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Vasileios Filis, Kevin Michael Smith, Jakub Kolarik, Frédéric Kuznik, Lucie Merlier. The indoor environmental quality and energy savings potential of room ventilation units compared to exhaust-only ventilation systems in France. *International journal of ventilation*, 2023, pp.1-11. 10.1080/14733315.2023.2198804 . hal-04265584

HAL Id: hal-04265584

<https://hal.science/hal-04265584v1>

Submitted on 31 Oct 2023

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

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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 were performed for a reference residential building under various French climatic conditions for a heating season. The three ventilation strategies investigated were Constant-MEV, RH-MEV and room-based ventilation with RVUs. The results demonstrated 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 indoor air quality (IAQ) (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 IAQ performance in dwellings with a central exhaust-only ventilation fan, is the non-uniform distribution of air 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 has a substantial air leakage due to infiltration through the building envelope, 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. Due to their compact size, they can be integrated into a façade wall in each room. Since no further ductwork is needed, they are suitable for renovation purposes in existing buildings where there is no available infrastructure to install a central mechanical ventilation system with heat recovery. 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). The RVUs are designed to perform optimally under balanced pressure conditions between indoors and outdoors. Their performance can be negatively affected in areas with high wind velocities, or with installation in multi-storey buildings with high underpressure conditions due to stack effect. This has been documented in several studies (Mikola et al., 2019), (Filis et al., 2021). Therefore, their design and application need careful consideration. The aim of this study was to investigate the potential of RVUs with respect to energy savings and IAQ performance in single family houses under various climatic conditions, and how their performance compares to the exhaust-only ventilation systems typically used in France. This study considers RVUs that are equipped with a supply and an exhaust centrifugal fan, as well as either a flat-plate or a rotary heat exchanger. In each unit, both fans operate with balanced supply and exhaust ventilation airflows, providing a constant air exchange rate to each room individually.

2 METHODOLOGY

2.1 The software

The simulation software used was IDA Indoor Climate and Energy (IDA-ICE 4.8 SP2). 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 main elements of moisture balance, like vapor sources (occupants, equipment, etc.) and airborne transport (air handling units, leaks, inter-zonal flow).

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, based on CSTB B.63, and 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 relevant 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/m²K)

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

Table 2: Heat gains from equipment and lighting

Equipment	Power [W]	Period	Lighting	Power [W/m ²]	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 105 W 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.

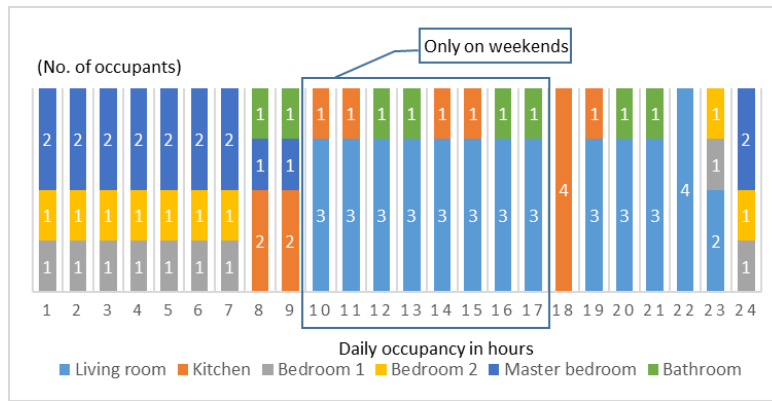


Figure 2. Occupancy schedule showing the number of occupants in each room. Based on French design recommendations (CCFAT, 2017). There are no occupants in the house on weekdays 09:00-17:00.

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 was set to 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 50 Pa. 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.

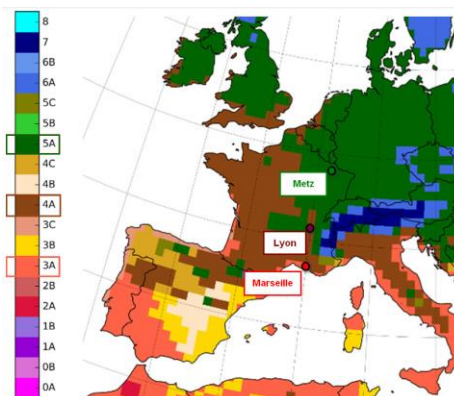


Figure 3. Climate zones according to ANSI/ASHRAE Standard 169. The 5A corresponds to cold and humid climates, 4A to mixed and humid, and 3A to warm and humid.

2.3 Ventilation strategies

2.3.1 Exhaust-only ventilation strategies

The investigated exhaust-only ventilation strategies were the constant mechanical exhaust ventilation (Constant-MEV) and the humidity-controlled mechanical exhaust ventilation (RH-MEV). Both of these strategies included 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, considering a house with 4 main rooms, the maximum airflow extracted in the kitchen was set to 33.3 L/s (120 m³/h). In the bathroom, which includes shower, WC and laundry equipment, the maximum extracted airflow was set to 16.7 L/s (60 m³/h). Therefore, the maximum total exhaust ventilation rate from the service rooms (kitchen and bathroom) was 50 L/s (180m³/h) and the specific fan power of the exhaust fan was 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 (living-room and bedrooms). Each main room is equipped with pressure-controlled air inlets, placed on the façade, that allow outdoor air to enter the rooms ensuring that the requested supply airflow will be provided. In this model, one pressure-controlled trickle vent was simulated in each bedroom and two in the living room, with a nominal airflow of 8.3 L/s (30 m³/h) at 10 Pa pressure difference. The power law coefficient was set to $3.23 \times 10^{-3} \text{ kg}/(\text{sPa}^n)$ where n is the power law exponent at 0.5 (dimless). For the simulations, all internal doors were 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 m² allowing an airflow of 25.8 L/s (93 m³/h) at 4 Pa pressure difference, discharge coefficient of 1, and air density at 1.2 kg/m³.

In the case of the Constant-MEV ventilation strategy the exhaust ventilation airflows in the kitchen and bathroom were kept constant at all times (Figure 4, left). In the case of the RH-MEV strategy, the humidity sensitive exhaust units in the kitchen and bathroom were adapting the exhaust airflows based on the indoor relative humidity levels (Table 3). The damper in the unit was controlled by a humidity sensor, so that when the indoor air is dry enough, the opening area and ventilation rate is at minimum, satisfying the requirements. 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 (Arrêté, 1982), 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) had to be extracted from the kitchen at all times. Consequently, the remaining 12.5 L/s (45 m³/h) was 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.

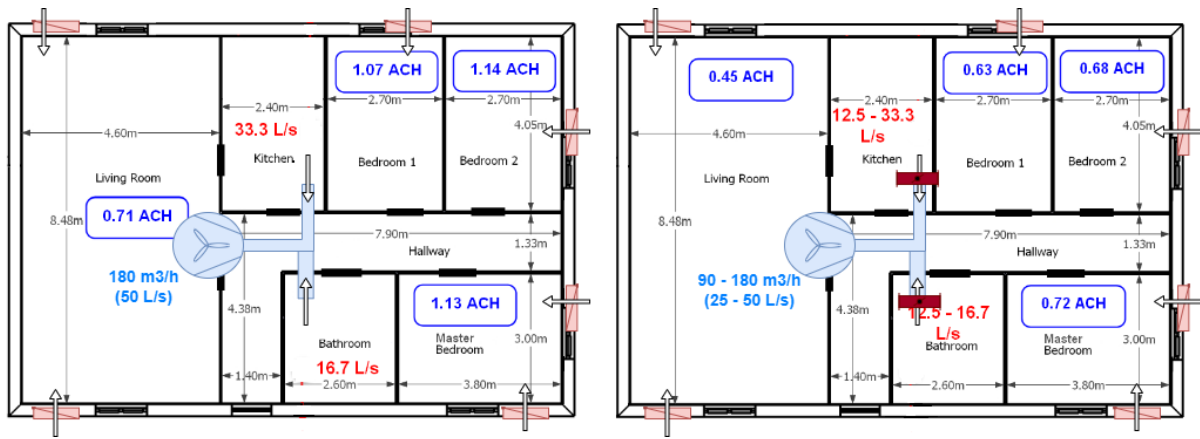


Figure 4. Exhaust ventilation rates for the Constant-MEV strategy (left) and RH-MEV strategy (right), and the resulting mean air changes per hour (ACH) in the main rooms for each strategy. Wind-driven infiltration/exfiltration is not included in these ACH values.

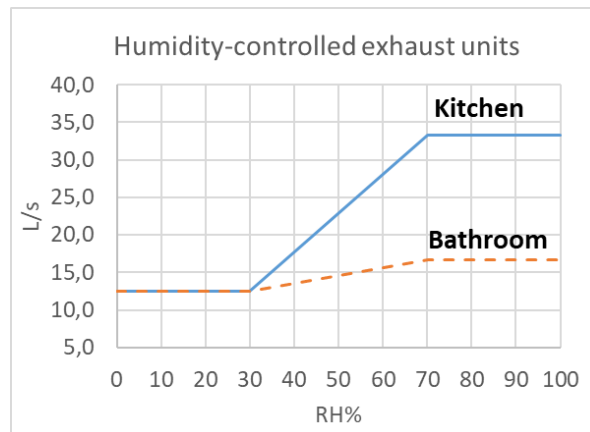


Figure 5. Relative humidity curves for the exhaust units in kitchen and bathroom for the RH-MEV strategy.

2.3.2 Room-based ventilation strategy

The room-based ventilation strategy includes one room ventilation unit (RVU) with heat recovery in each room operating at a constant ventilation rate (both supply and exhaust). The simulated RVUs were adapted from (Filis et al., 2021). They can operate at three distinct constant airflow rates: 7.5 L/s, 10.9 L/s and 13.9 L/s. The RVUs were 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 setting for the RVU in the kitchen was 13.9 L/s (50 m³/h) and 10.9 L/s (39 m³/h) for the bathroom. Additionally, the total exhaust ventilation rate in the kitchen during cooking preparation had to reach 33.3 L/s (120 m³/h). Since 13.9 L/s (50 m³/h) was the maximum ventilation rate than can be extracted by this RVU, the remaining 19.4 L/s (70 m³/h) was extracted by a kitchen hood during the cooking periods of lunch and dinner. For each child-bedroom (1&2) the ventilation setting for each RVU was chosen at 7.5 L/s. For the Master bedroom the chosen ventilation setting was chosen at 10.9 L/s. The ventilation setting in the living room was chosen at 13.9 L/s. The chosen ventilation rates are presented in Figure 6.

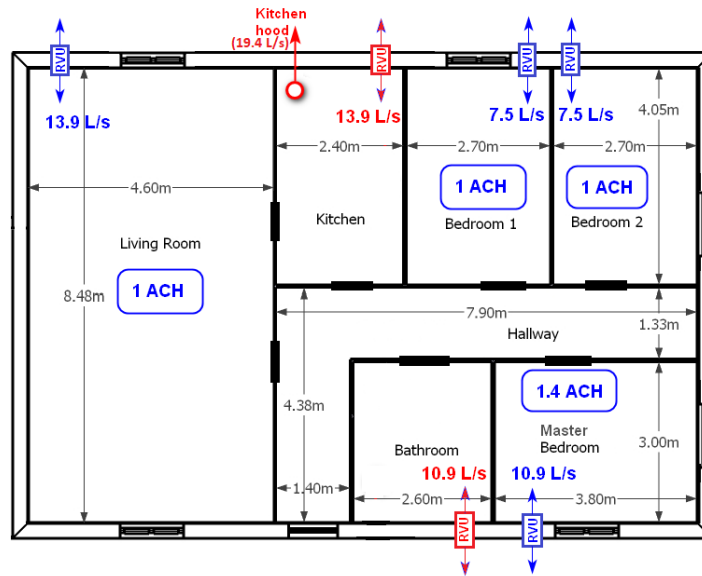


Figure 6. Mechanical ventilation rates for the room-based ventilation strategy in L/s and ACH. RVUs operated under constant airflows all the time, while the kitchen hood operated only during the cooking hours of lunch and dinner.

Table 4. Heat recovery efficiencies and SFP values 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 used a regenerative uncoated rotary heat exchanger, which can transfer sensible heat and condensation (latent heat) from one air stream to the other. For this type of 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 heat recovery in the RVUs for the supplied air was 20 °C. The units did 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 led to considerably lower energy use for heating when compared to exhaust-only ventilation strategies. This is, as expected, 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 was higher compared to exhaust only systems with one central exhaust fan. However, the increase in electricity consumption was 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

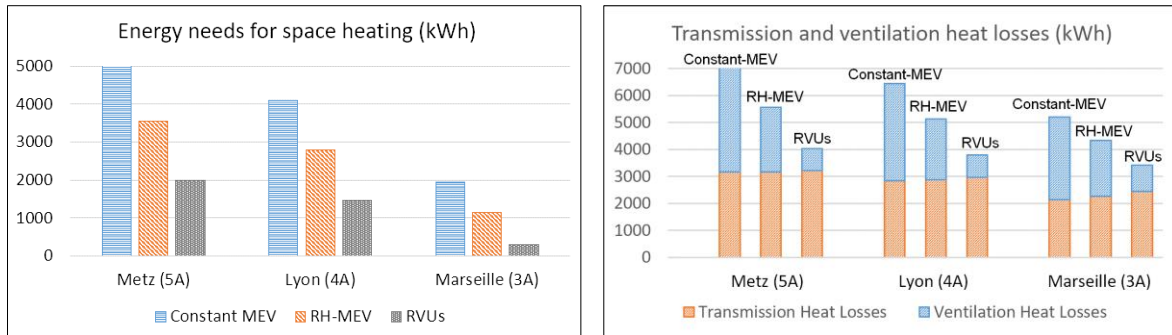


Figure 7. Total energy needs for space heating during the simulation period (October 15th to April 14th) on the left. Transmission heat losses from the building envelope and ventilation heat losses in kWh on the right.

3.2 Supply air temperature

In exhaust-only ventilation strategies the fresh air is entering the building through air inlets placed in each room. During winter, 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 was below 16 °C for more than 88% of the simulated period. Conversely the supply air temperatures from RVUs were higher than 16 °C for more than 93% of the time due to the incorporated heat recovery.

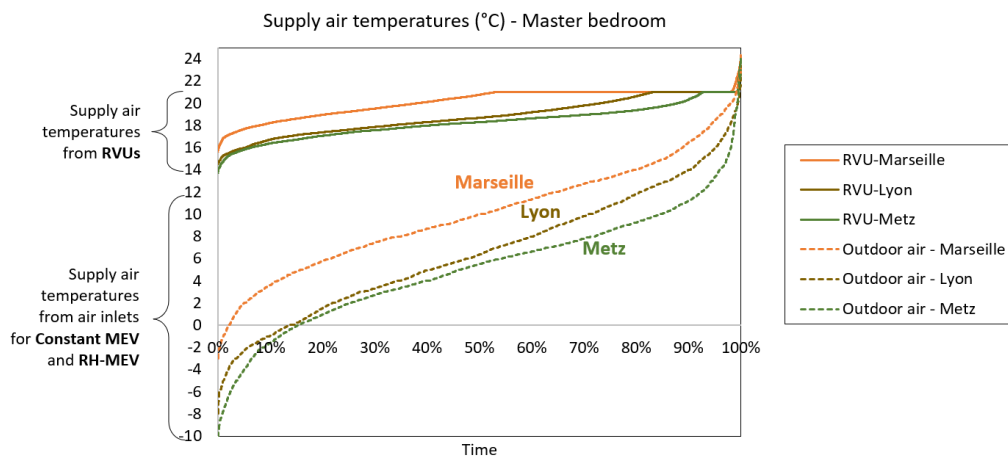


Figure 8. Supply air temperatures from the air inlets for exhaust-only ventilation strategies (Constant-MEV and RH-MEV), compared to supply air temperatures from RVUs with heat recovery.

3.3 Indoor air quality

The IAQ was evaluated based on CO₂ concentration and relative humidity levels in each room. Since the trends on IAQ results were almost identical for the three climatic conditions, the climate of Lyon was chosen as representative in this section. The duration graphs in Figure 9 display CO₂ levels for the kitchen, master bedroom and living room. The results show that the chosen ventilation rates for the RVUs kept 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 managed to keep the CO₂ concentration levels low for longer periods compared to the Constant-MEV. The reason was that in exhaust-only strategies the air entering the kitchen was coming from the other occupied rooms, thus having higher CO₂ concentration. Considering the CO₂ concentration, the RH-MEV strategy performed worst due to the restricted airflows at low indoor relative humidity (RH) levels.

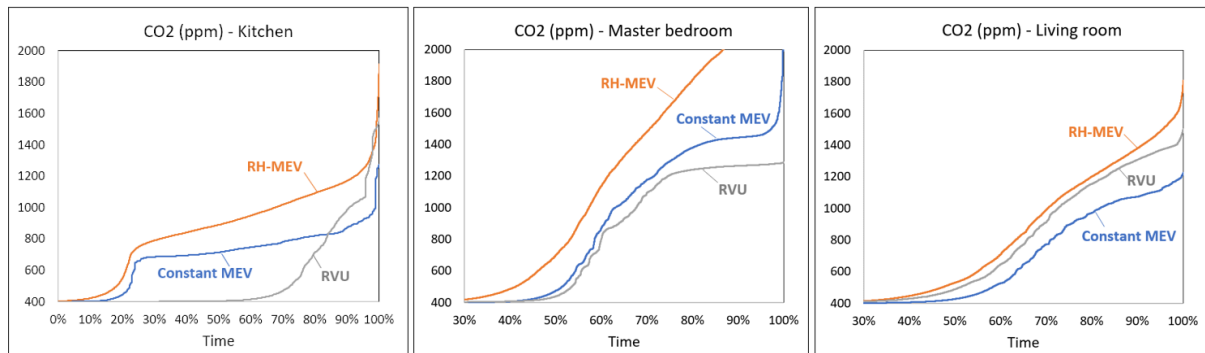


Figure 9. CO₂ concentration levels in the rooms with highest occupancy, for the investigated ventilation strategies under Lyon's climatic conditions.

The RH levels in the service (wet) rooms were quite similar under all strategies investigated, with no risks of condensation except in the case of RVUs where the relative humidity in the kitchen was 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.

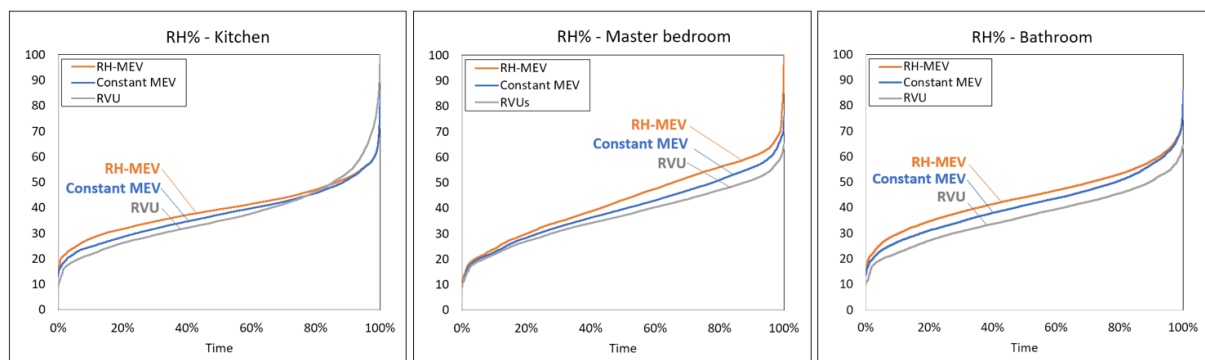


Figure 10. Indoor RH% levels in the service (wet) rooms, under Lyon's climatic conditions.

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 aggravated IAQ (Sowa & Mijakowski, 2020).

With exhaust-only ventilation strategies, the total required ventilation rate in the house is extracted by a central exhaust fan, and equivalent fresh air is supplied by air inlets around the building envelope. However, this exhaust fan-induced airflow is delivered to the house unevenly across the building envelope, resulting in a non-uniform distribution of fresh air among the dry rooms. This is also clear from the results of the present study. As shown in Figure 4, the resulting average ACH in each dry room was 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. In the case of RH-MEV in particular, the total exhaust airflow varied from a minimum of 25 L/s (90 m³/h) to 50 L/s (180 m³/h), and as result, the total amount of exhaust fan-induced airflow across the building envelope varied. This led to lower average values of ACH by ventilation in the dry rooms compared to Constant-MEV as shown in the Figure 4.

In the case of the room-based ventilation strategy, the supply and exhaust ventilation airflows from each RVU were assumed balanced and constant, resulting in fixed ACH and steady heat recovery performance in all the rooms. However several studies have shown that the fan performance in these units can be affected by the stack effect and wind-driven pressure differences across the building envelope resulting in unbalanced airflows and therefore reduced heat recovery performance and lower supply air temperatures (Mikola et al., 2019), (Filis et al., 2021). Moreover, fan noise generated by RVUs can potentially create acoustic discomfort based on the proximity to the occupants (Mikola, et al., 2021). 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.

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 16°C for more than 88% of the simulated period, while the temperature of air supplied from RVUs was above 16°C 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. This suggests that the application of RVUs would lead to improved indoor air quality.

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