The indoor environmental quality and energy savings potential of room ventilation units compared to exhaust-only ventilation systems in France

Vasileios Filis*[1,5], Kevin Michael Smith[2], Jakub Kolarik[2], Frédéric Kuznik[3,5] and Lucie Merlier[4,5]

1 Université de Lyon, CNRS, CETHIL UMR5008
F-69621, Villeurbanne, France
**Corresponding author: vasileios.filis@insa-lyon.fr*

2 Department of Civil Engineering,
Technical University of Denmark
Brovej, Building 118, DK-2800
Kgs. Lyngby, Denmark

3 Université de Lyon, INSA Lyon, CETHIL
UMR5008, F-69621, Villeurbanne, France

4 Université de Lyon, Université Lyon 1, CETHIL
UMR5008, F-69622, Villeurbanne, France

5 BHEE, CETHIL-EDF joint laboratory

ABSTRACT

Humidity-controlled mechanical exhaust ventilation (RH-MEV) has been widely used in France for over 35 years, demonstrating high durability and robustness. This exhaust-only ventilation strategy is widely used as an energy-saving measure, replacing constant mechanical exhaust ventilation (Constant-MEV) systems in residential buildings. It demonstrates energy savings due to the restricted airflows, but as a downside, the building's indoor air quality (IAQ) often deteriorates. Moreover, it is impossible to recover heat with exhaust-only ventilation systems, which means that energy consumption for space heating is still quite significant and cold supply air temperatures are frequently introduced to the heated spaces. Room ventilation units (RVUs) with heat recovery represent an alternative ventilation solution allowing simple installation through the façade and providing fresh outdoor air and exhaust ventilation to each room. This study investigates these units' energy saving potential and indoor environmental quality performance as an alternative solution to centralized exhaust-only ventilation systems. The dynamic simulations are performed for a reference residential building under various French climatic conditions for a heating season. The three ventilation strategies investigated are Constant-MEV, RH-MEV and room-based ventilation with RVUs. The results demonstrate 61-85% savings in space heating demand with the RVUs, compared to Constant-MEV under all climatic conditions. Compared to RH-MEV, the RVUs saved 44-75% energy for space heating while the CO2 concentration and relative humidity levels were decreased due to RVUs' constant air exchange rate. In all cases, RVUs provided considerably higher supply air temperatures due to the implemented heat recovery which can potentially improve indoor thermal comfort.

KEYWORDS

Room-based ventilation, room ventilation units, exhaust-only ventilation, humidity-controlled ventilation

1 INTRODUCTION

Humidity-controlled mechanical exhaust ventilation (RH-MEV) systems have been widely used in France for 35 years and are considered as a reference system in low-energy residential buildings, demonstrating high durability and robustness (Guyot, 2019). This type of demand control ventilation strategy is slowly replacing constant mechanical exhaust ventilation (Constant-MEV) systems in France over the past years (Guyot, 2018). With RH-MEV systems the energy needed to heat the ventilation air is reduced due to the restricted supply airflows. When compared to Constant-MEV, the total energy savings have been estimated about 30% to 50% (Savin & Bernard, 2009). However, the reduced energy consumption is accompanied by deterioration of air quality in the building (Sowa & Mijakowski, 2020). Another downside of both these types of exhaust-only ventilation strategies is that they do not recover heat from the exhaust air to preheat the supplied air, which means that energy consumption for space heating is still quite significant. Additionally, in situations where there is a central fan malfunction, the occupants are often unaware of the poor ventilation in their dwelling and do not compensate for instance by window opening (Savin & Bernard, 2009). A different issue that typically affect the indoor air quality (IAQ) performance in dwellings with a single exhaust-only ventilation fan, is the non-uniformly distributed air leakage through internal partitions and through the various supply air inlets on the building envelope, demonstrated by (Guyot et al., 2016). For example, if a room shows substantial air leakage due to infiltration through the building envelope and open internal doors, the airflow will be short-circuited between that room and the exhaust rooms, like kitchen and bathrooms, leaving the other rooms of the house under-ventilated (Carrie et al., 2006), (Du et al., 2012). Room-based ventilation units with heat recovery (RVUs) represent an alternative ventilation solution with the potential to tackle such issues mentioned above. Due to their compact size, they can be integrated into the façade wall in each room. Since no further ductwork is needed, they are ideal for renovation purposes in existing buildings where there is no available infrastructure to install a central ventilation system. These units are designed to perform optimally under balanced pressure conditions between indoors and outdoors. However, several studies have shown that in areas with high wind velocities, or in multi-storey buildings with high underpressure conditions due to stack effect, the performance of the units can be negatively affected (Mikola et al., 2019), (Filis et al., 2021). There are several types of RVUs found in the market with different configurations based on the design, type of heat exchanger and the type and number of fans they are equipped with (Smith & Svendsen, 2016), (Carbonare et al., 2020), (Bonato et al., 2020). This study considers RVUs that are equipped with a flat-plate or a rotary heat exchanger, as well as a supply and an exhaust centrifugal fan. Both fans operate with balanced supply and exhaust ventilation airflows, providing a constant air exchange rate to each room individually. The aim is to investigate the energy savings and IAQ performance potential of these units in single family houses under various climatic conditions, and how their performance is compared with the exhaust-only ventilation systems typically used in France.

2 METHODOLOGY

2.1 The software

The simulation software used was IDA indoor Climate and Energy (IDA-ICE 4.8 SP2) by EQUA. It is a whole-year dynamic multi-zone simulation software, allowing the modelling of HVAC systems, internal loads and indoor climate and provides simultaneous dynamic simulation of heat transfer and air flows. It implements detailed one-dimensional coupled heat and mass transfer models in the envelope, and includes the main elements of moisture balance, like vapor sources (occupants, equipment, etc.), airborne transport (air handling units, leaks, inter-zone flow) and sorption by materials in contact with the indoor air (Woloszyn et al., 2009).

2.2 Description of the building model

The simulations assumed a typical residential building that characterizes a newly constructed French single-family house for 4 people (CSTB), complying with the French Thermal Regulation 2012 (RT 2012). It represents realistic building characteristics and construction practices in France. It includes a living room, a kitchen, two child-bedrooms, one master bedroom and a bathroom with WC. The floor plan is presented in Figure 1 and the total U-values of the construction are summarized in Table 1. The heat gains from the equipment and lighting are presented in Table 2. The model assumes no additional heat losses from thermal bridges.

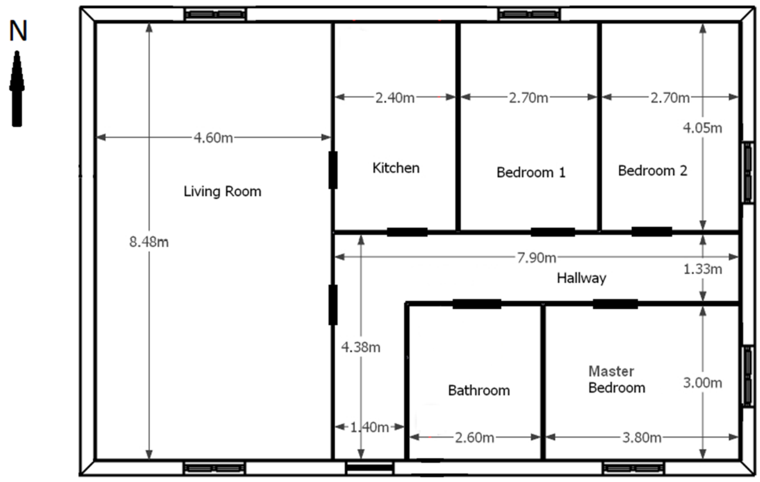

Figure 1. Floorplan of the simulated single-family house with interior dimensions.

Table 1: Construction – Total U-values (W/m^{2}K)

Construction	External walls	Ceiling	Pitched roof	Ground floor	Windows [*]	Front door
Total U-value	0.22	0.21	3.49	0.22	2.18	0.83

[*] with 30% frame fraction

Table 2: Heat gains from equipment and lighting

Equipment	Power [W]	Period	Lighting	Power [W/m²]	h/day
Refrigerator	20	Always	Corridor	6	1
Freezer	25	Always	WC	6	1
Television	130 (4 sleep mode)	4h/day	Living room	15	4
DVD player	130 (4 sleep mode)	1h/day	Kitchen	15	2
PC + printer	250	1h/day	Rooms	15	1.5
Cooking	2000	1h/day	Bathroom	6	2

Occupancy schedules and moisture production values for occupancy activities are based on the French design recommendations (CCFAT, 2017) presented in Figure 2 and Table 3. There are always 4 occupants at the house at any given time, except 09:00-17:00 on weekdays when the house is empty. The average activity level of each occupant was set at 1.0 MET, corresponding to a seated adult person at rest with heat emissions at 105W including both sensible and latent heat. IDA-ICE calculates the CO2 emissions from an occupant with activity level 1.0 MET, at 8.5 mg/s and the moisture production at 40-45 gr/h.

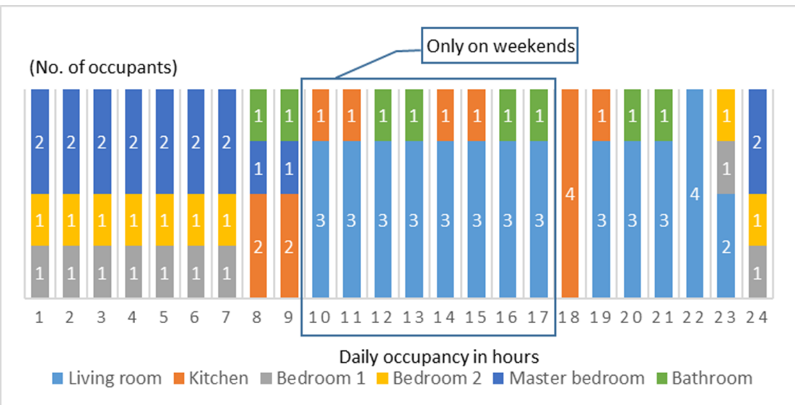

Figure 2. Occupancy schedule showing the number of occupants in each room. Based on French design recommendations (CCFAT, 2017). There are no occupants in the house on weekdays 09:00-17:00.

Table 3: Moisture production

Room	Source	Moisture production	Duration
Kitchen	Breakfast	50 gr/person	0.5 hours (06:00-06:30)
	Lunch	150 gr/person	1 hour - weekends (13:00-14:00)
	Dinner	300 gr/person	1 hour (17:00-18:00)
Bathroom	Shower	300 gr/shower/person	0.5 hours/shower (7-7:30) (8-8:30) (19-19:30) (20-20:30)
	Laundry	200 gr/laundry	2 hours (08:00-10:00) (Monday/Wednesday/Saturday/Sunday)
	Drying	1000 gr/drying	20 hours starting directly after laundry

The heating set-point temperature is 20°C. There is also a set-back temperature at 18°C every night (00:00-05:00) and weekdays (09:00-17:00). The heating is provided by ideal heating devices, able to meet the required indoor temperature set point under all weather conditions. The simulations assumed airtightness of 0.5 ACH at 50Pa. The infiltration flow is wind dependent, with zone distribution proportional to the external surface area.

The simulations were performed under the French climatic conditions which according to (ASHRAE Standard 169, 2013) are categorized as either 5A (cold humid), 4A (mixed humid) or 3A (warm humid). The three locations chosen to represent these specific climatic conditions were Metz (cold humid), Lyon (mixed humid) and Marseille (warm humid) shown in (Figure 3). The weather files used, are the ASHRAE IWEC 2 which are derived from Integrated Surface Hourly (ISH) weather data originally archived at the National Climatic Data Centre. The simulations were performed for the winter season from October 15th 00:00 AM to April 14th 12:00 PM. The initialization period was two weeks before the starting date of the simulations.

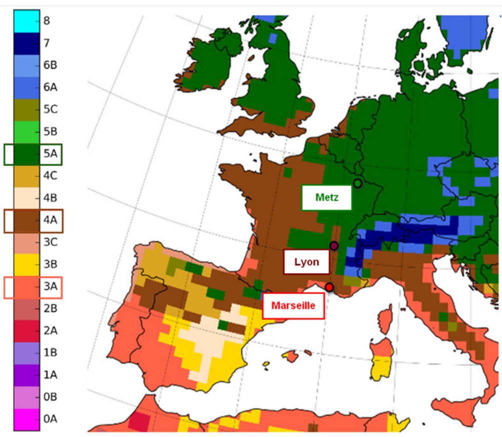

Figure 3. Climate zones according to ANSI/ASHRAE Standard 169. The 5A corresponds to cold and humid climates, 4A to mixed and humid, and 3A to warm and humid.

2.3 Ventilation strategies

2.3.1 Exhaust-only ventilation strategies

The investigated exhaust-only ventilation strategies are the constant mechanical exhaust ventilation (Constant-MEV) and the humidity-controlled mechanical exhaust ventilation (RH-MEV). The chosen design ventilation rates are presented in Figure 4. Both these strategies include extraction grilles in the service rooms (wet rooms) and air inlets in all the main rooms (dry rooms), according to the French airing regulations (Arrêté, 1982). Based on the regulations, and for a house with 4 main rooms, the airflow extracted in the kitchen was set to 33.3 L/s (120 m3/h) and 16.7 L/s (60 m3/h) in the bathroom which includes shower, WC and laundry

equipment. Therefore, the total exhaust ventilation rate from the service rooms (kitchen and bathroom) is 50 L/s (180m3/h) and the specific fan power of the exhaust fan is assumed at 0.75 kW/(m3/s). The combined exhaust airflow from kitchen and bathroom creates an underpressure in the house which requires the total airflow to be supplied by the main rooms. Each main room is equipped with pressure-controlled air inlets, placed on the façade, that allow outdoor fresh air to enter the rooms depending on the pressure difference conditions between indoors and outdoors. This type of air inlet ensures that the requested supply airflow will be provided. In this model, one pressure-controlled trickle vent was placed in each bedroom and two in the living room, with an operating rate of 8.3 L/s (30 m^3/h) at 10 Pa pressure difference. The power law coefficient is 3.23x10^{-3} kg/(sPa^n) where n is the power law exponent at 0.5 (dimless). For the simulations, all internal doors are considered always closed. In IDA-ICE, air can circulate among rooms when the doors are closed through a door leakage area following the orifice equation (Prignon & van Moeseke, 2017). The leakage area was set to 0.01 m^2 allowing an airflow of 25.8 L/s (93 m^3/h) at 4 Pa pressure difference, discharge coefficient of 1, and air density at 1.2 kg/m^3. In the case of the Constant-MEV ventilation strategy the exhaust ventilation airflows in the kitchen and bathroom were kept constant all the time (Figure 4, left). However, in the case of the RH-MEV strategy, the humidity sensitive exhaust units in the kitchen and bathroom adapt the exhaust airflows based on indoor relative humidity levels. The unit aperture is controlled by a humidity sensor, so that when the indoor air is dry enough, the opening area and ventilation rate is at minimum. When the humidity load is increased due to activities like cooking and showering, or for prolonged occupation, the opening area gets wider, and the ventilation rate is increased. For a house with 4 main rooms, and to satisfy the regulations, the minimum total exhaust ventilation rate was limited to 25 L/s (90 m3/h), where a minimum of 12.5 L/s (45 m3/h) must be extracted from the kitchen at all times. The rest is extracted from the bathroom (Figure 4, right). The operation of the humidity controlled exhaust units that regulate the airflows in the kitchen and bathroom, is displayed in
Figure 5.

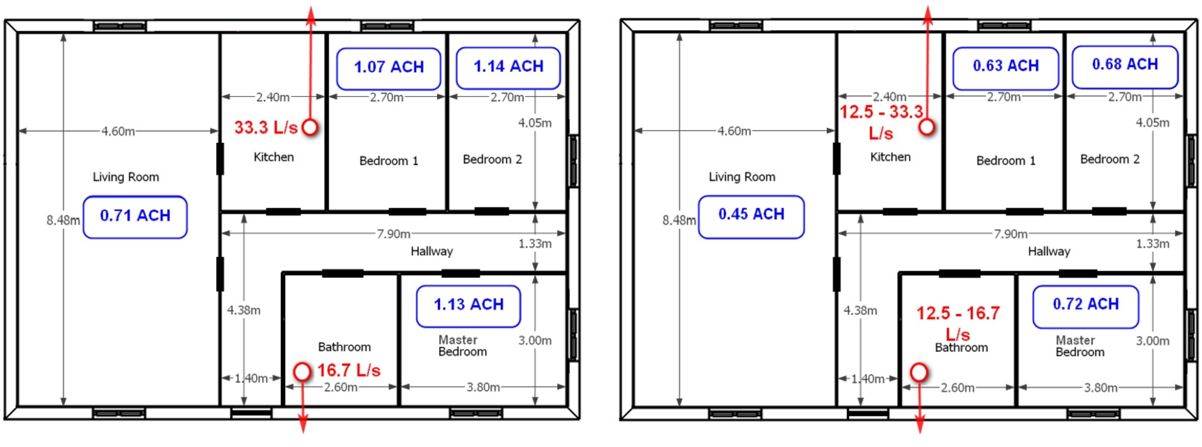

Figure 4. Exhaust ventilation rates for the Constant-MEV strategy (left) and RH-MEV strategy (right), and the resulting mean air changes per hour (ACH) in the main rooms for each strategy.

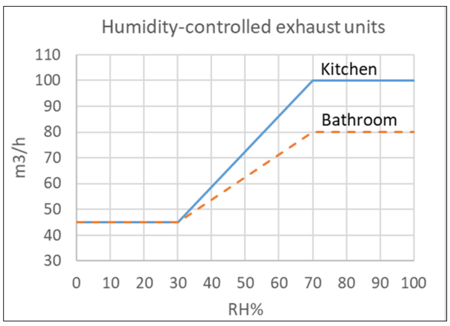

Figure 5. Relative humidity curves for the exhaust units in kitchen and bathroom for the RH-MEV strategy.

The total required ventilation rate in the house is extracted by the central exhaust fan, and equivalent fresh air is supplied by air inlets around the building envelope in the form of infiltration. However, this fan-induced infiltration is delivered to the house unevenly from around the building envelope. Therefore, and as shown in Figure 4, the resulting average ACH in each dry room is different and dependent on the floor plan of the house, the position and size of the room, its external surface area, the type of air inlets and the overall pressure conditions around the building envelope for each moment in time. In the case of RH-MEV in particular, the total exhaust airflow variates from a minimum 25 L/s to 50 L/s, and as result, the total amount of fan-induced infiltration around the building envelop is variable over time. This leads to lower average values of ACH in the dry rooms compared to Constant-MEV as shown in the right drawing in Figure 4.

2.3.2 Room-based ventilation strategy

The room-based ventilation strategy, include one room ventilation unit (RVU) with heat recovery in each room operating at a constant supply and exhaust ventilation rate. Each RVU supplies the room with fresh air from outdoors and extracts the same amount for air keeping a steady ACH. The simulated RVUs are adapted from (Filis et al., 2021) and they can operate at 3 distinct constant airflow rates: 7.5 L/s, 10.9 L/s and 13.9 L/s. The RVUs are assumed to use centrifugal fans operating at balanced supply and exhaust airflows, and their total specific fan power (SFP) values are presented in Table 4. To satisfy the French airing regulations (Arrêté, 1982) the chosen ventilation rate for the RVU in the kitchen is 13.9 L/s (50 m^3/h) and 10.9 L/s (39 m^3/h) for the bathroom. Additionally, the total exhaust ventilation rate in the kitchen during cooking preparation must be also able to reach 33.3 L/s (120 m^3/h). Since 13.9 L/s (50 m^3/h) is extracted by the RVU, the remaining 19.4 L/s (70 m^3/h) is extracted by a kitchen hood during the cooking periods of lunch and dinner. For each child-bedroom (1&2) the ventilation rate for each RVU is chosen constant at 7.5 L/s. For the Master bedroom the chosen ventilation rate is chosen constant at 10.9 L/s. The ventilation rate in the living room is chosen constant at 13.9 L/s. The chosen ventilation rates are presented in Figure 6.

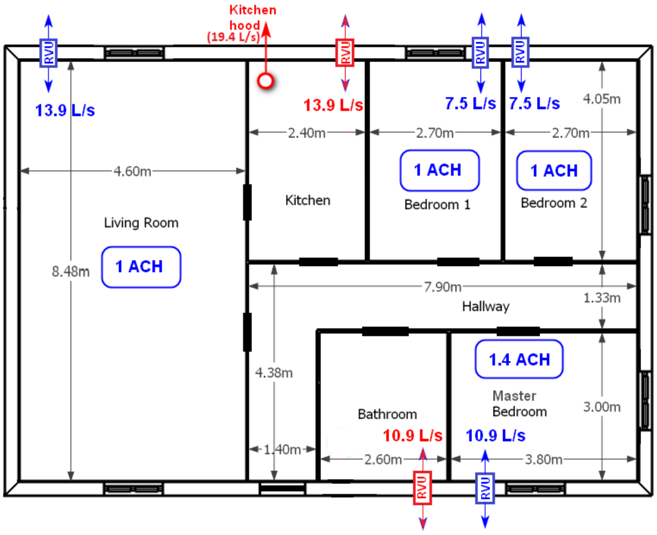

Figure 6. Ventilation rates for the room-based ventilation strategy. RVUs operate under constant airflows all the time, while the kitchen hood operates only during the cooking hours of lunch and dinner.

Table 4. Heat recovery efficiencies and SFP for the simulated RVUs adapted from (Filis et al., 2021)

	7.5 L/s	10.9 L/s	13.9 L/s

Heat recovery efficiency	88.8%	83.4%	78.7%
Total specific fan power (SFP) in J/m^3	422	890	1453

The simulated RVUs in the main (dry) rooms use a regenerative uncoated rotary heat exchanger, which can transfer sensible heat and condensation (latent heat) from one air stream to the other. For the rotary heat exchanger, the efficiency and rotor-speed adjustment calculations in IDA-ICE are based on methods described in (EN 16798-5-1, 2016). In the service (wet) rooms, in order to avoid excessive moisture recovery, the RVUs were simulated with a recuperative heat exchanger that doesn't transfer moisture from the exhaust to the supply side. The modelled heat recovery efficiencies are adapted from (Filis et al., 2021) and the values at each ventilation rate are presented in Table 4. The heating setpoint for the supplied air is 20 ºC. The units do not have a heating coil and the simulations did not include a frost protection control algorithm.

3 RESULTS

3.1 Energy performance

The results presented in Table 5 and Figure 7 show that the investigated room based ventilation strategy with RVUs provides considerable energy savings in heating compared to exhaust-only ventilation strategies due to the implemented heat recovery. The strategy with RVUs operating at constant airflows provided 61-85% savings in heating compared to Constant-MEV and 44-75% savings compared to RH-MEV. During the simulated period, the fan energy consumption for RVUs is higher compared to exhaust only systems with one central exhaust fan. However, in kWh the increase is relatively low compared to the energy savings for space heating. In Figure 7, the bar chart on the right shows the transmission heat losses from the building envelope as well as the ventilation heat losses during the simulated period.

Table 5. Total energy needs for heating and fan energy consumption during the simulation period. (October 15th to April 14th)

Energy for space heating (kWh/m^2)	Constant-MEV	RH-MEV	RVUs
Metz (5A)	47.3	33.2	18.6
Lyon (4A)	38.3	26.0	13.6
Marseille (3A)	18.1	10.6	2.7
Fan energy (kWh/m^2)	1.5	0.7	2.7

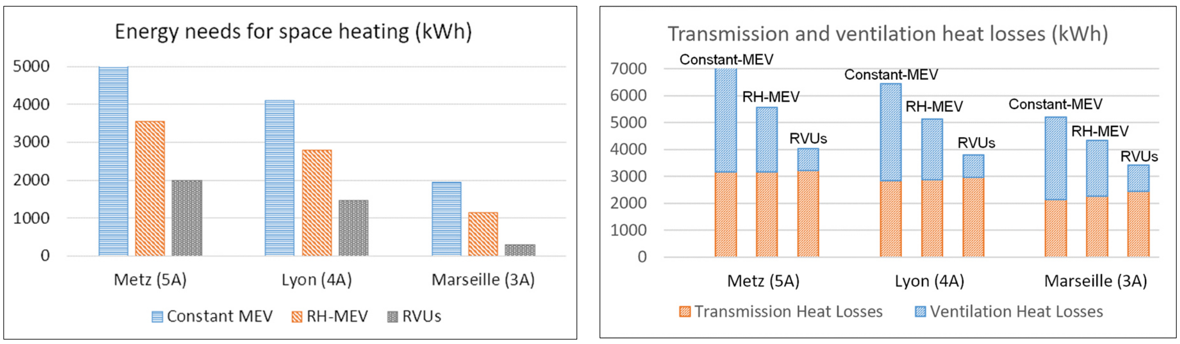

Figure 7. Total energy needs for space heating during the simulation period (October 15th to April 14th) on the left. Transmission heat losses from the building envelope and ventilation heat losses in kWh on the right.

3.2 Supply air temperature

In exhaust-only ventilation strategies the fresh air is entering the building through air inlets placed in each room. However, during winter period the cold outdoor air entering the building can cause thermal discomfort to occupants sitting close to the air inlets. Figure 8 shows that under all investigated climatic conditions, the air temperature of the supplied air through the air inlets for exhaust-only ventilation strategies is below 16ºC for more than 88% of the simulated period. Conversely the supply air temperatures from RVUs are higher than 16ºC for more than 93% of the time due to the incorporated heat recovery.

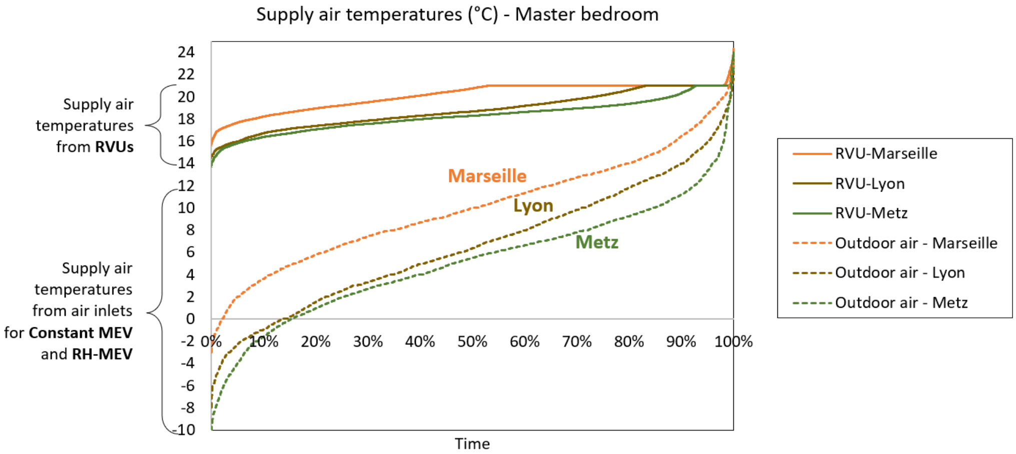

Figure 8. Supply air temperatures from the air inlets for exhaust-only ventilation strategies (Constant-MEV and RH-MEV), compared to supply air temperatures from RVUs with heat recovery.

3.3 Indoor air quality

The IAQ was evaluated based on the resulted CO2 concentration and relative humidity levels in each room. The duration graphs in Figure 9, display CO2 levels for the rooms with highest occupancy. The results show that the chosen ventilation rates for the RVUs keep the CO2 levels below 1200 ppm for 96% in the Kitchen, 75% of the time Master bedroom, and 83% in the Living room. In the Kitchen, the RVU manages to keep the CO2 concentration levels low for longer periods of time even though the RVU provides only 2 ACH (at 13.9 L/s) compared to the 4 ACH by the Constant-MEV (at 27.7 L/s). The reason is that in exhaust-only strategies the air entering the kitchen is supplied by air coming from the rest of the house where the rooms are occupied, and it has already higher CO2 levels. The RH-MEV strategy perform worse in all cases due to the restricted airflows when RH% is low.

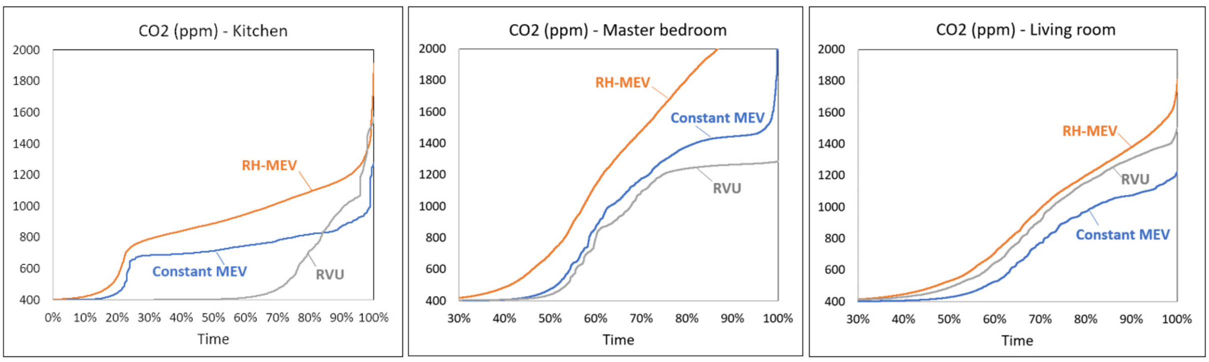

Figure 9. CO2 concentration levels in the rooms with highest occupancy, for the investigated ventilation strategies under Lyon's climatic conditions.

The RH% levels in the service (wet) rooms are quite similar in all strategies with no risks of condensation except in the case of RVUs where the relative humidity in the kitchen is above 75% for 58 hours during the heating season (Figure 10). For the Master bedroom the RH-MEV was above 75% for 32 hours during the simulated periods.

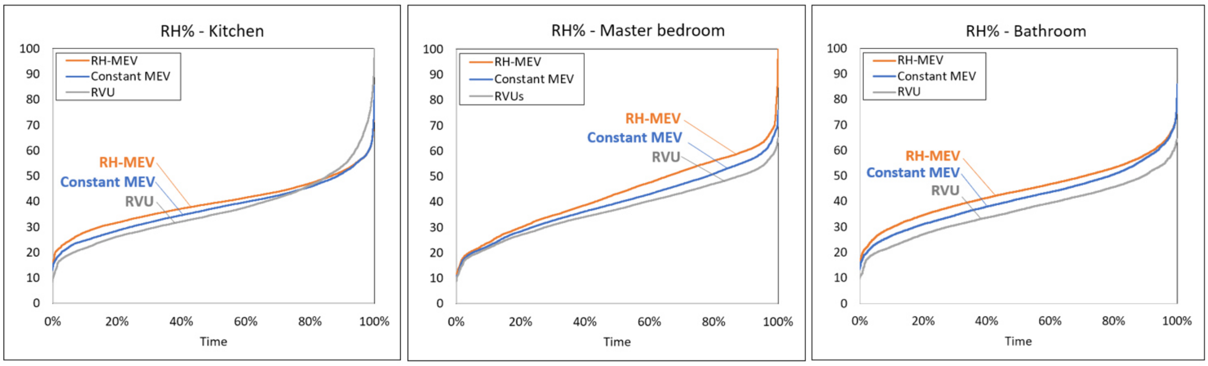

Figure 10. Indoor RH% levels in the service (wet) rooms, under Lyon's climatic conditions.

4 DISCUSSION

In contrast with several other European countries, in France and Belgium exhaust-only ventilation strategies are still a popular ventilation solution (Kolarik et al., 2020). Humidity-based mechanical exhaust ventilation systems attempt to reduce the exhaust airflows, and therefore the ventilation heat losses, compared to constant mechanical exhaust systems. Even though they demonstrate high durability and low maintenance during their lifetime, the lower exhaust airflows result in lower levels of IAQ. Another issue of the exhaust-only ventilation strategies is that the fan-induced infiltration is delivered to the house unevenly from around the building envelope, resulting in a non-uniform distribution of fresh air among the dry rooms. In the case of the room-based ventilation strategy, the ventilation airflow from each RVU is fixed and can be set according to the required design conditions of the room, attempting to provide a constant ACH and improve the IAQ. On the other hand, RVUs need more frequent maintenance and can be negatively affected by high pressure differences across the building envelope. Moreover, fan noise generated by RVUs can potentially create acoustic discomfort based on the proximity to the occupants. Ultimately, the choice of the ventilation system is a balance between overall performance, limitations during installation, ease of use, financial aspects as well as local regulations. In several European countries, central mechanical ventilation with heat recovery (MVHR) is a common ventilation strategy. Compared to MVHR, the main advantage of RVUs could be considered the room-based demand control ventilation, which the central system cannot achieve, but this comparison is not employed here and should be investigated in future research.

5 CONCLUSIONS

This study showed that RVUs with heat recovery and constant airflows can provide considerable energy savings for heating compared to exhaust-only ventilation strategies. The results showed 61-85% reduction in energy needs for heating compared to Constant-MEV and 44-75% savings compared to RH-MEV. Due to the incorporated heat recovery, RVUs provide higher supply air temperatures in the heated spaces which may minimize the risks of thermal discomfort during winter periods with low outdoor air temperatures. Results showed that for the exhaust-only ventilation strategies the supplied air temperature in the heated spaces was below 16ºC for more than 88% of the simulated period, while the temperature of air supplied from RVUs was above 16ºC for more than 93% of the time. The RH-MEV strategy showed 30-

41% savings in heating compared to Constant-MEV; results that are consistent with the literature for humidity-controlled ventilation in France. However, the CO2 concentration levels for RH-MEV were considerably higher due to the restricted airflows when indoor RH% is low.

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