A REVIEW OF POLLUTANTS AND SOURCES OF CONCERN AND PERFORMANCE-BASED APPROACHES TO RESIDENTIAL SMART VENTILATION

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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. This presentation discusses briefly the suitability of the measured parameters (pollutants of concerns, humidity, odours, CO_2, occupancy) for smart ventilation applications. Next, this presentation highlights that a favourable context exists in many countries, with regulations and standards proposing "performance-based approaches". The presentation gives an overview of such approaches in five countries, in the U.S and in Europe (France, Spain, Belgium, The Netherlands). The common thread in all these methods consists in using at least as metrics, the exposure to an indoor generated parameter, very often the CO_2, and the condensation risk. As the result, demand-control ventilation strategies (DCV) are widely and easily available on the market, with more than 20-30 systems available in some countries. This presentation is based on the report *Guyot G., Sherman M., Walker I., "Residential smart ventilation: a review", Report LBNL, 91 p., 2017*.

KEYWORDS

Ventilation, indoor air quality, energy, performance, residential buildings, DCV, review

1 INTRODUCTION

Energy-efficient homes require rethinking the ventilation and the air change rates, because of their increased impact on thermal losses. 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 which is influenced by ventilation. Because people spend most of the time in residential buildings (Klepeis et al., 2001),especially in their bedrooms (Zeghnoun et al., 2010), and60-90% of their life in indoor environments (homes, offices, schools, etc.) (Klepeis et al., 2001; European commission 2003; Brasche and Bischof, 2005; Zeghnoun et al., 2010; Jantunen et al., 2011), indoor air quality is a major factor affecting public health. Logue et al. (2011b) estimated that the current damage to public health from all sources attributable to IAQ, excluding second-hand smoke (SHS) and radon, was in the range of 4,000–11,000 μDALYs (disability-adjusted life years) per person per year. By way of comparison, this means the damage attributable to indoor air is somewhere between the health effects of road traffic accidents (4,000 μDALYs/p/yr) and heart disease from all causes (11,000 μDALYs/p/yr). 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.

Today we ventilate our buildings to provide a healthy and comfortable indoor environment, with attention to health, moisture and odor issues. Indoor pollutant sources include outside air, occupants and their activities, and the furnishings and materials installed in buildings.

As the list of identified indoor pollutants is long and may still increase, it has been impossible to create definitive IAQ metrics for standards and regulations governing residential buildings (Borsboom et al., 2016). Consequently, IAQ performance-based approaches for ventilation at the design stage of a building are rarely used. Instead, prescribed ventilation rates have been used, assuming that at the same time they would control human bio-effluents, including odors, they would control also any other contaminant as well (Matson and Sherman, 2004). As a result, standards and regulations, such as ASHRAE 62.2-2016 and others in Europe (Dimitroulopoulou, 2012), often prescribe ventilation strategies requiring three constraints on airflow rates:

1. A constant airflow based on a rough estimation of the emissions of the buildings, for instance one that considers size of the home, the number and type of occupants, or combinations thereof;
2. Minimum airflows (for instance during unoccupied periods);
3. Sometimes also provisions for short-term forced airflows to dilute and remove a source pollutant generated by activities as cooking, showering, house cleaning, etc.

In order to conciliate energy saving and indoor air quality issues, interest in a new generation of smart ventilation systems has been growing for 25 years. Thanks to “performance-based approaches”, such systems must often be compared either to constant-airflow systems (“equivalence approaches”) or to fixed IAQ metrics thresholds.

This paper provides a review of of suitability of control parameters and performance-based approaches used in 5 countries around the world for the assessment of smart ventilation strategies.

2 SMART VENTILATION AND DEMAND-CONTROLLED VENTILATION (DCV) DEFINITIONS

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 the same IAQ level as with a continuously operating system, or better.

The concept of “Demand-controlled ventilation (DCV)” is a specific subset of smart ventilation. Such strategies have been widely used in scientific literature and in materials associated with available technologies over 30 years. Different definitions of DCV are available. According to the IEA Annex 18, DCV denotes continuously and automatically adjusting the ventilation rate in response to the indoor pollutant load (Mansson et al., 1997). (Limb M.J, 1992) defines a DCV strategy as “*a ventilation strategy where the airflow rate is governed by a chosen pollutant concentration level. This level is measured by air quality sensors located within the room or zone. When the pollutant concentration level rises above a* *preset level, the sensors activate the ventilation system. As the occupants leave the room the pollutant concentration levels are reduced and ventilation is also reduced. Common pollutants are usually occupant dependent, such as, carbon dioxide, humidity or temperature*".

A recent meta-analysis of 38 studies of various smart ventilation systems with control based on either CO_2, humidity, combined CO_2 and TVOC, occupancy, or outdoor temperature shows that ventilation energy savings up to 60% can be obtained without compromising IAQ- even sometimes improving it (Guyot, Sherman, Walker, 2017). However, the meta-analysis did include some less-than favorable results, with energy over-consumption of 26% in some cases.

The concept of "smart ventilation" being more recently developed in the LBNL is 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 and Walker, 2011; Sherman et al., 2012) further developed in the paper, 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(Figure 1).

Ventilation energy savings were estimated to be at least 40% by studying diverse climates (16 California climate zones), various home geometries and values for envelope airtightness to give a good representation of the majority of the Californian housing stock. This reflects absolute energy savings between 500 and 7,000 kWh/year per household with a peak power reduction up to 2 kW in a typical house (Turner and Walker, 2012).

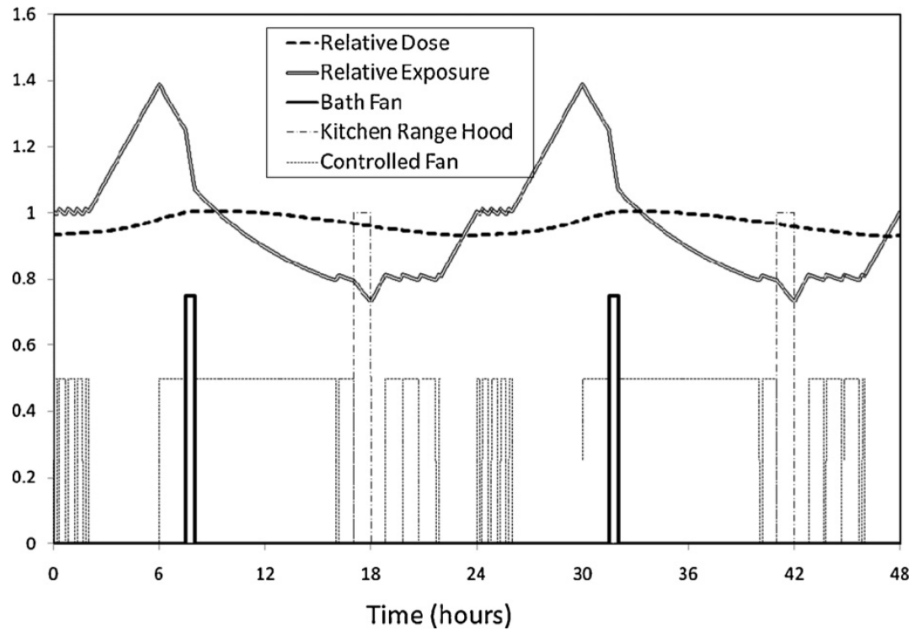

Figure 1 : Simulated controlled whole-house ventilation fan (continuous exhaust) with RIVEC and other household fan operation during the winter, source : (Sherman and Walker, 2011)

3 POLLUTANTS AND SOURCES OF CONCERN TO RESIDENTIAL SMART VENTILATION

The presentation gives an overview of:

- the suitability of various environmental variables for use as inputs in smart ventilation applications, (pollutants of concern, odors, CO_2, temperature, humidity, occupancy),
- the availability and reliability of the sensors used to measure these variables,
- and also describes control strategies used in smart ventilation applications.

As argued above, ventilation is not a panacea capable of ensuring good IAQ but should be considered a method to dilute remaining pollutants once they have been reduced at their source. With this in mind, it is important to separate from among the many pollutants of concern in residential buildings those which have been considered relevant for ventilation applications.

A synthesis of our literature review suggests the following pollutants can be considered as the most relevant in a smart ventilation approach, disregarding the availability and the accuracy of the corresponding sensors (Table 1).

Table 1: Selection from the literature of relevant pollutant for smart ventilation strategies

Relevant pollutants (chronic exposure)	Relevant pollutants (acute exposure)
1. Particulate matter	Acrolein
2. Mold and moisture	Chloroform
3. Formaldehyde	Formaldehyde
4. Acrolein	NO_2
	$PM_{2.5}$

Indoor air quality has also been subjectively evaluated by assessing the satisfaction of occupants (CEN, 2007; Fanger et al., 1988). Indoor air variables such as odors, temperature, CO_2 and humidity, strongly correlate to occupant activities, and can also be important to consider in a smart ventilation approach. CO_2 and relative humidity are the most commonly used parameters in demand-controlled ventilation systems. Their ability to represent overall indoor air quality, including their correlation with other types of indoor pollutants, has been partially studied in the literature.

Finally, as CO_2 or relative humidity measurements are often considered indicators of occupancy in the literature, there is also an interest in directly measuring occupancy.

The availability and reliability of sensors is also reviewed regarding their performance, size, extend of signal conditioning, reliability, robustness, maintainability, cost, … At the moment, only some CO_2 and humidity sensors seems reliable enough with affordable costs for residential smart ventilation.

The quality of the sensors is not the only question of interest regarding the smart ventilation performances. Also question of control strategies algorithms, regulation type, either centralized or per-zone, localization of sensors are worthwhile issues.

4 PERFORMANCE-BASED APPROACHES TO RESIDENTIAL SMART VENTILATION

A number of ventilation standards and national regulations have progressively integrated an allowance for smart ventilation strategies and/or DCV systems in residential buildings. Simultaneously, progressively energy performance regulations include the opportunity to claim credit in energy calculations for savings from such systems. Already in 2004 in the United States a federal technology alert concluded that the HVAC systems in buildings should use DCV to tailor the amount of ventilation air to the occupancy level, for energy and IAQ reasons (Federal Technology Alert, 2004). Some years later, an update to the ventilation standard ASHRAE 62.2 (ANSI/ASHRAE, 2013) allowed the use of smart ventilation technologies. To the best of our knowledge, smart ventilation systems cannot get an energy credit in calculations specific to each state at the moment. In Europe, several countries enable the use of DCV systems in ventilation codes, including Belgium, France, Spain, Poland, Switzerland, Denmark, Sweden, the Netherlands, Germany (Savin and Laverge, 2011 ; Kunkel et al., 2015 ; Borsboom, 2015). The corresponding energy regulations are more or less recent.

Smart ventilation and/or DCV systems must generally prove their IAQ performance through a performance-based approach, in order to comply with the ventilation regulation and get a credit in the energy-performance regulatory calculation.

Pushed by the international movement toward nearly-zero energy buildings, smart ventilation system success is not about to end. In Europe, two recently published directives n°1253/2014 regarding the eco-design requirements for ventilation units and n°1254/2014 regarding the energy labelling of residential ventilation units (European Parliament and the Council, 2014) are moving toward a generalization of low-pressure systems, DCV systems and balanced heat recovery systems at the 2018 horizon. According this second directive, for central- and local-DCV systems, it should be possible to use a correction factor of 0.85 and 0.65, respectively, in the energy consumption calculation performed specifically for this labelling.

Given these opportunities, DCV strategies have been used at massive scale, notably in France and in Belgium, for more than 30 years. August 1st 2016, 23 DCV systems in France, 34 in Belgium, 37 in the Netherlands have received an agreement. Most of them are CO_2 or humidity-based strategies.

IAQ performance-based approaches could be used in many ways. Each country uses different indicators, calculated with different methodologies and compared to different thresholds. The common thread in all of these methods is the use at a minimum, of the exposure to a pollutant generated indoors (very often the CO_2) and condensation risk. A minimum airflow rate for unoccupied periods is also often required.

Table 2 gives an overview of the described performance-based approaches in the presentation.

Table 2: Overview of performance-based approaches to residential smart ventilation

Country	Person in charge	Ventilation Equivalence method	Calculated IAQ indicators	Credit in EP-calculation	Minimum airflow
USA and Canada (ASHRAE 62.2 2016)	The manufacturer, specifier or designer is supposed to certify that the calculation meets the requirements.	Single zone modelling, $\Delta t<1h$, constant pollutant emission rate	No specifically defined pollutant Yearly average relative exposure R<1 At each time-step $R_i<5$	No	Can be null if the total airflow rate equivalence is required over any 3-hour periods
France	The manufacturer for each (humidity) DCV system shall pass through an agreement procedure	Multizone modelling with MATHIS, Δt =15 min, Conventional entry data	**Per room, over the heating period:** 1/CO_2 cumulative exposure indicator E_{2000} < 400,000 ppm.h 2/Number of hours $T_{RH>75\%}$ <600 h in kitchen, 1000 h in bathrooms, 100 h in other rooms	Average equivalent exhausted airflow (m^3/h) can be implemented in the EP-calculation	Switch off not allowed, minimum airflow is 10-35 m^3/h according to the number of rooms in the building
Spain (<2017)	The manufacturer for each DCV system shall pass through an agreement procedure	Multizone modelling with CONTAM, Δt =40 s, Conventional entry data	**Per room, over the year:** 1/ Yearly average CO_2 concentration < 900 ppm 2/ Yearly cumulative CO_2 exposure over 1600 ppm E_{1600} < 500,000 ppm.h	Yearly average ventilation airflow could be implemented in the EP-calculation	
Spain (future)	The designer of the building, of the base of information given by the manufacturer	A performance-based approach for all ventilation systems is going to be implemented, using a software and conventional data at the design stage of each building	**Per room, over the year:** 1/ Yearly average CO_2 concentration < 900 ppm 2/ Yearly cumulative CO_2 exposure over 1600 ppm E_{1600} < 500,000 ppm.h	Yearly average ventilation airflow could be implemented in the EP-calculation	The minimum airflow during unoccupied periods is set to 1.5 $l.s^{-1}$ in each room.
Belgium (< 2015)	The manufacturer for each DCV system shalls pass through an agreement procedure	Multizone modelling with CONTAM, Δt =5 min, conventional entry data both deterministic and stochastic	**Per room, over the heating period:** 1/CO_2 cumulative exposure indicator E'_{950} 2/Monthly average RH> 80% on critic thermal bridges from December 1st to March 1st 3/Exposure to a tracer gas emitted in toilets and in bathrooms They must be at least equal that the worst performing reference system.	An energy saving coefficient f_{reduc} is extrapolated and can be implemented in the EP-calculation	
Belgium (since 2015)	The person involved in EP-calculation and manufacturer for each DCV system	No-more existing. An advanced equivalence method has been performed by (Caillou et al., 2014) on all the systems having an agreement.	No-more existing.	Published conventional energy saving coefficients can be used directly in the EP-calculation. They depend on the sensing type, type of spaces and the regulation type	Minimum airflows over 10% of the minimum constant airflow for each room. An intermittent ventilation is allowed if the average on 15 minutes enables to comply with this 10%.

The Netherlands	The person involved in EP-calculation (standard approach) OR the manufacturer for each DCV system (equivalence approach)	Even if correction factors are given in the standard, a complementary equivalence approach can be performed, using the multizone pressure code COMIS, in a semi-probalistic approach	**Per person, over the heating period :** Cumulative CO_2 exposure over 1200 ppm: LKI_{1200} < 30,000 ppm.h	Either, correction factors given in the standard for quite a few DCV systems, are used directly in the EP-calculation, Or, Correction factors from the equivalence procedure can be used.	A function of the number of type of occupants

5 CONCLUSIONS

With the smart ventilation strategies, including demand-controlled ventilation (DCV) strategies, the concept consists in using controls to ventilate more at times 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, relative to a “dumb” base case.
This paper shows that a favourable context exists in many countries for development of such strategies and that as a result smart ventilation strategies, such as demand-control ventilation strategies, are widely and easily available on the market. The paper gives an overview of the regulations and standards proposing “performance-based approaches” in five countries to promote the use of smart ventilation strategies. The common thread in all of these methods is the use, at a minimum, of the exposure to a pollutant generated indoors (very often the CO2) and condensation risk. As a result, more than 30 compliant DCV systems are available in countries such as Belgium, France and the Netherlands.

This review highlights the need in smart ventilation design for a common metric, associated to a common evaluation method and why not a common threshold.

The present paper is a part of the project called “Smart Ventilation Advanced for Californian Homes” further developed in (Guyot, Sherman and Walker., 2017). This report includes a literature review on the suitability of common environmental variables (pollutants of concern, humidity, odors, CO_2, occupancy) for smart ventilation applications, the availability and reliability of sensors, the description of available control strategies. Next, a meta-analysis of 38 studies on smart ventilation used in residential buildings, develops the energy and indoor air quality performances, data on the occupant behaviour and the relevance of automatically control ventilation system and on the suitability of a multizone approach for ventilation. Finally, this report summarizes ongoing developments, including research into IAQ metrics and feedback on the lack of quality in ventilation installations.

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