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EXPERIMENTAL ASSESSMENT OF IAQ IMPROVEMENT IN NATURALLY VENTILATED EDUCATIONAL BUILDINGS

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Abstract *Indoor environmental conditions in classrooms, in particular temperature and indoor air quality, influence students' health, attitude and performance. In recent years several studies regarding indoor environmental quality of classrooms were published and natural ventilation proved to have great potential, particularly in southern European climate.*

This research aimed to evaluate indoor environmental conditions in 8 schools and to assess their improvement potential by simple natural ventilation strategies. Temperature, relative humidity and carbon dioxide concentration were measured in 32 classrooms.

Ventilation performance of the classrooms was deeply characterized by tracer gas measurements of the air change rate assuming different windows related boundary conditions. A total of 110 tracer gas measurements were made. The complete characterization of the classrooms ventilation performance was relevant for the definition of the ventilation protocol since air change rate helped to pinpoint the best ventilation strategy for each case study.

The results of the ventilation protocol implementation were very encouraging and, globally, a significant decrease on the CO_2 concentration was observed without modifying the comfort conditions.

This paper presents and discusses the main conclusions of the measurements campaign performed in the referred classrooms.

1. INTRODUCTION

It seems clear that indoor environmental conditions in classrooms, in particular temperature and IAQ, influence students' health, attitude and performance. Knowing that children spend a large amount of their time inside school buildings and that they are more susceptible than adults to the adverse effects of indoor pollutants, since their ratio of air breathed volume versus weight is greater and their tissues and organs are still growing [1], school buildings construction and rehabilitation must be properly planned to ensure that users have the adequate conditions for carrying out their work. In recent years several studies evaluating the effects of the classrooms environmental conditions on the learning process were published [2-6].

1.1. Air quality and hygrothermal comfort in schools

Several studies stated that, frequently, ventilation rate and CO_2 concentration limits are not complied, regardless of the ventilation system.

In France, a study was performed including 489 classrooms of 108 school building [7]. The most representative ventilation system was mechanical ventilation, installed in 20% of the schools, 60% of which had mechanical extraction. In the occupation period, 33% of the schools revealed CO_2 concentrations above 1700 ppm in more than 66% of the records. It was concluded that window opening was more frequent before classes, during breaks and at the end of classes, rarely during them. This behaviour was mainly conditioned by exterior noise and specific difficulties with opening systems. In unoccupied periods, median values of 0.12 h^{-1} (infiltration) and of 1300 ppm were obtained. These values suggest that the ventilation rate should be increased during the night so that in the morning children would be exposed to lower levels of CO_2.

Teli et al.[8-9], through questionnaires given to 230 students belonging to 8 classrooms in a UK naturally ventilated school concluded that, out of the winter season (April to July), children prefer lower temperatures than the ones predicted in PMV and adaptive models. It is addressed the need for adjustments in existing rules regarding the thermal comfort criteria, taking into account the differences between adults and children.

A literature review published by Frontczak and Wargocki [10] on the influence of various factors on human comfort concluded that thermal comfort is the most important parameter in IEQ evaluation and that occupants of buildings with natural ventilation revealed a more adaptive behaviour.

1.2. Natural ventilation in schools

In recent years several studies regarding IEQ were published, covering schools of different levels of education with natural ventilation systems (single-sided or cross ventilation), in continuous or purge ventilation. Natural ventilation proved to have great potential, particularly in southern European climate. However, the results, particularly in terms of thermal comfort (air temperature) and ventilation rate or levels of CO_2 concentration have not always been satisfactory.

Coley and Beisteiner [11-12] performed measurements in UK primary schools in winter (7 classrooms) and during summer (4 classrooms). The measurements took place during a week period in each classroom and it was concluded that opening windows between classes - purge ventilation - has the potential to reduce CO_2 levels to the recommended values. They concluded that opening windows was not commonly used due to their location (above the occupied zone), or to possible air drafts and also because the staff, including teachers, was reluctant to open the windows, especially because they are not sensitized to the issue of classrooms ventilation.

Santamouris et al. [13] monitored the IAQ in 62 classrooms of 27 naturally ventilated schools of Athens. Measurements were performed in spring and fall seasons when window opening is the main ventilation procedure. Three situations were assessed: a) empty rooms and windows closed; b) during classes, with some windows opened; c) between classes, with most of the windows opened. The average flow rates obtained were 1.5 l/s/person, 4.5 l/s/person and 7 l/s/person, respectively. During the three measurement periods, 52% of the classrooms presented a CO_2 concentration greater than 1000 ppm with a median value of 1070 ppm. At the end of the class period, there was a maximum concentration of 3000 ppm with a median of 1650 ppm. A statistically significant relationship between the window opening and the difference in indoor-outdoor temperature was confirmed.

Giuli et al. [6] evaluated 7 Italian primary schools (28 classrooms), all naturally ventilated. Measurements took place in spring and the average CO_2 concentration above the exterior concentration varied between 45 and 3635 ppm. 12 classrooms exceeded this value by more than 1000 ppm. Through surveys, it was concluded that indoor conditions strongly depend on teachers' preferences and behaviour and that windows are mainly opened during breaks.

1.3. Research motivation

Natural ventilation, as other ventilation systems, has advantages and disadvantages. However, towards the goals of reducing energy consumption and considering the adaptive possibilities of students, we believe that in Portugal and in other southern European countries, natural ventilation in schools, both new and refurbished, has a great potential for successful implementation [14]. This was the basis of the present study development.

2. METHODOLOGY

This paper focuses on the IAQ and thermal comfort and their relation with enclosure airtightness and the effect of different natural ventilation protocols in Portuguese school buildings.

The project comprises 8 schools of different levels of education (from kindergarten to college) located in the town of Viseu. A total of 32 classrooms, installed in buildings of different types and ages, and with different orientations and sun exposure, were evaluated (Table 1). Classrooms had an approximate average area of 50 m² and an internal height of 3 m. All have bottom-hung windows on the façade (exception is classroom D4) and several had small openings in the interior with adjoining corridors, allowing for the implementation of a cross ventilation strategy as described in section 4. Regarding heating systems, all the schools have hot water radiators, except G and H. However, the use of all the systems was, during most of the time, discontinuous and dependent on the school board instructions.

School			Classrooms				
Designation	Year Built	Level of education	Designation	Building floor	Orientation	Windows type[a]	Ventilation system[b]
A	1993	College	A1	0	S	TT + BH	MV off
			A2	0	S / W		
			A3	1	S		
			A4	1	S / W		
B	1991	Lower secondary	B1	0	NE	S + BH	NV
			B2	0	SW		
			B3	1	NE		
			B4	1	SW		
C	2004	Kindergarten	C1	0	SE	BH	NV
			C2	0	NW		
		Primary	C3	1	SE		
			C4	1	NW		
D	1968	Lower secondary	D1	-1	S	SH + BH	NV
			D2	1	S		
			D3	1	S		
			D4	-1	S / E	S	
E	1996	Primary	E1	0	E	SH + BH	NV
		Lower secondary	E2	0	S / E		
			E3	1	E		
			E4	1	W / S		
F	1958	Primary	F1	0	S / N	S + BH	NV
			F2	1	S / N		
			F3	0	S / N		
			F4	1	S / N		
G	2011	Kindergarten	G1	0	E	TT + BH	HVAC
			G2	0	W		
		Primary	G3	1	S		
			G4	1	S		
H	2011	Kindergarten	H1	0	E	SH + BH	HVAC
			H2	0	W		
		Primary	H3	1	W		
			H4	-1	E		

[a]TT - tilt and turn; BH - bottom hung (tilting); SH - side hung (casement); S - sliding (horizontal sash).
[b]MV - mechanical ventilation; NV - natural ventilation; HVAC - heating, ventilation and air conditioning.

Table 1. School building characterization.

The research was developed in 3 campaigns:

- spring 2013 (March - May): measurements were performed during 4 consecutive days in each school in occupied classrooms - hygrothermal performance (*T* and *RH*) and IAQ (CO_2) were evaluated;
- summer 2013 (July - September): *ACH* rate measurements were performed using the tracer gas method - decay technique, in unoccupied classrooms and according to various conditions concerning window and door positions;
- autumn 2013 (September - October): same parameters as for the first campaign were measured during 2-4 days. However, in each school, 2 classrooms were selected with specific conditions for single-sided or cross ventilation and a ventilation protocol was

imposed. The other 2 classrooms had no control on the window opening.

3. IEQ ASSESSMENT

Classrooms IEQ was evaluated according to the previously described methodology. Descriptive statistical analysis of the results is presented in Table 2, which includes information about indoor temperature, relative humidity and CO_2 concentration, during the period of occupation and the correspondent weather conditions, temperature and relative humidity, both daily (T_{ext} and RH_{ext}) and only considering the period of occupation (T_{occ} and RH_{occ}).

School	T_{int} [ºC]	RH_{int} [%]	CO_2[ppm]			T_{ext} [ºC]	T_{occ} [ºC]	RH_{ext} [%]	RH_{occ} [%]
	μ±σ	μ±σ	μ±σ	max	min	μ±σ	μ±σ	μ±σ	μ±σ
A	20.9±1.8	58.1±4.5	2318±666	3708	443	9.3±2.6	11.0±2.6	66.4±16.5	59.0±17.4
B	19.7±1.1	64.3±5.3	1820±787	4270	366	10.6±2.5	12.4±2.2	73.1±12.0	68.9±13.5
C	20.2±2.1	61.8±6.5	1490±724	4038	394	14.9±5.3	19.1±3.9	57.5±21.2	42.4±14.3
D	21.4±1.9	45.7±5.4	1711±686	3456	358	13.3±5.9	15.9±6.0	49.8±15.5	41.8±15.0
E	23.5±1.3	50.6±6.2	1606±654	4028	376	16.9±5.4	20.5±5.0	49.7±18.7	38.7±14.3
F	22.1±1.3	62.1±6.2	2513±893	4032	444	14.6±4.3	16.7±4.6	65.5±17.9	58.2±19.4
G	21.6±1.5	46.2±6.8	945±520	3052	270	15.9±6.4	20.7±4.1	54.9±22.0	36.8±10.3
H	22.0±1.1	46.3±7.3	1210±578	3136	308	20.3±6.3	24.2±4.6	62.3±18.9	50.2±16.1

Table 2. IEQ results (spring 2013).

A clear distinction between the hygrothermal and the IAQ results must be made. Temperature and relative humidity results revealed a performance within the comfort zone according to the Portuguese regulation: average temperature above 20.0 ºC (the only exception is school B with 19.7 ºC), with a relatively small dispersion of results; relative humidity mean values varied between 46% and 64%, and the overall oscillation is limited to the range 30-77%, usually considered as adequate indoor conditions [15]. No evident relation between indoor environment and external conditions was found, both for temperature and relative humidity. The use of heating systems for temperature correction is the most reasonable explanation.

On the indoor air quality evaluation a completely different scenario was observed with high CO_2 concentrations being identified, with a magnitude that, in some situations, should be a matter of concern for the building administration. Maximum values were above 3000 ppm in all school buildings and in four of them they have increased up to 4000 ppm. Considering average values for the all period, only schools G and H presented concentrations below 1250 ppm (the Portuguese regulation concentration limit); in 6 buildings the mean value was higher than 1500 ppm and in 2 of them it was higher than 2000 ppm. The best performing schools, G and H (with HVAC), are also the most recent constructions, indicating that most modern buildings tend to perform better. On the other hand, the worst scenarios were observed in schools A and F. Since the first one is a college and the other, a primary school, no evidence of a relation between IAQ and level of education/age of students has been found. High standard deviation values of also indicate that a large spreading of results was observed (Figure 1).

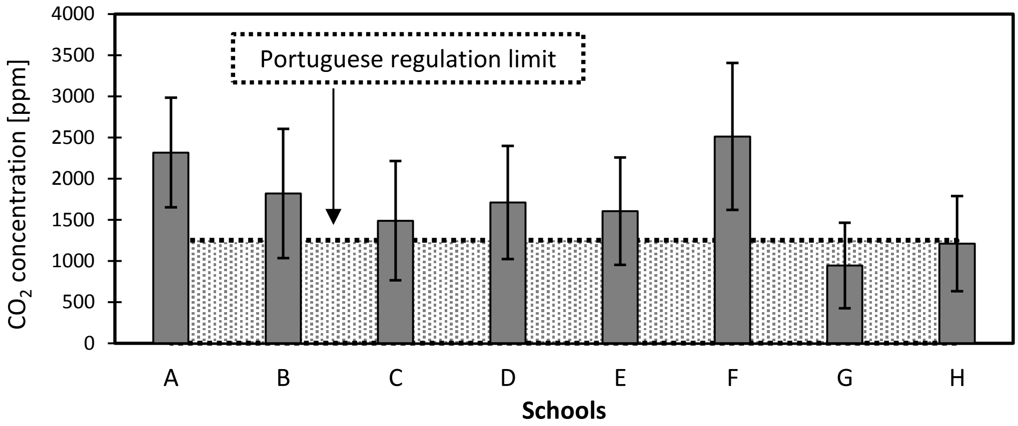

Figure 1. CO_2 concentration average and standard deviation (spring 2013).

4. ACH MEASUREMENTS

ACH measurements were made on unoccupied classrooms, during summer break (August), using the tracer gas method - decay technique. According to the specific conditions of each classroom, such as windows type and position, several experimental set-ups were assessed in order to evaluate the different possibilities for natural ventilation: everything closed (only infiltration), single-sided ventilation, cross ventilation, with and without door opened. A total of 110 measurements were performed on the 32 classrooms under study. All the measurements were made according to the specified on ASTM E741: 2011.

Natural ventilation potential was assessed in the following conditions:

- everything closed or “in use” position (ex.: permanent openings above the entrance door): it is intended to simulate the current conditions of natural ventilation achieved by infiltration only;
- single-sided ventilation: it was used when classrooms did not have interior windows or other openings and 2 exterior windows were opened;
- cross ventilation: it was used when classrooms had exterior and interior openings (interior openings adjacent to the corridor) and 2 exterior and 2 interior windows were opened;
- cross ventilation and door opened: identical to the previous set-up but with the entrance door opened (≈0,8×2,0 m²).

Table 3 details the classrooms windows characteristics.

Results exposed very airtight enclosures. For the scenario of windows closed (Cl), the *ACH* average ranged from 0.04 h^{-1} in school C to 0.5 h^{-1} in school B, with exception of school D that presented 1.5 h^{-1}. In fact, school D is a special case since the wood on the window frames is deteriorated and in a very poor condition, allowing uncontrolled airflow. Another interesting conclusion is that, when available, cross ventilation (CV) has a great potential.

In this condition, results varied between 1.6 h^{-1} and 7.6 h^{-1}. Regarding the single-sided (SS) ventilation, results were more modest, ranging from 0.6 h^{-1} to 2.9 h^{-1}, although still being an interesting approach to improve the IAQ.

School	Exterior windows				Interior windows			
	Type[a]	Area of 1 window: w×h [cm^2]	Opening at the top[b] [cm]	Height to floor [m]	Type[a]	Area of 1 window: w×h [cm^2]	Opening at the top[b] [cm]	Height to floor [m]
A	BH	110×60	25	2.46	-	-	-	-
B	BH	54×43	19	2.24	BH	73×45	25	2.10
C	BH	168×56	27	1.70	-	-	-	-
D	BH	79×42	15	2.50	L	90×51	-	2.78
E	BH	92×71	14	2.34	L	86×42	-	2.50
F	BH	121×42	26	2.23	-	-	-	-
G	BH	100×197	10	0.72	BH	47×82	7	1.89
H	BH	157×136	14	0.90	-	-	-	-

[a] BH - bottom hung (tilting); L - louvred.
[b] Horizontal distance between movable and fixed frame.

Table 3. Windows characteristics.

Table 4 summarizes the results in each school, including the number of samples (*N*).

School		Set-up[a]			
		Cl	CV	CV + door	SS
A	N	4	2	5	4
	$\mu \pm \sigma$	0.2 ± 0.1	5.7 ± 1.7	6.4 ± 3.5	1.8 ± 0.8
B	N	3	4	4	1
	$\mu \pm \sigma$	0.5 ± 0.2	2.3 ± 0.7	3.3 ± 1.0	1.1 ± 0.0
C	N	4	-	5	5
	$\mu \pm \sigma$	0.04 ± 0.03	-	7.2 ± 4.6	2.0 ± 1.4
D	N	4	3	4	1
	$\mu \pm \sigma$	1.5 ± 0.1	3.9 ± 1.0	4.3 ± 2.8	2.9 ± 0.0
E	N	4	3	4	1
	$\mu \pm \sigma$	0.2 ± 0.1	1.6 ± 0.7	2.0 ± 0.4	0.6 ± 0.0
F	N	4	-	4	7
	$\mu \pm \sigma$	0.1 ± 0.03	-	2.7 ± 0.8	0.7 ± 0.7
G	N	4	2	6	4
	$\mu \pm \sigma$	0.3 ± 0.1	7.6 ± 1.0	5.0 ± 4.9	0.9 ± 0.7
H	N	4	-	5	5
	$\mu \pm \sigma$	0.2 ± 0.04	-	3.9 ± 1.4	1.1 ± 0.5

[a]Cl - windows closed; CV - cross ventilation; CV+door - cross ventilation + door; SS – single-sided ventilation.

Table 4. *ACH* tests in each school (unoccupied classrooms).

The variability of the results was also analyzed. Figure 2 presents the results box-plot.

Enclosure permeability, which corresponds to the situation of windows closed, is the one that presents less variability, the other scenarios having a wider range of results. For this situation median *ACH* was 0.2 h^{-1} clearly confirming that infiltration is not sufficient to control and dilute de CO_2 internal production. Therefore, additional ventilation must be provided. For that purpose results revealed that the two ventilation modes that can be implemented during classes (CV and SS) should significantly improve the IAQ. A median

ACH of 2.8 and 1.0 h^{-1} were found for *CV* and *SS*, respectively. As it would be expected, *CV* has a higher potential. The ventilation mode *CV+door*, which can be implemented during breaks, presents the higher median value, 3.4 h^{-1} and can provide an important contribution for the control of CO_2 concentration. CV modes are the ones that present higher variability with maximum values up to 8.3 and 14.2 h^{-1} for *CV* and *CV+door*, respectively.

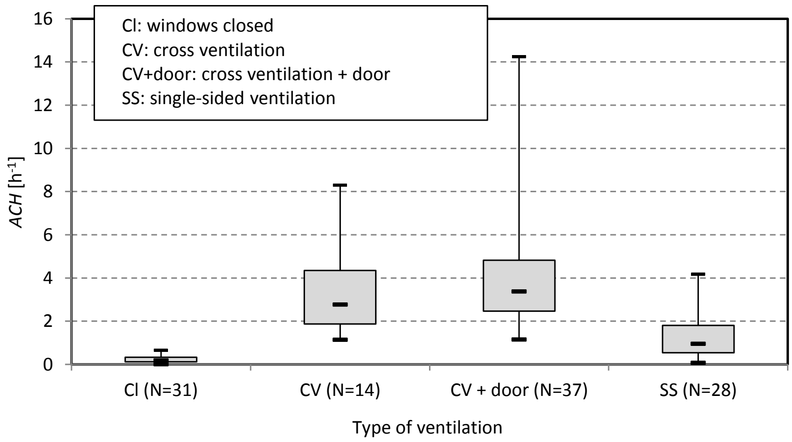

Figure 2. Box-plot of the results of the *ACH* measurements (unoccupied classrooms).

5. IEQ ASSESSMENT WITH VENTILATION PROTOCOL

The following step on this investigation was then to improve the ventilation rates by simple adjustments based on a ventilation protocol, which should be implemented in such a manner that classrooms' comfort conditions are not neglected. Therefore, in the last measurement campaign (September - October) the parameters of the first campaign were measured during 2-4 days. However, in each school, there were 2 classrooms where specific conditions for cross or single-sided ventilation were imposed (ventilation protocol - VP). This ventilation protocols were established according to the *ACH* results and the use of cross ventilation was limited to the situations where interior openings were available. The other 2 classrooms had no control on the window opening (NVP). Although the implementation of ventilation protocols, users had the possibility to change the conditions. The idea was to test a simple and feasible protocol, which could be applied in regular classes. Therefore, in this research were tested protocols, which were easy to implement, and that do not imposed teachers to perform specific actions during classes.

Table 5 shows the average values of air temperature, relative humidity and CO_2 concentration separately for scenarios with and without ventilation protocol. The percent improvement in terms of CO_2 concentration is also indicated, with positive values corresponding to a reduction in concentration.

The introduction of a ventilation protocol resulted on an improvement of the IAQ in 6 schools. The only exception was school building C. Apart this particular situation, the implementation of the ventilation protocol was very positive: the most interesting performance was obtained in school H with a reduction of 47% in the CO_2 concentration. Another important result that must be underlined is that the comfort conditions were not neglected with this protocol since no significant difference of temperature between VP and NVP classrooms was found. Comparing results (statistically analyzed) between campaigns was the strategy to evaluate changes in comfort levels and no significant differences were found.

School	T_{int} [ºC]		RH_{int} [%]		CO_2[ppm]		
	VP	NVP	VP	NVP	VP	NVP	%
A	24.1	24.7	67	70	978	1436	32
B	27.7	26.6	46	53	788	1279	38
C	26.6	27.0	45	45	1611	1222	-32
D	23.0	24.0	67	66	1059	1576	33
E	26.5	26.6	54	57	768	949	20
F	24.4	24.2	48	51	954	1316	28
H	24.3	22.9	52	64	1370	2485	47

Table 5 - Air temperature, relative humidity and CO_2 concentration with and without ventilation protocol (autumn 2013).

6. CONCLUSIONS

A simple ventilation protocol based on a cross and single-sided ventilation strategy was implemented in several occupied classrooms. Results were very encouraging and, globally, a significant decrease on the CO_2 concentration was observed without modifying the comfort conditions. This strategy should continue to be explored and validated for winter conditions but from this research some recommendations can already be pointed:

- Regarding ventilation (and also lighting) improvement, interior openings should always be provided;
- Both exterior and interior windows (eg. bottom hung) should be as high as possible (opening axe > 2.00 m). and guarantee a maximum opening area (eg. for bottom hung at least 20 cm);
- A strategy based on opening doors during breaks and at the end of the day should be implemented. School board should create awareness of the consequences of poor IAQ and promote training for both teachers and school staff in order to encourage the use of the ventilation protocols;
- A protocol based on a cross and single-sided ventilation should, therefore, be implemented in Southern European countries at least during spring and fall.

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