ 3% of measured value at 20°C | ±2%<br>±0.4°C<br>±50ppm |
| External Relative humidity<br>External Temperature | GD13Ecf/ Eltek | 0-100%/ 0.1%<br>-40 to +85°C/ 0.1°C | ±2%<br>±0.4°C |
| Wind Speed / Wind direction | Davis Anemometer connected to GD18Wcf /Eltek/ Wind vane cup anemometer | 0-58m/s /<br>0.45m/s & 1° | ±5%/ 7° |
| Air velocity (inside the system) connected to an Eltek GS 44 voltage transmitter | AVS Series 1000-bidirectionl/ Degree Controls Inc. Thermistor based sensor | -2.5 to +2.5m/s /<br>256 steps | From 15-35°C, 5% of full scale, 3% of full scale at 21°C |
| Temperature (inside the system) connected to an Eltek GS34 transmitter | Thermistor/ ELCM-U-VS-02-0 | -50°C to +150°C | ±0.1°C |

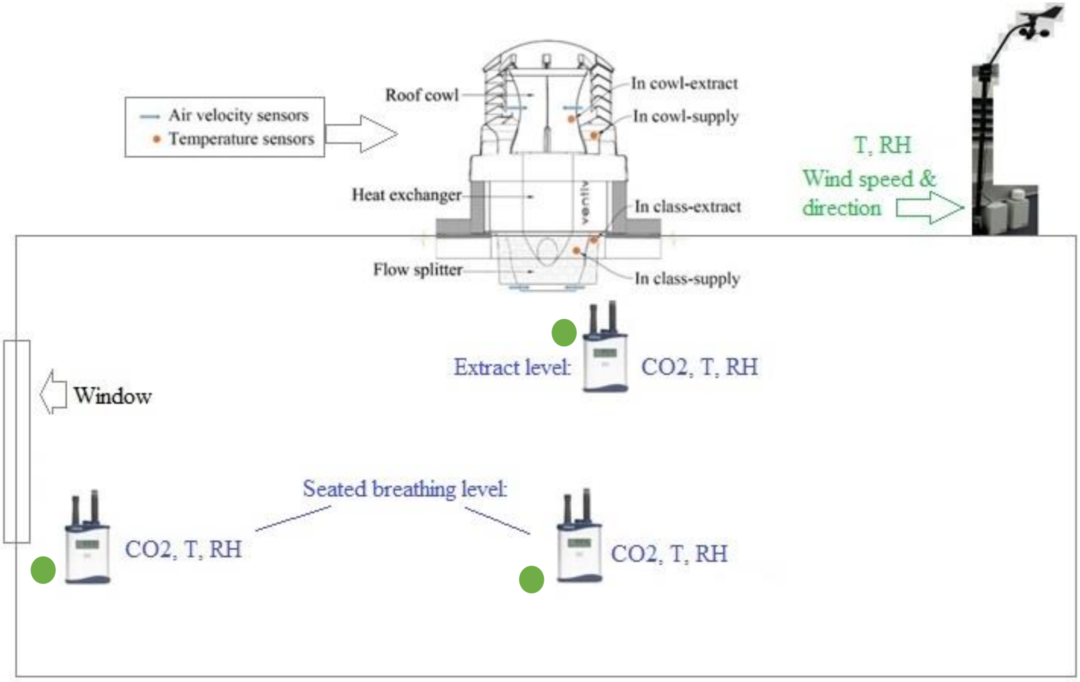

**Figure 8: Classroom's section showing the location of sensors and monitoring parameters measured in the classrooms, within the system and the outdoor environment during the short term monitoring period**

- ***Ventilation rates***

Time varying ventilation rates in each of the two classrooms were estimated using the mass balance equation. The rate of change in the concentration of the monitored gas is a function of the concentration of the incoming air to the concentration of the outgoing air plus the internal generation rate of the gas under investigation. In this case the gas was $CO_2$. The time derivative of the monitored concentration is given by the following formula (Coley and Beisteiner 2002):

$$\boldsymbol{V\,\frac{dC(t)}{dt} = G + Q\,C_{ext} - Q\,C(t)} \quad \textbf{(Eq.1)}$$

The integrative solution of the above equation gives:

$$\boldsymbol{C(t) = C_{ext} + \frac{G}{Q} + \left(C_{in} - C_{ext} - \frac{G}{Q}\right) e^{-\left(\frac{Q}{V}\right)t}} \quad \textbf{(Eq.2)}$$

Where C(t) is the internal concentration of $CO_2$ in ppm (time dependant), $C_{ext}$ is the external concentration of $CO_2$ in ppm, $C_{in}$ is the initial concentration of $CO_2$ in ppm, G is the generation rate of $CO_2$ within the classroom ($cm^3/s$, depending on the activity performed by the students), Q is the internal-external exchange rate ($m^3/s$), V is the volume of the room and t is the time (s).

The ventilation rates (Q) were estimated with Matlab by using the integrative solution of the mass balance equation (Eq.2). The methodology used by Coley and Beisteiner 2002 was adopted in which 20 minutes averaged blocks of data were considered (to suppress noise). Data was analysed in 20 minute segments to reduce noise from varying $CO_2$ production (students leaving or entering the classroom) and short term fluctuations in $CO_2$ levels and ventilation rate relating to varying wind pressures. Student's presence along with their level of physical activity, sex and age were logged in detail on daily basis throughout the short term monitoring period from which a generation rate of $CO_2$ was estimated. The averaged generation rate of $CO_2$ for students was equal to 0.0043 l/s/p and for teachers was equal to 0.0052 l/s/p, which are in agreement with Persily, 1997. A preliminary estimation of the uncertainty of the ventilation rates calculated through Eq. 2 above, is calculated using the Monte Carlo simulation method.

- ***Characterising air leakage and infiltration in the classrooms***

The performance of the PVHR system depends upon the characteristics of the respective classrooms and the amount of infiltration that may be expected which varies depending on wind speed and direction as well as other conditions. To help characterise the two classrooms, two approaches were taken into account and the results are shown in Table 3.  In the first approach air tightness measurements were made with a Retrotec 3000 fan, following ISO EN 9972: 2015 (EN ISO 13829). Due to the large and disjointed form of the school, air tightness measurements were performed in both classrooms individually. As such, the air leakage between the classroom and other internal spaces (20% and 30% in classroom #1 & #2 respectively) and the external environment cannot be distinguished. The performance of the PVHR system and overall IAQ are both depending upon the existing fabric. Therefore, a tracer gas decay method was used to estimate the infiltration rates. In this case the classroom was empty from students and teachers and the tracer gas of $CO_2$ was artificially released according to the ASTM E741-11 and ASTM: D6245-12 aiming to estimate the unintentional introduction of air into the classrooms, helping to characterise the space. $CO_2$ decays were measured at different locations within the classrooms with fans used to provide a well-mixed space. Variations between sensors were therefore lower than the 10% prescribed by ASTM E741. The infiltration rates were estimated in air change rates (ACH) from the tracer gas concentration curve considering the two-point decay method (Cui et al., 2015):

$$\boldsymbol{ACH_{inf} = \frac{1}{\Delta t}\left[\ln\left(C_o - C_{bg}\right) - \ln\left(C_f - C_{bg}\right)\right]} \quad \textbf{(Eq. 3)}$$

Where $ACH_{inf}$ are the infiltration rates expressed in air changes per hour (ACH), $C_o$ and $C_f$ are the concentrations at the initial and final points of the decay curve, Δt is the time between the initial and final point expressed in hours and $C_{bg}$ are the background (external) $CO_2$ concentrations.

**Table 3: Air permeability and air tracer gas decay results from the two classrooms**

| | System sealed (baseline) | System fully open | Infiltration rates (System fully open) : Tracer gas decay (ACH) |
|---|---|---|---|
| | Mean air permeability $q_{50}$ at 50 Pa | Mean air permeability $q_{50}$ at 50 Pa | |
| Classroom #1 | 13.4 $m^3h/m^2$ ~ 4.46 ACH | 26.68 $m^3h/m^2$ ~ 8.89 ACH | 0.46 |
| Classroom #2 | 10.23 $m^3h/m^2$ ~ 3.42 ACH | 23.81 $m^3h/m^2$ ~ 7.94 ACH | 0.51 |

The infiltration rates using the tracer gas decay method were equal to 0.46ACH in classroom #1 and 0.51 ACH in classroom #2. It should be noted that the slope of the $CO_2$ concentration decay was the same in the different locations that $CO_2$ measurements were taken inside the classrooms. The baseline air permeability, with the ventilation system sealed, was greater than the worst allowable air permeability for new buildings ($10m^3/m^2h$ @ 50Pa) according to the approved document L2A. Considering that the PVHR system is designed for airtight buildings with recommended airtightness≤5 $m^3h/m^2$ @ 50Pa, it is assumed that even though the designed ventilation rates were achieved, the system's heat recovery performance was undermined in this particular installation. These results mean that higher rates of infiltration through the building fabric can be expected, resulting in the system being more likely to operate within purge mode (see Figure 6).

## 3 Results and Discussion

As previously described in section 2.2 and shown in Figure 4, the measurement campaign consisted of the long- and the short-term sub-monitoring periods. This chapter presents the monitoring results arising from these two periods in the classrooms.

### 3.1 Long-term monitoring period

The long-term monitoring period only took place in classroom #1 for a 15-month long period from February 2016 until June 2017. The results presented in the following sub-section refer to the findings from the measurements of the thermal environment and $CO_2$ concentrations inside classroom #1 and the corresponding ones from the outdoor thermal environment. It should be noted that only school days and timetables hours are included within the analysis.

- ***Thermal environment***

The monthly ranges of indoor temperature and relative humidity during the long-term monitoring period in classroom #1 (Feb 2016 to Jun 2017) are shown on Figure 9 in box plots (left and right respectively). The monthly averaged external temperature and relative humidity (left and right respectively) are also shown in the same figure in a red star. Monthly indoor temperatures and their ranges are seen to be influenced by external temperatures, heating schedules and window opening behaviour. Warmer temperatures are seen in the summer, whilst larger ranges can often be seen in the transition periods, where ranges in external conditions and in behaviours are expected. Note that during both December and August the school is largely closed for holidays, therefore these months were excluded from the analysis.

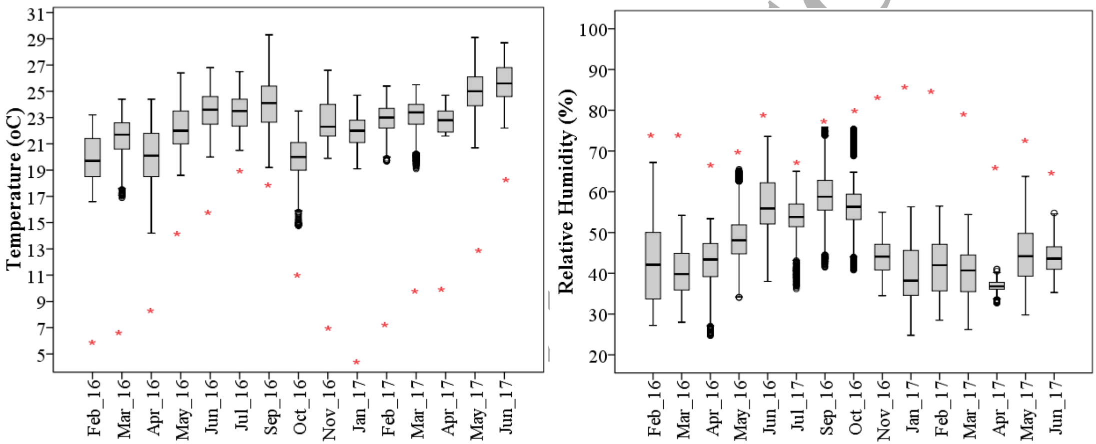

**Figure 9: Box-plots of temperature (left) and relative humidity (right) during the long-term monitoring period (classroom 1)-weekdays and core teaching hours only. Red star shows the corresponding external monthly averages**

In order to get a detailed indication of the extend of variation of the two parameters throughout the school hours, hourly averaged seasonal values were estimated for both temperature and relative humidity (Figure 10). As expected, the temperature is gradually increasing in each case,, while relative humidity is steadily decreasing throughout the teaching hours without any significant fluctuations. The increase in the temperature is partly attributed to the increase in external temperature, solar gains, the provision of heating and the presence of students within the classrooms. The relative humidity decreases due to the increase of temperature which increases the amount of water vapour the air can hold.

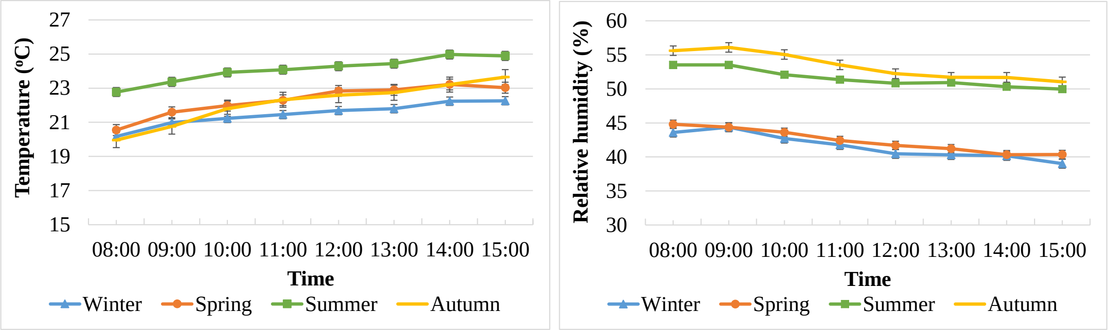

**Figure 10: Hourly averaged seasonal variations of temperature (left) and relative humidity (right)**

Descriptive statistics of the external temperature and relative humidity are shown in Table 4. The indoor monthly averaged temperatures ranged from 19.9 °C (Feb 16') to 25.7 °C (Jun 17') while the indoor monthly averaged relative humidity ranged from 37% (Apr 17') to 59% (Sep 16'). The thermal environment of the classroom throughout the year is rather satisfactory, and the temperatures were for 90% of the time within the recommended ranges by BB101. The recommended ranges for temperature are between 19-21°C for the winter season and 21-23°C for the summer season and for relative humidity 40-75%. In addition, temperature within the classroom did not rise above 28°C for more than 120 hours from the 1st of May until the 30th of September during the occupied hours (9:00-15:30), satisfying overheating criteria of BB101 as well.

**Table 4: Descriptive statistics of weather data**

| | | **2016** | | | | | | | | | | | **2017** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **July** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** |
| **Temperature** | **Aver** | 5.8 | 6.9 | 8.9 | 14.1 | 16.6 | 18.9 | 19.5 | 17.4 | 11.9 | 6.9 | 6.7 | 3.6 | 7.0 | 10.2 | 10.7 | 14.8 | 18.7 |
| | **Max** | 14 | 15 | 18 | 27 | 26 | 33 | 33 | 33 | 20 | 16 | 14 | 11 | 18 | 22 | 25 | 28 | 34 |
| | **Min** | -3 | -2 | 0 | 2 | 9 | 10 | 10 | 8 | 4 | -4 | -4 | -4 | -1 | 2 | 0 | 5 | 9 |
| **Relative Humidity** | **Aver** | 74 | 74 | 69 | 68 | 79 | 67 | 67 | 75 | 79 | 83 | 90 | 87 | 86 | 76 | 64 | 71 | 65 |
| | **Max** | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | **Min** | 30 | 14 | 17 | 18 | 21 | 13 | 18 | 25 | 22 | 26 | 39 | 30 | 37 | 15 | 18 | 25 | 22 |

- ***$CO_2$ concentrations***

The monthly averaged $CO_2$ concentrations during occupied hours were below1500ppm all throughout the year and show a decreasing trend moving from winter towards summer months possibly related to the additional ventilation rates through openable windows during warmer months (Figure 11, left). For both years of 2016 and 2017 May and June were the months of the lowest averaged $CO_2$ concentrations. According to the BB101 for teaching spaces where natural ventilation is used, sufficient outdoor air should be provided to achieve a daily average concentration of carbon dioxide during the occupied period of less than 1500 ppm, and the maximum concentrations should not exceed

2000ppm for more than 20 consecutive minutes each day. During the 15-month period of the long-term monitoring, on 16 out of 186 days (8.6%), the $CO_2$ concentrations at breathing level temporarily exceeded 2000ppm on at least one occasion, for durations ranging between 30min and 180min. For this particular installation, purge ventilation was to be manually provided with exceedance of 2000ppm communicated by red ‘traffic light’ on the classroom sensor (as stipulated in the BB101). In the cases where $CO_2$ concentrations remained above 2000ppm, the windows have not been opened. However, the percentage of time that the $CO_2$ exceeded 2000 ppm throughout the long-term monitoring period was equal to just 2%. Following this study, the guidance has been issued to replace the LED lights of the sensor with a large colour display and include automatic purge ventilation in all future PVHR projects to address this user dependent variability.

Aiming to understand the parameters affecting the variation of $CO_2$ concentrations throughout the school hours in the classroom, the hourly averaged seasonal variations were estimated (Figure 11, right). Figure 11 right, shows that during all seasons the $CO_2$ concentrations are increasing from the time the students enter the classroom (8:50a.m.) and are decreasing between 10:00-11:00 a.m., time range during which the students are leaving the classroom for a 30min break. $CO_2$ are further decreasing between the lunch break of 12:30 and 13:00p.m. and are increasing again until the end of the school day. Further, it is clear that during the summer period the $CO_2$ concentrations are lower in comparison to other season, a fact attributed to the additional ventilation rates through the windows.

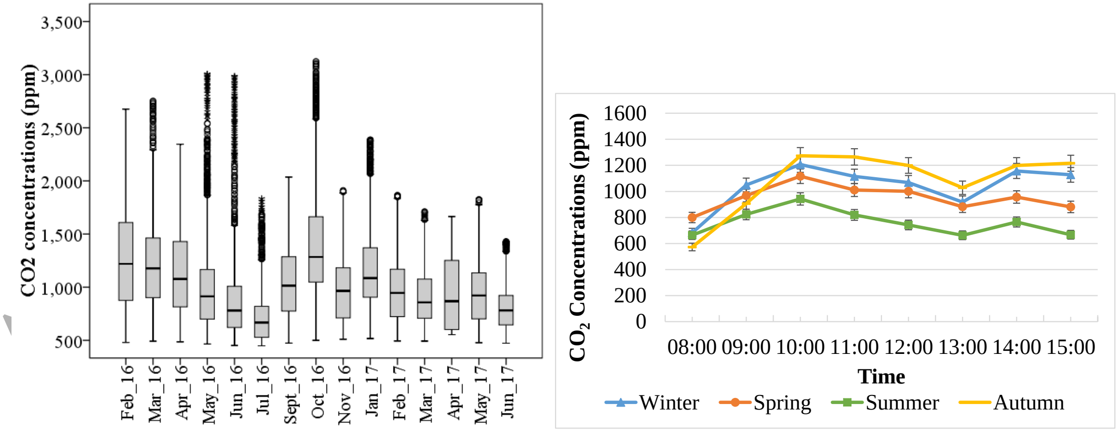

**Figure 11: Box-plots of $CO_2$ concentrations during the long term monitoring period (left) and hourly averaged seasonal variations of $CO_2$ concentrations (classroom #1)**

**Table 5: Descriptive statistics of weather data**

| | | 2016 | | | | | | | | | | | | 2017 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **July** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** |
| **Temperature** | **Aver** | 5.8 | 6.9 | 8.9 | 14.1 | 16.6 | 18.9 | 19.5 | 17.4 | 11.9 | 6.9 | 6.7 | 3.6 | 7.0 | 10.2 | 10.7 | 14.8 | 18.7 |
| | **Max** | 14 | 15 | 18 | 27 | 26 | 33 | 33 | 33 | 20 | 16 | 14 | 11 | 18 | 22 | 25 | 28 | 34 |
| | **Min** | -3 | -2 | 0 | 2 | 9 | 10 | 10 | 8 | 4 | -4 | -4 | -4 | -1 | 2 | 0 | 5 | 9 |
| **Relative Humidity** | **Aver** | 74 | 74 | 69 | 68 | 79 | 67 | 67 | 75 | 79 | 83 | 90 | 87 | 86 | 76 | 64 | 71 | 65 |
| | **Max** | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | **Min** | 30 | 14 | 17 | 18 | 21 | 13 | 18 | 25 | 22 | 26 | 39 | 30 | 37 | 15 | 18 | 25 | 22 |

## 3.2 Short-term monitoring period

The following section summarises the results from the two intense short-term monitoring periods during the heating (Jan-Feb 2017) and non-heating seasons (June 2017) in the 2 classrooms. Short-term monitoring also involved observational studies that served for the recording of the number of students in the classrooms throughout the day. The results are presented at classroom and system level. At classroom level, an in detail analysis of $CO_2$ concentrations and ventilation rates is performed. $CO_2$ concentrations are examined at a seasonal basis and at point/location of measurement base, while ventilation rates are examined in terms of wind and buoyancy. At system level, the ventilation effectiveness is examined through seasonal air flows, wind pressures on the exposed facades and through the different modes of operation of the system.

### 3.2.1 Classroom level

- ***Indoor air quality***

In this section the $CO_2$ distributions are examined in particular for the heating and non-heating periods of the short-term monitoring, during which $CO_2$ levels were, as before, measured at 3 different point within the classrooms. The cumulative frequency distributions of $CO_2$ at the three different locations within in classroom #1 are shown in Figure 12, left. Again, it can be seen that the $CO_2$ concentrations are higher during the heating period compared to the non-heating period for a similar occupancy level. In both monitoring periods the concentrations at the extract level are seen to be greater than near the window and mid-level (seated breathing level, 1.1m). As may be expected, window $CO_2$ levels were slightly below those in the centre of the room, indicating reasonably free air movement between these points. $CO_2$ was lower than 1500ppm at the seated level for 95% of the time during the heating period while during the non-heating period $CO_2$ were lower than 1000 ppm for 90% of the time. The two short-term monitoring periods showed significant variability in the user's operation of the room. For short term monitoring during the heating season, the windows were fully open for 11% of all occupied hours, with at least one window partially open for 51% of this time. During the non-heating period this increased to fully open for 71% and partially-open for 96% of occupied hours. The lower concentrations during the summer period taking into account that the classrooms were occupied with similar number of students can be attributed to the extended period of open windows. A similar seasonal profile of $CO_2$ concentrations was also observed for classroom #2 in which concentrations are higher during the winter for a similar occupancy (Figure 12, right). During the winter period the concentrations of $CO_2$ in classroom #2 at the extract and middle level were higher in comparison to the corresponding ones in classroom #1, due to shorter periods of time that the windows were kept open.

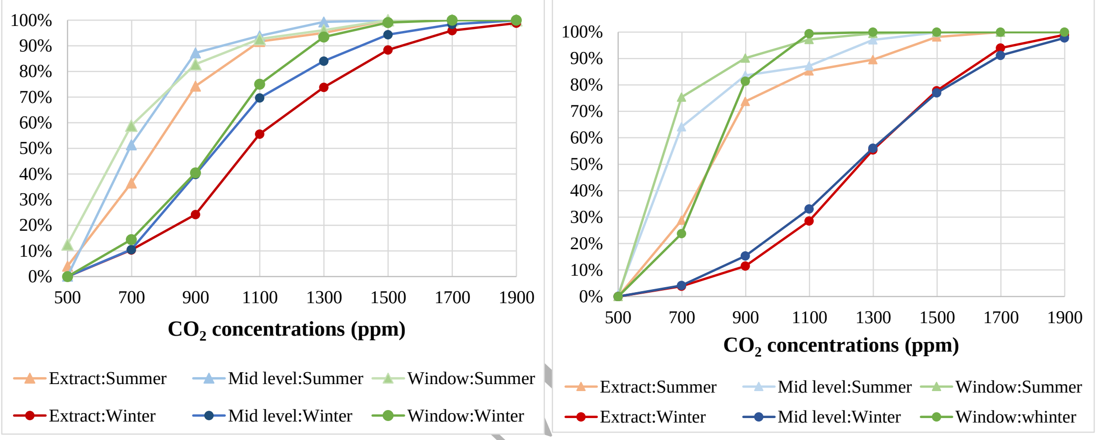

**Figure 12: Cumulative frequency distributions of $CO_2$ concentrations at extract level, middle point and window level of classrooms #1 (left) and #2 (right) during the heating and non-heating monitoring weeks**

In order to get a clearer understanding of the $CO_2$ fluctuations in classroom #1, the diurnal variation of two typical days during the heating and non-heating periods along with the corresponding occupancy are shown in Figure 13. For both days during the heating and non-heating period the background concentrations start from about 700 to 800ppm at 8:50a.m. This can be attributed to the fact that cleaning activities including sweeping and moping took place inside the classroom from about 8:05 for approximately 20 minutes in both dates increasing the initial background concentrations from about 500ppm to approximately 700 and 800 ppm for the two days respectively. Also, for both dates two teachers were present in the classroom from the ending of the cleaning activities until the students entered the classroom (8:50). Much steeper fluctuations of $CO_2$ concentrations are observed during the heating period compared to the non-heating period. The difference between the extract level and seated breathing level at middle point is more obvious during the heating period (difference of about 200ppm). As it can be seen even though the occupancy is similar throughout the day for both seasons, the concentrations are greater during the heating season. This is attributed to the additional ventilation rates through the windows as on the 13/6/17 all windows were open throughout the day while on the 23/1/17 half of the windows were open from 9:30am-9:40am, 9:50am-13:30pm and from 14:50pm-15:30pm (shown in light blue background). The same diagram also presents the variation of the wind speed. Throughout these days the wind speed was moderate with an average of approximately 1m/s.

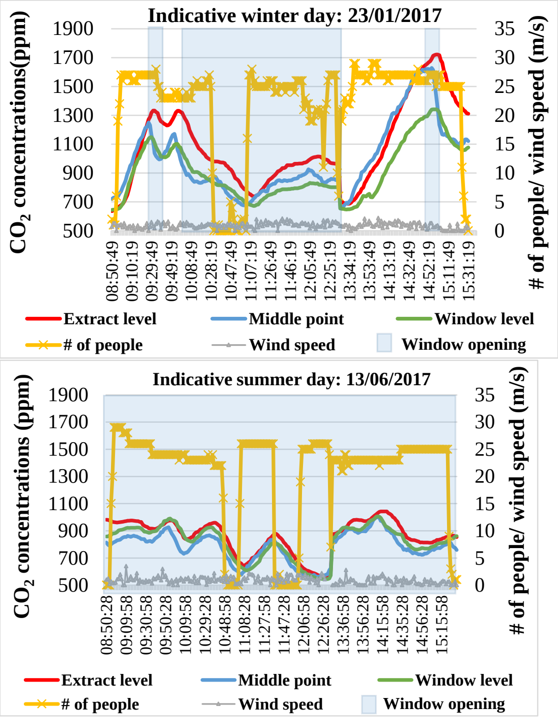

**Figure 13: Diurnal variations of $CO_2$ concentrations during teaching hours for typical days during the heating (left) and non-heating periods (right) in classroom #1 (note: $CO_2$ levels are elevated dut to intermittent occupancy before core hours)**

The $CO_2$ concentrations were further compared for periods of full occupancy when the windows were open and closed (by-pass or purge mode and heat recovery mode respectively). It was found that window opening reduced the averaged $CO_2$ concentrations by approximately 200ppm in average in both classrooms over the two week monitoring period in the heating season. Table 6 summarises the descriptive statistics of $CO_2$ concentrations at the three points of measurement in the two classrooms during the heating and non-heating periods of measurement. During both seasons $CO_2$ concentrations remained in satisfactory levels in both classrooms.

**Table 6: Descriptive statistics of $CO_2$ concentrations duirng the short term monitoring periods in the heating and non-heating seasons**

| | Heating Period | | | | | | Non-heating Period | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Classroom #1 | | | Classroom #2 | | | Classroom #1 | | | Classroom #2 | | |
| | Extract level | Middle point | Window level | Extract level | Middle point | Window level | Extract level | Middle point | Window level | Extract level | Middle point | Window level |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Average | 1103 | 1011 | 956 | 1259 | 1252 | 793 | 789 | 722 | 713 | 845 | 730 | 649 |
| Median | 1063 | 961 | 944 | 1258 | 1243 | 799 | 770 | 687 | 642 | 792 | 667 | 570 |
| Min | 526 | 546 | 513 | 562 | 515 | 513 | 492 | 513 | 482 | 540 | 490 | 504 |
| Max | 2030 | 1914 | 1583 | 1952 | 2014 | 1285 | 1429 | 1307 | 1423 | 1616 | 1508 | 1319 |
| St. Dev | 307 | 267 | 220 | 293 | 319 | 118 | 221 | 182 | 219 | 239 | 225 | 173 |

- ***Ventilation rates***

Time varying ventilation rates were estimated for the heating period using the mass balance Eq.2 for 20min blocks of data, following the methodology of Coley and Beisteiner (2002). For the estimation of the ventilation rates, internal concentrations of $CO_2$, the generation rate of $CO_2$ based on the number of students/teachers inside the classrooms, their age and their activity performed, the volume of the classroom and the external $CO_2$ concentrations are taken into account. The descriptive statistics of the ventilation rates during the short-term monitoring conducted heating period, expressed in l/s/p along with the corresponding indoor to outdoor temperature difference and wind speeds are shown in Table 7. It can be seen that the averaged ventilation rates in both classrooms are above the minimum required rates of 3l/s/p referenced in BB101. The daily averaged recommended minimum of 5l/s/p was achieved during half of the monitored days in the short-term monitoring of the heating period. The corresponding indoor to outdoor temperature differences are expected considering that the examined period is winter. The prevailing wind speeds averaged for that period were rather low.

**Table 7: Desprictive statistics of ventilation rates, temperature difference between indoors and outdoors and wind speed during the short-term monitoring in the heating period**

| | Classroom #1 | | Classroom #2 | | |
|---|---|---|---|---|---|
| | Ventilation rates (l/s/p) | ΔT ($T_{indoor}$-$T_{outdoor}$) | Ventilation rates (l/s/p) | ΔT ($T_{indoor}$-$T_{outdoor}$) | Wind speed (m/s) |
| Average | 5.9 | 16.5 | 4.2 | 17.6 | 0.9 |
| Median | 5.5 | 16.5 | 3.4 | 17.2 | 0.9 |
| Min | 0 | 10.7 | 0 | 10.7 | 0 |
| Max | 17.7 | 23.4 | 13.6 | 25.0 | 2.2 |
| St. Dev. | 3.9 | 3.3 | 3.6 | 3.1 | 0.5 |

The distributions of the ventilation rates across the different ventilation bins in the two classrooms, during the non-heating monitoring period, are shown in histograms in Figure 14, left. It can be seen that ventilation rates are rather steadily spread in an extended set of bins, resulting from the range of environmental conditions and configurations of operation. The ventilation rates during periods of fully open (purge mode) and closed (heat recovery and bypass modes of operation) windows along with the corresponding wind speeds are presented in Figure 14, right. When windows are fully open (purge mode) there is an increase by 13% in the average ventilation rates of classroom#1 and an increase by 24% in the average ventilation rates of classroom #2 under similar wind conditions. Additionally, although indoor to outdoor temperature difference ranged from 10-24 $^{o}$C, no clear correlation was found between ventilation rates and ΔT.

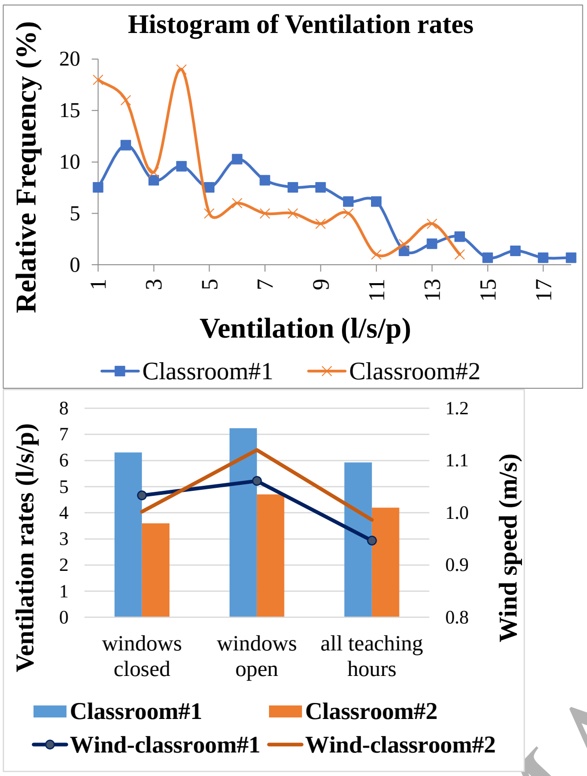

**Figure 14: Histogram of ventilation rates in the two classrooms during the heating period (left), Ventilation rates during periods with windows open and closed during the heating period (right).**

A preliminary estimation of the uncertainty of the ventilation rates that were calculated through Eq. 2 is further approached by using the Monte Carlo simulation method. For each independent variable of the equation, a list of factors that contribute to the uncertainty was created and then converted to a distribution using a combined uncertainty (quadratic sum). In particular, the major factors contributing to the uncertainty of the internal $CO_2$ concentrations are the instrument's accuracy and resolution (Table 2) as well as its spatial variation $(u(x)_{spatial} = \frac{s(x)}{\sqrt{n}}$, s(x): st. dev., n: number of sensors-3 in this case). As for the external $CO_2$ concentrations, only instrument's accuracy and resolution were considered as it was assumed that there isn't significant spatial variation of $CO_2$ outdoors. A range of bibliographic generation rates of $CO_2$ (0.0041-0.0045l/s/p) was used as input factor considering that the age and activity of the kids were known. From the above distributions and standard deviations and by taking into account the measured internal and external $CO_2$ concentrations as well as the initially estimated generation rates, Monte Carlo simulation tool was applied for the generation of a random population. The generated population for each distribution was then used as input to re-estimate the ventilation rates that would consider the uncertainties. The percentage of deviation of ventilation rates considering the uncertainties to the ventilation rates without taking them into account, was then calculated. At 95% confidence intervals, the average absolute uncertainty was estimated as 20%, indicating the significant uncertainty associated with such a method and in particular the higher relative uncertainty seen at low ventilation rates. This uncertainty reduces when considering longer time aggregations but even with these high resolution observations, systematic uncertainties could have a significant impact on the interpretation of results. Clearly more work is needed to fully identify and estimate uncertainties from such in-situ methods.

### 3.2.2 System level

- ***Ventilation effectiveness at system level***

As aforementioned, by considering the readings of the bi-directional air velocity sensors in the supply and extract ducts, the air flows were separated into "positive" (+ve, present in heat recovery and bypass modes) and "negative supply" (-ve, present in purge mode) (classroom, ceiling level) and "positive" and "negative extract" (cowl, roof level). Here, negative supply indicates that the system is operating in purge mode, with air drawn in through the building fabric and/or window openings and exhausted through both supply and extract channels of the PVHR system (Figure 6). When the supply is 'positive', the PHVR system is drawing supply air from roof level into the classroom whilst extracting through the exhaust, either in heat recovery or 'bypass' mode (Figure 6).

Table 8 shows the descriptive statistics of the supply air terminals in the two classrooms at ceiling level and the corresponding prevailing conditions in terms of wind speed, indoor to outdoor ΔT as well as window opening. When the wind direction was predominantly South Eastern and/or the windows were predominantly open the systems operated mainly in purge mod, registering "negative" supply for 81% (classroom 1) and 91% (classroom 2). When the wind direction was predominantly South Western and the windows were predominantly closed the systems operated mainly in the supply and extract mode. It is worth noting that due to the very high air permeability of the building the wind blowing directly at the façade contributed to significant infiltration even when windows were closed. The systems of both classrooms worked as “positive supplies” for greater wind speeds and indoor to outdoor temperature difference, ΔT in comparison to the period that the system was working under “negative supply” (Table 8). As expected, the windows were closed for the great majority of time (81% in classroom#1 and 96% in classroom#2) that the systems in both classrooms worked as “positive supply”.

**Table 8: Descriptive statistics of the supply air terminal in the classroom at ceiling level & prevailing weather conditions**

| | | Positive supply (19% of time in Classroom #1 & 9% of time in Classroom #2) | | | | | | Negative supply (81% of time in Classroom #1 & 91% of time in Classroom #2) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Supply air velocity (m/s) | Supply air flow ($m^3/s$) | ΔT | Wind speed (m/s) | % of time with windows closed | Predominant wind direction | Extract air velocity (m/s) | Extract air flow ($m^3/s$) | ΔT | Wind speed (m/s) | % of time with windows closed | Predominant wind direction |
| Classroom#1 | Mean | 0.17 | 0.022 | 17.1 | 1.32 | 81 | SW | 0.27 | 0.035 | 16.5 | 0.92 | 26 | SE |
| | Median | 0.14 | 0.018 | 16.2 | 1.30 | | | 0.25 | 0.033 | 16.6 | 0.90 | | |
| | Min | 0.01 | 0.001 | 10.0 | 0.00 | | | 0.01 | 0.001 | 0.0 | 0.00 | | |
| | Max | 0.96 | 0.125 | 23.7 | 3.40 | | | 1.91 | 0.248 | 23.7 | 4.10 | | |
| | St. Dev. | 0.13 | 0.017 | 3.7 | 0.77 | | | 0.18 | 0.023 | 3.2 | 0.68 | | |
| Classroom#2 | Mean | 0.29 | 0.037 | 20.9 | 1.75 | 96 | SW | 0.72 | 0.093 | 18.4 | 0.91 | 54 | SE |
| | Median | 0.18 | 0.023 | 20.7 | 1.70 | | | 0.73 | 0.095 | 18.2 | 0.90 | | |
| | Min | 0.01 | 0.001 | 11.3 | 0.30 | | | 0.01 | 0.001 | 10.0 | 0.00 | | |
| | Max | 1.83 | 0.238 | 25.7 | 3.80 | | | 2.00 | 0.260 | 26.0 | 4.10 | | |
| | St. Dev. | 0.31 | 0.041 | 4.1 | 0.74 | | | 0.33 | 0.043 | 3.2 | 0.67 | | |

The averaged air flows in the supply (classroom level) and extract (roof level) air channels at which ‘positive’ and ‘negative’ supply and extract occurred during the heating and non-heating periods are shown in Figure 15. The values shown on top of each bar represent the percentage of time that each of these occurred, summed up per supply (dashed frame) and extract (continuous lined frame), per monitoring period. It can be seen that the extract flow (positive extract, negative supply) was approximately 2 times higher to the supply flow (positive supply). Since the negative supply (purge mode) at classroom level accounted for a great percentage of time, it was examined in more detail for both classrooms. It was found that when the windows were open during the heating period, the “negative supply” (extracting) air flows increased by 28% and 46% in classrooms#1 and #2 respectively in comparison to the periods that the windows were closed during the heating period.

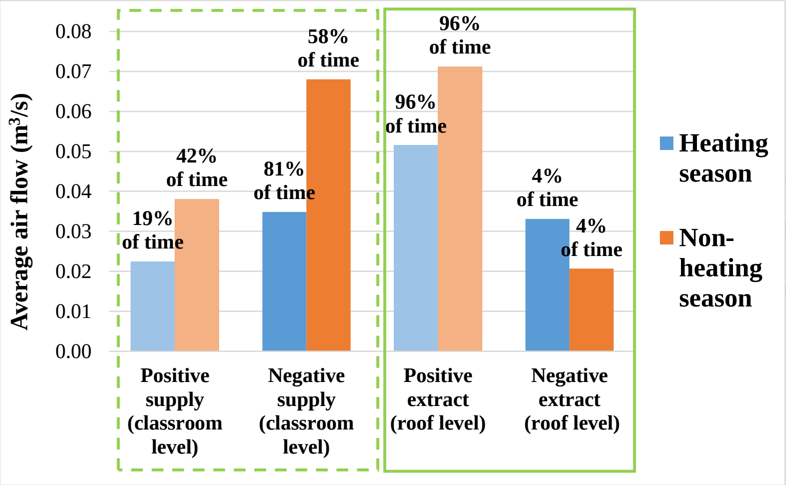

**Figure 15: Comparison between supply and extract air flows in the heating and non-heating seasons in classroom #1**

In order to understand the effect of the external weather conditions on the ventilation system’s performance, the impact of wind pressures on the air direction within the supply channel of the ventilation system was next examined. It is worth mentioning that the impact of the wind pressure concerns the pressure of wind on the classroom’s external facade which then affects the direction of air within the ventilation system. A preliminary study of wind pressures on the ventilation system has shown that due to its round shape, it is not greatly influenced by the wind direction. Figure 16 presents histograms of the distribution of air velocities in the supply channels including both “positive supply” (+ve) and “negative supply” (-ve) for positive (left) and negative (right) pressures of wind on classroom’s #1 exposed facade. At this point it should be reiterated that both classrooms were facing WNW while positive wind pressures were considered for all orientations within an angle of $45^o$ perpendicular to the WNW facing facade. The yellow area in each figure highlights the positive supply air velocities. It can be seen that when the classroom is under negative wind pressure (leeward, Figure 16, right) the system is supplying (positive air velocities) more air into the classrooms compared to positive wind pressures (windward, Figure 16, left). It can be said that for negative pressures exfiltration is predominant, while for positive pressures, infiltration is predominant. The same analysis was performed in both classrooms and it was estimated that under negative pressure the system was supplying by three times more in comparison to positive pressures on the facade in classroom #1, while in classroom #2 during the heating period, the system was supplying by more than two times under negative pressure.

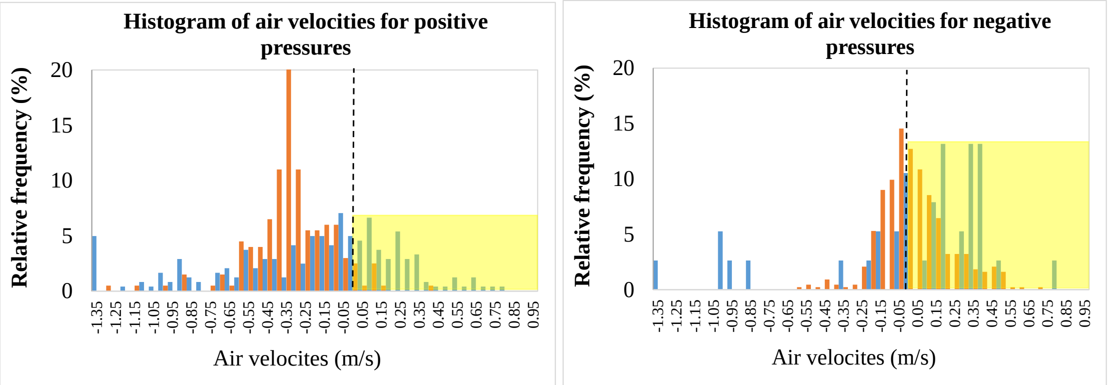

**Figure 16: Histogram of air velocities in the supply duct for positive (left) and negative (right) pressures on the classrooms' exposed facades**

Next, the effect of wind speed on the overall supply and extract air flows within the ventilation system is examined. Figure 17 shows the relative frequencies of the ventilation system directly supplying fresh air ('positive supply') and extracting ('negative supply') to and from the two classrooms during the heating period. The green patterned bars (dark green for classroom #1 and light green for classroom #2) are the relative frequencies of the air flows that the supply terminal of the system directly supplied air in the classrooms ('positive supply: 19% of time in classroom#1 and 9% of the time in classroom #2). The blue bars (dark blue for classroom #1 and light blue for classroom #2) are the relative frequencies that the system only extracted air from the classrooms to the outdoor environment ('negative supply' or purge mode: 81% of the time in classroom #1 and 91% of the time in classroom #2) with all of the supply coming from infiltration. In both classrooms the distributions of air flows for the case of the supply are extending towards higher wind speeds (2-3m/s) whereas in the case of the extract air flows the distributions are peaking closer to lower wind speeds (1-2m/s). Similar analysis was performed to examine the buoyancy effect, beyond wind, however no specific pattern was identified.

In a further analysis of the system's effect on the overall $CO_2$ levels of the classrooms, it was found that the $CO_2$ concentrations were similar when the system was either supplying ('positive supply'17% of time) or mainly extracting ('negative supply'or purge 83% of time) at full occupancy (Figure 12).

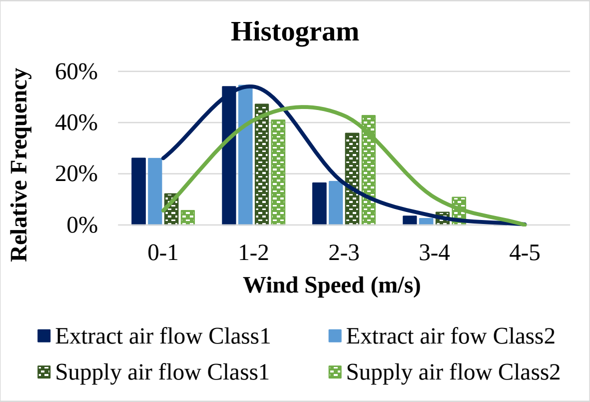

**Figure 17: Histogram of extract (blue) and supply (green patterned) air flows in the 'supply ductwork' of the systems for several wind speed bins in the two classrooms**

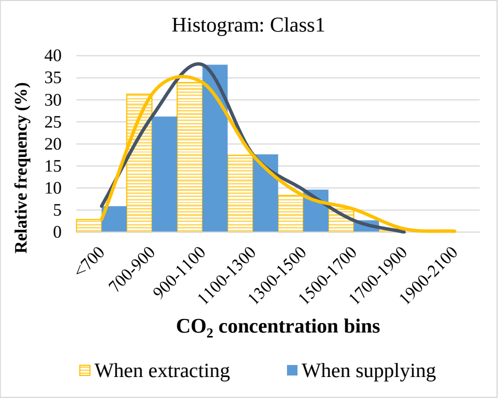

**Figure 18: Relative frequency distribution of $CO_2$ concentrations when the system was working as 'positive' and 'negative supply**

The diurnal variations of the wind speed and air velocities in the supply (positive supply) and extract (positive extract) of the systems as well as the indoor to outdoor ΔT in the 2 classrooms were examined and it was found that the supply (positive supply-classroom level) is more sensitive to the wind than to changes in ΔT. This was further quantitatively confirmed through the estimation of Pearson's and Spearman's correlation coefficients between the supply air flows ("positive supply") and wind speed and ΔT between indoors and outdoors- buoyancy (Table 9). Results indicate that the supply air flows are more strongly correlated to wind speed than buoyancy effects in both classrooms (Table 9). No significant correlation was found between internal-external temperature gradients and air flow, despite suitable temperature gradients. This indicates that the PVHR operates through wind driven pressures differences, although this relationship itself is not perfect, influenced by the intermittent wind speeds, direction, the non-linear relationship between wind pressures and wind speed as well as the use of windows and internal openings.

**Table 9: Pearson's and Spearman's correlation coefficients between supply air flows, wind speed and ΔT**

| | Pearson's Correlation | Spearman's Correlation | Pearson's Correlation | Spearman's Correlation | Sample size |
|---|---|---|---|---|---|
| | Wind Speed | | $\Delta T(T_{indoor} - T_{outdoor})$ | | |
| Supply air flow-classroom #1 | 0.197** | 0.202** | 0.035 | -0.005 | 493 |
| Supply air flow-classroom #2 | 0.151* | 0.174** | 0.052 | 0.050 | 245 |

*Correlation is significant at the 0.05 level (2-tailed)
**Correlation is significant at the 0.01 level (2-tailed)

Figure 19 shows an increasing trend of the extract airflows ('negative supply', blue bars) when more openings are present (either dampers or windows), while supply air flows are higher for more sealed conditions (windows and dampers closed). This confirms the operational modes of the PVHR system (Figure 6) at which the system is balanced equally supplying and extracting at more airtight conditions.

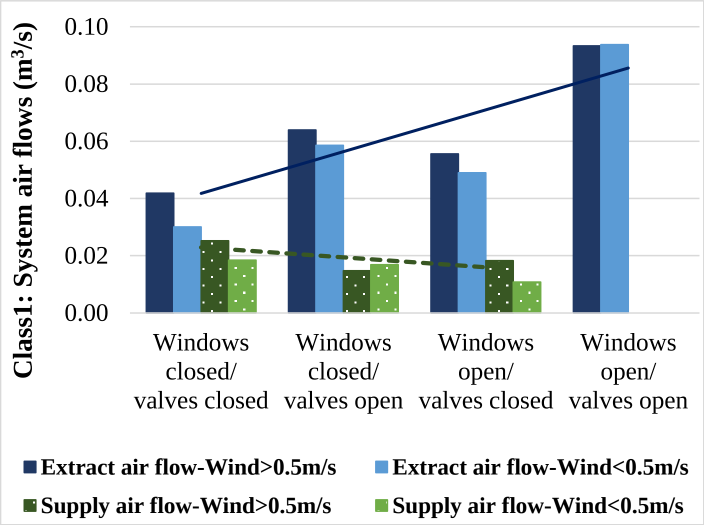

**Figure 19: Air flows in supply and extract pathway of the ventilation system in classroom #1**

For 81% of the time that the system in classroom #1 was working as “negative supply” (or extract, purge mode) the average air flows through the system when the windows were open were by 28% higher in comparison to the air flows when the windows were closed. In classroom #2 the system was working as “negative supply” or purge for 91% of the time. During that period the air flows through the system when the windows were open were by 46% higher in comparison to the cases of windows closed.

## 4 Conclusions

The aims of this study were to evaluate the *in situ* performance of a passive ventilation system with heat recovery (PVHR) installed in two school classrooms. Specifically, this focused on an assessment of the indoor environmental quality provided by the system, understanding the modes of operation and the influence of both the external and internal environment upon system performance.

Long-term environmental monitoring indicates that both internal temperatures and $CO_2$ levels fell within the ranges prescribed for schools by UK guidelines, being lower than 1,500ppm for 95% of occupied hours in both classrooms. At the same time, indoor temperatures fell within BB101 recommended limits for 90% of all occupied hours, simultaneously meeting overheating criteria and indicating suitable performance in both seasons.

The two PVHR systems were found to operate in purge mode for a significantly higher proportion of time (71% and 81% of occupied hours) during the heating season, than in by-pass mode, predominantly due to significant air infiltration through the building fabric and therefore restricting the heat recovery. Tracer gas and pressure test results confirmed the leaky nature of both classrooms, allowing significant air flow through the fabric even when windows are closed, helping to contextualise these results illustrating the impact of building fabric on system performance. The influence of both the building fabric and window opening indicate the importance of suitably characterising spaces, the external environment and ensuring correct operation of the system in order to make the most of the PVHR systems. Periods of supply (balanced) operation were then found to be driven by higher wind speeds and temperature differences between indoors and outdoors and only whilst windows were closed.

It was further identified that in the monitored setting the PVHR system is more sensitive to changes in wind speed and direction than to buoyancy, where significant positive Spearman's and Pearson's correlation coefficients were found between supply air flows and wind speed. External conditions had a significant effect on the system's operational performance where for negative pressures on the classrooms' facades, the ventilation system was supplying by two to three times more air directly in comparison to positive pressures. Additionally, the air flows within the system for the case of positive supply were extending towards higher wind speeds (2-3m/s) whereas in the case of purge or negative supply the distributions were peaking closer to lower wind speeds (1-2m/s).

In conclusion, the assessment of the ventilation performance of such natural ventilation systems depending solely on wind and buoyancy is complicated as they are dynamic and constantly balancing systems with both the indoor and the surrounding conditions, and their operation is strongly influenced by the airtightness of the building's envelope and the operation of room level openings. The influence of both indicates the importance of suitably characterising internal spaces and external environments as part of feasibility assessments as well as providing suitable controls and hand-over processes to help enable suitable operation.

# 5 Acronyms & Abbreviations

| | |
|---|---|
| PVHR | Passive Ventilation System with Heat Recovery |
| $CO_2$ | Carbon dioxide |
| IAQ | Indoor Air Quality |
| IEQ | Indoor Environmental Quality |
| CFD | Computational Fluid Dynamics |
| T | Temperature |

| | |
|---|---|
| RH | Relative Humidity |
| C(t) | Internal concentration of $CO_2$ in ppm |
| $C_{ext}$ | External concentration of $CO_2$ in ppm |
| $C_{in}$ | Initial concentration of $CO_2$ in ppm, |
| G | Generation rate of $CO_2$ within the classroom ($cm^3/s$) |
| Q | Internal-external exchange rate ($m^3/s$) |
| V | Volume of the room and t is the time (s) |
| ACH | Air Change per Hour |
| $C_o$ | $CO_2$ concentrations at an initial points of the decay curve |
| $C_f$ | $CO_2$ concentrations at a final point of the decay curve |
| $\Delta t$ | Time between the initial and final point expressed in hours |
| $C_{bg}$ | Background (external) $CO_2$ concentrations |
| Inf | Infiltration rates expressed in air changes per hour |
| $q_{50}$ | Mean air permeability at 50 Pa ($m^3h/m^2$) |

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