Performances of a demand-controlled mechanical supply ventilation system under real conditions: indoor air quality and power distribution for thermal comfort

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ABSTRACT

This study aims to evaluate the performances of a VMI, a demand-controlled mechanical supply ventilation system, in an experimental house, in terms of indoor air quality (IAQ), energy performance and thermal comfort. The positive input ventilation draws fresh air from the outside, filters and preheats or precools it before blowing it every dry rooms. The air circulates through doors' undercuts and is naturally extracted thanks to exhaust orifices in every wet rooms. A heat exchanger supplied with water from a reversible heat pump is used to preheat or precool the blown air. On the one hand, this combination is expected to improve the IAQ by blowing fresh and filtered air in the rooms where occupants spend most of their time. On the other hand, the VMI is supposed to contribute to the thermal comfort by bringing or removing heat to or from the dwelling. To quantify the influence of the VMI on the parameters described above, a VMI and its heat exchanger are set up in an experimental house. The IAQ part is reduced to the analysis of the CO_2 concentration in the experimental house's master room, the relative humidity in the shower room and the PM2.5 concentration indoor and outdoor. The thermal comfort is reduced to the analysis of the supplied air temperature. Results are promising and show that the studied system is a good way to reduce stuffiness in the most occupied bedroom, evacuate humidity in the most occupied shower room and to reduce PM 2.5 level indoor. Results are also encouraging in terms of thermal comfort, since the VMI brings a significant part of the heat, enhancing thus the heating reactivity.

KEYWORDS

VMI, demand-controlled mechanical supply ventilation, IAQ, thermal comfort, energy performance.

1 INTRODUCTION

In the past three decades, building energy performance has been significantly enhanced. Since then, demand-controlled ventilation systems (DCV) have been identified as a key actors in reaching both indoor air quality and energy targets. The most widespread DCV in France is a mechanical extraction ventilation system (MEV) based on passive water vapor sensors allowing to modulate the flowrate in each wet room and sometimes in each dry room as well, depending on their humidity level. Nevertheless, other DCV can present a good compromise between IAQ, energy savings and even thermal comfort. For instance, mechanical balanced systems (MBS) with heat recovery can ensure the outdoor thin particles filtration and can preheat or precool supplied air. However, such systems are usually not chosen by French single-family houses (SFH) builders due to their cost, their technical installation complexity and their gains regarding mean France climate.

VMI can be an alternative that is more affordable and easier to install. Indeed, as well as for balanced systems, VMI can filter the outdoor air and can use the mechanical air supply to bring or remove heat. Even though such systems are available for three decades, few studies are identified about VMI: (Rahmeh, 2014), (Ouvrier-Bonnaz, Rahmeh, Stephan, & Potard, 2015).
VENTILAIRSEC GROUP (www.ventilairsec.com) conceives nowadays a demand-controlled VMI that seeks to comply with IAQ and thermal comfort objectives. The principle is simple: outdoor fresh air is filtered, preheated or precooled and then blown in main rooms of the dwelling. The air circulates through the door's undercuts and is naturally extracted in every wet rooms, through designed openings. The VMI supply flowrate varies according to the indoor relative humidity and the outdoor absolute humidity.
This study focuses on an experimental feedback of a VMI on two main points: IAQ and power distribution for thermal comfort.
Thereafter, the experimental field is presented in terms of envelope and equipment (heating, ventilation, and energy production systems), followed by a description of the global monitoring in terms of location and types of sensors. The IAQ and power distribution results are then presented. Finally, some discussion and conclusion are proposed.

2 EXPERIMENTAL HOUSE DESCRIPTION

In this section, the experimental dwelling is presented, in terms of location, envelope and equipment with a particular attention to the ventilation system. Lastly, the monitoring is detailed.

2.1 Context

The experimental dwelling is part of COMEPOS project, a French experimental program that aims to quantify the performances of innovative systems for SFH. Systems can be from envelope component to heat generators and emitters including ventilation systems as well. Around twenty experimental houses are included in this program all over France (www.comepos.fr)

2.2 Experimental field global description

The experimental dwelling is located in Brest, France. It is a two-floor house. On the ground floor, there are one open kitchen to the living-room, one toilet and one bedroom with a separate shower room. On the first floor, there are one bathroom, one toilet, a room, an office and a mezzanine. The global living area is 180 m².
This house is equipped with photovoltaic solar panels coupled to a 5kW.h electro chemistry storage system. A reversible water to water heat pump coupled to geothermal pipes ensures heating, cooling and domestic hot water. The heating and cooling emission is ensured by radiative ceilings on each floor, including a room by room temperature control. The heat production equipment is also coupled to the VMI supplied air through a water to air heat exchanger for both air cooling and heating purposes.
The VMI operation is as described above. The exhausts consist in vents in the window frames in the ground-floor toilet, bathroom, shower room, a 5 m^3/h-mechanical extractor in the first-floor toilet and a vertical duct in the kitchen. The global airflow modulation follows the increasing or decreasing indoor relative humidity and outdoor absolute humidity. The supplied air in each room is balanced by the airflow network. Measurements are realized in each dry room for several total flowrate setpoints. Table 1 describes the total flowrate distribution for those setpoints:

Table 1: Distribution of the VMI total flowrate in the dwelling's dry rooms

		Total flowrate repartition for several setpoints				
Set point	**Total flowrate [m3/h]**	**Living room (%)**	**Ground-floor bedroom (%)**	**Mezzanine (%)**	**Office (%)**	**First-floor bedroom (%)**
1	77	41.2	16.1	11.5	15.5	15.6
2	134	39.8	15.2	16.6	15.2	13.2
3	157	38.9	17.8	13.8	15.2	14.3
4	186	38.7	16.6	14.8	15.3	14.6
5	217	36.4	17.1	15.3	16.2	15.0
6	248	37.7	17.5	14.2	14.7	15.8
7	267	36.9	18.5	14.9	15.0	14.7

Figure 1 shows the two floors' organization as well as the airflow network of the VMI.

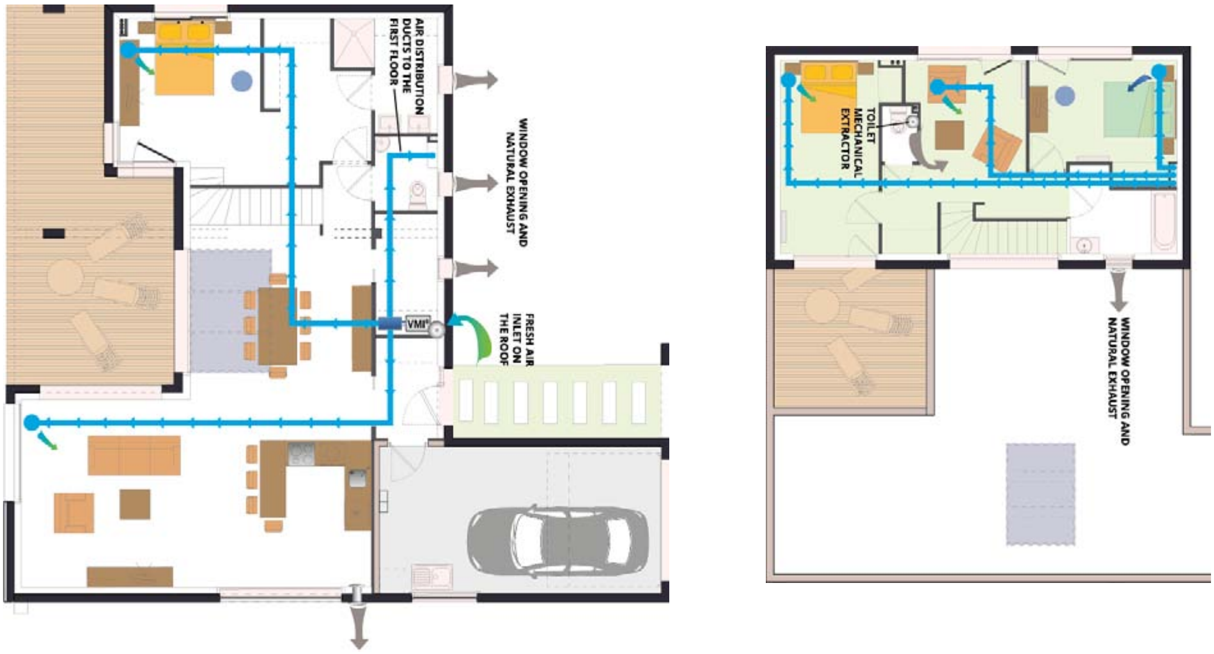

Figure 1: Ventilation network – ground floor and first floor

2.3 Monitoring

The experimental house is largely monitored. Table 2 summarizes the sensors used for this study:

Table 2: Monitoring description

Location	**Measured quantity**
Outdoor	Temperature (north face) / Relative humidity (RH) / PM 2.5 concentration (next to the main VMI air inlet)
Ground-floor bedroom	Temperature / Relative humidity (RH) / Carbon dioxide (CO_2)
Shower room – ground floor	Temperature / Relative humidity
Living-room – ground floor	Temperature / Relative humidity / Carbon dioxide (CO_2) / PM 2.5 concentration
VMI and heat exchanger	Electrical power / Supply air temperature / Inlet water temperature / Outlet water temperature

The monitoring used is based on a wireless communication protocol in order to be as less intrusive as possible.

Relative humidity measurement is based on capacitive technology whereas temperature measurement is made by a thermal resistance. A window opening detector is used in the shower room. PM 2.5 measurement is based on a laser diffraction scattering method. CO_2 sensors are based on solid electrolyte (SE) technology with an automatic background calibration (ABC) method.

Doubts can be emitted about the reliability of this last measurement technology. Therefore, a comparison has been made in some experimental sites for COMEPOS project between this sensor and another one based on a non-dispersive infra-red (NDIR) technology with a dual band calibration. Figure 2 represents the CO_2 level measured by two sensors located side by side. Only raw data are reported thus.

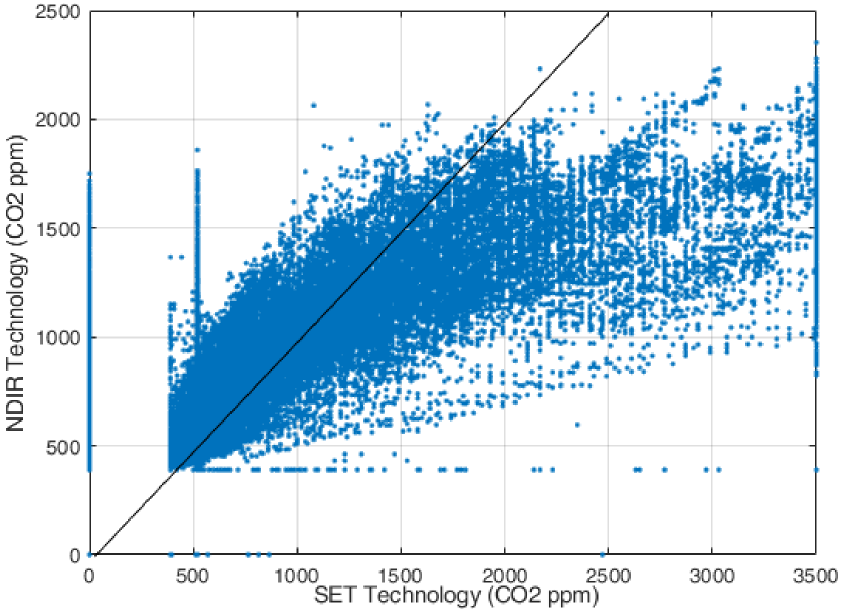

Figure 2: correlation between SE and NDIR technologies

SE technology gives CO_2 values mainly either equivalent or higher than NDIR values. Thus, using SE technology seems to be a conservative approach as long as global analyses are made Besides, in the following, the same sensor is used for all the different considered configurations.

3 RESULTS

In this section, IAQ results will be presented in matter of CO_2 concentration in the master bedroom, absolute humidity in the shower room and PM 2.5 concentrations indoor and outdoor.

3.1 Influence of the ventilation system on the CO2 level

CO_2 concentrations are studied for two specific periods: with the VMI turned off (from 2017.12.25 to 2018.01.18) and with the VMI turned on (from 2018.12.11 to 2019.01.11).

During these periods, two adult persons sleep in the master bedroom every night, except during days 19 and 20 (10th and 11th of December 2017), in the “VMI turned off” case.

Raw data are first presented. Two criteria are then computed, used in several studies in the IAQ field. Their description is given below.

Figure 3 presents raw data through heat map graphs for the two periods mentioned above. It represents the measured concentration in ppm for each day (x axis) and along each day from midnight to noon (y axis). It enables to identify the repeatability of the occupant daily behavior.

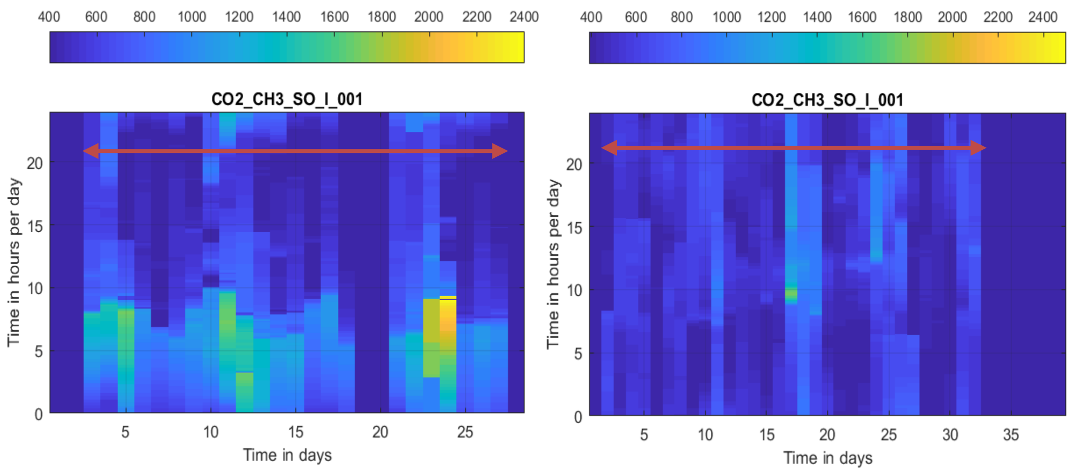

Figure 3: CO2 heat maps VMI turned off (left) and VMI turned on (right)

One of the criteria mentioned above is the ICONE index. It is an air stufinness index proposed by (Ribéron, et al., 2016). Even if initialy defined for schools it can be also used for dwellings analysis (Ribéron, et al., 2016). It follows relation (1).

$$\mathrm{ICONE} = \frac{2.5}{\log(2)} \log(1 + f_1 + 3\, f_2) \qquad (1)$$

f_1 : time fraction during which $1000\ \mathrm{ppm} \leq CO_2\mathrm{concentration} \leq 1700\ \mathrm{ppm}$
f_2 : time fraction during which $CO_2\mathrm{concentration} > 1700\ \mathrm{ppm}$

ICONE is between 0 and 5. 0 means an excellent air change rate whereas 5 reflects a poor one. ICONE is calculated for the same two periods used for the heat map graphs, only between 1am and 5am, in order to be compared to other studies in the IAQ field.

The results are compared to ICONE values obtained in the study conducted by (Derbez, et al., 2017) in nine energy-efficient SFH equipped with turned on MEV or MBV, during one week of heating period, between 1am and 5am.

Table 3 shows the index for this experiment extracted from the same time lags and the values reported in (Derbez, et al., 2017):

Table 3: ICONE - present study and literature

ICONE	VMI OFF	VMI ON	Derbez et al.
0	43%	100%	38%
1	20%	0%	38%
2	27%	0%	12%
3	7%	0%	0%
4	3%	0%	0%
5	0%	0%	12%

For this specific experiment and during the considered period, the ICONE index never goes above zero when the VMI is turned on. It confirms that VMI provides, in the present study, an staisfying ACR.

In order to complete the comparison between the present study and (Derbez, et al., 2017), a third criterion is used, consisting in some statistical values, presented in Table 4. The considered periods are the same as for the first two criteria.

Table 4: Temporal distribution of CO2 concentrations in the master bedroom - present site and literature

Values	**Villa E-Roise**		**Derbez et al.**
	VMI ON	**VMI OFF**	
Mean	521	1005	1041
25th percentile	414	829	857
Median	508	958	1071
75th percentile	605	1189	1071
Maximum	895	1909	Not documented

These are statistics over nine dwellings while being compared to only one experiment in the present study. Nevertheless, the “VMI on” values are half those obtained in the (Derbez, et al., 2017) study and the « VMI off » case.

The three criteria converge to the same conclusion: for this experiment, VMI is very effective in terms of air renewal in the master bedroom at night.

3.2 Humidity level in the main bathroom

This study underlines that VMI, like MBV, is an effective solution to avoid stuffiness in the master bedroom, due to the mechanical supply directly in the room when the CO_2 source is located. On the opposite, in wet rooms, MEV is supposed to be more efficient than VMI or any MSV. For the present site and several other experimental houses’ bathrooms, absolute humidity values are compared, based on a relative humidity and temperature measurements. The Rankine formula is used to compute absolute humidity values, defined by relation (2).

$$\phi = \frac{P_o Y_{H_2O} \frac{M_{air}}{M_{H_2O}}}{P_o \exp(13.7 - \frac{5120}{T})} \quad (2)$$

Φ: relative humidity,
T: temperature,
P_o: atmospheric pressure,
Y_{H_2O}: the absolute humidity
M_{air}, M_{H_2O}: respectively air and water molar masses.

Figure 4 represents the absolute humidity temporal distribution of the bathrooms’ sites mentioned above.

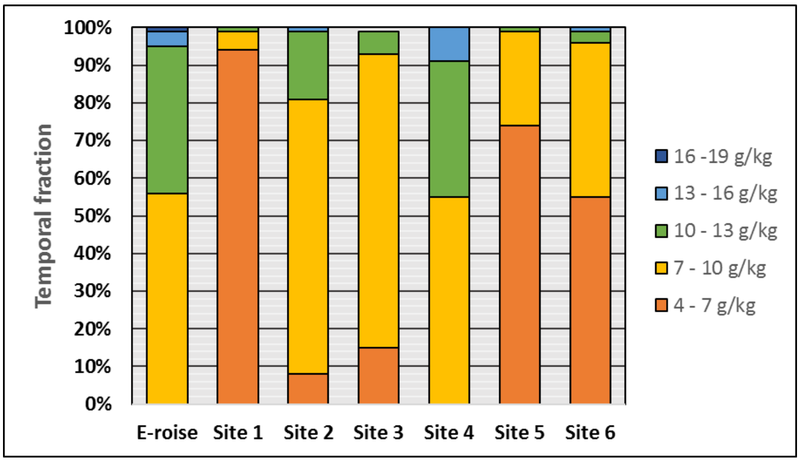

Figure 4: Temporal distribution of absolute humidity in several COMEPOS’ bathrooms

It shows that the global absolute humidity is slightly higher in the present site shower room than in the other sites’ bathrooms, except for the site 4. Indeed, VMI does not extract humidity in wet rooms as quickly as MEV can do. Nevertheless, this graph underscores for instance the ability of the VMI to keep absolute humidity under 13 g/kg 95 % of the time.

Using relation (2) again, it is possible to estimate the corresponding relative humidity at a chosen temperature in order to normalize all the absolute humidity to comparable relative humidity values. For a hypothetical 21 °C temperature in the bathroom, relative humidity would be between 40 % and 60 % one third of the time, between 30 % and 70 % three quarters of the time, lower than 75% 90 % of the time.

Another phenomenon is highlighted in the present site's shower room: the absence of ventilation seems to have an impact on the occupants' behavior, regarding the number of window openings. It is summed up in Table 5:

Table 5: Impact of the presence of the VMI on the occupants' behaviour in the shower room

VMI	Period	Showers	Window openings	Window opening percentage
OFF	2017.12.25 - 2018.01.18	29	6	21%
ON	2018.12.11 - 2019.01.11	43	2	5%

The occupants are not informed that the VMI is turned off, so that their behaviours remain not influenced. Table 5 shows a direct impact of the ventilation system on the number of window openings.

3.3 Particulate matter (PM 2.5)

The outdoor and indoor PM 2.5 concentrations have been studied with the VMI on, with and without filter.

Measurements are realized for four months, with and without filter, thanks to identical sensors positioned outdoor next to the main air inlet and indoor in the living room. The occupants are were not living in the dwelling yet but the punctual presence happens for visiting purposes. The temporal distribution of the PM 2.5 concentrations is a consistent indicator to quantify the impact of the filter removal on PM 2.5 concentrations. It is represented in Figure 5.

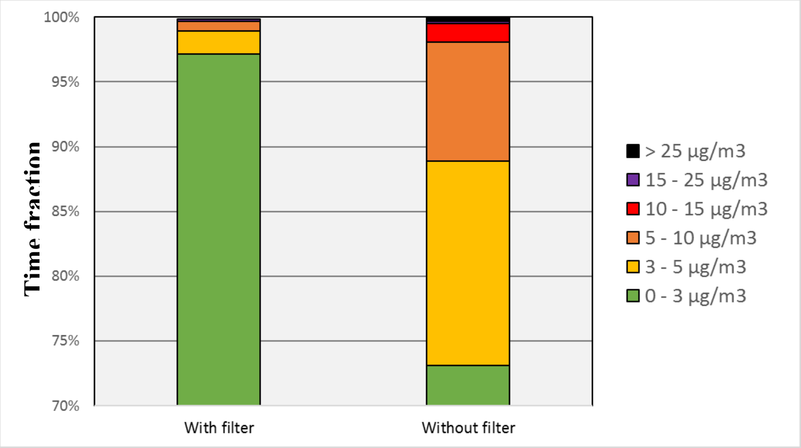

Figure 5: Temporal distribution of indoor PM 2.5 concentration with and without filter

Figure 5 highlights that in both cases, World Health Organization (WHO) thresholds, reported in Table 6, are respected.

Table 6: WHO PM2.5 thresholds

Exposition	Thresholds
Long term	10 µg/m^3
Short term	25 µg/m^3

That is why other thresholds must be considered, based on several references such as:

- "Health damages are observed for low concentrations (…) from 3 to 5 µg/m^3" (AFSSET, 2004),
- "Any reduction of the (…) PM 2.5 concentration leads to a positive health impact" (ANSES, 2017).

Figure 5 underlines that:

- The filtration leads to concentrations lower than 3 µg/m^3 97 % of the time, which means less than 2 days of potential exposure at concentrations higher than 3 µg/m^3,
- The absence of filtration leads to concentrations lower than 3 µg/m^3 73 % of the time, which means 18 days of potential exposure at concentrations higher than 3 µg/m^3.

When dealing with particles concentrations, it is necessary to consider the outdoor level variations, that might be impactful, especially when the filter is absent. Therefore, relation (3) is used to plot Figure 6.

$$I/O = \frac{\text{PM 2.5 indoor concentration}}{\text{PM 2.5 outdoor concentration}} \qquad (3)$$

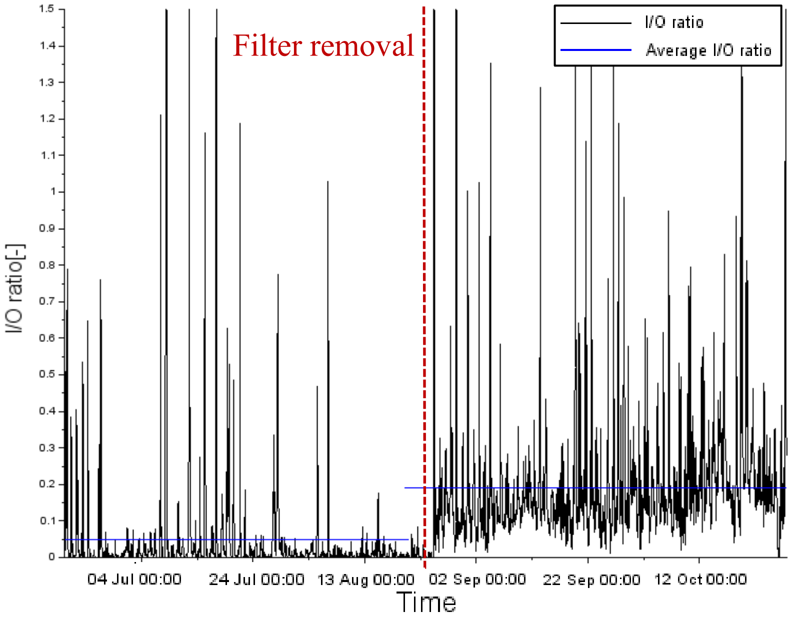

Figure 6: I/O ratio plotted against time

The several peaks observed are likely due to windows and door openings, happening during the house visits. Globally the filtration leads to I/O values four times lower than those obtained without filtration.

3.4 VMI system contribution to thermal comfort

The VMI water to air heat exchanger described above is supplied with 35 to 45 °C water. Figure 7 shows the outdoor and supplied air temperatures during the heating season.

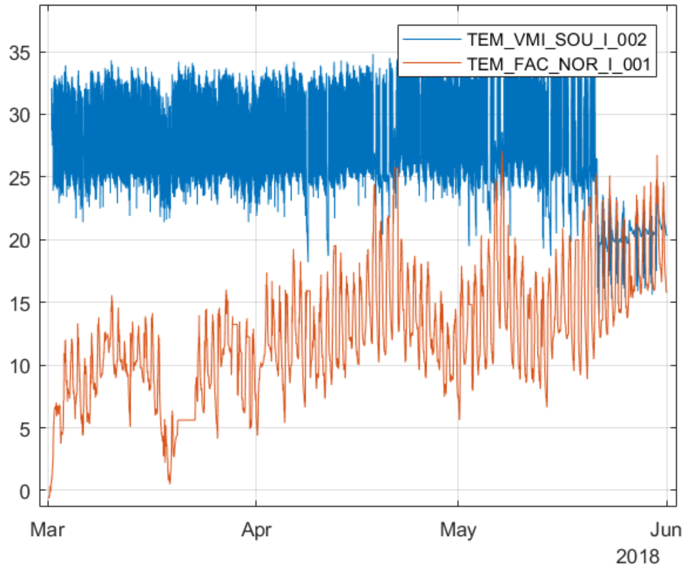

Figure 7: Outdoor and supplied air temperatures during the heating season

The heat exchanger has a significant impact on the gap between outdoor and supplied air temperatures: between 10 °C and 25 °C, participating effectively in the occupants' comfort, regarding their positive feedbacks. From the end of May, the heating is turned off, but the cooling is not activated yet: the VMI heat exchanger is supplied with 20 °C-water (ground temperature). It explains why the supplied air is slightly precooled during the day and slightly preheated at night.

By preheating the supplied air temperature, the VMI contributes to the house heating needs. Figure 8 describes the temporal evolution of thermal power supplied by the ceiling and the VMI.

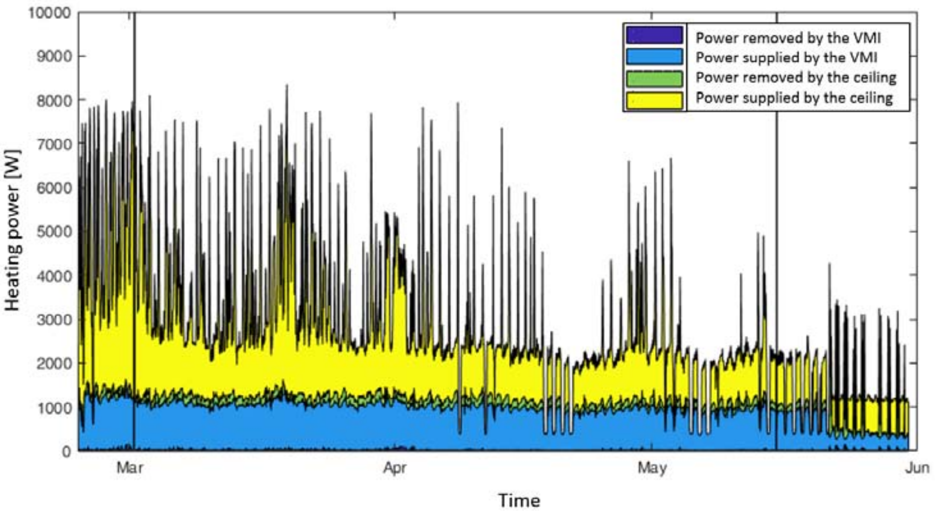

Figure 8: Power supplied by the radiative ceiling and the VMI with its heat exchanger

Thanks to its heat exchanger, the VMI delivers continuously between 1000 and 1500 W. Thus, the VMI covers between 25 % and 40 % of the house's total needs during the heating season, becoming thus a hybrid solution between ventilation and power emitter. The same study is realized during the cooling season. From the end of May, due to the heating switch off, the VMI heating is reduced but is not worth zero: the air keeps being preheated at night. The "passive" cooling mentioned above is not significant enough to be visible on Figure 8.

4 CONCLUSION

A demand-controlled mechanical supply ventilation system called VMI and its water to air heat exchanger are installed in a largely monitored experimental house. The purpose is to determine the system performances in terms of IAQ and power distribution for thermal comfort. IAQ results are reduced to indoor CO_2, absolute humidity and PM 2.5 concentrations analysis. Thermal comfort is reduced to supply air temperature analysis.

The present study highlights the VMI ability to reduce significantly the master room stuffiness: CO_2 concentrations statistical values are worth half the values obtained when the VMI is off or the values obtained in the dwellings studied by (Derbez, et al., 2017).

Moreover, during the same month of winter, it is underlined that VMI allows to keep humidity between 30 and 70 % three quarters of the time in the shower room, despite the natural extraction. The slight overpressure generates enough air renewal in the shower room.

Regarding the fine particles, it is brought to light that the VMI filtration maintains a PM 2.5 concentration below 3 $\mu g/m^3$ 97 % of the time, whereas this threshold is exceeded one quarter of the time when the filter is removed. Furthermore, the I/O ratio is four times higher when the filter is absent.

The study emphasizes the VMI ability to raise the supplied air temperature up to 25 °C compared to the outdoor during winter. As a direct consequence, the VMI participates in the house's heating, covering thus in average one third of the house's total needs.

Therefore, it seems legitimate to consider the VMI as a credible alternative to more traditional systems.

Based on the results presented in this study, industrial partnerships have been created with heat pumps and emitters manufacturers. The purpose is to develop specific regulations optimizing heating and cooling capacities of the VMI. Lastly, the VMI flow rate regulation can be discussed. Prototypes are being developed, involving one or several other sensors in order to comply even more with either, IAQ, thermal comfort and energy consumption.

5 REFERENCES

AFSSET. (2004). *AVIS de l'Agence française de sécurité sanitaire de l'environnement et du travail relatif à la proposition de valeurs guides de l'air intérieur pour les particules Auto-Saisine Afsset*.

ANSES. (23th of may 2017). *ANSES recommends pursuing efforts to improve ambient air quality*. https://www.anses.fr/fr/content/l%E2%80%99anses-recommande-de-poursuivre-les-efforts-pour-am%C3%A9liorer-la-qualit%C3%A9-de-lair-ambiant

Derbez, M., Wyart, G., Le Ponner, E., Ramalho, O., Ribéron, J., & Mandin, C. (2017). Indoor air quality in energy-efficient dwellings: Levels and sources of pollutants. *Wiley*.

Ouvrier-Bonnaz, O., Rahmeh, M., Stephan, L., & Potard, M. (2015). Whole-house air distribution with a supply-only ventilation system VMI® for an optimum air change. *CLIMAMED 2015 Congress Sustainable Energy Performance of Buildings*. Juan Les Pins.

Rahmeh, M. (2014). *Etude expérimentale et numérique des performances de la ventilation mécanique par insufflation : qualité de l'air intérieur dans les bâtiments résidentiels*. La Rochelle: Université de la Rochelle.

Ribéron, J., Ramalho, O., Derbez, M., Berthineau, J., Wyart, G., Kirchner, S., & Mandin, C. (2016). Indice de confinement de l'air intérieur : des écoles aux logements. Air stuffiness index: from schools to dwellings. *Pollution atmosphérique*.