Performance of smart ventilation in residential buildings: a literature review

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ABSTRACT

Smart ventilation in residential buildings has gained rising attention recently for the benefits of reducing energy consumption and improving indoor environmental quality. This paper presents a review of the smart ventilation in residential buildings papers published from January 2017 to August 2023, as a continuation of (Guyot, Sherman, and Walker 2018) who reviewed the publications in this area up to 2016. A systematic approach was used following the PRISMA protocol. Smart ventilation in residential buildings has been rapidly developed over the past seven years, compared to being an emerging technology prior to 2016. In total, 44 papers were analysed, which consisted of 22 journal articles and 22 conference papers. Belgium appears as the country with the most research activity in this field, followed by France, the United States, and Denmark. Most of these smart ventilation studies have been conducted via the simulation approach. Single-family dwellings and a unit in apartment buildings are the settings for most of the reviewed studies. The findings show the evolution of trends in smart ventilation over the years, in which health has emerged as an indicator for evaluating ventilation system performance. Furthermore, the new developments include performance-based assessment, decentralised ventilation, using data-driven methods to form control strategy, and the Internet of Things. Regarding indoor air quality, in addition to CO_2 and relative humidity, new indicators have been applied, such as formaldehyde, $PM_{2.5}$ and volatile organic compounds. The challenge related to the diversity of simulation model input data and the performance indicators was highlighted. Though the research in this area has rapidly grown, international collaborations are lacking, as is the field testing of the proposed strategies.

KEYWORDS

Demand-controlled ventilation, indoor air quality, energy consumption, occupant behaviour, performance indicators

1 INTRODUCTION

With the goal of reducing ventilation energy consumption and improving the level of thermal comfort and indoor air quality (IAQ), the concept of smart ventilation was introduced in 1980. A working group of Air Infiltration and Ventilation Centre (AIVC) experts has defined smart ventilation as ‘a process to continually adjust the ventilation system in time, and optionally by location, to provide the desired IAQ benefits while minimizing energy consumption, utility bills, and other non-IAQ costs, such as thermal discomfort or noise (Durier, Carrié, and Sherman 2018). The key concept of smart ventilation is to use controls to ventilate more where and when it provides either an energy or IAQ advantage or other non-IAQ cost, and less where and when it provides a disadvantage (Guyot et al., 2018). The parameters to which smart ventilation systems can respond include occupancy, indoor temperature and/or contaminants, outdoor temperature and humidity, outdoor air quality, electricity grid needs, and the operation of other air moving or cleaning systems (Durier et al. 2018). Smart ventilation, which responds to the direct sensing of indoor contaminants, is a form of demand-controlled ventilation (DCV). Thus, smart ventilation includes DCV.

The goal of this paper is to provide an update on developments in the smart ventilation field from 2017 to 2023 as a continuation of the literature review conducted by (Guyot et al. 2018). This previous review showed that up to 60% of ventilation energy savings can be obtained without compromising IAQ. Since 2016, there have been many new developments in residential smart ventilation. Energy savings in the building sector are highly demanded, as is the need to provide an acceptable IAQ, which makes ventilation play a more crucial role. Since residential buildings are often unoccupied or occupied at a lower level, the smart ventilation strategy is extremely important to achieve the high potential of energy savings and assure a good IAQ. In this context, a review is conducted with the aim of summarizing the evidence of the benefits of implementing smart ventilation in residential homes, focusing on the ventilation strategies related to energy consumption, IAQ, comfort, health, and other advantages. This paper mainly shows the review results of the occupant's pattern (behaviour), pollutants and contaminants generation scenarios, and ventilation system performance indicators.

2 METHODOLOGY

A systematic review was performed according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Statement) recommendations (Liberati et al. 2009). The search process aimed to answer the questions: How much is the indoor environment quality (IEQ) improved, and how much energy savings are obtained with the use of smart ventilation in residential buildings compared to a reference system? The electronic databases used to perform the search were the Web of Science, Scopus, and AIVC collections. The AIVC is the International Energy Agency's information centre on energy-efficient ventilation. This review included articles published from January 2017 to August 2023.

The string used in searching the database combined three groups of keywords related to ventilation, IEQ, and energy efficiency, as presented as follows: {“advanced control” OR “airflow control” OR “algorithm” OR “building ventilation” OR “demand-controlled ventilation” OR “demand ventilation” OR “emission control” OR “performance based” OR “smart ventilation” OR “ventilation control” OR “ventilation system” OR “window open”} AND {”cost” OR “energy” OR “consumption” OR “efficiency” OR “power demand”} AND {"indoor air quality" OR "IAQ" OR "air quality" OR "home" OR "residential" OR “indoor environment” OR “humidity” OR “thermal comfort”}. The search string was permuted in both the Web of Science and Scopus databases, with an integrated search in the article title, abstract, and keywords. Our search was limited to publications written in English. The AIVC bibliographic database AIRBASE was searched using the ‘Title contains (1 word)’ option with the words ‘demand’ or ‘control’ or ‘smart’ in the publication title from 2017 to 2023. After the databases were searched, the duplicated papers were excluded, and inclusion and exclusion criteria were generated to guide the selection process of the articles. This process was carried out by using the platform Rayyan, which is a free tool that enables authors to classify articles in a blinded mode, reducing the risk of bias.

3 RESULTS

3.1 Papers context

Out of 754 papers (after removing the duplicates) obtained from the search, 681 papers were excluded based on manually reviewing their titles and abstracts, and 29 papers were excluded after fully reviewing the paper. In total, 44 papers were included in this review, which consisted of 22 journal articles and 22 conference papers. Belgium, France, and the United States appear as the countries with the majority of publications in this research topic, where 61% of the included papers originated from these three countries. Considering the climatic conditions, many studies on residential smart ventilation were carried out in Northwest Europe, where winters are mild and summers are cool.

When analysing the co-occurrence of keywords reported in the included papers, the evolving trends in smart ventilation publications reveal a shift. Publications from 2017 to 2021 focused on themes such as CO_2 and humidity-based control ventilation, energy savings, and building-generated pollution, while publications after 2022 emphasize themes such as health, pollutant-based approaches such as volatile organic compounds (VOCs) and $PM_{2.5}$, performance-based assessment, decentralised ventilation, data-driven methods, and the Internet of Things (IoT).

From the total included papers, 75% (33 studies) used the simulation approach, 20% (nine studies) were experimental studies that measured the performance of the ventilation system, and 5% (two studies) combined both the simulation and experimental approaches. Regarding the study subjects, 80% used either single-family detached houses, typical apartment units, or both. This review paper focuses on results of the simulation studies.

3.2 Occupant's pattern, and pollutants and contaminants generation scenarios

The occupant's pattern has a significant impact on ventilation performance because their behaviour dictates the pollutant emission scenarios, whether bio-effluents or pollutants from indoor activities such as cooking, showering, and cleaning, among others. In addition, the knowledge of occupancy behaviour enables the prediction of occupant exposure to pollutants. Many efforts have been devoted to addressing occupant behaviour in residential buildings, including monitoring occupancy, developing occupant behaviour models, and applying those models in building performance simulation (Balvedi, Ghisi, and Lamberts 2018; Franceschini and Neves 2022). When analysing the schedule pattern used by the authors in this review, we observed wide differences related to the occupants' number (ranging from 1 to 4), time spent at home, school, and work, the schedule of weekdays and weekends, and the occupant's activities. The occupant’s pattern data used by authors were often defined according to standards (Carbonare et al. 2019, 2020) or derived from time-use survey data, as presented by (De Jonge and Laverge 2022; Poirier et al. 2021).

The pollutants and contaminants generation scenarios used in the simulation studies, including occupant’s bio-effluents and occupant’s main activities, are summarised in Table 1. In this review paper, humidity is considered as a contaminant. The generation scenario of these pollutants and contaminants is either from a standard or from an in-situ measurement. In Table 1, the emission rate column shows the values or ranges used by different authors. As it can be observed, the variations are not only the values or ranges but also the units from one study to another. This variation in pollutant generation scenarios results in distinct outcomes in ventilation system performance, making it impractical to compare ventilation strategies.

Table 1: Pollutant and contaminant emission generation scenarios used in simulation studies.

Pollutants and contaminants		**Emission rate**	**Reference**
CO_2 (bio-effluent)	Adult awake	12 L.h^{-1}, 14.4 L.h^{-1}, 16 L.h^{-1}, 18 L.h^{-1}, 19 L.h^{-1}, 10 mg.s^{-1}, 8.5 mg.s^{-1}, 0.25 L.min^{-1} varying from1.86 e-4 m^3.s^{-1} to 9.69e-4 m^3.s^{-1} depending on the activity level, varying from 15 dm^3.h^{-1} to 35 dm^3.h^{-1} depending on the activity level	(Van Gaever, Laverge, and Caillou 2017) (Pecceu, Caillou, and Gaever 2018) (Poirier et al. 2021) (Walker et al. 2021) (Ghijsels, Jonge, and Laverge 2022) (De Jonge, Ghijsels, and Laverge 2022) (Carbonare et al. 2020) (Belmans et al. 2019) (Filis et al. 2023) (Kim, Kim, and Moon 2022) (Müller and Dębowski 2020) (Rojas 2022) (Shin et al. 2018)
	Adult asleep	10 L.h^{-1}, 15 L.h^{-1}, 6.5 mg.s^{-1}, 1.65e-4 m^3.s^{-1}, 10 dm^3.h^{-1}, 0.20 L.min^{-1}	
	Child awake	6.5 mg.s^{-1},12 L.h^{-1}, 12.6 L.h^{-1}, 9 L.h^{-1}	
	Child asleep	4 mg.s^{-1}, 8 L.h^{-1}	
H_2O (bio-effluent)	Adult awake	55 g.h^{-1}, 15 mg.s^{-1}, 45 g.h^{-1}, 40 – 45 g.h^{-1}	
	Adult asleep	40 g.h^{-1}, 9 mg.s^{-1}	
	child awake	10 mg.s^{-1}, 41.3 g.h^{-1}, 35 g.h^{-1}	
	child asleep	6 mg.s^{-1}	
H_2O (human activities)	cooking	1. morning and noon 0.5 L.s^{-1} (10min); evening 0.6 L.s^{-1} (10min) + 1 L.s^{-1} (10 min) + 1.5 L.s^{-1} (10min), 2. Breakfast 1512 g.h^{-1}, lunch 2268 g.h^{-1}, dinner 2844 g.h^{-1}, 3. 140 mg.s^{-1}, 4. 500 g.h^{-1}, 5. Breakfast 50 g/person, lunch 150 g/person, dinner 300 g/person, 6. 1.33·10^{-4} kg.s^{-1}	(Van Gaever et al. 2017) (Poirier et al. 2021) (Ghijsels et al. 2022) (De Jonge et al. 2022) (Carbonare et al. 2020) (Belmans et al. 2019) (Filis et al. 2023) (Johnston et al. 2020) (Kim et al. 2022)
	dishwashing	130 mg.s^{-1}, 200 g.h^{-1}	
	shower	0.5 L.s^{-1} per shower (10min), 1440 g.h^{-1}, 330 mg.s^{-1}, 500 g.h^{-1}, 300 g/shower/person, 7.22·10^{-4} kg.s^{-1}	
	Laundry room	0.06 L.s^{-1} (12h), 252 g.h^{-1}, 250 g.h^{-1}, Laundry + dry 136.8g/h, 200 g/laundry, 1000 g/drying	
H_2O plants		30 g.h^{-1}	
VOCs Proportional to the floor area		From 4.5 µg.h^{-1}m^{-2} to 23.6 µg.h^{-1}.m^{-2}	
PM$_{2.5}$ from cooking		1). 0.0208 mg.s^{-1}, 2). From 1.26 mg.min^{-1} to 2.55 mg.min^{-1}, 3). Per activitie: 70 µg.min^{-1} – vacuuming 10 µg.min^{-1} - oven 283 µg.min^{-1} – grilled, 1483 µg.min^{-1}- fried	
Generic contaminant		18 µg/m^2/h	(Walker et al. 2021)
Formaldehyde		3.06 µg.h^{-1}.m^{-2} for furniture (wood), 4.50 µg.h^{-1}.m^{-2} for doors (wood), 3.00 µg.h^{-1}.m^{-2} for cushion, 4.27 µg.h^{-1}.m^{-2} for carpet	(De Jonge and Laverge 2022)
Benzene		1.40 µg.h^{-1}.m^{-2} for furniture (wood), 2.00 µg.h^{-1}.m^{-2} for cushion, 0.21 µg.h^{-1}.m^{-2} for carpet	
Naphthalene		5.68 µg.h^{-1}.m^{-2} for furniture (wood) and 0.47 µg.h^{-1}.m^{-2} for carpet	
Toluene		11.00 µg.h^{-1}.m^{-2} for Cushions, 0.20 µg.h^{-1}.m^{-2} for carpet, 0.5 µg.h^{-1}.m^{-2} for gypsum	
Limonene		1912 µg.h^{-1}.m^{-2} for cleaning, 24.8 µg.h^{-1} for dishes1200 µg.h^{-1} for shower (soap/shampoo), 2000 µg/event for deodorant	
Naphthalene		3.76 µg.h^{-1} Shower (soap/shampoo)	

3.3 Ventilation system performance indicators

The most employed indicators to evaluate ventilation performance can be categorised into five groups: IAQ, energy savings, building air exchange rate, comfort, and health impacts. CO_2 and RH are the parameters frequently employed to evaluate smart ventilation performance. This consistent with the findings previously presented by (Guyot et al. 2018). The indicators applied to evaluate IAQ included CO_2 concentration, CO_2 unmet hours for a specific threshold, CO_2 cumulative exposure exceeding the reference value, percentage of time that CO_2 was above a threshold, $PM_{2.5}$ exposure exceeding the reference value, formaldehyde exposure exceeding the reference value, TVOC and VOCs cumulative exposure, and generic pollutant cumulative exposure and concentration. The reference threshold value for CO_2 ranges from 600 ppm to 2000 ppm (Carbonare et al. 2020; Faure et al. 2018; Müller and Dębowski 2020; Van Gaever et al. 2017).

The indicators applied to evaluate energy savings included annual ventilation energy consumption, total energy consumption (by all appliances and the ventilation system), space heating and ventilation system, fan energy savings, energy consumption for cooling, and primary energy consumption. The air exchange rate and air flow rates are related to ventilation indicators, and they have a great effect on energy savings since higher values ventilation demand higher energy consumption for space cooling or heating. On the other hand, higher values indicate higher levels of pollutants dilution, improving IAQ.

The indicators used to evaluate comfort included the percentage of time that temperature is outside the reference range, the unmet hour in which temperature is outside the reference range, the unmet hour in which RH is outside the reference range, and the overheating risk. The air temperature reference ranges from 15 °C to 27 °C (Belmans et al. 2019; De Maré et al. 2019; Johnston et al. 2020). For RH, the setpoint for ventilation control varies, such as $35\% < RH < 70\%$ (De Jonge et al. 2022), $30\% < RH < 70\%$ (Carbonare et al. 2020; De Maré et al. 2019), $25\% < RH < 70\%$ (Belmans et al. 2019), $25\% < RH < 60\%$ (De Maré et al. 2019), and $20\% < RH < 80\%$ (Johnston et al. 2020). Some authors specify indoor comfort ranges according to standards such as EN16798-1 (2019) (De Maré et al. 2019) and NBN EN 15251 (Belmans et al. 2019). Comfort analysis in these studies adopts various definitions, including thermal comfort based solely to air temperature (Cakyova et al. 2021; Grygierek and Ferdyn-Grygierek 2022; Johnston et al. 2020; Laffeter et al. 2019), both air temperature and RH, and indoor comfort encompassing temperature, RH, and CO_2 (Carbonare et al. 2019; De Jonge et al. 2022; De Maré et al. 2019).

Regarding health impact, some studies employed indicators such as pollutant relative exposure and DALYS (Disability-Adjusted Life Years). Additionally, some authors investigated indicators related to building performance, such as condensation risk on building materials ($RH > 70\%$), mould growth risk, financial payback time of the ventilation system, and peak power demand reduction.

3.4 Smart ventilation control strategies and performance

To evaluate smart ventilation performances, authors have used different calculation methods and parameters based on a wide range of ventilation systems and controls. The ventilation control strategies described include (1) occupancy-based control, (2) outdoor conditions-based control, (3) CO_2, $PM_{2.5}$, wind speed, and temperature-based control applied for hybrid ventilation and ventilation for cooling, (4) temperature, humidity and/or CO_2 based control ventilation for decentralized systems, and (5) others using DCV based on CO_2, humidity, and TVOCs. The main findings are summarised as follows.

Due to the occupant's generation of pollutants in the indoor environment, many studies have developed occupancy-based ventilation control strategies. (Clark et al. 2019) used the relative exposure approach to assess the IAQ and energy savings of three occupancy-based ventilation strategies for residential buildings located in the four California climate zones. Results showed that when ventilation is completely turned off during the unoccupied period, in addition to the occupants experiencing a peak of exposure to pollutants when re-entering the environment due to the increase in the pollutant's concentration during the off period, the energy consumption on ventilation to recover the air quality indices makes this strategy not viable. The addition of a pre-occupancy flush period by turning on the ventilation 1 hour or 2 hours prior to the occupants returning home proved to be the best strategy in terms of energy savings and exposure to peak pollutants, which can result in up to 60% energy savings for the 2-story buildings with an ACH_{50} of 5.

Regarding the outdoor conditions-based approach, simulation results showed that outdoor temperature-based strategies can save ventilation energy up to 33% while maintaining the equivalent IAQ compared to the constant ventilation system. Ambient temperature-based controlled ventilation is less effective in cold climate regions due to its lack of the cooling season and low diurnal temperature swings. More energy savings are obtained from buildings located in regions with higher cooling demands, and from buildings with less-tight envelopes, as observed across simulation cases with 1, 3, and 5 ACH_{50} (Less et al. 2019). Another outdoor conditions-based simulation study performed by (De Jonge et al. 2022) conducted in a typical Belgian apartment unit, assumed that the outdoor air quality is not always better than the IAQ and consequently sometimes not be suitable for diluting indoor pollutants (De Jonge et al. 2022). The authors investigated two ventilation control strategies: one considering both the outdoor air quality and the IAQ, and another strategy only considering the IAQ, evaluating health, comfort, and energy use performance indicators. Simulation results showed that, compared with the control algorithm only based on IAQ, the control algorithm taking into account both IAQ and outdoor air quality achieved 44% of the energy savings and reduced about 10% of the total DALYs count. However, the trade-off was less comfort due to increased exposure to high levels of indoor CO_2 (De Jonge et al. 2022).

Regarding hybrid ventilation systems, the studies performed by (Belmans et al. 2019) showed that mixed-mode ventilation performed equally well as DCV systems in winter in terms of energy consumption and IAQ achieved. However, hybrid ventilation can minimize energy consumption in summer to achieve good thermal comfort as less mechanical ventilation is needed and more free cooling natural ventilation can be supplied (Belmans et al. 2019). Hybrid ventilation was also applied for cooling by (Cakyova et al. 2021) and they found that for energy demand, night ventilation through window openings (turning off the CAV system at night) provided 28% of the reduction compared to constant mechanical ventilation.

For decentralised ventilation systems, (Carbonare et al. 2019) proposed two comfort-oriented control strategies based on the façade integrated room-based ventilation unit and compared these two strategies with the commonly used linear and step control strategies. On average, 10% energy savings were achieved from these two proposed strategies, compared to the linear and step control strategies. In another simulation study on façade integrated room-based ventilation units, (Carbonare et al. 2020) evaluated four control strategies, namely linear, steps, comfort-oriented, and fuzzy control. The fuzzy controlled strategy is defined by a mathematical model based on the interpretation of indoor RH and CO_2 concentration. Then, the fan speed is controlled based on real-time measurements of these two parameters. The proposed fuzzy controlled strategy achieved about 25% energy savings compared to a constant airflow strategy and about 12% energy savings compared to a step-controlled DCV system (Carbonare et al. 2020). (Smith and Kolarik 2019) also simulated and assessed a manifold of fans that connects to an apartment level air-handling unit to control the supply of airflow to each room in an apartment. The results showed that this system was effective in saving energy and maintaining IAQ targets related to CO_2, RH, and temperature, where 74% savings in fan energy consumption relative to the reference constant air volume system were achieved. CO_2 only exceeded the limit in the bathroom, where it did not have CO_2-based control.

For centralised systems, (Baptiste Poirier, Guyot, Woloszyn, et al. 2021) employed five indicators to effectively demonstrate the IAQ achieved through DCV systems. These are CO_2 cumulative exposure (thresholds of 1000 d ppm.h), humidity from the health perspective (percentage of time spent by an occupant with RH outside of the range between 30% and 70%), humidity from the condensation risk perspective (percentage of time with RH above 70%), cumulative formaldehyde exposure (threshold of 9 d $\mu g\ m^{-3}.h$), and cumulative $PM_{2.5}$ exposure (threshold of 10 d $\mu g\ m^{-3}.h$), in which d is the simulation duration in hours (h). Simulation studies during the heating season in Lyon, France, showed that among the constant-MEV, constant balanced mechanical ventilation, and humidity-based DCV systems, none of them can achieve all five proposed IAQ targets. The $PM_{2.5}$ targets are not reached under any of the ventilation strategies (Baptiste Poirier, Guyot, Woloszyn, et al. 2021; B. Poirier, Guyot, and Woloszyn 2021). Another study conducted by (Poirier et al. 2022) applied the proposed five IAQ indicators to assess the performance of five DCV systems in a newly renovated Danish apartment building and found a similar result: none of the investigated ventilation systems were able to achieve the targeted $PM_{2.5}$ exposure. The MVHR resulted in a better IAQ in terms of CO_2 and formaldehyde exposure. However, none of the investigated DCV and non DCV systems resulted in acceptable formaldehyde exposure when the emission rates were in the medium and high scenarios.

(Sowa and Mijakowski 2020) analysed a humidity-based DCV system that was installed in an eight-floor multiunit residential building in Poland. They discovered minimal variation in ventilation performance among units on the same floor level when different ventilation options were implemented. The efficiency of passive stack ventilation is influenced by outdoor temperature and wind conditions, leading to increased instances of unwanted backflows and significant airflow discrepancies between units situated on lower and higher floors of the building, such as between the second and eighth floors. Humidity-controlled stack ventilation systems resulted in fewer backflows but less air flow into the building compared to passive stack ventilation systems and were unable to achieve the required ventilation rate. However, the difference in the air flows on different levels of the building is lower, and the air flow is not dependent on the ambient temperature. Compared with the humidity-controlled stack ventilation system, the performance of the ventilation system was better when this system had exhaust fans mounted on the roof above the individual exhaust ducts to support airflows induced by natural forces when needed, and no unwanted backflows occurred under this ventilation option. The average CO_2 concentrations under these three ventilation options were, respectively, 1146 ppm (passive stack ventilation), 1289 ppm (humidity-controlled stack ventilation), and 1053 ppm (humidity-controlled ventilation with a roof-mounted exhaust fan). Using humidity-controlled ventilation with a roof-mounted exhaust fan ventilation, the energy needed to heat the ventilation air is 21% lower than passive stack ventilation.

4 CONCLUSION

This study evaluated 44 papers published from 2017 to 2023, on smart ventilation in residential buildings and showed that new developments have been emerged. The new developments include performance-based assessment, decentralised ventilation units, data-driven approach to form the optimal strategy, and the IoT-enabled devices and sensors. Belgium, France, and the US are the top three countries where smart ventilation studies have been conducted. Single-family houses and apartment units are the most investigated building types. Over the past seven years, smart ventilation concepts have been applied to some new areas, for example, ventilation for cooling and hybrid ventilation. The use of DALYs to estimate the health impacts of operating DCV is also a new development, as includes the financial analysis of the system. Decentralized DCV is an emerging area, as it is beneficial to apartment unit renovation where the building may not have the space to install the central unit and to meet the individual needs of occupants in every zone within a building. However, the energy consumption by multiple fans in the decentralized DCV system might be a shortcoming of this system.

Most studies consider that outdoor air is always cleaner than indoor air and that it is suitable to dilute indoor pollutants, but only a few studies point out that this is not always the case. The analysis of IAQ indicators has revealed that in addition to the most widely used parameters of RH and CO_2, other IAQ parameters have been used to indicate the air quality, for example, HCHO, $PM_{2.5}$, and TVOC. The DALYs approach to estimating the health impacts shines a light on the importance of balancing energy savings and the IAQ. The challenge related to the diversity of input data and the performance indicators was highlighted. Though the research in this area has rapidly grown, international collaborations are lacking, as is the field testing of the proposed strategies.

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