Experimental study on the in-situ performance of a natural ventilation system with heat recovery

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ABSTRACT

Combining heat recovery with natural ventilation is a relatively new topic of significant academic and commercial interest. The present study shows the performance of a recently developed Passive Ventilation system with Heat Recovery (PVHR) installed in a primary school building. The study includes (i) long term (12-month period) monitoring of the thermal environment and CO_2 concentrations and (ii) intense short term monitoring (2-week period during the heating season) of the environmental conditions in two classrooms, including detailed monitoring of the temperatures and bi-directional air speeds within the system itself. Airtightness measurements using the Blower Door test method were performed, while time-varying ventilation rates within each classroom were estimated by using a form of continuity equation taking into account CO_2 generation rates by occupants. Preliminary results show that average ventilation rates in the two classrooms ranged between 4.20 l/s/p and 5.93 l/s/p, above the recommended minimum set by BB101 (3 l/s/p). Furthermore, CO_2 concentrations for the majority of the monitoring period were below 1500ppm, while future research steps are also suggested.

KEYWORDS

Natural ventilation, Infiltration, PVHR, Air tightness, Indoor Air Quality (IAQ), Schools

1 INTRODUCTION

Natural ventilation strategies consume negligible amount of energy by utilizing natural driving forces of wind and buoyancy and provide a viable alternative to energy consumption by mechanical ventilation and air-conditioning systems, and a fundamental method towards energy efficient design of buildings (Calautit and Hughes 2014).

Several studies have been published on the evaluation of the performance of wind driven ventilation techniques such as the wind towers. These studies are mainly based on numerical methods (Montazeri 2011) such as CFD models (Ghadiri et al., 2013) and analytical methods (Hedeyat et al., 2015) using alternative semi-empirical approaches (Jones and Kirby 2009) or envelope flow models. The measurement of the performance of such systems has been restricted to laboratory conditions (wind tunnel tests) and only a few of them are examined *in situ* (Kirk and Kolokotroni 2004), making this a critical approach which needs further research.

According to Shao et al, 1998 passive stack systems that are designed without heat recovery may lead to wasteful heat loss. Natural ventilation systems combined with the application of heat recovery techniques which utilize internal dissipated heat, can lead to significant 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' *in-situ* performance (Lipinski et al., 2017).

This study reports on the preliminary results and the main objectives are: 1. to evaluate aspects of the indoor environmental quality of the classrooms that have a natural ventilation system combined with heat recovery installed; 2. to examine to which extend the required ventilation rates are being achieved in context of the air tightness levels of the classrooms; 3. to give a preliminary indication of the heat recovery performance and the parameters that are affecting the air flows within the system.

2 METHODOLOGY

2.1 Sampling site description and monitoring period

The study took place in 2 classrooms (#1 & #2) of a primary school building built in 1971 and located at Forest Hill, in South East London within the London Borough of Lewisham. The school is located in a suburban residential area and has low to moderate traffic on its adjoining streets.

The monitoring period involved both the short and the long term monitoring in order to cover a broader source of information. Long-term measurements were carried out in one classroom (#1) from February until November 2016 while short-term monitoring took place in two classrooms (#1 and #2) for two consecutive weeks from the 19th of January until the 2nd of February 2017. Monitoring is still ongoing but for the purpose of the paper a specific period was chosen to present the preliminary findings. Both classrooms had natural ventilation systems with heat recovery installed and were selected in order to meet the requirements set by Mumovic et al., 2009 having "reasonable occupancy patterns, typical teaching activities and microclimatic conditions which would not reduce the potential for natural ventilation". The classrooms also had central heating systems (with multiple radiators positioned around the classroom) and windows on a single façade (North-West). Table 1 summarizes some of the main characteristics of the two classrooms.

Table 1: Main characteristics of the classrooms

	Floor area (m^2)	Volume (m^3)	Window area/ openable area(m^2)	Orientation	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

2.2 Passive Ventilation with Heat Recovery: description

The PVHR system consists of three key components: the roof cowl, the coaxial heat exchanger and the flow splitter as shown in Figure 1. 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 two 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 by means of convection and conduction. Further details on the system's description can be found on Lipinski et al., 2017.

Figure 1: Key components of the PVHR system

2.3 Parameters measured and instrumentation

Indoor temperature, relative humidity and CO_2 concentrations were measured throughout both the long term and short term monitoring periods. CO_2 concentrations were monitored at 3 different locations within each of the two classrooms in order to examine the horizontal and vertical distribution of CO_2 concentrations. Two of the sensors were located at seated breathing level (1.10m) according to the ISO 7726: 2001, with one at the centre of the classroom and one next to the window. The third CO_2 sensor was placed at high level (2.70m) near the system's extract. All monitoring equipment was calibrated before installation and correction factors between the monitoring instruments were estimated during preliminary measurements in a lab under constant conditions.

Outdoor weather conditions including temperature, relative humidity, wind speed and wind direction were simultaneously monitored throughout the short term monitoring period. Moreover, temperatures and air velocities were measured in both the supply and extract air channels before and after the heat exchanger of each of the systems in the two classrooms (Figure 2). It should be noted that the air velocity sensors were bi-directional in order to examine in detail the characteristics of air flows inside the system. The technical specification of the monitoring equipment used is summarized in Table 2. The logging interval for all of the aforementioned parameters was 90s.

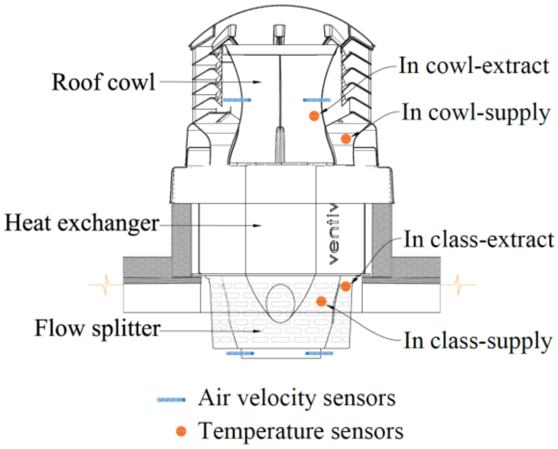

Figure 2: PVHR section and location of air velocity (blue bars) and temperature sensors (orange dots)

Table 2: Technical specification of monitoring equipment

Parameter Measured	Sensor Type/ Supplier/ Principle of operation	Range/ Resolution	Accuracy
1xbuilt-in RH 1x built in T 1xbuilt-in CO_2	GD47/ Eltek Ltd/ NDIR infrared sensors Compliant to: EN300-220-1 EN16000-26	0-100%/ 0.1% -20-60ºC/0.1 ºC 0-5000ppm/ 3% of measured value at 20ºC	±2% ±0.4ºC ±50ppm
External RH External T	GD13Ecf/ Eltek	0-100%/ 0.1% -40 to +85⁰C/ 0.1ºC	±2% ±0.4ºC
Wind Speed / Wind direction	Davis Anemometer connected to GD18Wcf /Eltek/ Wind vane cup anemometer	0-58m/s / 0.45m/s & 1º	±5%/ 7º
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 / 256 steps	From 15-35ºC, 5% of full scale, 3% of full scale at 21ºC
Temperature (inside the system) connected to a GS34 transmitter	Thermistor/ ELCM-U-VS-02-0	-50ºC to +150ºC	±0.1ºC

2.4 Data processing and analysis

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):

$$V\frac{dC(t)}{dt} = G + QCex - QC(t) \text{ (Eq.1)}$$

The integrative solution of the above equation gives:

$$C(t) = Cex + \frac{G}{Q} + \left(Cin - Cex - \frac{G}{Q}\right)e^{-\left(\frac{Q}{V}\right)t} \text{ (Eq.2)}$$

Where C(t) is the internal concentration of CO_2 in ppm (time dependant), Cex is the external concentration of CO_2 in ppm, Cin 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 methodology used by Coley and Beisteiner 2002 was adopted in which 20min averaged blocks of data were considered (to reduce noise). 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 per person and for teachers was equal to 0.0052 l/s/p, which are in agreement with Persily, 1997. Eq. 2 was solved using MATLAB R2012b. The assessment of uncertainties of this methodology will be presented in detail in a future study.

Air permeability

Air permeability measurements took place in the two classrooms using a Retrotec DM2 gauge and a 3000 fan. In the present study both pressurization and depressurization tests were performed in general following to the ISO EN 9972 (EN ISO 13829), according to the method of a building in use, fulfilling the following measurement conditions: 1.The results from the indoor to outdoor temperature difference (in Kelvin) multiplied by the height (in m) should be less than 250mK, 2. The wind speed should be less than 6m/s. However, some critical differentiations were considered. Due to the size of the building and for matters of simplification the airtightness test was performed in each of the two classrooms. In this way the expected result would measure all barriers of a single zone and would include the air leakage related both to the indoor and outdoor environment. For this reason the envelope area that was taken into account in the calculations of the air permeability was equal to the entire envelope area of each of the classrooms including floor, ceiling, external and internal walls. Two different modes of air tightness were measured in each of the two classrooms, with the natural ventilation system being sealed (baseline airtightness) and unsealed. In this study the Blower Door device was supplemented with smoke tests for a qualitative examination of the air flows.

3 RESULTS AND DISCUSSION

3.1 Indoor Environmental conditions and CO_2 concentrations

The daily average concentrations of CO_2 throughout the long term monitoring period (Feb-Nov 2016) of classroom #1 are shown in Figure 3. The daily average concentrations for the entire period were below 1500ppm for the majority of the cases. Also, there is a decreasing trend on the average concentrations moving from winter to summer months possibly related to the additional ventilation rates through openable windows during summer months. According to the BB101 for teaching spaces that natural ventilation is used, the maximum concentrations should not exceed 2000ppm for more than 20 consecutive minutes each day. For this case for 15 days out of 110 days (13.6%) of monitoring in total during the long term measurements, the CO_2 concentrations at breathing level exceeded 2000ppm for durations that ranged between 30min and 180min. However, the percentage of time that the CO_2 exceeded 2000 ppm throughout the long term monitoring period was equal to 3%. In this particular installation purge ventilation was to be manually provided by the user with exceedance of 2000ppm communicated by red 'traffic light' on the classroom sensor (as stipulated in the BB101). It appears that in the cases where CO_2 concentrations remained above 2000ppm the windows have not been opened. Following the study the guidance has been issued to include automatic purge ventilation in all future PVHR projects to address this user dependent variability.

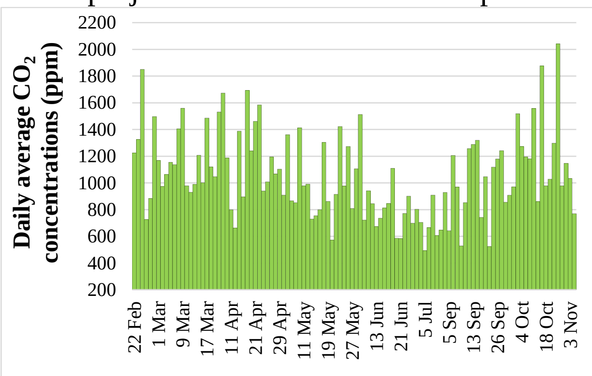

Figure 3: Daily average of CO_2 concentrations during the reaching hours at the long term monitoring period

The monthly ranges for temperature and relative humidity are shown in Figure 4. Monthly average temperatures ranged from 19 to 24°C while relative humidity ranged from 40 to 59% indicating a satisfactory thermal environment throughout the year.

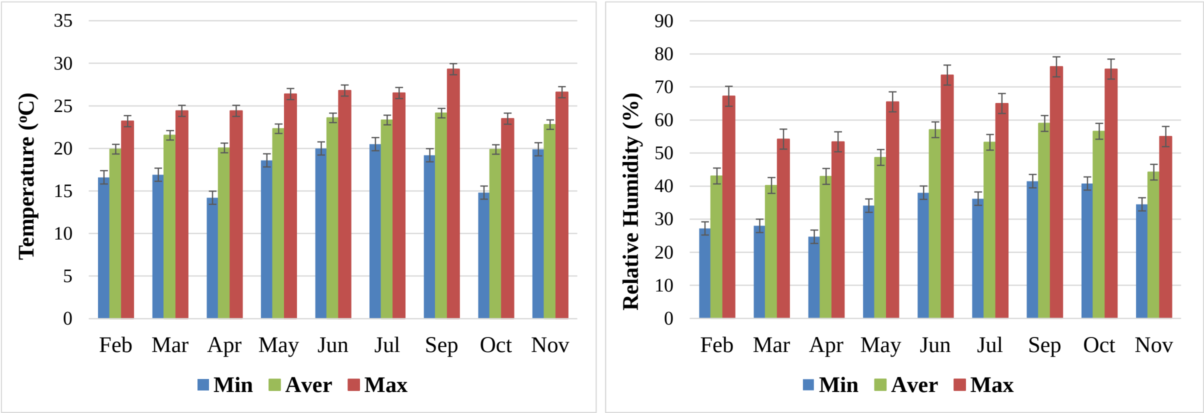

Figure 4: Monthly ranges of temperature (left) and relative humidity (right) during the long term monitoring period

Descriptive statistics of temperature, relative humidity and CO_2 concentrations during the teaching hours (8:50AM -15:30PM) for the short term monitoring period (19/1-1/2/17) are summarised in

Table 3. Average temperatures in both of the classrooms are slightly above the recommended winter comfort temperatures set in CIBSE guide A (19-21ºC) by 0.9ºC in Classroom #1 and 2.9ºC in classroom #2. Relative humidity levels remained low in both classrooms. Mean CO_2 concentrations for both classrooms were below 1500ppm.

Table 3: Descriptive statistics of indoor environmental parameters during the teaching hours

		Mean	Median	Min	Max	St Dev
Classroom #1	Temperature (ºC)	21.9	21.9	19.2	24.1	1
	Relative Humidity (%)	39	37	25	56	7
	CO_2	995	950	546	1914	263

Figure 5 presents the cumulative frequency distribution of CO_2 concentrations in the two classrooms (classroom #1 depicted in the left chart, classroom #2 on the right) for the short term monitoring period. As can be seen, for 5% of the cases at the middle point (representative of the classroom's mean concentration) of classroom #1 and approximately 20% of the cases in classroom #2 CO_2 levels exceeded 1500ppm. Also, the CO_2 concentrations near the window of classroom #2 were significantly lower compared to the corresponding readings at the extract level and middle point (difference of about 460ppm), likely indicating fresh air supply from the window at that point (or higher levels of infiltration). CO_2 concentrations at the extract level and middle point (mean concentration of the room) were very similar in classroom # 2 which according to the definition of the contaminant removal effectiveness (CRE), of REHVA can be considered as a fully mixed situation.

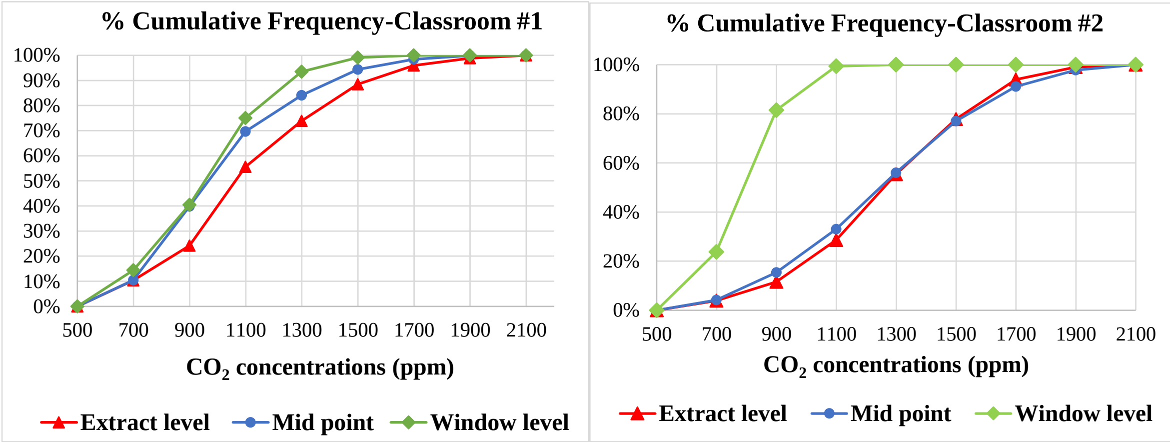

Figure 5: Cumulative frequency distributions of CO_2 at extract level, middle point and window level

3.2 Ventilation rates

As aforementioned, time varying ventilation rates were estimated using the mass balance equation for 20min blocks of data (using time-averaged values of CO_2 and G). Table 4 presents the descriptive statistics of ventilation rates in l/s/p, the corresponding indoor to outdoor temperature difference and wind speed in each of the two classrooms during the short term monitoring period. It can be seen averaged ventilation rates in both of the classrooms are above the minimum ventilation rates of 3 l/s/p required by BB101.

Table 4: Descriptive statistics of Ventilation rates, corresponding Indoor/outdoor temperature differences and wind speed

	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	5.93	16.5	4.2	17.62	0.9
Median	5.50	16.5	3.35	17.23	0.9
Min	0	10.7	0	10.72	0
Max	17.74	23.4	13.57	25.01	2.2
Stdev.	3.97	3.3	3.57	3.13	0.5

The diurnal variation of CO_2 concentrations, the number of people and corresponding estimated ventilation rates for one indicative day in each of the classrooms are shown in Figure 6. The trend of the CO_2 concentrations follows the number of students inside the classrooms while the ventilation rates are inversely correlated to the CO_2 concentrations with some time lag being evident. In classroom #1 (Figure 6, left) half of the windows opened at11:03AM and remained open until the rest of the day. As for classroom #2, half of the windows opened from 11:24AM until the end of the day.

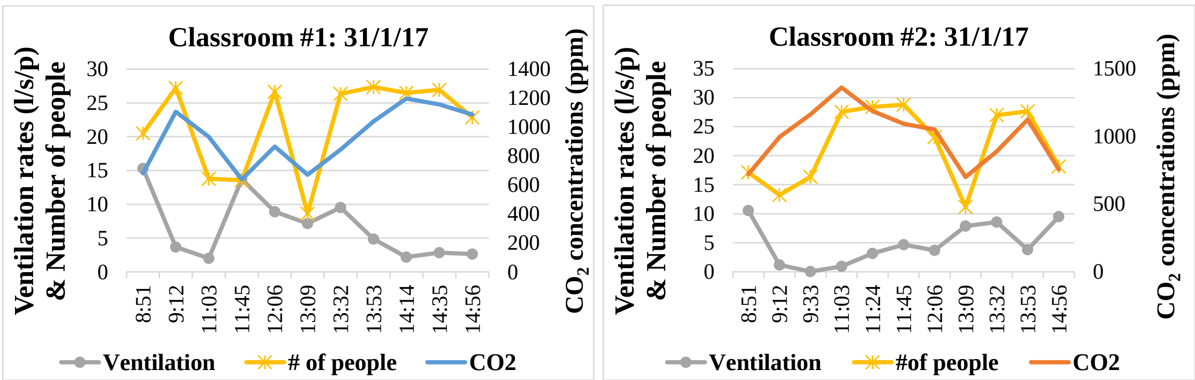

Figure 6: Diurnal variation of CO2, number of people and ventilation rates

3.3 Air permeability

Air permeability values are summarized in Table 5. According to the approved document L2A classification, the worst allowable air permeability for new buildings is $10m^3/m^2h$ at 50Pa. Baseline air permeability in both classrooms (with ventilation systems sealed) was greater than this value. To this end, considering that the PVHR system is designed for airtight buildings (recommended airtightness≤5 m^3h/m^2 at 50Pa) it can be assumed that the system's heat recovery performance is undermined in this particular case.

Table 5: Air permeability rates in the two classrooms

	System sealed (baseline)		System fully open	
	Mean air permeability q_{50} at 50 Pa (m^3h/m^2)	Mean air leakage n_{50} at 50 Pa (ACH)	Mean air permeability q_{50} at 50 Pa (m^3h/m^2)	Mean air leakage n_{50} at 50 Pa (ACH)
Classroom #1	13.4	15.83	26.68	31.42
Classroom #2	10.23	12.19	23.81	28.25

3.4 System

Since PVHR is a natural ventilation system, driven exclusively by wind and buoyancy, the surrounding conditions (e.g. window opening) will influence its operation and the balance of supply and extract. Using the output of the bi-directional air velocity sensor located in the air flow terminal of the system (within the classroom, ceiling level), the air flows were categorized in "positive supply" and "negative supply". The system in classroom #1 supplied fresh air ("positive supply") in the classroom for 19% of the occupied hours during the short term monitoring period, while the system in classroom #2 supplied fresh air in the classroom for 9% of that time. At this point it is worth mentioning that the installation of the system in classroom #2 was found to be defective (due to fitting inaccuracies) therefore its performance could have been affected. In addition for the above, considering amount of time that the systems "positively supplied" fresh air in the two classrooms, the windows were closed for 81% of that time in classroom#1 and for 96% of that time in classroom #2. Negative supply is a design feature of Purge ventilation mode and is enabled by opening windows. When PVHR system is installed in particularly 'leaky' buildings it can occur also at times when windows are closed due to high levels of infiltration.

Figure 7 (left for classroom #1 and right for classroom #2) presents the relative frequencies of the systems' supplying fresh air ("positive supply") and extracting stale air ("negative supply") to and from the classrooms. In green stripped bars are the relative frequencies of the air flows that the terminal of the system supplied fresh air in the classroom ("positive supply", 19% of the time for classroom #1 and 9% of the time for classroom#2) for five wind speed bins. The blue and orange bars are the corresponding relative frequencies of air flows for classrooms #1 and #2 respectively that the system extracted fresh air from the classroom to the outdoor environment ("negative supply", 81% of the time for classroom#1 and 91% of the time for classroom#2). It can be seen that in both classrooms, the distributions of air flows for the case of the "positive supply" are extending towards higher wind speeds (2-3m/s) whereas in the case of the "negative supply" (extract air flows) the distributions are peaking closer to lower wind speeds (1-2m/s).

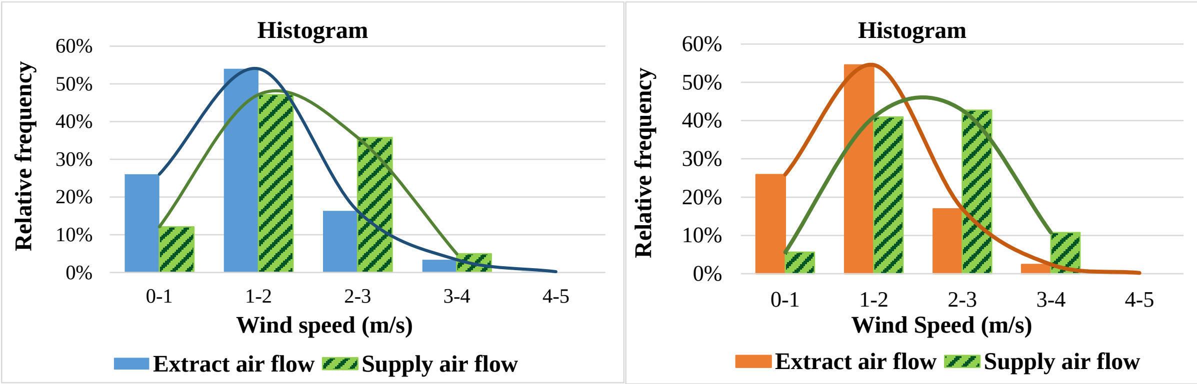

Figure 7: Histogram of extract and supply air flows in the "supply ductwork" of the system for several wind speed bins in classroom #1 (left) and classroom #2 (right)

Figure 8 presents average temperatures developed inside the PVHR system, the classroom and the external environment across the short term monitoring period for the cases that the system was supplying fresh air ("positive supply") to the classrooms (left: classroom#1, right: classroom#2). The exact location of the temperature sensors is shown in orange dots in Figure 2. As it can be seen, the temperature increased by approximately 10ºC and 16ºC in classrooms 1 and 2 respectively from the point right before the air entered the heat exchanger (in cowl-supply) and the point the air was supplied in the classrooms (in class-supply). It can further be seen that the supplied air temperature of the system to the classroom (in class-supply) is very similar to the indoor temperature of the classroom. Considering the following formula the heat recovery efficiency was calculated.

$$E_{\text{Heat Recovery}} = \frac{T_{\text{in class supply}} - T_{\text{in cowl supply}}}{T_{\text{in class extract}} - T_{\text{in cowl supply}}} \text{x}100\% \quad \text{(Eq.3)}$$

Preliminary findings show that for the percentage of time that the system was supplying fresh air in the classrooms, the heat recovery efficiency was equal to 82% in classroom #1 and equal to 88% in classroom#2. These heat recovery efficiencies are unexpectedly high. A further CFD study is being conducted to establish whether higher than expected supply temperatures are influenced by the classroom air temperature or due to specific airflow balance within the system itself.

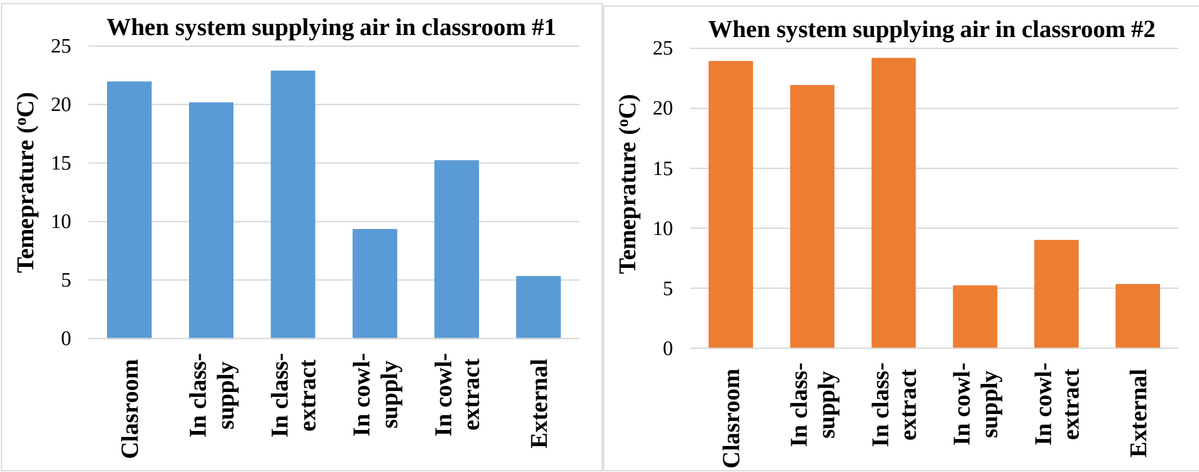

Figure 8: Average temperatures within the systems' ductworks when the system is supplying air in the classrooms

4 CONCLUSIONS

This paper presented preliminary findings of a study in progress of the performance of a passive ventilation system with heat recovery (PVHR) installed in two classrooms of a refurbished school.

The thermal environment of the classrooms with the ventilation system was satisfactory overall, being within the recommended thermal guidelines of CIBSE guide A and IAQ guidelines of BB101. As for the CO_2 concentrations, they were below 1500ppm for 95% and 80% of the cases in the two classrooms. Regarding the ventilation performance based on occupant generated CO_2 concentrations, the average estimated ventilation rates were equal to 5.93 and 4.2 l/s/p in the two classrooms, both above minimum requirements of 3l/s/p set in the BB101. The air permeability measurements indicated relatively leaky building's fabric, a fact that directly impacts the ventilation balance within the system and the system's heat recovery performance. As for the preliminary results of impact of environmental conditions, it was found that for higher wind speeds (between 2 and 3 m/s) the system was mainly supplying fresh air in the classrooms while for lower wind speeds (between 1 and 2m/s) the system was mainly extracting stale air from the classroom to the outdoor environment. The heat recovery efficiency of both systems in the two classrooms was higher than designed. A further CFD study is being conducted to establish parameters that are affecting the supply air temperature and are contributing to the air flow balance of the system and the surrounding environment. Further research will also involve the estimation of uncertainties on the calculation of ventilation rates using the occupant generated CO_2 concentrations.

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