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A review of smart ventilation energy and IAQ performance in residential buildings

Gaëlle Guyot[1], Max Sherman[2] and Iain Walker[2]

[1]Cerema, France, [2]Lawrence Berkeley National Laboratory

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ABSTRACT
In order to better address energy and indoor air quality issues, ventilation needs to become smarter. A key smart ventilation concept is to use controls to ventilate more at times it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. This would be done in a manner that provides improved home energy and IAQ performance, relative to a “dumb” base case. A favorable context exists in many countries to develop smart ventilation strategies. As a result, DCV systems are largely and easily available on the market, with more than 20-30 DCV systems approved and available in countries such as Belgium, France and the Netherlands. This paper proposes a literature review on smart ventilation used in residential buildings, developing the energy and indoor air quality performances. Analysis of 38 studies with various smart ventilation systems based on CO2-, humidity-, combined CO2- and TVOC-, occupancy-, outdoor temperature-controlled ventilation and smart ventilation strategies, shows that ventilation energy savings up to 60% could be obtained without compromising, and sometimes improving, IAQ. But that sometimes worst performances were obtained with an order of magnitude of energy savings between -26% and +60%.

KEYWORDS
Ventilation, indoor air quality, performance, residential buildings, demand-controlled ventilation, review

1. BACKGROUND

Through updates to California building codes, California is leading the way in reducing energy use in residential buildings, and is even on the way to mandating zero net energy homes. This is also the case in other municipalities, in Europe, for example, which has issued the energy performance building directive (European Parliament, 2010). Such energy-efficient homes require rethinking their ventilation strategies, because of ventilation’s substantial impact on the heat balance and associated conditioning energy in homes.

For these high-performance homes, envelope airtightness treatment becomes crucial (Erhorn et al., 2008) and should be combined with efficient ventilation technologies. Indoor air quality is another major area of concern in buildings and is influenced by ventilation. Because people spend 60–90% of their life in indoor environments (homes, offices, schools, etc.), indoor air quality is a major factor affecting public health (Klepeis et al., 2001; European Commission 2003; Brasche and Bischof, 2005; Zeghnoun et al., 2010; Jantunen et al., 2011). (Logue et al., 2011b) estimated that the current damage to public health in disability-adjusted life years (µDALY) per person per year from all sources attributable to IAQ, excluding second-hand smoke and radon, was in the range between the health effects of road traffic accidents (4,000 µDALY/p/yr) and heart disease from all causes (11,000 µDALY/p/yr). By way of comparison, this means that, according to the World Health Organization (WHO, 2014), 99,000 deaths in Europe and 81,000 in the Americas were attributable to household (indoor) air pollution in 2012.Health gains in Europe (EU-26) attributed to effective implementation of the energy performance building directive, which includes indoor air quality issues, have been estimated at more than 300,000 DALYs per year.

As a result, interest in a new generation of ventilation systems has been growing. “Smart ventilation” strategies, including demand-controlled ventilation (DCV), usually denote the use of controls to ventilate more when doing so provides an energy or IAQ advantage (or both) and less when it provides a disadvantage, relative to a “dumb” base case. DCV strategies have been considered in the literature (Laverge et al., 2011) as a cost/energy and IAQ measure, including in existing buildings. DCV strategies have the potential for energy reductions for all ventilation systems.

A favorable regulatory context exists in many countries to develop such strategies (Guyot et al., 2017). Consequently, more than 20 DCV systems with an agreement are available in countries such as Belgium, France and the Netherlands.

2. SMART VENTILATION

The key smart ventilation concept is to use controls to ventilate more at times it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. The fundamental goal of this concept is to reduce ventilation energy use and cost while maintaining or improving IAQ relative to a continuously operating system (Durier et al., 2018).

Demand-controlled ventilation (DCV)

The DCV concept is a specific subset of smart ventilation. DCV systems generally use indicators of demand for ventilation, such as excess CO2 or humidity, to control a ventilation system. Such strategies have been widely used in the scientific literature and in materials associated with the technologies available over the past 30 years. Several types of DCV are currently available in the literature and on the market depending on the type of building regulation, the type of sensing combinations, and the types of control algorithms. For instance in Belgium (Caillou et al., 2014b; Moniteur Belge, 2015), DCV systems have been classified according to measured IAQ-related parameters such as CO2, relative humidity, occupancy; type of space(s) (humid and/or dry); local vs. centralized control; sensor location (distributed vs. central), and airflow direction (exhaust only, supply only, balanced).

Residential Integrated Ventilation-Energy Controller (RIVEC)

With the Residential Integrated Ventilation-Energy Controller (RIVEC), the LBNL has more recently been developing another subset of smart ventilation. It was developed in order to control fans to minimize energy use (Sherman and Walker, 2011; Walker et al., 2011; Turner and Walker, 2012; Walker et al., 2014). This smart ventilation concept uses the equivalent ventilation principle (Sherman, 2004) to allow for modulation of ventilation airflows in response to several factors, including outdoor conditions, utility peak loads, occupancy, and operation of other air systems. Equivalent exposure compares the exposure for the system being evaluated to that from a continuous ventilation system (assuming a continuously generated pollutant).

This generic approach allows for any smart ventilation strategy to have real-time control by targeting a relative exposure of unity. This has been integrated into ASHRAE Standard 62.2 (ANSI/ASHRAE, 2013,2016) as an optional compliance path. This concept was further developed (Sherman et al., 2011) to be applied under a variety of ventilation rates, emission rates, and the evaluation periods for the dose of pollutants.

Conclusion

In smart ventilation strategies, the type of measurements used can also depend strongly on the quantity being measured (CO2, RH, pollutants, occupancy), the type of measuring technology, the type of spaces (humid and/or dry), the type of airflow control (mechanical or electronic inlet and outlet cross-sectional area, direct control of the fan speed, or control of dampers). The type of control algorithm (for example, the value of the set-points and the rules for control between set-points) is also an important topic that can have a substantial impact on IAQ and energy performance.

3. REVIEW PROCEDURE

In this paper, we analyzed field and modeling studies on energy and/or IAQ benefits of residential smart ventilation from 1979 to 2016. The summaries presented above are instructive and provide a valuable resource to initiate the current work even though many of the summarized studies are for non-residential buildings.

As part of the International Energy Agency Annex 18, (Raatschen, 1990) reviewed 31 papers from 1979 to 1989, including four studies on implementation of DCV systems in homes (Anon, 1983; Barthez and Soupault, 1984; Nicolas, 1985; Sheltair scientific Ltd., 1988). A further review (Fisk and De Almeida, 1998) on sensor-based demand-controlled ventilation combined 13 other papers from Annex 18 including six case studies on implementation of DCV systems in homes (Mansson, 1993), together with 15 additional papers published before 1997, including only one on a residence (Kesselring et al., 1993). The vast majority of these studies considered only relative humidity-based control, and in some rare cases CO2-based control.

A recent review of sustainable, energy-efficient and healthy ventilation strategies in buildings (Chenari et al., 2016) devoted a large section to DCV systems, including 15 additional papers from 2004 to 2013. Four of these concern smart ventilation in residential buildings (Jreijiry et al., 2007; Laverge et al., 2011; Nielsen and Drivsholm, 2010; Pavlovas, 2004). Between these three existing reviews there are 15 papers on smart ventilation, all DCV, in residential buildings.

In the present review, we analyzed 23 additional studies of interest on residential smart ventilation: 13 cover various smart ventilation systems based either on CO2 control or on humidity control; one presents a combined CO2- and TVOC-controlled ventilation system; three study occupancy-based smart ventilation systems; three study outdoor temperature-controlled smart ventilation; and three concern other smart ventilation strategies based on the RIVEC. The results of these 38 studies are summarized in a table at the end of the article. We must stress that it is very difficult to compare performance results between different studies, for at least four reasons:

1- Differences in the types of smart ventilation strategies used: there is often a lack of precise data on the type and location of sensors, the method of air flow regulation and the type of ventilation system.

2- A lack of information on the conditions of the studies (climate, occupancy, energy performance level, range of ventilation rates, building materials emission and absorption characteristics). A study can give poor results for given conditions, but this does not necessarily mean that the ventilation system is bad.
3- Differences in measuring IAQ-related parameters: there is neither a single parameter or set of parameters common in these studies, nor a universal method to calculate the indicators. There are often differences on the metrics used to evaluate the IAQ parameters. For instance, the average CO2 concentration is often given without information on either the location of the measurement (which room) or the averaging time used (1 day, 1 week, 1 year).
4- Differences in reference cases: reference cases, including reference airflow rates, are different in each standard or code to which each building regulation refers. Despite these differences it was possible to find commonalities and derive general guidance from the reviewed papers.

4. OVERVIEW OF THE REVIEWED LITERATURE
A summary table is provided (Guyot et al., 2018) containing IAQ and energy performance in all the reviewed papers and studies. We give here an overview of the type of smart ventilation being studied in the literature.

Historically, humidity and CO2 have been used as indictors of IAQ and therefore used to control DCV systems. Humidity is one of the prioritized pollutants of concern (Borsboom et al., 2016). CO2 is often used in DCV strategies, not to prevent negative health effects directly attributed to it, but because it can be representative of other parameters such as concentrations of bio-effluents (Zhang et al., 2016) or ventilation rates. The only health threshold on which several studies converge is an exposure of 10,000 ppm for 30 min, corresponding to respiratory acidosis for a healthy adult with a modest amount of physical load (ANSES 2013), far from concentrations observed in indoor environments. Nevertheless, CO2 exposure has often been used in the literature, describing a time-integrated concentration. As a result, most of the literature includes CO2 and humidity controlled ventilation.

Some other smart ventilation strategies are based on other pollutants, occupancy, or outdoor temperature. More recently concerns about constantly emitted pollutants (e.g., VOCs including formaldehyde) mean that occupant-only-related indicators may be considered inadequate to control smart ventilation strategies. The performance of occupancy-based smart ventilation systems has been demonstrated in some modeling and field studies. The performance of outdoor temperature-controlled smart ventilation systems as well, sometimes in conjunction with hybrid ventilation systems.

Other control strategies for smart ventilation systems were also studied during the development of the RIVEC (Sherman and Walker, 2011). This update to their previous work consisted of an intermittent ventilation strategy controlled by the operation of other air devices in the house and with a switch-off during the 4-h period of peak energy demand.

Lastly, another aspect of smart ventilation is that it is designed to control exposure to outdoor pollutants – typically particles and ozone.

5. CONCLUSIONS AND OBSERVATIONS

With smart ventilation strategies, including demand-controlled ventilation (DCV) strategies, the concept consists in using controls to ventilate more at times when it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. This can be done in a manner that provides improved home energy and IAQ performance. A favorable regulatory context exists in many countries to develop such strategies. As a result, more than 20 DCV systems with an agreement are available in countries such as Belgium, France and the Netherlands.

This article begins to address the fact that under the umbrella of "CO2-based DCV systems" or "humiditybased DCV systems" or "smart ventilation systems," there can be a wide variety of systems and strategies, with differences in the type of sensors, type of regulations, type of control algorithms, etc. To correctly analyze the performance of such systems, it is also very important to clearly define them and give a precise description of how they work.

Through this meta-analysis of 38 studies of various smart ventilation systems with control based on CO2, humidity, combined CO2 and TVOCs, occupancy, outdoor temperature, or other control strategies, we learned that:
- demand-controlled ventilation based on CO2 or humidity is well established in some countries with standardized performance calculation procedures and readily available controls and ventilation systems;
- there is clearly a potential for improved indoor air quality using smart ventilation strategies;
- significant energy savings up to 60% can be obtained, with less favorable results including 26% overconsumption in some cases.

The low number of studies reviewed, 38 since 1983, suggests that smart ventilation is still an emerging technology. In this review highlighting the lack of data on ventilation strategies controlled by other parameters than humidity or CO2, we identified issues that require greater understanding:
- What are the relevant pollutants to sense for residential ventilation control and can we sense them with sufficient accuracy and reliability for control?
- Can we ignore building and materials pollutants when homes are unoccupied? Can we ignore outdoor pollutants? Current regulations and the demand-controlled ventilation systems reviewed do not account for these effects.
- Can we reliably detect occupancy so as to realize the potential savings?

As a perspective for the future for real-time controllers like RIVEC compared with current DCV approaches, we would also suggest research in those areas, in order to:
- develop better indoor air quality metrics for residential ventilation control including the use of accurate and reliable sensing devices;
- better understand the differences between contaminant sources between occupied and unoccupied dwellings;
- include air cleaning in ventilation controls.

The present review paper is a short version of (Guyot et al., 2018) and part of the project called "Smart Ventilation Advanced for Californian Homes" (SVACH) further developed in the Lawrence Berkeley National Laboratory (LBNL) report (Guyot et al., 2017). This report addresses several aspects of smart ventilation: the suitability of various environmental variables for use as inputs in smart ventilation applications, the availability and reliability of the sensors used to measure these variables, a description of relevant control strategies, an overview of the regulations and standards proposing “equivalence methods” in order to promote the use of smart ventilation strategies, the available systems on the market in different countries, and a summary of ongoing developments in research areas related to ventilation, including IAQ metrics and feedback from on-site implementations.

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