Indoor climate assessment of a classroom with mechanical ventilation and operable windows

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ABSTRACT

Ventilation air may be provided in buildings by means of natural or mechanical strategies. When a HVAC system is installed, thermal comfort and indoor air quality (IAQ) may be controlled with higher precision. However, especially between the 70s and the 90s, mechanical ventilation systems have been installed on formerly naturally ventilated buildings without providing any control for natural ventilation. The two ventilation systems are therefore overlapping, without any energy or comfort oriented control strategy, and the occupants are operating windows without any consistent understanding of IAQ and comfort conditions, neither of energy consumption. It may both lead to a substantial energy waste and to low indoor climate conditions. A typical university classroom with exhaust mechanical ventilation and operable windows without switching control has been assessed, in order to understand how occupant behaviour and different ventilation scenarios may influence indoor climate conditions.

KEYWORDS

Thermal comfort; indoor air quality; ventilation strategies

1 INTRODUCTION

In European countries, 40% of the consumed energy is dedicated to buildings. Whereas, with 46% of the total energy consumption, the building sector remains the largest consumer in France. More than half of this energy is dedicated to ventilation and air conditioning systems. The application of energy policies developed to reduce energy consumption, led in past decades to reduce ventilation rates, decreasing indoor climate quality (ICQ) and causing, especially in the 80s, the appearance of the so called sick building syndrome (SBS). New strategies were nevertheless developed to minimize energy consumption while meeting the requirements for indoor climate quality: CO_2 or humidity driven ventilation systems, high-efficiency heat recovery units and hybrid ventilation strategies.

Low ventilation airflow rates are often associated with problems of IAQ. A ventilation system is designed to ensure a sufficient air change to remove the pollutants contained within the building. In addition, ventilation is closely linked to thermal comfort. In the early 90s, the relationship between thermal comfort and air distribution in indoor environments has been reduced to the notions of «draught rate» and «draught risk». A criterion was included in the standards for thermal comfort through the DR index that estimates the percentage of persons exposed to draught through a combination of air speed, temperature and turbulence (Fanger et al., 1985). In 1998, ASHRAE has launched a study to investigate the effect of DR on thermal comfort. The occupants showed a tendency to prefer the presence of air movements. Other studies have proven that in warm microclimates, occupants felt comfortable with air velocities between 1 m/s and 1.5 m/s (Candido et al., 2010). The distribution of air temperature and velocity is strongly related to the ventilation system. According to the characteristics of the ventilation system (inlet and outlet air flow, inlet air temperature, location of vents) discomfort effects may occur (vertical temperature gradients, draught) (Tomasi et al., 2013).

This study focuses on a school classroom and concerns users thermal perception and thermal comfort measurements; it includes also IAQ measurements, considering CO_2 as an indirect indicator of contaminants related to human activities. The main objective of the present work is to assess ICQ (thermal comfort and indoor air quality) according to various ventilation strategies in a typical French classroom. The investigated classroom is equipped with mechanical exhaust and manually operable windows. The field study includes both physical measurements on thermal comfort and CO_2 concentration, and subjective assessment by means of survey questionnaires.

2 CASE STUDY

The study was performed at ESTP, a civil engineering school located in Cachan (5 km south of Paris). According to the Köppen-Geiger climate classification, the climate in Cachan is defined as Cfb (warm temperate, fully humid and warm summer) with a moderate seasonality. The annual average temperature is around 11°C. In winter the average temperatures are typically below 5°C, and in summer they do not exceed 25°C.

The investigated classroom (Figure 1) is inside Laplace building, a newly constructed building (2008) devoted to teaching. This classroom is equipped with water-filled radiators which operate only during the heating season (early November to mid-April). The classroom is not equipped with a cooling system. In order to guarantee thermal comfort in summer and minimum air changes throughout the year, the classroom is equipped with a mechanical ventilation system (extraction only) and natural ventilation (manually operable windows). The classroom is characterized by a large glazing area (18 m^2) spread over 15 double glazing windows. However, only two windows (facing north and west respectively) are operable. The operable windows can be used both in tilted or swing position. In the present study, the opening of the two windows is performed only in tilted position with an opening area of 0.45 m^2 (for each window).

Table 1: Classroom's characteristics

Classroom	**V[m^3]**	**A[m^2]**	**WFR**	**WO**	**NS**	**NW**	**W_w[m]**	**W_h[m]**	**W_{oa}[m^2]**
Laplace 21	216.4	81.3	0.21	N-W	40	2	0.84	1.39	0.90

Note: V=volume [m^3]; A= area [m^2]; WFR=window to floor ratio; WO= windows orientation; NS= number of seats; NW=amount of operable windows; W_w=windows width; W_h=windows height; W_{oa}=windows opening area

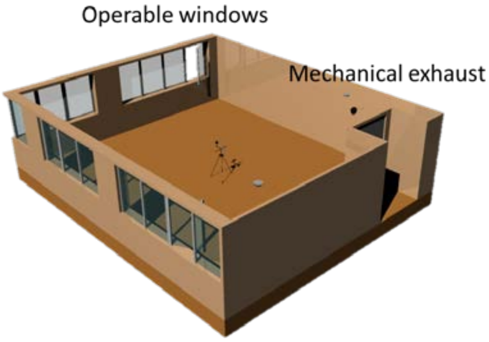

Figure 1: Investigated classroom

3 METHODOLOGY

3.1 Measurement protocol

The field study was performed during the winter period for 12 weeks (from January 5th to March 27th). Before it, a preliminary campaign was conducted in order to analyze the spatial distribution of the indoor climate parameters and to establish a reference point for the following assessment campaign. Homogeneity tests were performed using different spatial measurements at different levels and zones in the classroom according to ISO 7726. The classroom was divided into four zones according to occupation, façades orientation and location of heating terminals. For each zone the operative temperature was recorded at four levels (10 cm; 60 cm; 110 cm; 170 cm). After an analysis of the results, no significant differences were observed. The reference point was then chosen at the center of the effective occupied zone on a level of 110 cm.

The actual assessment campaign was then divided into two sessions. The first session was carried out from January 20th to February 27th and it was dedicated solely to thermal comfort assessment using both physical measurements for PMV calculations, and subjective survey questionnaires. A dedicate indoor climate station was used to record air temperature, globe temperature, air velocity and relative humidity. Table 2 shows the characteristics of the indoor climate station (LSI portable thermal environment monitoring system). The measurements were performed continuously during the occupancy period (from 8:00 am to 5:00 pm) with 1 minute time step. Due to the globe thermometer time response, the measurements were extended 30 minutes before and after the measurement period.

The second session was carried out from March 2nd to March 27th and was dedicated to the study of ventilation strategies effect on ICQ. Four ventilation strategies were considered:

- M1: mechanical extract and infiltration supply (windows closed)
- M2: mechanical extract and windows supply
- N1: natural ventilation on single side (without mechanical extract)
- N2: natural ventilation on two sides (without mechanical extract)

This session included two sets of parallel measurements: long term measurements (continuous measurements for the whole period) and short term measurements (measurements during the occupancy period only). The long term measurements were recorded using a KTHCO2-E data logger (Table 2) including the measurement of air temperature, relative humidity and CO_2 concentration (5 minutes time step). As for the first session, the short term measurements were recorded using the LSI portable thermal environment monitoring system, including the measurements of air temperature, globe temperature, air velocity and relative humidity with 1 minute time step. The outdoor physical parameters were recorded using a KTHCO2-E (air temperature, relative humidity and CO_2 concentration). Wind speed and direction were obtained from the weather database of Météo France.

Table 2: characteristics of measuring instruments

	Quantity	symbol	Measuring range	Accuracy
LSI portable thermal environment monitoring system	Air temperature	T_a	-50-70°C	± 0.1 °C
	Globe temperature	T_g	-40-80°C	± 0.15°C
	Relative humidity	RH	0-100%	± 1.5 %
	Air velocity	V_a	0.01-20 m/s	± 0.05+0.05V_am/s
KTHCO$_2$-E dataloger	Air temperature	T_a	-20-70°C	± 0.5 °C
	Relative humidity	RH	0-100%	±0.88 RH %
	Carbon dioxide	CO_2	0-5000ppm	±50 ppm

3.2 Indoor climate assessment

The thermal comfort assessment is based on the calculation of PMV and PPD indexes according to ISO 7730 methodology. The analysis is carried out comparing the calculated PMV values to the limits fixed by the EN 15251 and ISO 7730 standards. The indoor air quality assessment (second session) is carried out by comparing the measured CO_2 concentrations above outdoor level with the limits fixed by EN 15251 standard. Table 3 summarizes the limits fixed by the EN 15251 for thermal comfort and indoor air quality.

Table 3: The EN 15251 classification

Category	PMV	PPD [%]	CO_2 max above outdoor
I	-0.2<PMV<0.2	< 6	350
II	-0.5<PMV<0.5	< 10	500
III	-0.7<PMV<0.7	< 15	800
IV	PMV<-0.7; or +0.7>PMV	> 15	<800

The second session aims to study the impact of ventilation strategies on both thermal comfort and indoor air quality. Thus, in addition to the analysis of thermal comfort and indoor air quality, the air change rate, i.e. air change per hour (ACH) is estimated for each ventilation strategy. Usually, the ACH estimation is made by means of tracer gas measurements adopting the concentration decay, the constant emission, or the constant concentration method (Sherman, 1990) with SF_6, CO_2 or another tracer gas. Despite the uncertainties of the measurements related to its presence in the air, carbon dioxide is not less interesting for the ACH estimations. In fact, the CO_2 produced by occupants in a building decays exponentially after the occupancy period. For a decay period t-t_0 corresponding to the end of occupancy period (C_0, maximum CO_2 concentration) and the end of the decay period, the integral form of the mass balance is obtained as:

$$C(t) - C_{ext} = (C_0 - C_{ext}) * \exp\left[-n\,(t-t_0)\right] \qquad (1)$$

where, C(t) is the measured CO_2 at time t, C_{ext} the outdoor CO_2 concentration and *n* the ACH. The ACH is then obtained by fitting the concentrations against time with an exponential regression. It is therefore possible to estimate the ACH adopting CO_2 produced by occupants.

3.3 Subjective assessment

A questionnaire survey was performed in order to assess the occupants' perception in parallel to short term measurements, both for the first and for the second session. The questionnaire was set up in accordance with standard EN ISO 10551 and adapted to school environments according to previous studies on subjective assessment in schools (Pereira et al., 2014). Thus, students and teachers were invited to express their perception on ICQ by filling a questionnaire twice a day, according to the school time schedule. The questionnaire was filled by the occupants at the end of each period, respecting the 30 minutes adaptation time, required by the standard EN ISO 10551 for the relevance of the vote.

The questionnaire was divided into three parts. The first part concerns personal information (age, sex, height, weight, clothing for PMV calculation, possible diseases). The second part focuses on thermal comfort perception including:

- overall thermal perception (based on the ASHRAE 7 points scale);
- thermal discomfort on a five point scale: comfortable, slightly uncomfortable, uncomfortable, very uncomfortable, extremely uncomfortable;
- thermal preference on a 7 points scale: a lot warmer, warmer, a bit warmer, no change, a bit colder, colder, a lot colder;
- thermal acceptability on a 2 points scale: acceptable, not acceptable.

The questionnaires, which showed contradictions between the thermal perception, discomfort and preference, were removed. The Thermal Sensation Index (TSI) was calculated as the mean value of the vote on the overall thermal perception, whereas the thermal dissatisfaction was estimated as a combination of the thermal perception (persons who answered ± 2 and ± 3) and the thermal preference (persons asking for a change).

The third part of the survey focuses on the perception of indoor air quality based on the judgment of the odor, and on the air quality and movement perception. Due to the limited amount of space, the analysis of this part is not included in the present paper.

In total, more than 390 subjects were interviewed and 350 questionnaires were validated. In fact, only questionnaires which present no contradiction between the TSI, thermal discomfort index (TDI) and thermal preference index (TPI) were considered reliable. Table 4 lists the occupant's typology (general details) in the investigated classroom.

Table 4: statistical summary of the subjective assessment

Sample size	**Gender**		**Age (years)**				**Height**				**Weight (kg)**			
	M	F	Max	Min	Mean	SD	Max	Min	Mean	SD	Max	Min	Mean	SD
350	238	112	40	19	22	2	1.97	1.49	1.77	0.9	120	48	71	13

Note: M=Male; F=Female; Max=Maximum; Min=Minimum; SD=Standard Deviation

4 RESULTS AND DISCUSSIONS

4.1 Weather data analysis

Table 5 summarizes the averages values of outdoor parameters (air temperature, wind speed and relative humidity) for the two sessions.

The recorded values correspond to the local winter climate. The average outdoor temperatures were respectively 3.8 °C and 5.7°C for the first and the second session. The average CO_2 concentration was 386 ppm. However, some peak values (501 ppm) were recorded and may be due to the urban effect (pollution peak).

4.2 First session: thermal comfort analysis

Figure 2 shows the cumulative frequency distribution of indoor air temperature, mean radiant temperature and operative temperature. The mean value of operative temperature (20.9 °C) was within the comfort range fixed by the standards. However, considerable differences were remarked during some periods. In fact, the maximum and minimum recorded values were respectively 26.1 °C and 16.5 °C (Table 6). 20 % of the recorded operative temperatures values were below the lower limit (19 °C) fixed by ISO 7730 for school environments in winter periods (22 ± 3 °C).

Table 5: summary of the weather data during the assessment campaign

Parameter/session Symbol	Air temperature T_{out} [°C]	Relative humidity RH_{out} [%]	Wind speed W_s [m/s]	CO_2 concentration [ppm]
Session 1				Not recorded
Mean	3.8	82	3.94	/
Min	-2.6	43	0.00	/
Max	13.1	98	10.00	/
Session 2				
Mean	5.7	85	4.49	386
Min	-4.2	48	0.05	295
Max	17.6	98	16.65	501

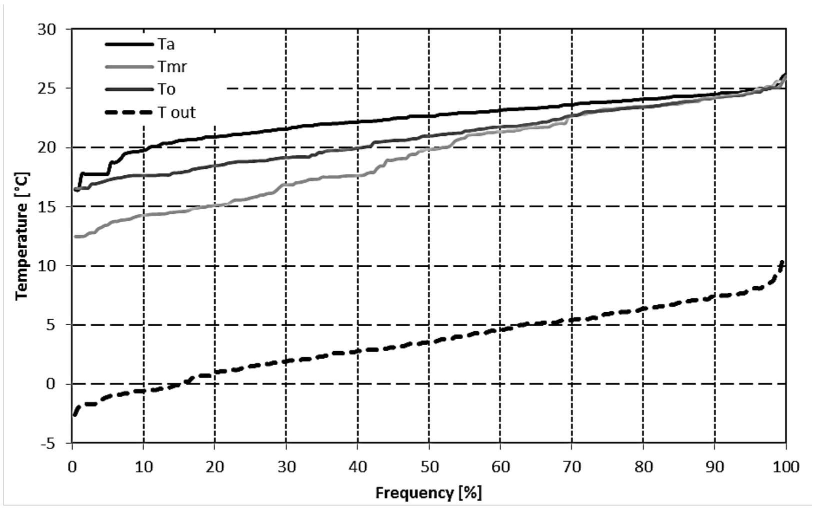

Figure 2: cumulative frequency distribution of air temperature (Ta), mean radiant temperature (Tmr), operative temperature (To) and outdoor temperature (Tout)

Figure 3 shows the cumulative frequency of PMV. Almost 40 % of the PMV values during the occupancy period were below the lower limits fixed by the standards for a classroom in category III, adequate for existing buildings, whereas the value rises to 55% if category II limits are adopted and to 70 % for category I. Thus, the classroom may be assumed to be a cold environment according to the first session of physical measurements.

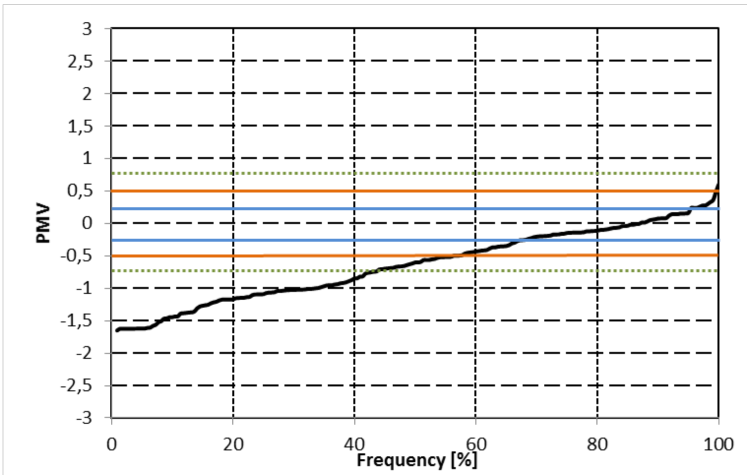

Figure 3: cumulative frequency distribution of PMV for the whole first session plotted with the limits corresponding to the three categories fixed by the EN15251 (blue for category I, orange for category II and dotted green for category III)

Table 6: statistical summary of indoor measured physical parameters

Parameter	RH	T_a	T_{mr}	T_o	V_a
Max	67	26.2	25.9	26.1	0.11
Min	15	16.5	12.5	16.5	0.00
Mean	36	22.4	19.5	21.0	0.05
SD	14	1.9	3.8	2.4	0.07

Note: Max=Maximum; Min=Minimum; SD=Standard Deviation

The analysis of the subjective responses leads to some different conclusions. The mean TSI was, in fact, around -0.3, i.e. within category I limits. In order to better understand the reported discrepancy, the TSI and the PMV were contrasted against the operative temperature measurements (Figure 5) and the adaptive PMV (aPMV) proposed by Yao (Yao et al., 2009) was additionally calculated, according to the cold climate:

$$aPMV=PMV \div (1+a\times PMV) \qquad (2)$$

In his adaptive PMV, Yao have estimated the "a" factor to be 0.293 and -0.125 for warm and cool conditions respectively. According to the results, the "a" factor was set as -0.125.

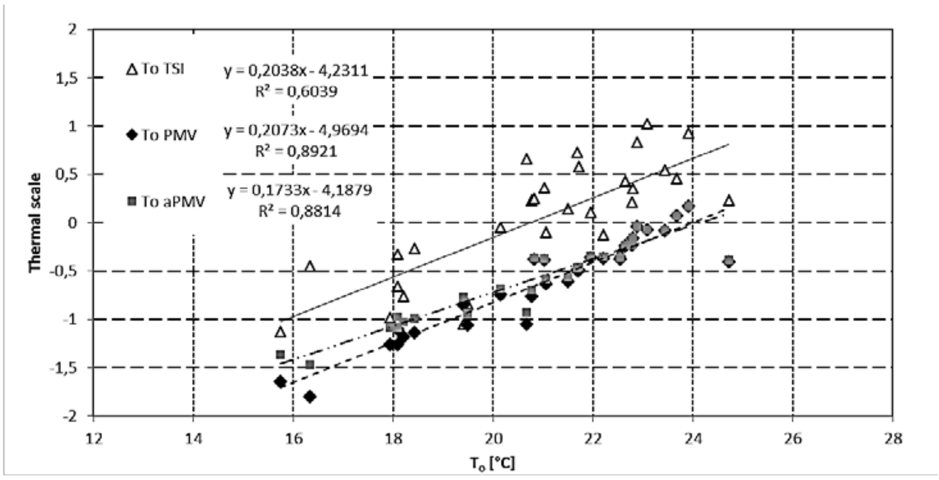

Figure 4: comparison between TSI; PMV and $_{a}$PMV with T_o

The results plotted in Figure 4 shows that occupants are less sensitive to cold condition compared to the prediction made on the basis of standard PMV. In particular thermal neutrality results between 20 and 22 °C for the real occupants, whereas it is around 24 °C when applying PMV and aPMV models.

4.3 Second session: indoor climate quality analysis

According to the outdoor data analysis, a total of 12 days were selected for the analysis of the ventilation strategies (three days for each strategy). Figure 5 shows the cumulative frequency distribution of operative temperature for the four ventilation strategies, while table 7 gathers average values of indoor and outdoor physical parameters for each ventilation strategy. As expected, the single side natural ventilation strategy (N1) shows a slight overheating. On the contrary, double side natural ventilation (N2) shows 80% of the occupied period below 19°C. The two mechanical strategies have a considerable gap. In fact, the mechanical exhaust with window supply (double side) M2, shows the lowest temperatures. The mechanical exhaust coupled with infiltration supply (M1) shows temperatures in the middle of all the other configurations. These variations can be explained by the different amount of fresh air supplied by each strategy. However, also night time ventilation could affect the results, since, to be able to estimate the ACH, windows were left open in scenario N1, N2 and M2 also at night time, and this may have affected thermal mass activation and temperatures drop.

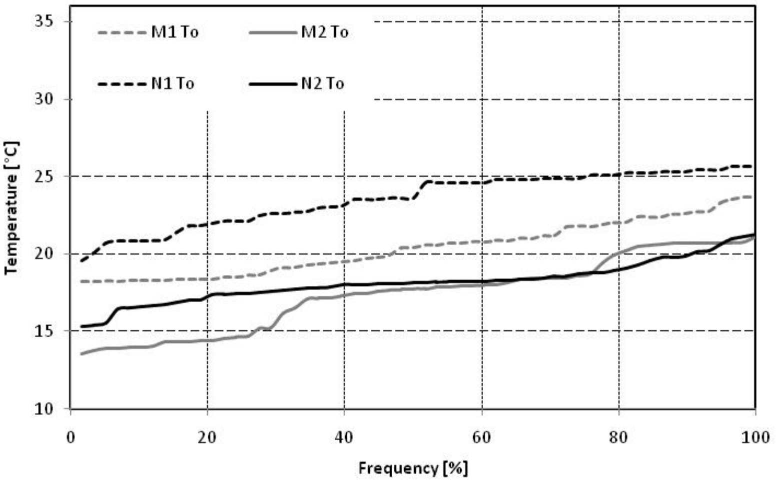

Figure 5: cumulative frequency distribution of the operative temperatures for the four strategies

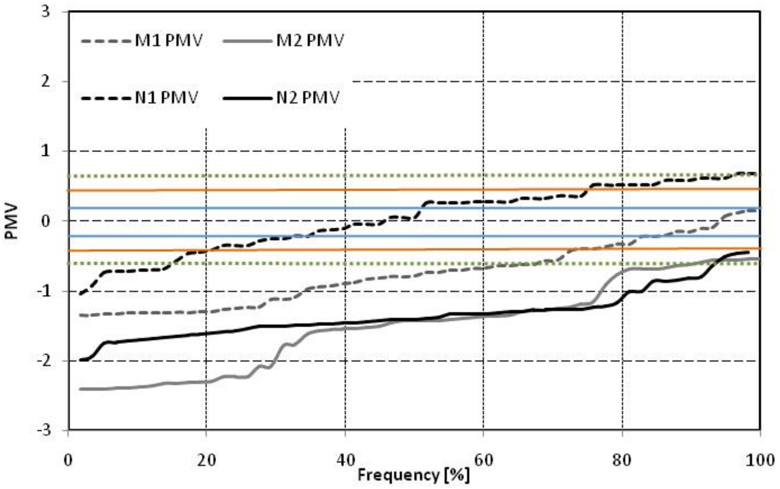

Figure 6: cumulative frequency distribution of the predicted mean vote for the fourth strategies with the three limits corresponding to the three categories fixed by the EN15251 (blue for category I, orange for category II and dotted green for category III)

Figure 6 shows the cumulative frequency distribution of the PMV for the four strategies. The trends for each strategy correspond to the trends shown for operative temperatures and it confirms the substantial influence of operative temperature on PMV. Strategy N1, i.e. natural ventilation on one side, shows the warmest conditions, with 40% of the values out of category II. M2 and N2 strategies show, instead, 100% of the values below the limits of the category II.

CO_2 concentration plotting (Figure 7) clearly shows the influence of occupancy on IAQ. Peak values are, in fact, recorded during the occupation time whereas the lowest values happen during non-occupied periods (nights and weekends). Students and teachers are the only source of CO_2 in the room, so CO_2 may be assumed as an indirect indicator of human related bio-effluents or contaminants related to human activity. During the occupancy period, the CO_2 concentration inside the classroom reaches 4900 ppm (Figure 7) an extremely high value. Figure 8 shows the cumulative frequency distribution of CO_2 concentration above outside. More than 20% of the measured concentrations exceeded outside values for more than 2500 ppm, with a peak value of 4500 ppm. Quite beyond the limits reported in standard EN 15251.

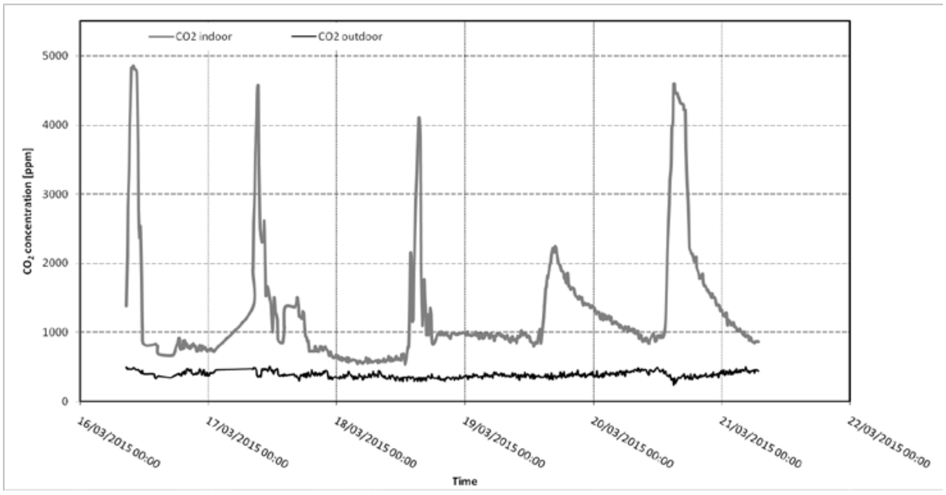

Figure 7: inside, outside CO_2 concentration during a reference week

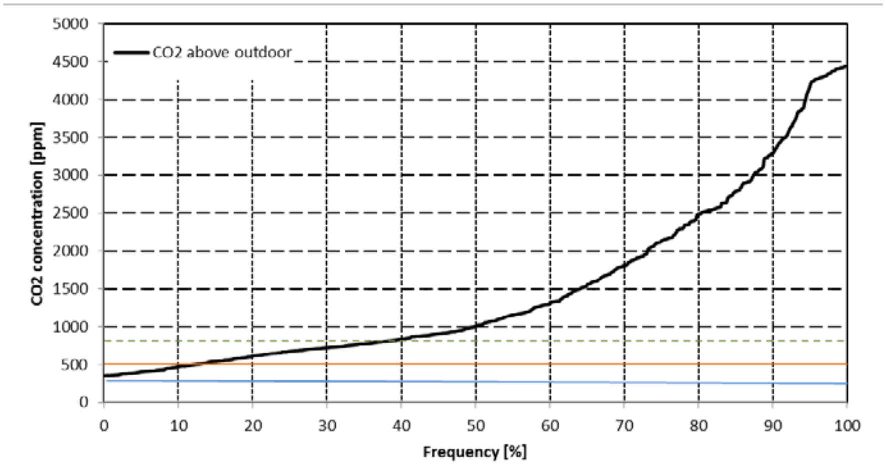

Figure 8: cumulative frequency distribution of CO_2 concentration above outdoor value, plotted with the three limits corresponding fixed by EN15251

As explained in section 3.2, the ACH was estimated from the end of the occupancy period, assuming a maximum value of CO_2 concentration, until the decay to the outdoor level. Table 7 shows the mean values of ACH for each strategy. In fact, three decay periods were selected for each strategy. As expected, the most effective strategy is M2, i.e. mechanical exhaust and windows supply. The ACH values for the two mechanical strategies M1 and M2 were respectively 0.42 h^{-1} and 0.69 h^{-1}. The natural strategies show lower values, 0.06 $h^{-1}$and 0.19 h^{-1} for N1 and N2 respectively.

The ACH values are nevertheless quite low. Previous studies which were performed on mechanically ventilated classroom shows ACH values within a range of 0.73-1.91 h^{-1}(You et al., 2011). Others studies (Dorizas et al., 2015) presented values around 0.29 h^{-1}in a naturally ventilated classrooms.

Table 7: averages values of indoor and outdoor physical parameters for each ventilation strategy

Parameter/strategy	**N1**	**N2**	**M1**	**M2**
Operative temperature	23.6	18.2	20.4	17.4
Outdoor temperature	8.6	8.6	8.9	8.1
Wind speed	3.13	3.35	3.84	4.23
ACH	0.06	0.19	0.42	0.69

5 CONCLUSIONS

This paper presents the results of an in-situ experimental campaign and survey related to ventilation strategies and thermal comfort in a typical French classroom during the heating season. The survey includes thermal comfort and indoor air quality assessment using four ventilation strategies. Long term and short term experimental measurements were made in parallel to the survey. The results on thermal comfort show that the classroom was slightly cold. However, the subjective results collected through 350 questionnaires, showed a sensible adaptation of occupants to cold conditions, whereas they show more sensitive to warm conditions.

The results of indoor air quality based on the CO_2 concentrations show values quite above the thresholds suggested by standards. The CO_2 concentration peak values reach 4500 ppm above outdoor level, which is consequence of the poor ventilation and of the high occupation value.

The results of the second experimental session, which focused on the assessment of various ventilation strategies, showed significant variations among them. As expected, the strategies based on mechanical exhaust showed the best results in terms of ventilation rates, although the air change rates resulted always very low. It was not instead possible to establish whether mechanical or natural ventilation performs better in terms of thermal comfort. Further investigations on ventilation air flow distribution (tracer gas measurements) will be undertaken to better characterize the ventilation effectiveness of the investigated ventilation strategies.

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