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Ventilation rates and thermal comfort assessment in a naturally ventilated classroom

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Abstract

Ventilation systems are meant (i) to guarantee good indoor air quality (IAQ) by providing and distributing fresh air to the occupied/breathing zone and (ii) to dilute and remove pollutants emitted by indoor sources. On the other hand, inadequate ventilation rates can induce discomfort issues and excessive energy consumption. This study focuses on the performance assessment of natural ventilation strategies in university classrooms, which are characterized by a high occupancy level and the necessity to provide high levels of comfort to perform intellectual work. The high occupancy level creates challenging conditions both in terms of internal gains and CO₂ concentration. This paper presents an experimental performance assessment of four natural ventilation strategies applied to a university classroom: single side ventilation, cross ventilation, stack ventilation with and without window supply. Each strategy is evaluated in terms of thermal comfort and air change rate measurements. Thermal comfort assessment were performed during occupancy period (physical parameter measurements and questionnaires) whereas air change rate measurements, based on tracer gas techniques, were performed during unoccupied periods.

Keywords - Ventilation performance assessment, ventilation strategy, tracer gas, thermal comfort

1. Introduction

The building industry covers more than 40% of the final energy consumption in European countries [1] and represents therefore a key sector towards reducing EU energy demand. Moreover, the growing interest for users comfort puts us in front of new challenges that implies an increasing focus on the definition and assessment of micro-climatic requirements to ensure an adequate user satisfaction, i.e. an improved indoor environmental quality (IEQ). Besides ensuring users' overall comfort, which is moving to higher standards, the indoor microclimatic conditions are nowadays increasingly investigated especially in tertiary sector. A number of studies pointed out the

benefits on workers' productivity related to higher levels of IEQ [2; 3; 4]. When it comes to educational buildings, the relevance of comfort is also substantial and requires a higher attention because of the specific characteristics of these buildings compared to other construction. In addition to its strong link with health issues [5], a number of studies pointed out the impact of IEQ on performances in schools [6]. This issue was investigated by Wargocki [7] through a series of studies on a total of 380 children exposed to various conditions. The author pointed out the relevance of IEQ on learning performance and showed that poor IEQ can reduce performances by 30% [7]. Indoor climate quality issues in schools and educational buildings depend on the high level of occupancy of classrooms (around $1.8 \text{ m}^2/\text{person}$) [8]. Without suitable HVAC system, a high occupancy can affect both thermal comfort and indoor air quality (IAQ). A high occupancy is connected to high thermal gains and can lead to overheating in classrooms. Seppannen [9] showed through 148 performances tests under various temperatures, that occupant's performances can decrease by 1% for each temperature rise of 1°C (above the comfort temperature). On the other hand, a high occupied space with unsuitable ventilation rates may result in very high CO_2 concentrations and lead to poor IAQ. The effect of high CO_2 concentration on occupants was widely investigated. A recent experimental study correlates CO_2 concentrations and occupants' performance (decision making) for different exposure and pointed out significant effects above 2500 ppm [10].

The present paper follows a previous study conducted on a classroom in a French university campus [11]. The early study, conducted during December 2014, aimed to assess the effect of various ventilation strategies on thermal comfort and IAQ by means of an in-situ experimental campaign including thermal comfort measurements, subjective assessments by questionnaires and CO_2 concentration measurements. This paper presents the results of a second assessment conducted on the same classroom one year later. The new study aims to investigate the performance ventilation strategies operating under the real conditions. In fact, the classroom is designed to operate with mechanical ventilation. However, the mechanical ventilation is not operating. The most realistic ventilation strategies were then assessed. Thus, in addition to thermal comfort and CO_2 measurements (held during occupancy period), the ventilation performance was assessed in terms of air change rates (ACR) and mean age of air, using tracer gas technique during unoccupied period.

2. Case study

The study was performed on a classroom in a French university campus (ESTP) located in Cachan (5km south of Paris). The classroom is within the 2nd floor of the newest building of the campus (built in 2008). The building is certified RT2005 (réglementation thermique 2005), according to French energy performance code. So, according to the climatic zone (H1 north and center) and the energy supply (gas), the performance indicator fixed by the

regulation is 130kWh/m².year including heating, cooling, DHW and lighting. As shown in Figure 1, two walls are exposed to the outdoor environment, while the two other walls are adjacent to the corridor and a classroom respectively. Fifteen double glazed windows of 1.39 x 0.84 m for a total glazing area of 18 m², are installed on the walls exposed to the outdoor environment. Concerning the HVAC system, the classroom is equipped with water-filled radiators for the heating, and a double flux mechanical ventilation system for ventilation. However, the mechanical ventilation system was not operating. Thereby, the ventilation is operated through infiltrations (envelope), windows and the vents which were initially designed for mechanical ventilation. In fact, the two vents (figure 1) are connected to outdoor (rooftop) through ventilation ducts. Two windows are manually operable for natural ventilation. The operable windows can be used both in tilted or swing position. In the present study, the opening of the two windows was performed only in tilted position with an opening area of 0.45m² (for each window). The two windows are respectively facing North (0° N) and West (270°W) as showed in Figure 1. In the present study, the ventilation is assessed as it operates under real conditions i.e natural ventilation through windows and vents. The main characteristics of the classroom are presented in Table 1.

Table 1. Classroom's characteristics

Parameter	V[m ³]	A[m ²]	W _{FR}	W _O	W _{oa} [m ²]
Results	216.4	81.3	0.21	F ₁ : 270°W; F ₂ : 0°N	0.90

Note: V=volume [m³]; A= area [m²]; W_{FR}=window to floor ratio; W_O= windows orientation; F₁: window 1; F₂: window 2; N: north; W: west; W_{oa}=windows opening area

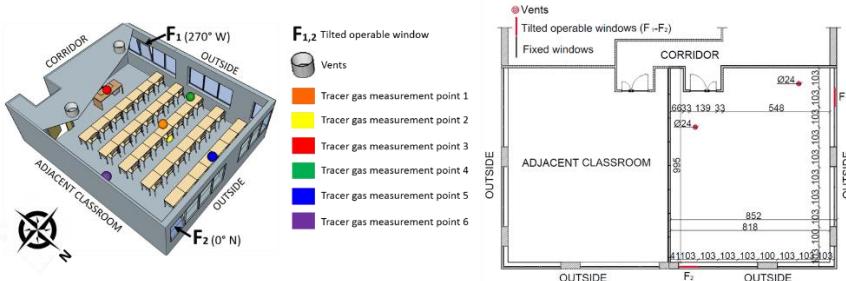


Figure 1. 3d view of the classroom with the measurement points and windows orientation (on the left) and 2d plan of the classroom (on the right)

3. Methodology

As shown above, the classroom is equipped with two manually operable windows and two vents (Figure 1). Four natural ventilation strategies were applied during the measurement period, with two measurement days for each strategy: NV1: single side ventilation (with one window); NV2: cross

ventilation (with two windows); NV3: stack exhaust with infiltration supply; NV4: stack exhaust with one window supply. Natural ventilation was investigated regarding four main issues: thermal comfort, CO₂ concentration, air change rates and mean age air. The assessment was performed during the school term and include tests during both the occupied and unoccupied period.

The indoor climate quality (thermal comfort and CO₂ measurements) was assessed during the occupied period, typically from 8:30 to 18:30. The thermal comfort assessment was performed by means of physical parameters measurements and questionnaire surveys, while the IAQ was indirectly assessed on the basis of relative CO₂ concentrations (indoor-outdoor). The present paper does not include the results of thermal comfort analysis (PMV calculation, questionnaire analysis), but it considers the thermal conditions relevant to evaluate the impact of each strategy on comfort temperatures.

The ventilation performance (i.e air change rates and mean age of the air) was assessed during the unoccupied period, typically from 18:30 to 22:00. A methodology based on 3 steps was set up: (i) auxiliary measurements for the characterisation of the experimental conditions, (ii) air change rates measurements, (iii) age of the air measurements. Auxiliary measurements do not concern the assessment of ventilation performances but the analysis of the investigated room layout, and the outdoor and indoor conditions during the tests. The analysis of the classroom layout was carried out upstream the ventilation measurements and implies: the characterisation of the ventilation system (location of the windows, effective opening area); the measurement of the air tightness of envelope by means of blower door tests and the measurements of the effective volume. The effective volume is the volume occupied by the air and defined by Rifat [12] as “the volume in which mixing occurs and is not necessarily equal to the physical volume of the zone”. It is worth noting that the estimation of the effective volume is crucial when converting air change rates to air flow rates. In fact, by using an accurate value of the real volume (effective volume) the uncertainties in the estimation of the airflow rate could be reduced from 14.5% to 4.5% [12]. The measurement of the airtightness was carried out using a blower door test according to the NF EN 13829 [13]. The characterisation of the climatic conditions (indoor and outdoor) was made in parallel with the ventilation measurements and implied: the measurements of outdoor air temperature, relative humidity, wind speed, wind direction and CO₂ concentration; the measurement of the indoor climatic conditions by means of data loggers (air temperature, relative humidity and CO₂ concentration). Table 2 shows the characteristics of indoor data loggers and outdoor weather station.

The measurements of the ventilation rates were carried out by means of tracer gas techniques. In the present work, the concentration decay was adopted to measure the air change rates (ACR) according to the ASTM E741 [14] using CO₂ as tracer gas. As the measurements were performed after each lesson, the CO₂ concentration was relatively high at the beginning of the tracer

gas test. Therefore, the CO₂ produced by the occupants was used as tracer gas. However, the CO₂ concentration was not always constant, depending on the ventilation strategy and the occupancy. Therefore, to ensure homogeneity among tests, the starting decay concentration was fixed to constant concentration of 2500 ppm, and adjusted, when required, by injecting additional CO₂. According to the standard ASTM E 741 [14], fans were used to mix the air to ensure the spatial uniformity of concentration criterion before activating the ventilation strategy (beginning of the decay). Tracer gas measurements were performed using a multipoint sampler and doser Innova 1303 for the gas supply and a Photoacoustic Gas Monitor Innova 1412i for the measurement of the CO₂, which was used as tracer gas.

Table 2. Characteristics of the data loggers and outdoor weather station

Parameter	Symbol	Range	Accuracy
Data loggers (indoor)			
Air temperature	T _a	[-20...-70]°C	± 0.5°C
Relative Humidity	RH	[0...100]%	±0.88 RH%
Carbon dioxide	CO ₂	[0...5000]ppm	±50ppm
Weather station (outdoor)			
Air temperature	T _{aout}	[-20...50]°C	±0.2 (-20...50)°C ±0.5 (>-30°C)
Relative Humidity	RH _{out}	[0...100]%	±2 RH%
Wind speed	W _s	[0...30]m/s	0.3
Wind direction	W _d	[0...359.9]°	<0.3° (W _s > 1 m/s)

The measurements of mean age of the air were performed during the tracer gas tests according to the NT VVS 19 standard [15]. As shown in Figure 1, the age of the air was measured in six points: five points in five zones of the classroom (center, back, front and on the wings) fixed at the breathing level (110cm) an one point in the center of the classroom fixed at 60cm above the floor.

4. Results

The present study was carried out during the winter period for two weeks (from December 4th to December 18th). The assessment of the indoor climate quality was carried out during 12 days continuously (3 days for each strategy) in parallel with ventilation performance measurements, as explained above. A total of 8 ventilation performance tests (2 tests for each strategy) including airflow rates and age of air measurements were carried out.

The envelope airtightness was characterized through three successive blower door depression tests. The results reveals a quite poor airtightness with measured n₅₀ around 6.67 h⁻¹. The three tests presents n₅₀ values around 6.56 (± 5.08%) h⁻¹; 6.96 (± 5.04%) h⁻¹; 6.49 (± 5.13%) h⁻¹, respectively.

The effective volume was measured through two successive tests (uncertainty 10%) using the tracer gas method provided by Rifat [12] and

according to the direct method provided by the ASTM E741 standard. The measured effective volume was 235m^3 while the geometrical volumes were 216m^3 below the false ceiling and 243m^3 including the false ceiling space. The difference depends on furniture and false ceiling mostly.

Cachan climate is defined as Cfb (warm temperate, fully humid and warm summer) according to the climate classification Köppen-Geiger, with a moderate seasonality. The annual average temperature is around 11°C . The winter average temperatures are typically below 5°C . During the experimental campaign, the weather was quite cold and humid, as expected, with an average outdoor temperature around 8°C and an average relative humidity around 83%. The relative humidity was quite constant during the campaign, while strong temperatures fluctuations were measured (from 1.4°C to 16.1°C). As explained above, the outdoor conditions affects strongly the results in the present study (natural ventilation). Therefore, each day the impact of outdoor conditions on the ventilation performances was analysed.

Figure 2 shows the frequency distribution of indoor air temperature according to each strategy during the occupied period. The minimum value of temperature was approximately equal for all the strategies (18°C) except for NV4 strategy (16°C). The maximum recorded temperature varies between 21.5°C and 22.8°C depending on the strategy. Significant differences were noted for the strategy NV4 with 20% of the recorded temperature values below 19°C and 40% of the recorded temperatures values below 20°C . The temperatures during NV3 strategy, conversely, remain almost always above the measured temperatures for the others strategies. As expected the strategy NV3 shows a slight overheating with more than 60% of the recorded values above 20°C . The strategies NV1 and NV2 shows respectively 28% and 35% of the recorded values below 19°C . If one considers the 21°C defined by the standards as a hypothetical comfort temperature, 80% of the recorded temperatures were under this condition.

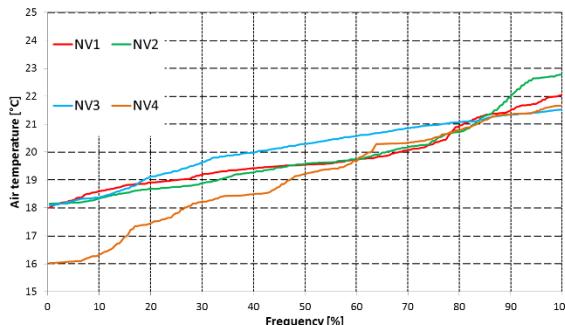


Figure 2. Frequency distribution of the measured temperatures according to each ventilation strategy during the occupied period

Figure 3 shows the frequency distribution of the recorded CO₂ above outdoor for the whole occupied period and for each ventilation strategy. It is worth noting that outdoor CO₂ was quite high with an average value of 414 ppm while the minimum and maximum values were respectively 397ppm and 450ppm. The recorded CO₂ values above outdoor for the whole occupancy period were clearly high and varies between 401ppm and 4400ppm. If one considers the limits fixed by the standards (EN15251), only 2% of the whole period correspond to the category II (<500ppm) while 20% of the period within the limits of the category III (<800ppm). Finally, 80% of the recorded CO₂ concentrations correspond to the category IV (>800ppm).

In terms of ventilations strategies, the results showed in Figure 3 reveals significant differences. The strategy NV3 shows the worst results, with 90% of the recorded CO₂ concentrations above the limits fixed by the EN15251 for category III (800ppm). On the contrary, the strategy NV2 presents the best results with 30% of the recorded values within the category III. The strategies NV1 and NV4 presents respectively 10% and 20% of the recorded values within the limits of the category III.

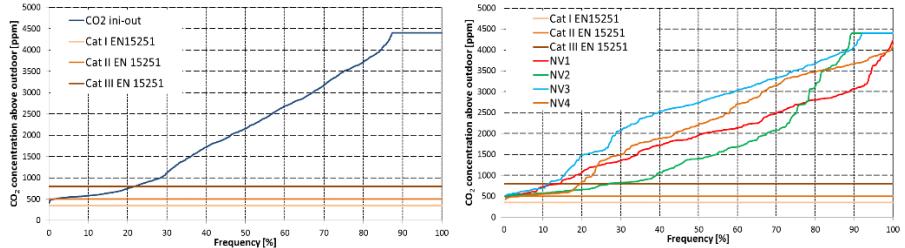


Figure 3: Frequency distribution of the measured CO₂ concentration above outdoor for the whole occupied period (on the left) and for each ventilation strategy during the occupied period (on the right)

Table 3 presents the results of the ventilations performance measurements including both air change rates and the room mean ages of the air for each ventilation strategy. The average air change rate varies between 0.10h⁻¹ and 3.20 h⁻¹. The highest values in terms of air change rates were recorded during the strategy NV2 (cross ventilation) with 1.79h⁻¹ and 3.20h⁻¹ for the two tests. These results seem to be coherent if we consider the CO₂ concentrations. In fact, the strategy NV2 presents the lowest CO₂ values. The averages values for the strategies single side (NV1), stack with infiltrations (NV3) and stack with windows supply (NV4) were respectively 1.04, 0.82 and 1.42 h⁻¹.

It is worth noting that results are strongly influenced by the outdoor climate. The parameters considered in the present study for the natural ventilation are: wind speed, the wind direction and the temperature gradient

(indoor-outdoor). The wind speed differences between the strategies were not significant. The values varies between 0.32 m/s and 0.57 m/s. The wind direction during the tests varies on average between 8° (North) and 73° (East).

The temperatures gradients indoor-outdoor were significant with values between 6.72°C and 17.19°C for the whole period. By comparing the strategies, the temperature gradient varies by 2°C on average between each strategy. The ventilation performance is mainly affected by the temperature gradient and the chosen ventilation strategy, and only in a limited manner by wind. The results between the tests for the single side confirms this, resulting in an ACR of 0.71h⁻¹ for a temperature gradient of 7.84°C and an ACR of 1.37h⁻¹ for a temperature gradient of 15.13°C.

As expected, the age of air is inversely proportional to the ACR, independently from the ventilation strategy i.e the highest values of ACR correspond to the lowest mean age of air. The cross ventilation is the most efficient strategy in providing fresh air to the breathing zone (around 1316s on average). The mean ages of air for the strategies NV1, NV3 and NV4 were respectively 2786s, 9436s and 2174s.

Table 3. Ventilations measurements results including room mean age of air, air exchange rates; airflow rates, temperatures gradients and wind speed for each strategy

Parameter/Strategy [Units]	Room mean age of the air [s]	ACR [h ⁻¹]	Airflow rate [m ³ /h]	Tin-Tout [°C]	Wind speed [m/s]	Wind direction [°]
NV1						
Test 1	3386	0,71	166,68	7,84	0,53	73
Test 2	2153	1,37	321,52	15,13	0,55	22
NV2						
Test 1	1548	1,79	421,77	13,44	0,45	8
Test 2	1162	3,20	752,26	17,19	0,57	20
NV3						
Test 1	16831	0,10	23,75	12,58	0,52	33
Test 2	2035	1,53	360,29	6,72	0,32	35
NV4						
Test 1	1879	1,66	390,04	14,92	0,37	19
Test 2	2548	1,18	277,34	8,10	0,48	35

Figure 4 shows the spatial distribution of mean ages of air in each measurement point (Figure 1). The results showed significant differences between point 3 and 4, especially for the strategies NV1 and NV4. In fact, the point 3 presents lower values in terms of mean age of air, because it is the closest to the window. On the contrary, point 4 presents quite high values of mean age of air, which means that the supply of fresh air is less efficient.

If one considers the spatial distribution of the mean age of air (Figure 4), the cross ventilation is the best performing strategy, while the single side ventilation (NV1) is clearly providing little fresh air to point 4 and 5.

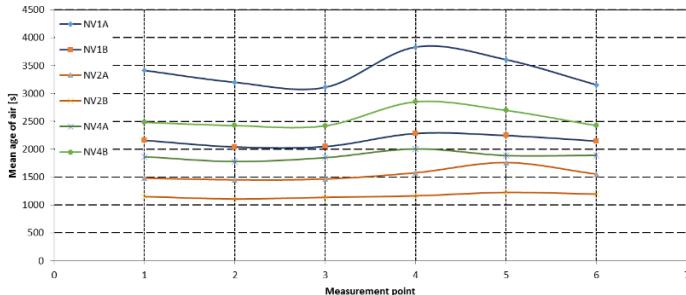


Figure 4. The measured mean age of air in each zone of the classroom for each strategy (2 tests per strategy: test A and test B)

5. Conclusions

This paper presented an experimental assessment of four natural ventilation strategies applied to a classroom: single side ventilation, cross ventilation, stack ventilation with infiltration supply and stack ventilation with windows supply. The performance of each strategy is expressed through the indoor average air temperatures, the indoor air quality based on CO₂ concentrations, air exchange rates and age of air in the occupied zones.

The measured temperatures were mainly between 18°C and 23°C, except for stack ventilation with windows supply (NV4) which presents quite low values. On the other hand, the recorded CO₂ concentration were clearly high, with 80% of the values above the limits fixed by the standards. Significant differences were reported between the strategies both through the CO₂ concentrations, the ACR and the age of air measurements. The analysis of the results in terms of ACR and age of the air shows the best results for cross ventilation (NV2) with on average 2.5h⁻¹ and an average mean age of the air of 1316s. The strategy NV4 is quite efficient in terms of ACR (1.42h⁻¹ on average) and average age of the air (2174s on average), but it shows low temperature values during occupancy and quite poor IAQ if one considers CO₂ concentrations. The performances in terms of age of air and through the different investigated points, the NV4 seem to be quite poor in providing fresh air in all the zones as well as the single side ventilation.

The single side strategy (NV1) shows quite lows CO₂ values in comparison with NV4 even if the ACR were below those measured for the NV4. This cannot be explained with ACR results which express averages values but with the analysis of air exchange efficiency. In fact, the presence of dead zones (zones 1, 4 and 5 for instance) could clearly affect the air exchange

effectiveness. However, the measurement of the air exchange effectiveness on natural ventilation is limited by the lack of methods and standards.

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