



HAL
open science

Impact of Affordable Blown Mechanical Ventilation on CO₂ and PM_{2.5} to Improve Air Quality in Schools

Maela Adam, Olivier Lavastre

► **To cite this version:**

Maela Adam, Olivier Lavastre. Impact of Affordable Blown Mechanical Ventilation on CO₂ and PM_{2.5} to Improve Air Quality in Schools. *International Journal of Science and Research*, 2023, 12 (6), 10.21275/SR23526122556 . hal-04257447

HAL Id: hal-04257447

<https://hal.science/hal-04257447v1>

Submitted on 25 Oct 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Impact of Affordable Blown Mechanical Ventilation on CO₂ and PM_{2.5} to Improve Air Quality in Schools

Maëla ADAM¹, Olivier LAVASTRE²

IMEP - LAHC Building 21, Institut de Microélectronique, Electromagnétisme et Photonique – Laboratoire d'Hyperfréquences et de Caractérisation. UMR 5130 - CNRS/Grenoble - INP/UGA/USMB. Domaine universitaire Le Bourget du Lac, 73376 Le Bourget du Lac, France

²Corresponding author Email: [olivier.lavastre\[at\]univ-smb.fr](mailto:olivier.lavastre[at]univ-smb.fr)

Abstract: *Background:* Young children are part of the most vulnerable segment of the population. They spend a huge part of their lifetime at primary school. Several studies have already been conducted in schools, showing that a poor Indoor Air Quality is linked to a wide range of discomforts and health problems, such as asthma, allergies, lack of focus and decline in cognitive functions. *Methods:* Concentration of carbon dioxide (CO₂) was assessed in three rooms in a French primary school, with no ventilation system. A Blown Mechanical Ventilation (BMV) was installed in the school and new CO₂ concentration was assessed consecutively, as well as the concentration in fine particle matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}). *Results and conclusions:* CO₂ concentration was significantly reduced after installing BMV (maximum values measured over a month decreased from 3072ppm to 1500ppm) Moreover, it was demonstrated that BMV prevents outside PM_{2.5} from entering the classes. The affordable cost and easy installation of BMV are key factors to allow a fast deployment, even in developing countries.

Keywords: Indoor air quality (IAQ), carbon dioxide (CO₂), particle matter (PM), school, blown mechanical ventilation (BMV), children.

Abbreviations

Indoor air quality (IAQ),

Carbon dioxide (CO₂),

Particle matter (PM),

Particle matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}),

Mechanical ventilation system (MVS),

Blown mechanical ventilation (BMV).

Highlights

- Children in classrooms are often subjected to excessive levels of CO₂.
- Opening the windows or using classic mechanical ventilation systems (MVS) lets outdoor particles matters (PM), dust, humidity and too cold or too hot air enter the classrooms.
- The solution we evaluated: Blown Mechanical Ventilation (BMV), that filters and blows outdoor air inside the room.
- Blown Mechanical Ventilation (BMV) provides particle free renewed indoor air.
- After installing a Blown Mechanical Ventilation (BMV) in the primary school, CO₂ levels were significantly reduced in each classroom, without big investments or works.

1. Introduction

The quality of the air we breathe is of utmost importance, as it brings to our bodies the essential oxygen our cells need to live and carry out their activities: oxygen is thus the main contribution to our daily energy.

However, the attention paid to air quality, in particular to Indoor Air Quality (IAQ) in the places we live and work, is still too slight due to a public ignorance of the issues and risks of poor air quality and/or excessive cost of efficient double flow ventilation systems¹.

And yet, it has been proven that within buildings, air quality is often worse than outside, condensing in confined spaces pollutants such as Particle matter (PM), Volatile Organic Compound (VOC), carbon dioxide (CO₂) accumulation²⁻³.

Vulnerable groups, such as young children, are especially affected by poor air quality⁴, notably poor inside air quality as they spend a large part of their time at home or at school.

Several studies have been conducted and have shown that the presence of PM, VOC and other pollutants in the air is directly related to children's health problems such as asthma, allergic rhinitis⁵⁻¹¹, or increase in blood pressure¹².

Other studies have proven that high CO₂ levels, notably in confined spaces such as classrooms, impact learning abilities of children, decreasing their ability to focus¹³⁻¹⁴ and causing fatigue and discomforts such as headaches¹⁵.

Moreover, the recent COVID - 19 pandemic has created an opportunity to carry out further studies that have shown a relation between confined rooms and high levels of air pollutants, bacteria and fungi¹⁶. A common recommendation has been to open the windows. But this is a real problem when it is too cold or too hot outside, for instance cold enters and heating calories are lost.

Implementing a ventilation system in a building has been proven to be an effective solution to decrease CO₂ levels and

reduce symptoms, whether it be a natural ventilation¹⁷⁻¹⁸ or a mechanical ventilation system¹⁹⁻²¹. As reviewed²², adequate ventilation is an important condition for a healthy school environment.

In this paper, we investigate the efficiency of ventilation using insufflation principle, called Blown Mechanical Ventilation (BMV), to measure its impact on providing fresh, healthy and particle free air to children, without big investments or works in the building to install the ventilation system.

2. Materials and Methods

2.1 Sensors

In this study, three UHOO air monitoring devices²³ were used to measure the quality of the air in three rooms and to establish an initial assessment of the situation in the primary school. Various parameters were monitored: carbon dioxide (CO₂), fine particle matter with aerodynamic diameter ≤ 2.5 μm (PM_{2.5}), temperature, humidity, Volatil Organic Compounds (VOC), carbon monoxide (CO), nitrogen dioxide (NO₂), ozone (O₃).

Sensors in the device were calibrated to measure these parameters within a specific detectable range, which are presented in the following table.

Table 1: Detectable range for sensors and ideal range of parameters

Sensor	Detectable range	Ideal range
CO ₂	400 – 10000 ppm	< 1000 ppm
PM _{2.5}	0 – 200 $\mu\text{g}/\text{m}^3$	< 15 $\mu\text{g}/\text{m}^3$ (24h)
Temperature	- 40° – 85°C	19 – 24 °C
Humidity	0 – 100 %	40 – 60 %
VOC	0 – 30000 ppb	Case by case
CO	0 – 1000 ppm	< 4 $\mu\text{g}/\text{m}^3$ (24h)
NO ₂	0 – 1000 ppb	< 25 $\mu\text{g}/\text{m}^3$ (24h)
O ₃	0 – 1000 ppb	< 100 $\mu\text{g}/\text{m}^3$ (8h)

The ideal range corresponds to the limit values recommended by World Health Organization (WHO) for PM_{2.5}, CO, NO₂ and O₃, and other standards, without being strict regulations²⁴.

Please note, that for CO₂, the current regulatory and normative limit values usually vary from 1000 to 1500 ppm. A widely accepted standard is the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 62²⁵. Within the framework of this standard, CO₂ concentrations are recommended to be maintained at — or below — 1,000 ppm in schools²⁶.

Above 2000 ppm, recent studies have shown that the blood shows inflammatory changes and leakage of fluid from blood vessels into brain tissue in mice²⁷, and 15% above normal range, sleepiness, headaches and irregular heart rate²⁸.

2.2 Initial assessment

The initial assessment lasted one month. A monitoring device was installed in three rooms where it operated day and night, both when children were present in the rooms and when they were absent and during weekends and holidays. The present study focused on CO₂ and PM levels within the three rooms, to principally study the confinement degree of the rooms.

We retrieved the results of the assessment and extracted and analyzed the data, in order to check the impact of a Blown Mechanical Ventilation (BMV) solution to the primary school.

2.3 Blown mechanical ventilation (BMV)

2.3.1 Principle of operation

It was decided to install a Blown Mechanical Ventilation (BMV) in the three rooms and to observe the impact of the ventilation on the CO₂ concentrations.

A BMV works as follows: outside air is taken in through a single air vent, located high up the ventilator to avoid ground pollutants. The air is then filtered with HEPA filters to eliminate particle matter (PM). The air could be preheated if the air is colder than the inside temperature of the building.

High efficiency Particulate Air Filters, known as HEPA filters are widely used in the field of air ventilation and/or air conditioning. These filters remove from the air that passes through at least 87% of particles whose diameter is equal to 0,3 μm . The filtration efficiency increases for particle diameters greater than 0,3 μm such as 2,5 μm (96,7%) or 10 μm (99,3%).

The BMV then blows the filtered (and possibly preheated) air into the desired rooms, which are connected by tubing to the BMV.

The new fresh air replaces the stale air by expelling it through air outlets located around windows or doors.

The light overpressure created in the rooms makes it possible to evacuate all eventual indoor pollutants (CO₂, particles, moisture, odors, COV...). Indoor air is then constantly renewed and replaced by healthy fresh air.



Figure 1: Operation principle of a BMV

The school was equipped with BMV systems with a flow rate ranging from $100\text{m}^3/\text{h}$ to $220\text{m}^3/\text{h}$. Two different BMV systems were used: VMI cube from VentilAir Sec (France)²⁹ and VPE - expert 125 from Econology (France)³⁰. They were placed in the attic above the roofs as indicated in Figure 1. They give similar results.

2.3.2 Difference with respect to a classic mechanical ventilation system (MVS)

The BMV works by insufflation. This operating principle is the opposite of that of a classical mechanical ventilation system (MVS) that works by suction.

Indeed, a MVS takes in stale indoor air at several points, usually in the bathroom and kitchen, through air vents using air suction principle and expels it outside.

Air suction creates a light air depression in the rooms, that causes outside air to automatically enter through air vents located above doors and windows.

Certainly, with this classic MVS, odors, humidity and CO_2 are ejected outside, but inside air is replaced by unfiltered outside air. Thus, outdoor pollutants such as particle matter (PM), can enter in the rooms, contributing to a globally polluted air³¹.

Moreover, incoming air is at the same temperature as outside air, which implies that cold (respectively heat) enters easily

into the rooms in cold (respectively hot) periods, requiring an even higher energy expenditure to warm up (respectively cool down) the entire volume of the rooms.

Concerning double flow mechanical ventilation, entering outdoor air is filtered and there is a calorie swap with outgoing polluted air. Thus, entering air is preheated and particle free as with a BMV. But its price is very high, so it is rarely installed in buildings, particularly in developing countries. As with a classical MVS, the building is under light air depression, which implies that each time a door or a window is opened, it makes it possible for PM or dust to enter. There is no possible filtration at this step.

On the contrary, the BMV, with the little overpressure created in the rooms, is advantageous to prevent outside pollution from entering inside. This principle is by the way well known for clean rooms in the microelectronic industry and for operating rooms in hospitals.

2.4 Place

In the primary school, several rooms were equipped with the BMV: 3 classrooms for children, 1 room for teachers and a resting room for children.

The following figure shows a map of the school for calculation of the different rooms.

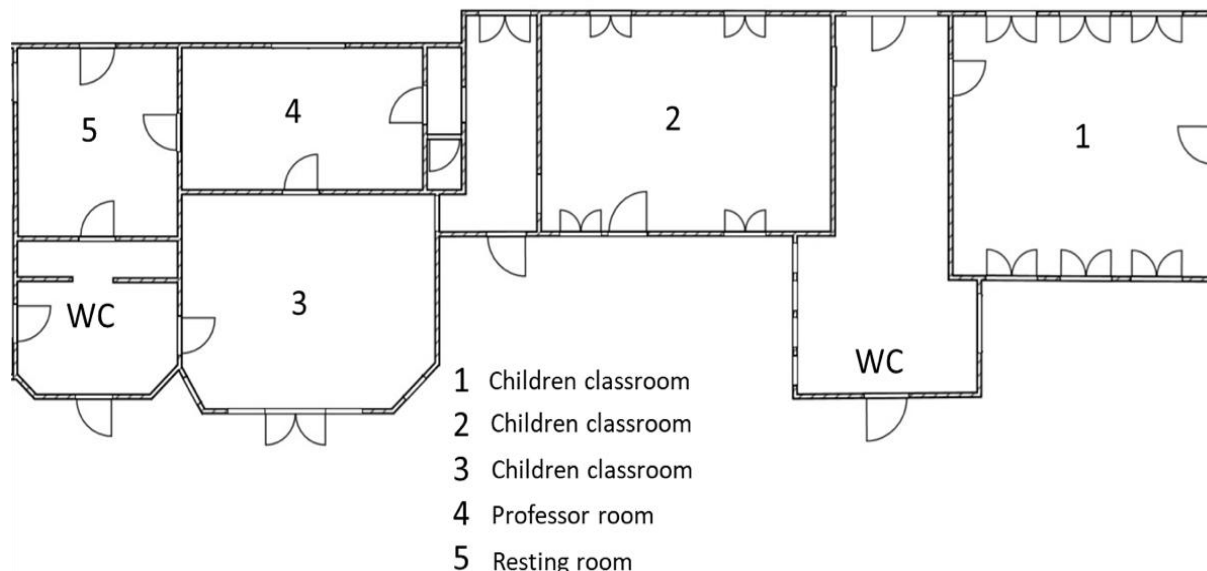


Figure 2: Map of the school for measurement of the surface and the volume of the rooms

The ventilation system installed in the school is based on the principle of positive ventilation. Thus, it is a key point to inject more air inside than the air openings can eject outdoor. In addition, it is mandatory to renew $\frac{1}{2}$ of the total volume of a given room every hour.

For instance, for a room with a dimension of 7, 9m x 6, 8m, corresponding to a surface of 55m² and a height of 3m62, the global volume is 200m³. Thus, a minimum of 100m³ of stale air per hour must be removed. The air input flow rate was selected to 150m³/h and the total air openings were chosen to allow 130m³/h of ejected air. Ideally the air openings could be several window trickle vents with permanent opening flow at 10, 20 or 30 m³/h. If it is not possible to use window trickle vents, it is possible the air opening could be a small space (around 1cm) between the lower part of doors and the floor. It is also possible to use adjustable flow rate air vents in the roof if there is an attic above the roof connecting to the outside.

Additionally, in each room, the air paths necessary to implement the renewal of air in an optimal way were studied, and the locations of the air vents for insufflation of fresh filtered outside air and the air outlets strips for exhaust of the stale inside air were consequently decided in order to have an optimum flushing of the rooms.

2.5 Final assessment

A final assessment was made during one month in the primary school, in the same conditions as the initial assess-

ment. We focused on CO₂ levels within the different rooms, to compare it with the levels found during the initial assessment and also on fine particle matter (PM_{2.5}) concentration, in order to prove that the ventilation system did not contribute to letting outside particles enter the rooms.

Again, the results of the assessment were extracted and analyzed, in order to observe the impact and benefits of the ventilation system.

3. Results and discussion

3.1 CO₂

3.1.1 CO₂ results of the initial assessment (without BMV)

The initial assessment showed that the CO₂ levels in all the three chosen classrooms were much too high, especially when the children were inside the classrooms.

On the figure 3a, which is an overview of the results in classroom n°2, days are indicated below the curve as “m, t, w, t, f, s, s” for “Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, Sunday”. We can note obvious peaks of CO₂ on Monday, Tuesday, Thursday and Friday, i. e. school days.

Within each peak, we note two smaller peaks that correspond to the presence of children in the morning, and then in the afternoon. CO₂ levels generally did not decrease sufficiently between the two half days to drop below 1000ppm.

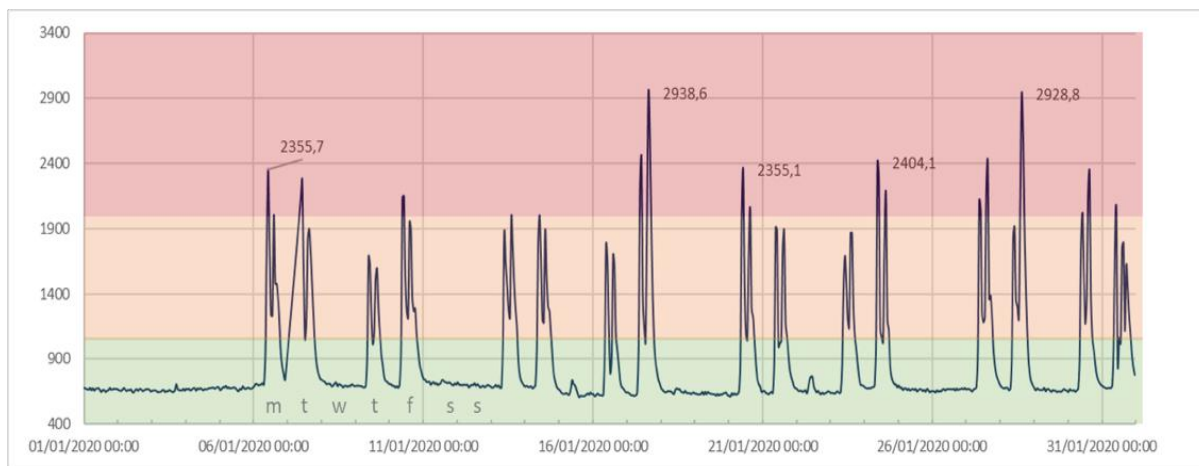


Figure 3a: CO₂ measured during the initial assessment without operating BMV

The table below shows the maximum CO₂ values reached during the assessment period, in different rooms.

Table 2: Maximum value of CO₂ measured during the initial assessment

	Classroom n°1	Classroom n°2	Restroom
Maximum CO ₂ level registered during initial assessment	3072 ppm	2938 ppm	1316 ppm

These values are well beyond the recommended limit value of 1000 ppm in schools.

We explained these high values by:

- The presence of the children and teachers breathing all together,

- The lack of ventilation,
- No opening of the windows because the primary school was next to a road and the teachers did not want to let the outside pollution and traffic noise come inside.

3.1.2 CO₂ results of the final assessment (with BMV)

After installing the Blown Mechanical Ventilation (BMV), the final assessment made it possible to observe a great decrease in CO₂ levels in all rooms.

As shown on the figure 3b, which is an overview of the results in classroom n°2, the average level of CO₂ when the children are inside the classroom is around 1000ppm and drops below 800ppm each time the children go out, notably between the morning and the afternoon.

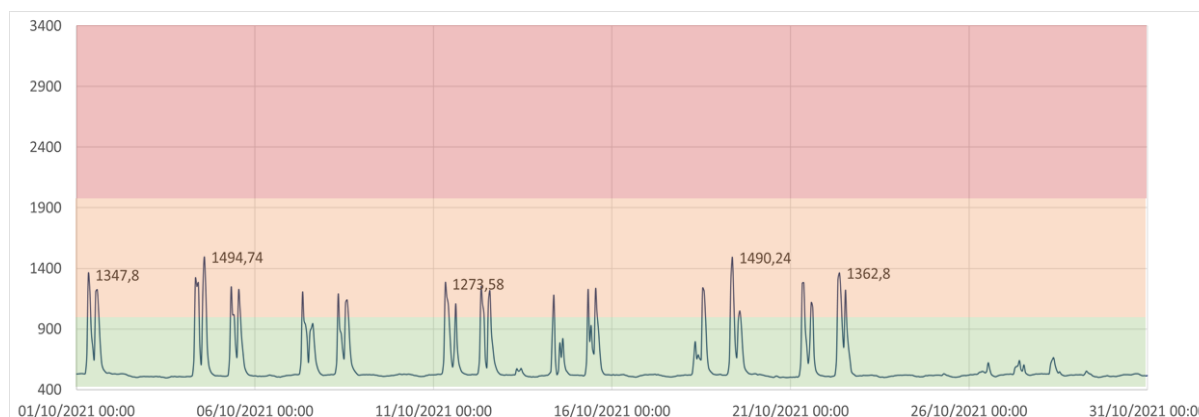


Figure 3b: CO₂ measured during the final assessment with operating BMV

Maximum values reached in this classroom n°2 are below 1500ppm, i. e. twice less than the previous maximum value of 2938ppm reached during the initial assessment (see table 2).

Therefore, we can say that the BMV which was installed in the primary school is an efficient ventilation system to renew inside air and avoid CO₂ accumulation.

The final assessment showed that the concentration of fine particle matter (PM_{2,5}) in the classrooms was low, close to zero, below the recommended limit value of 15 µg/m³.

It can be seen on the figure 4 as the blue curve, which is an overview of the results in classroom n°2.

We can note some double peaks, as in the curves for CO₂ (see figures 3a and 3b), which materialize in the moments the children are present in the classroom.

The orange curve represents the concentration of outside fine particle matter (PM_{2,5}) provided by the air quality analysis service provider (named ATMO in France). This concentration is higher and the curve shows some narrow and intense peaks of particle pollution, certainly due to out-

door conditions such as dense traffic, street work, fires, sandstorm. . .

What to remember from this graph is that the inside PM_{2.5} concentration is much lower than the outside PM_{2.5} concentration. The BMV then effectively filters the particles when taking air from the outside to blow it inside.

The inside concentration of PM_{2.5} shows a constant pattern, independent from the outside PM_{2.5} concentration variations (notably the narrow and intense peaks). The small increases in the classroom are certainly due to children and teachers bringing dust in with them from the outside, moving, etc. The relation between the children's presence, in particular during some activities such as painting, gluing and drawing, and ultrafine particle concentration inside was already reported³².

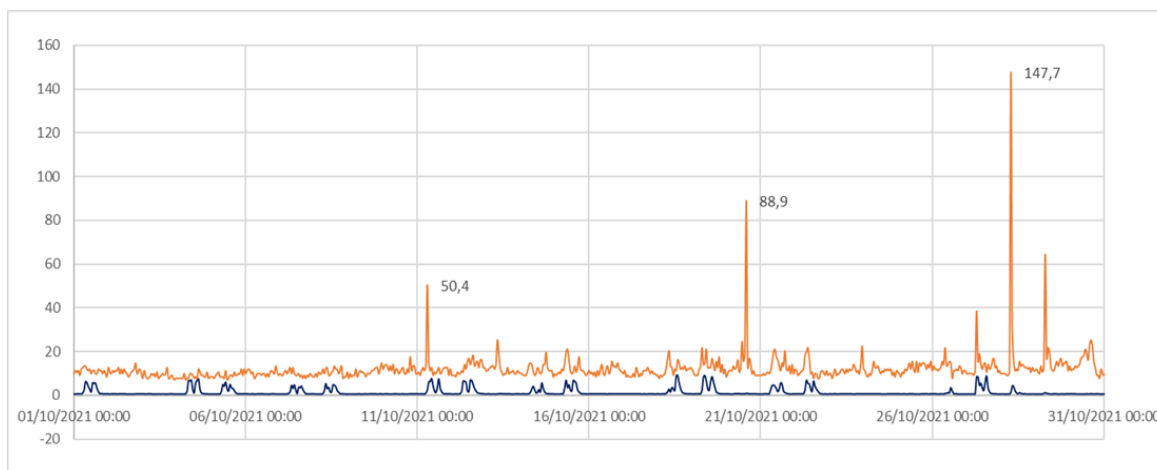


Figure 4: PM_{2.5} measured during the final assessment with operating BMV (10.2021)

Consequently, we can say that the BMV which was installed in the primary school is efficient to filter outside fine particle matter (PM_{2.5}). BMV is reliable to provide particle free, fresh and healthy air within the rooms without big investments.

4. Conclusions

This study made it possible to show that a Blown Mechanical Ventilation (BMV) is a reliable and effective ventilation system which permits to disperse CO₂ accumulation in order to provide children with renewed air that complies with the recommended limit values of CO₂.

Moreover, this study showed that a Blown Mechanical Ventilation (BMV) is adapted to provide fresh air, taking it from outside, without introducing harmful particles into the rooms and complying with the recommended limit values of fine particle matter (PM_{2.5}).

The simplicity of BMV installation and the interesting impact to improve air quality for children, even if the outside air is polluted by fine air particles, could be easily duplicable in any other indoor areas such as offices, retirement homes. The affordable cost and easy installation of BMV in existing buildings are key factors for fast deployment anywhere in the world in order to improve air quality, thus life quality.

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author wishes to thank the City Major of Duingt, France for the access to the data and buildings of the public under-

graduate school. We also would like to thank Ava Sangster for language editing the previous version of this manuscript.

5. Funding

This research did not receive any specific grant from commercial or for - non - profit sectors. O Lavastre thanks the CNRS National Center for Scientific Research for his Research Director position. This study was carried out at: Institut de Microélectronique, Electromagnétisme et Photonique – Laboratoire d'Hyperfréquences et de Caractérisation. UMR 5130 - CNRS/Grenoble - INP/UGA/USMB. Le Bourget du Lac, 73376 Le Bourget du Lac, France.

References

- [1] Eds. C. Baecher, F. Sohui, L. Ball and O. Masson, 2020. **Indoor air quality: tackling the challenges of the invisible.** *Field Actions Sciences Reports*, 2020, Special Issue 21.
- [2] J. L. Adgate, T. R. Church, A. D. Ryan, G. Ramachandran, A. L. Fredrickson, T. H. Stock, M. T. Morandi, K. Sexton, 2004. **Outdoor, indoor, and personal exposure to VOCs in children.** *Environmental Health Perspectives*, 2004, 112 (4): 1386–1392. <https://doi.org/10.1289/ehp.7107>
- [3] K. L. Alford, N. Kumar, **Pulmonary Health Effects of Indoor Volatile Organic Compounds - A Meta - Analysis.** *International Journal of Environmental Research and Public Health*, 2021, 18 (4), 1–11. <https://doi.org/10.3390%2Fijerph18041578>
- [4] W. D. Bennet, K. L. Zeman, **Deposition of fine particles in children spontaneously breathing at rest.** *Inhalation Toxicology*, 1998, 10 (9): 831–842. <https://doi.org/10.1080/10914869808838888>

//www.tandfonline.

com/doi/abs/10.1080/089583798197402

- [5] I. Annesi - Maesano, D. Moreau, D. Caillaud, F. Lavaud, Y. Le Moullec, A. Taytard, G. Pauli, D. Charpin, **Residential proximity fine particles related to allergic sensitisation and asthma in primary school children.** *Respiratory Medicine*, 2007, 101 (8): 1721–1729. <https://doi.org/10.1016/j.rmed.2007.02.022>
- [6] I. Annesi - Maesano, M. Hulin, F. Lavaud, C. Raherison, C. Kopferschmitt, F. De Blay, D. Charpin, D. Caillaud, **Poor air quality in classrooms related to asthma and rhinitis in primary schoolchildren of the French 6 Cities Study.** *Thorax*, 2012, 67 (8): 682–688. <http://dx.doi.org/10.1136/thoraxjnl-2011-200391>
- [7] I. Annesi - Maesano, N. Baiz, S. Banerjee, P. Rudnai, S. Rive & on behalf of the SINPHONIE Group, **Indoor Air Quality and Sources in Schools and Related Health Effects.** *Journal of Toxicology and Environmental Health, Part B*, 2013, 16 (8): 491 - 550. <https://doi.org/10.1080/10937404.2013.853609>
- [8] S. C. Sofuoglu, G. Aslan, F. Inal, A. Sofuoglu, **An assessment of indoor air concentrations and health risks of volatile organic compounds in three primary schools.** *International Journal of Hygiene and Environmental Health*, 2011, 214 (1): 36–46. <https://doi.org/10.1016/j.ijheh.2010.08.008>
- [9] L. Chatzidiakou, D. Mumovic, A. J. Summerfield, **What do we know about indoor air quality in school classrooms? A critical review of the literature,** *Intelligent Buildings International*, 2012, 4 (4): 228 - 259. <https://doi.org/10.1080/17508975.2012.725530>
- [10] Z. Hashim, N. S. Mohamad Fadzil, S. R. MohdFuad, S. B. Shamsudin, K. N. Mohd Isa, T. T. Song, J. Sieman, S. Mohd Elias, J. H. Hashim, **School Indoor Air Pollutants: In Relation to Allergy and Respiratory Symptoms among School Children in Urban Areas.** *Pollution*, 2022, 8 (3): 948 - 962. <https://doi.org/10.22059/poll.2022.336619.1313>
- [11] S. Sadrizadeh, R. Yao, F. Yuan, H. Awbi, W. Bahnfleth, Y. Bif, G. Caof, C. Croitorug, R. de Dear, F. Haghghat, P. Kumar, M. Malayeri, F. Nasiri, M. de Ruud, P. Sadeghian, P. Wargocki, J. Xiong, W. Yu, B. Li, **Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment.** *Journal of Building Engineering*, 2022, 57: 107908. <https://doi.org/10.1016/j.jobe.2022.104908>
- [12] O. Eunjin, C. Kyung - Hwa, K. S. Roul, K. Ho - Jang, B. Sanghyuk, **Association of indoor and outdoor short - term PM_{2.5} exposure with blood pressure among school children.** *Indoor Air*, 2022, 32 (3). <https://doi.org/10.1111/ina.2022.13013>
- [13] J. Yi - Kai, C. Yi, **The influence of indoor environmental factors on learning: An experiment combining physiological and psychological measurements.** *Building and Environment*, 2022, 221: 109299. <https://doi.org/10.1016/j.buildenv.2022.109299>
- [14] D. A. Coley, R. Greeves, B. K. Saxby, **The effect of low ventilation rates on cognitive function of a primary school class.** *International Journal of Ventilation*, 2016, volume 6 (2): 107 - 112. <https://doi.org/10.1080/14733315.2007.11683770>
- [15] S. Bogdanovica; J. Zemitis; R. Bogdanovics, **The Effect of CO₂ Concentration on Children's Well - Being during the Process of Learning.** *Energies*, 2020, 13, 6099. <https://doi.org/10.3390/en13226099>
- [16] M. A. Bhat, F. N. Erslan, A. Awad, S. Malkoç, Ö. Ö. Üzmez, T. Döğeroğlu, E. O Gaga, **Investigation of indoor and outdoor air quality in a university campus during COVID - 19 lock down period.** *Building and Environment*, 2022, 219: 109176. <https://doi.org/10.1016/j.buildenv.2022.109176>
- [17] D. A. Coley, A. Beisteiner, **Carbon dioxide levels and ventilation rates in schools.** *International Journal of Ventilation*, 2002, 1 (1): 45–52. <https://doi.org/10.1080/14733315.2002.11683621>
- [18] C. C. Vassella, J. Koch, A. Henzi, A. Jordan, R. Waerber, R. Iannaccone, R. Charrière, **From spontaneous to strategic natural window ventilation: Improving indoor air quality in Swiss schools.** *International Journal of Hygiene and Environmental Health*, 2021, 234, 113746, <https://doi.org/10.1016/j.ijheh.2021.113746>
- [19] P. Rajagopalan, M. M. Andamon, J. Woo, **Year long monitoring of indoor air quality and ventilation in school classrooms in Victoria, Australia.** *Architectural Science Review*, 2022, 65: 1, 1 - 13. <https://doi.org/10.1080/00038628.2021.1988892>
- [20] Zs. Bakó - Biró, D. J. Clements - Croome, N. Kochhar, H. B. Awbi, M. J. Williams, **Ventilation rates in schools and learning performance.** *Building and Environment*, 2012, 48: 215–223. <https://doi.org/10.1016/j.buildenv.2011.08.018>
- [21] T. Godish, J. D. Spengler, **Relationships between ventilation and indoor air quality: a review.** *Indoor Air*, 1996, 6 (2): 135–145. <https://doi.org/10.1111/j.1600-0668.1996.00010.x>
- [22] J. M. Daisey, W. J. Angell, M. G. Apte, **Indoor air quality, ventilation and health symptoms: an analysis of existing information.** *Indoor Air*, 2003, 13 (1): 53–64. <https://doi.org/10.1034/j.1600-0668.2003.00153.x>
- [23] UHOO smart Air monitor (<https://getuhoo.com>).
- [24] World Health Organization (WHO), **2021 Press information note on the launch of the WHO Global Air Quality Guidelines** https://worldhealthorg-my.sharepoint.com/personal/creswickj_who_int/_layouts/15/onedrive.aspx?ga=1&id=%2Fpersonal%2Fcreswickj%5Fwho%5Fint%2FDocuments%2FCOMMS%2FLWE%2FAir%20quality%2F2021%20AQG%20launch%2FWHO%20AQG%20launch%20%28external%29%2FAQG%20press%20information%20note%20FINAL%20090921%20%5BEN%5D%2Epdf&parent=%2Fpersonal%2Fcreswickj%5Fwho%5
- [25] **ASHRAE position document on indoor carbon dioxide,** 2022 https://www.ashrae.org/file%20library/about/position%20documents/pd_indoorcarbondioxide_2022.pdf
- [26] R. Prill, **Why Measure Carbon Dioxide Inside Buildings?** *Washington State University Extension Energy Program WSUEEP07*, 2000, vol3. <https://www.energy.wsu.edu/documents/co2inbuildings.pdf>

- [27] S. R. Thom, V. M. Bhopale, J. Hu, M. Yang, **Inflammatory responses to acute elevations of carbon dioxide in mice.** *J ApplPhysiol*, 2017, 123 (2): 297 - 302. <https://doi.org/10.1152%2Fjappphysiol.00343.2017>
- [28] T. Vehviläinen, H. Lindholm, H. Rintamäki, R. Pääkkönen, A. Hirvonen, O. Niemi, J. Vinha, **High indoor CO₂ concentrations in an office environment increases the transcutaneous CO₂ level and sleepiness during cognitive work.** *Journal of Occupational and Environmental Hygiene*, 2016, 13: 1, 19 - 29. <https://doi.org/10.1080/15459624.2015.1076160>
- [29] <https://www.ventilairsec.com>
- [30] <https://econology.fr>
- [31] H. Guo, L. Morawska, C. He, D. Gilbert, **Impact of ventilation scenario on air exchange rates and on indoor particle number concentrations in an air - conditioned classroom.** *AtmosphericEnvironment*, 2008, 42 (4): 757–768. <https://doi.org/10.1016/j.atmosenv.2007.09.070>
- [32] L. Morawska, H. Congrong, J. Graham, H. Guo, E. Uhde, G. Ayoko, **Ultrafine particles in indoor air of a school: possible role of secondary organic aerosols.** *Environmental Science and Technology*, 2009, 43 (24): 9103–9109. <https://doi.org/10.1021/es902471a>