Numerical performance evaluation of ventilation systems for energy-efficient retrofitting of existing houses in France

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ABSTRACT

More and more single-family houses are being retrofitted to achieve better energy efficiency levels. In this retrofitting process, the building envelope's airtightness is usually improved, and a ventilation system becomes necessary to create and sustain a healthy indoor air quality (IAQ). However, in France, as in many other western countries, ventilation requirements exist for new dwellings but not for residential retrofitting. Ventilation professionals as well as inhabitants are facing a lack of knowledge, recommendations and decision tools to choose, design, and install the most efficient system in retrofitted houses. The work presented in this paper was carried out as part of the French JUSTAIR national research project (2022-2025) which aims to tackle this issue.

A consultation of ventilation stakeholders and a review of the scientific literature were performed to identify the most commonly used ventilation systems for individual house retrofitting in France and to develop a methodology for assessing the performance of such systems. The performance is assessed by a numerical approach using the NIST's multizone software CONTAM. As a first step of this project, numerical models of the various ventilation systems are created based on a specific test case: a 100 m² experimental single-family house of two stories, representative of the French building stock. Only the ventilation terminal devices, filters and heat exchangers are modelled to simulate the ventilation systems. The calculation is performed in winter, under a French south-eastern climate, and the indoor temperature is considered as constant.

This paper presents the selected 8 ventilation systems with a potential for single-family house retrofitting, including commonly installed systems (balanced and exhaust mechanical systems, with and without humidity control) as well as more emerging systems (thermodynamic, decentralized and balanced without supply ducts). The methodology for the performance evaluation of these systems is also detailed, with in particular the indicators identified to assess the physical performance and the scenarios used for the model: occupation, pollutants and humidity emissions.

Finally, the results of the numerical study are presented with the simulation of the 8 ventilation systems applied to the test case building and a performance comparison based on a set of eight indicators. In the next steps, three of the studied ventilation systems will be implemented in the experimental house for the model's validation. The validated models will be used to perform sensitivity analysis under different configurations and climate conditions.

KEYWORDS

Ventilation, retrofitting, indoor air quality, energy efficiency, performance

1 INTRODUCTION

Generally, people spend more than 90% of their time indoors, considering the time at home, at work, at school, and so on (Ortiz et al., 2020). However, the indoor environments to which people are exposed not always provide a good air quality, and can cause negative effects for health, productivity and comfort (Guyot et al., 2018; Ortiz et al., 2020). The improvements to reach energy efficiency in buildings can aggravate these effects.

To achieve the requirements set by energy-efficiency programs, many countries have focused on the renovation of the housing stock. Retrofitted buildings tend to be air-tighter and more thermally insulated generating problems related to humidity, pollutants and overheating. In this context, ventilation plays an important role to create and sustain a healthy indoor air quality (IAQ). Meanwhile, in France, as in many other western countries, ventilation requirements exist in regulation for new dwellings but not for residential retrofitting. Hence, the professionals as well as inhabitants involved in renovation currently are facing a lack of knowledge, recommendations and decision tools to choose, design, and install the most efficient and suitable system in retrofitted houses.

In order to tackle this issue, the ongoing research project JUSTAIR (2022-2025) aims at developing and testing the tools needed to draw up a future technical reference framework for ventilation in the renovation of single-family homes. This project is divided in four subtasks that comprises (1) the analysis of households and building professionals feedbacks, (2) the identification of relevant ventilation strategies in renovation, (3) the development of a numerical methodology for evaluating their global performance, integrating at least the IAQ, the risks of condensation for the building, heating needs and electricity consumption, and finally (4) test the strategies experimentally.

The work presented in this paper was carried out as part of the subtask 3, focusing on the numerical evaluation of the global performance of the ventilation strategies. Several important aspects influence the choice of a ventilation system and must be included in the concept of global performance. They are, without hierarchy: IAQ, humidity, energy consumption, thermal comfort, acoustic comfort (both external and internal noise including registers and casing), total cost (covering purchase, installation, maintenance, servicing, and filter component replacement), durability of system components and performance, installation feasibility and aesthetics, as well as maintenance and design considerations.

Almost all of the residential mechanical ventilation system in France installed in buildings built after 1983 has humidity-based control (Jardinier et al., 2018; Leprince et al., 2023; Mélois et al., 2019). This system proved to be very effective in controlling humidity in buildings, however, its effectiveness in mitigating other pollutants is still under investigation. In addition, to optimize energy performance, the innovation possibilities are limited due to the prescriptive regulations (Leprince et al., 2023). As an alternative, it has been developed a performance-based approach for ventilation system regulation to evaluate the ability of a ventilation system in providing good IAQ and avoiding risks for occupant's health (Leprince et al., 2023; Poirier et al., 2023).

When working with performance-based approach for ventilation, several questions arise regarding which pollutants and/or relevant parameters should be used in the calculation of performance indicators, which indicators should be used, how to define the relevant input data and at what level of detail should be used to model air flows and pollutants throughout the house. These questions were previously raised by Poirier (Poirier et al., 2023) in the context of the design stage. In this article, we want to obtain these answers for the renovation scenario.

In this context, the objective of this study is to compare eight ventilation strategies used in single-family house retrofitting, including commonly installed systems (Jardinier et al., 2018; Poirier et al., 2023, 2022) as well as emerging systems and identify which ones are suitable for renovation and later test them experimentally. The results were evaluated in terms of the indicators defined to assess indoor air pollution, humidity and energy consumption.

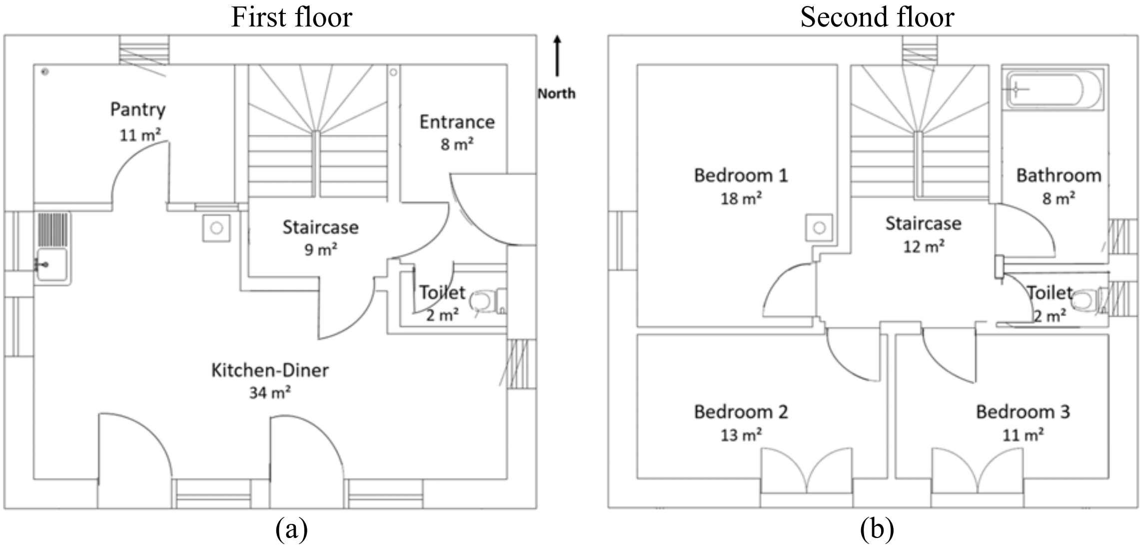
2 METHOD

2.1 Case study

2.1.1 House

The case study is an experimental low-energy house located in the city of Chambery in the south-eastern France, characterized by a temperate oceanic climate (Cfb according to the Köppen classification) (Schreck et al., 2024). It is a 128m² single-family house comprising two stories and an unused attic space, typical of French houses, as illustrated in Figure 1.

The first floor features a spacious living room with an open kitchen, and a toilet (WC1), while the second floor accommodates three bedrooms, a bathroom and a second toilet (WC2). The air tightness under 4 Pa Q4Pa-surf is 0.9 m^3 $h^{-1}m^{-2}$ per external surface unit.



(a) (b)

Figure 1: Plan of the house used in simulation (a) first floor and (b) second floor.

2.1.2 Ventilation systems

After consulting ventilation stakeholders and performing a literature review to identify the most commonly used ventilation systems for individual house retrofitting in France, eight systems were selected and are described as follow:

1. Mechanical exhaust only ventilation with humidity control (EV-rh-b): Exhaust Air Terminal Device (ATD) with humidity control in the wet rooms and air inlets with humidity control on the facades in the living room and the bedrooms. Described by Jardinier (Jardinier et al., 2018)
2. Mechanical exhaust_ only ventilation with humidity control (EV-rh-a): Exhaust Air Terminal Device (ATD) with humidity control in the wet rooms and air inlets without control on the facades in the living room and the bedrooms.
3. Mechanical balanced ventilation with constant air volume (BV-cav): Constant airflow supply in bedrooms and living room and constant airflow exhausts in bathroom, kitchen and WC. Supply ATD is equipped with a $PM_{2.5}$ filter (e65)
4. Demand-controlled mechanical supply with humidity control (SV-rh): Supply air Terminal Device (ATD) in the living room at the first floor (60% of total flow) and in the circulation area at the second floor (40% of total flow), controlled by relative

humidity. The supply ATD is equipped with a $PM_{2.5}$ filter (e65) and provides an airflow varying from 120 $m^3 h^{-1}$ for RH<30% to 280 $m^3 h^{-1}$ RH >70%. Air outlets without controls are located on the façades in each room.

5. Decentralized mechanical balanced ventilation with heat recovery and humidity control (DBV-rh): Room-based mechanical balanced ventilation with heat recovery. Supply and exhaust in the same device, installed one in the living room and another in the circulation area. The air flow is controlled by the RH measured in the living room and in the circulation area, varying from 15 $m^3 h^{-1}$ for RH<30% to 70 $m^3 h^{-1}$ for RH >70%.
6. Mechanical balanced ventilation without supply duct with CO_2 control (BV-nsd-CO_2): Supply air is centralized at the first floor using a Flair unit system (high-performance fan with heat exchanger), controlled by the CO_2 concentration measured in the circulation area. The supply air flow varies from 50 $m^3 h^{-1}$ for [CO_2] <600 ppm to 200 $m^3 h^{-1}$ for [CO_2] >1000 ppm. Fan coils draw in air above bedroom doors and discharge it to the circulation area. The extraction is located in the wet rooms and is proportional to the supply flow, splited in 35% in kitchen, 35% in the bathroom, 15% in WC1 and 15% in WC2.
7. Mechanical balanced ventilation with constant air volume coupled with heat pump (BVHP-cav): Constant air supply in bedrooms (40 m^3/h in bedroom 1 and 20 m^3/h in bedroom 2 and 3) and living room (130 m^3/h), and constant air extraction in bathroom (30 m^3/h), Kitchen (120 $m^3.h^{-1}$) and WC (30 $m^3 h^{-1}$). Supply ATD is equipped with a $PM_{2.5}$ filter (e65).
8. Distributed Mechanical Ventilation (DEV-rh60): Independent exhaust ATD in kitchen, bathroom and WC (ON/OFF when RH>60%) and air inlets with humidity control on the facades in bedrooms and living room.

2.2 Evaluation approach

The ventilation performance was assessed by a numerical approach using CONTAM. The two-stories single family house was modelled using 12 zones, represented by each room including the attic space, with the kitchen-diner modelled as a single zone. A 10-min time step calculation was performed in winter, from October 1st (00:00 a.m.) to May 31st (12:00 p.m.), with the weather conditions of Chambery, and a constant indoor temperature at 20°C.

Only the ventilation terminals, filters and heat exchangers were modelled to simulate the ventilation systems.

The variable wind pressure at the building was calculated from the weather data. The wind pressure modifier coefficient was determined as 0.36 according to CONTAM manual, resulting from a power law used, considering the terrain characteristics as suburban type (0.6) and the house elevation 8.5 m. The pressure coefficients were based on EN 15242, varying from 0.5 on the upwind facades to - 0.7 on the downwind facades.

The infiltration was assumed to be pressure driven by a power-law model Q= C(dP)^n, where C is the flow coefficient and n is the flow exponent, being estimated as $4.97e^{-5}$ $m^3.s^{-1}.Pa^n$ and 0.67, respectively. This infiltration level corresponds to an air tightness level Q4Pa-surf of 0.9 $m^3 h^{-1}m^{-2}$ per external surface unit. The Q4Pa-surf is the airflow rate at 4 Pa divided by the envelope surface area excluding lowest floor (Moujalled and Mélois, 2023). For the wall leakage, two relative elevations were considered (1/3 and 2/3 of the ceiling height of the zone). The doors and windows were considered closed, with a 85-cm² leakage area for the interior doors, corresponding to a 1-cm undercut. No other leakage through the interior wall were considered.

We assumed outdoor constant concentrations of 9.4 $\mu g.m^{-3}$ for $PM_{2.5}$, 2.9 $\mu g.m^{-3}$ for formaldehyde and 400 ppm for CO_2 (Poirier *et al.*, 2021).

2.2.1 Input parameters for simulation

The detailed inputs scenarios for pollutant emissions and occupancy schedules are presented in Table 1.

Table 1: Input data for occupants schedules and pollutant emissions scenario

Occupants schedules			
Room/Occupants	**Occupants 1 and 2**	**Occupant 3**	**Occupant 4**
Kitchen and living (5h30/occupant)	7:00-8:30 12:00-14:00 19:00-21:00	6:20-8:30 12:00-14:00 19: 00-20:20	6:20-8:30 12:00-14:00 19:00-19:40 20:20-21:00
Bathroom (40 min/occupant)	6:20-7:00 (WC1 and 2)	20:20-21:00	19:40-20:20
Bedroom (9h20/occupant)	21:00-6:20 **(Bedroom 1)**	21:00-6:20 **(Bedroom 2)**	21:00-6:20 **(Bedroom 3)**
Pollutants and humidity emissions scenarios*			
Bio effluents (occupied room)	CO$_2$	Awake: 18 L.h^{-1}/person	6:20 – 21:00
		Asleep: 15 L.h^{-1}/person	21:00-6:20
	Humidity	Awake: 55 g.h^{-1}/person	6:20 – 21:00
		Asleep: 40 g.h^{-1}/person	21:00-6:20
Cooking (kitchen)	PM$_{2.5}$	2.55 mg.min^{-1}	6:20 -6:35, 12:00 – 12:30 and 19:00 – 19:40
	Humidity	1512 g.h^{-1}	6:20 -6:35
		2268 g.h^{-1}	12:00 – 12:30
		2844 g.h^{-1}	19:00 – 19:40
Shower (bathroom)	Humidity	1440 g.h^{-1}	10 min/person at 6:20 (occ1),6:40 (occ2), 19:40 (occ4) and 20:20 (occ3)
Laundry (kitchen)	Humidity - wash machine	252 g.h^{-1}	5 times a week, 2h/time- Mondays, Tuesdays, Wednesdays, Saturdays and Sundays, at 19:00h
	Humidity – dryer (naturally) (living room?)	136.8 g.h^{-1}	5 times a week, 11h/time - Mondays, Tuesdays, Wednesdays, Saturdays and Sundays, at 21:00h
Building-related emission (all rooms)	Formaldehyde	23.6 µg.h^{-1}.m^{-2}	Continuous in all rooms, per m² of floor space

*(Poirier et al., 2021)

2.2.2 Key-performance indicators

For evaluating the physical performance, we proposed a reduced set of IAQ performance indicators as output data. The methodology for calculating the IAQ indicators is detailed by Poirier (Poirier *et al.*, 2021).

1. E_CO$_2$ – CO$_2$ cumulative exposure concentration above the reference concentration of 1000 ppm and divided by the time of exposure, calculated for the occupants (ppm).
2. E_RH - Percentage of time in which relative humidity is outside the range [40-60%] considering health risks for all rooms in the building during occupied hours (%).
3. E_RH70: Percentage of time in which relative humidity is above 70% in all rooms, considering condensation risk (%).

4. E_HCHO - Long-term cumulative exposure to formaldehyde, calculated for the occupants and divided by the time of exposure (µg.m^{-3}).
5. E_PM2.5 - Long-term cumulative exposure to $PM_{2.5}$, calculated for the occupants and divided by the time of exposure (µg.m^{-3}).
6. Energy_tot – This energy indicator is the sum of the heat loss due to air changes (including the heat recovery for BV) and the electrical consumption of the fans (kWh).
7. Cons_Fan – Electric consumption due to the ventilation system operation (kWh$_{el}$.m^{-2})
8. q_{v_mean} - The mean air flow rate extracted/supplied by the mechanical ventilation system (m^3.h^{-1} or vol.h^{-1}).

3 RESULTS

3.1.1 Comparison of the behaviour of ventilation systems

Figure 2 shows the variation in total flowrate for all systems throughout the day of 01/02. These flowrates and control strategies were defined for each system based on respective technical documentation or after consultation with ventilation constructors.

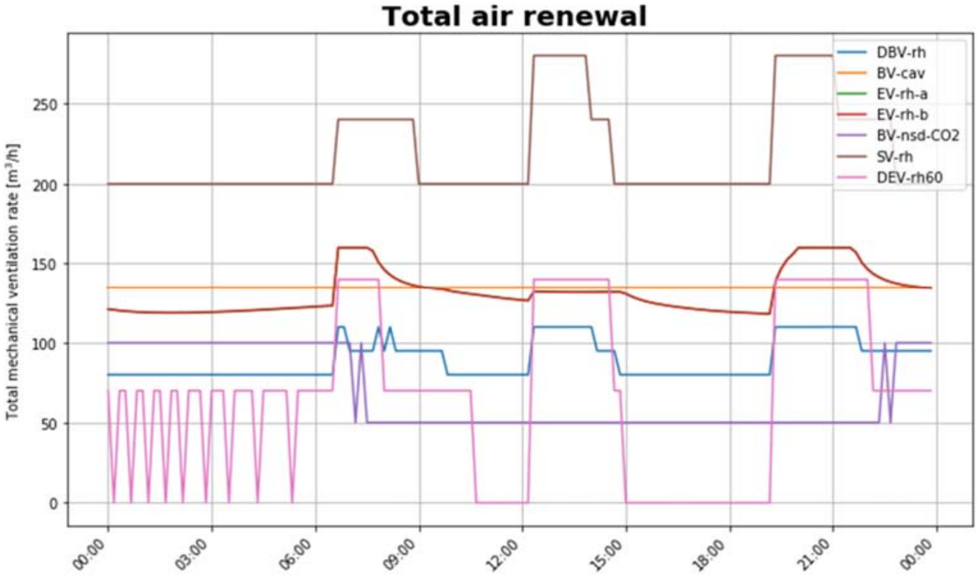
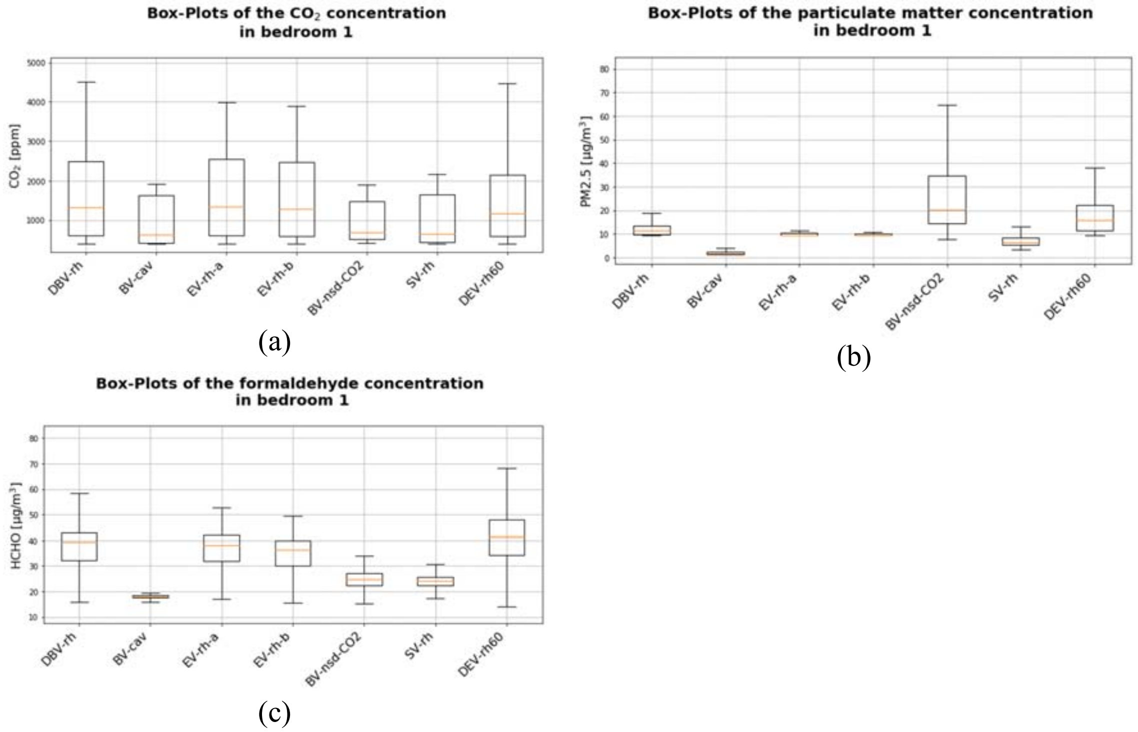


Figure 2: Total flowrate for all systems throughout the day February 1st.

BVHP-cav is not represented in this section, as its behaviour is the same as BV-cav: only the energy consumption differs due to the use of a heat pump in the case of BVHP-cav.

Airflow rates vary significantly across different systems. With the exception of BV-cav, which maintains a constant airflow rate of 140 m^3 h^{-1}, all other systems exhibit variable airflow rate profiles. These profiles maintain a constant base value (ranging from 0 m^3 h^{-1}for DEV-rh60 up to 200m^3 h^{-1}for SV-rh), with peak values occurring during periods of occupants' activities such as cooking or showering (ranging from 70m^3 h^{-1}for DBV-rh up to 280 m^3 h^{-1} for SV-rh). The dynamics of variation vary according to the control strategy (CO_2 or RH). SV-rh exhibit the highest rates among all the systems at all time. DEV-rh60 shows the lowest rates during the base hours, while DBV-rh and BV-nsd-CO2 show the lowest rates during peak hours. EV-rh-a and EV-rh-b present very similar trends in the whole study: the exhaust flowrates are the same for both, the only difference is the amount of air entering the building through the air inlets, and its distribution among the different rooms.

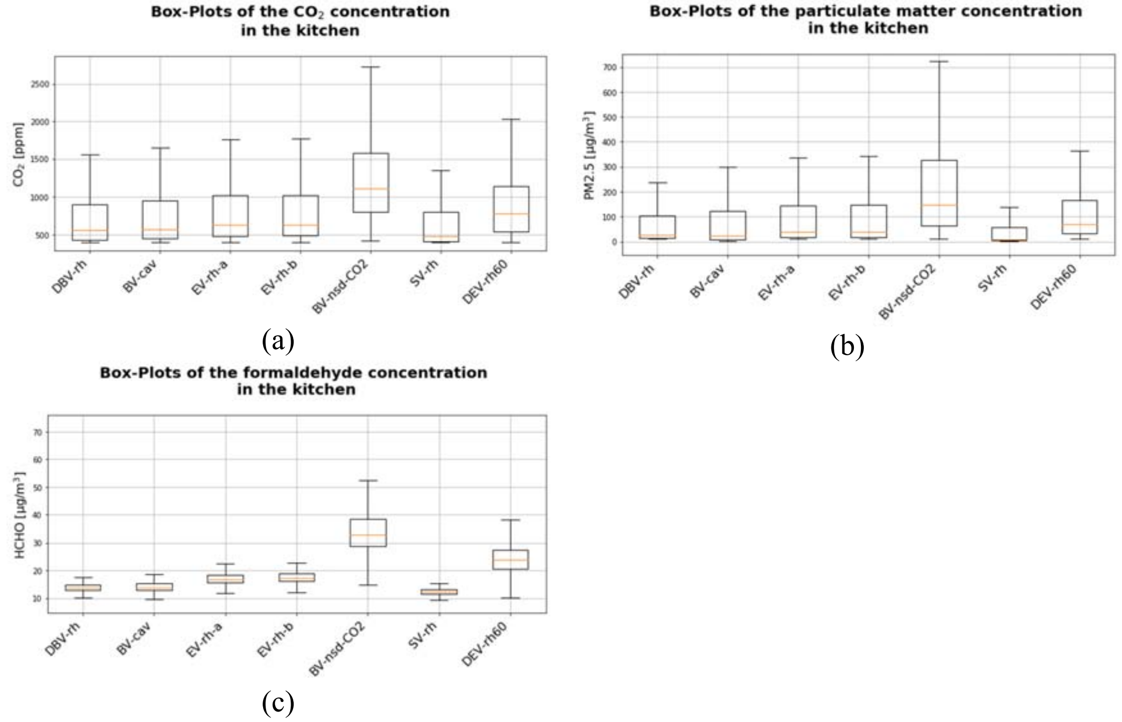


(a)

(b)

(c)

Figure 3: Comparison of (a) CO_2 concentration in ppm, (b) $PM_{2.5}$ concentration in µg.m^{-3} and (c) formaldehyde concentration in µg.m^{-3} in bedroom 1 obtained for each ventilation system.



(a)

(b)

(c)

Figure 4: Comparison of (a) CO_2 concentration in ppm, (b) $PM_{2.5}$ concentration in µg.m^{-3} and (c) formaldehyde concentration in µg.m^{-3} in kitchen obtained for each ventilation system.

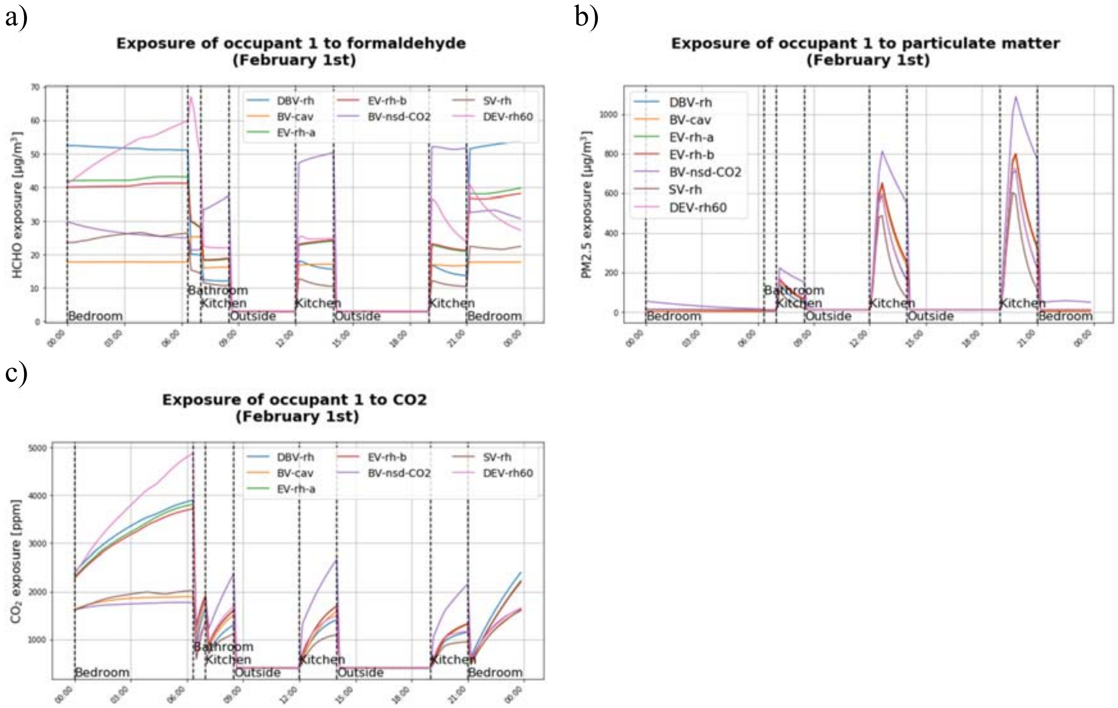


Figure 5: Occupant 1 exposure to (a) formaldehyde, (b) $PM_{2.5}$ and (c) CO_2 throughout the day February 1st.

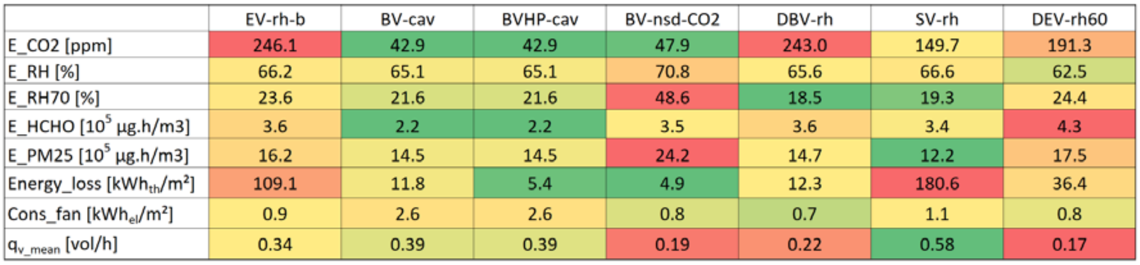
Figure 3 and Figure 4 illustrate the boxplots of the pollutant concentrations in the main bedroom and the kitchen respectively, and Figure 5 the typical profile of occupant1 exposure during a single day. The exposure to formaldehyde is higher in the bedrooms than in other rooms (except for BV-nsd-CO2). BV-cav, SV-rh and BV-nsd-CO2 have quite stable levels, the other systems show important variations over time due to the variation of air flowrate according to humidity and CO_2 level.

The outdoor concentration in $PM_{2.5}$ being fixed to very low level in these calculations, the exposure to particles matter is only due to the cooking activities. A strong increase of the $PM_{2.5}$ exposure is observed at each cooking period, this peak is then quickly balanced by the air changes, with a peak value and a slope that depend on the considered system.

For all systems (except BV-nsd-CO2), the moment of highest exposure to CO_2 is at night. Indeed, the CO_2 emitted by the occupants themselves by metabolic activity concentrates all night long. In comparison, the exposure in the kitchen is roughly half-way smaller than the highest one reached in the bedroom. We can notice that none of the considered systems is able to remove the CO_2 as fast as it is emitted.

3.1.2 Analysis of the performance

Table 2: Analysis of the performance indicators for all ventilation systems.



	EV-rh-b	BV-cav	BVHP-cav	BV-nsd-CO2	DBV-rh	SV-rh	DEV-rh60
E_CO2 [ppm]	246.1	42.9	42.9	47.9	243.0	149.7	191.3
E_RH [%]	66.2	65.1	65.1	70.8	65.6	66.6	62.5
E_RH70 [%]	23.6	21.6	21.6	48.6	18.5	19.3	24.4
E_HCHO [10^5 µg.h/m3]	3.6	2.2	2.2	3.5	3.6	3.4	4.3
E_PM25 [10^5 µg.h/m3]	16.2	14.5	14.5	24.2	14.7	12.2	17.5
Energy_loss [kWh_{th}/m^2]	109.1	11.8	5.4	4.9	12.3	180.6	36.4
Cons_fan [kWh_{el}/m^2]	0.9	2.6	2.6	0.8	0.7	1.1	0.8
q_{v_mean} [vol/h]	0.34	0.39	0.39	0.19	0.22	0.58	0.17

We can observe in Table 2 that no system is superior to all others for all indicators, even though the balanced ventilation systems BV-cav and BVHP-cav present good results overall.

All systems present poor results in terms of air humidity: the relative humidity in occupied rooms is outside the range [40-60%] around 70% of the time for all systems. On the contrary, all systems (except BV-nsd-CO_2) trespass 70% relative humidity less than 20% of the time. The exposure to formaldehyde and particulate matter varies from simple to double depending on the considered system.

For better readability of Table 2, the indicators for the ventilation system EV-rh-a are not represented as they are all very similar to EV-rh-b. Indeed, despite the difference of air inlets (and with similar air outlets and fan), the flowrates are similar in both cases as can be seen on Figure 2. This similar air renewal induces very similar IAQ and energy consumption indicators.

The energy loss due to air renewal (Energy_loss) shows great variation: the balanced ventilation associated to a heat pump (BVHP-cav) and the balanced ventilation without supply duct with CO_2 control (BV-nsd-CO2) lead to about 5 $kWh.m^{-2}$ consumption over the heating period, whereas the exhaust-only system EV-rh-b leads to more than 109 $kWh.m^{-2}$ consumption, and more than 180 $kWh.m^{-2}$ for the supply ventilation SV-rh over the same period. These results must be taken with a pinch of salt, as no thermal simulation was performed. Neither the thermal loss through the walls nor the solar gains are taken into account. This difference in energy consumption is notably due to the presence or not of a heat recovery unit (and to a heat pump for BVHP-cav). Another factor which contributes to explain this energy consumption variation is the difference in *mean total air changes* q_{v_mean}, which range from 0.17 $vol.h^{-1}$ only for DEV-rh60, to 0.58 $vol.h^{-1}$ for SV-rh.

The electric consumption due to the ventilation system operation Cons_fan is very small compared to the loss due to air renewal, especially for the system which does not include a heat exchanger. For the balanced ventilation systems, this consumption represents up to 33% of the Energy_loss (for BVHP-cav) due to both a smaller Energy_loss with the heat exchanger, and a high electrical consumption due to the operation of two fans and a significant pressure drop through the heat exchanger.

4 CONCLUSION

This paper presents a numerical performance evaluation of ventilation systems, based on a methodology which was developed considering ad-hoc benchmark and review of the scientific literature.

This simulation work results in the computation of IAQ and energy indicators in winter period for eight ventilation systems, among which very usual ones in the French context but also more innovative ones.

According to the simulations, the ventilation systems lead to various performance levels for these indicators. All systems present advantages and limitations: depending on the room, the moment of the day and the pollutant considered -or the energy consumed or the heat loss by air changes, all systems seem alternatively better or less performant than others.

The upcoming work within the scope of the JUSTAIR project will involve enriching the simulation model. This enhancement will notably include constructing a thermo-aeraulic coupling to account for temperature changes, enabling thus simulations to be performed during the summer period. Additionally, the set of indicators will be enriched by incorporating thermal comfort and total cost considerations.

Another crucial step of the project will be the installation and testing of 3 different ventilation systems in the experimental house on which the present simulations are based. Pollutant emissions similar to the scenarios presented in this paper will be implemented and a set of sensors will be installed and monitored to evaluate the actual performance of these systems in operation.

These further steps will enhance the understanding and comparison of all the studied ventilation systems.

5 ACKNOWLEDGEMENTS

The authors would like to thank ADEME (Ecological Transition Agency - Auvergne-Rhône-Alpes) for its support through the grant number N°2204D0013.

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