Resilient Demand Control Ventilation system for dwellings

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ABSTRACT

Demand Control Ventilation strategy resilience is analysed through the envelope leakage distribution. Global building envelope leakage has great impact on energy consumption and targeted tightness values are systematically decreased in the several thermal regulations around the world. This leads to a more controlled ventilation system, but also to a more sensitive system to the leakage distribution. Considering fixed test cases with known entry data, two types of relative humidity based DCV strategy are analysed through their response to randomized envelope leakage distribution. A set of one hundred simulations is realized. Results shows that impact on energy is almost negligible while it is major on internal air quality. More than 50% of the simulations would have led to reject such DCV strategy while it passes all the threshold values for an evenly distributed envelope leakage. A double sensor based DCV strategy is presented in order to avoid the leakage sensitivity. Both experimental and numerical analyses are presented. Two extra indicators are then proposed to be considered in performance based approaches for multiple sensor based DCV strategy, in order to avoid undesired effects as the one observed for single sensor based DCV.

KEYWORDS

Numerical analyses, resilient ventilation systems

1 INTRODUCTION

Demand control ventilation (DCV) seems to be the main way to comply with both energy and internal air quality (IAQ) concerns. Largely spread in non-residential building since more than 2 decades (Fisk, 1998) because of large potential energy savings, its application for the residential sector is nowadays coming the basis of ventilation systems for dwellings. Indeed, thermal regulations for residential buildings in several countries give targets that are difficult to reach with constant air changes rates. In France, the successive higher thermal regulation requirements have led to the development of humidity based DCV systems for the last 3 decades. Since RT2005, and reinforced recently by the RT2012, DCV including both humidity controlled inlets and outlets has become the reference ventilation system for new construction. This development, and not restricted to France, have led to the definition of different criteria for DCV evaluation in residential. A recent review (Guyot, 2018) shows that even though a common thread using at least CO2 concentration exposure is identified, some quite different threshold values are proposed in several countries. These performance based evaluations for ventilation system are realized through numerical simulations using single or multi-zone modelling assumptions. The DCV strategies are implemented and several cases are considered with conventional entry data. In France, the cases and entry data are available in (CCFAT, 2017). It gives internal architecture, occupancy, moisture buffering effect model, climatic conditions including wind effect, scheduled occupancy and domestics' activities through water vapour fluxes and CO2 emission in the different zones. Manufacturer are invited to design their system on such fixed assumption and to match the IAQ requirements in each room and for each case. Aside from IAQ outputs, the global extracted airflow are used as inputs for thermal regulation analyses. Despite, the quite detailed simulation procedure that could lead to important benefits in term of guaranteed performance, the fixed parameters logically lead to systems optimized on the outputs used in the thermal regulation. Thus, the apparent efficiency for specific assumptions might be quite impacted by some others. Sensitivity of DCV to different parameters has been in the scope of many studies, but mainly on the energy impact (Laverge, 2011), (Rackes, 2017), among others. (Fisk, 1998) already pointed out the strong impact of building type, occupancy, and climate on the potential energy savings that could be expect from DCV. Aside from the moisture buffering effect that might have great effect on the airflow ranges used in modulation for humidity based systems, the external envelope leakage has an important influence. Envelope leakage impact on ventilation has been widely studied in the past. However, since DCV is supposed to ensure a minimum inside air quality, only the energy savings were generally considered. From several countries, the envelope leakage was identified as being responsible of up to one third of the energy consumption. Following this consensus, the different thermal regulations worldwide have decreased the limit of envelope tightness. In France, during the last decade the maximum building leakage was lowered from 1.2 to 0.6 $m^3/h/m^2$ under 4 Pa of pressure difference. Measurements (using blower doors) and quality policies by the building contractor are even required by the last thermal regulation (RT2012). This increasing building tightness made the previous DCV strategies less resilient to real site diversity and especially on its air quality guarantee.

The aim of the present study is to analyse the resilience of some DCV strategies to different leakage distribution along the building envelope. Two different standard cases are considered with each 2 different single sensor DCV strategies. At last, a particular DCV strategy coupling another sensor is used in order to increase the system resilience.

In the following, the test cases and DCV strategies are presented. The method for studying the leakage impact is then presented followed by results in a statistical form. At last, a double sensor based DCV strategy is proposed as an alternative to limit the leakage influence. Both experimental and numerical approaches are presented. A conclusion is finally proposed.

2 TEST CASE AND DCV STRATEGIES

2.1 Test cases

The test cases consist in 2 single family dwellings of 4 and 6 habitable rooms, respectively named F4 and F6 in the following. Both are two floor configurations. The F4 has kitchen and living room on the first floor and 3 bedrooms, a bathroom and toilet on the second floor. An open stairway makes the link between the two floors and all zones. The F6 configuration has kitchen, living room, one bedroom, a bathroom and toilet on the first floor and 4 bedrooms, a bathroom and toilet and the second floor. As for the previous case, an open stairway makes the link between the two floors and all zones. For all the tested strategies, airflows are extracted from all wet rooms (kitchen, bathroom and toilet) and air inlets are positioned in all dry rooms (bedroom and living room). All the configuration parameters (internal architecture, internal moisture buffering effect, occupancy and domestic activities schedules and source fluxes) are presented in (CCFAT, 2017). The global external envelope leakage is taken as mentioned in the French thermal regulation (0.6m^3/h/m² under 4Pa of pressure difference) and is evenly distributed all around the building envelope into 17 wind oriented leakage flow paths for the F4 configuration and 22 wind oriented leakage flow paths for the F6 configuration.

2.2 DCV strategies

The studied DCV strategies are humidity based. For each case (F4 and F6), two DCV strategies are considered and named hygro A and hygro B in the following. The hygro A strategy consists in humidity based outlets in wet room and pressure based inlets in dry rooms while the hygro B strategy consists in both humidity based outlets and inlets. Table 1 presents the different modulation laws for the two configurations. The values present the modulation range for air flow (m^3/h) and the corresponding relative humidity (%) (i.e. Q_{min}-Q_{max} / RH_{min}-RH_{max}). Within the modulation range, airflow evolves linearly with relative humidity. For pressure based air inlets, the values M45, M30 and M22 indicate the airflow (m^3/h) under 20Pa of pressure difference. Below, a simple quadratic orifice law is applied and airflow is kept constant above 20Pa.

Table 1: DCV modulation laws

	F4		**F6**	
zone	**Hygro A**	**Hygro B**	**Hygro A**	**Hygro B**
Kitchen	20-50 / 30-55	9-39 / 35-65	14-44 / 30-55	9-39 / 33-58
Bathroom	14-44 / 33-58	9-39 / 30-55	20-50 / 30-55	9-39 / 30-55
Living room	M45	6-45 / 46-61	M22+M30	6-45 / 46-61
Bedroom	M45	6-45 / 46-61	M22	12-90 / 46-61

For both configurations, extracted airflows in the toilet are constant at 5m^3/h and goes up to 30m^3/h two times a day for 30min. In the same way, the maximum airflow in the kitchen is activated two times a day for 30min. This maximum is fixed at 120m^3/h and 135m^3/h respectively for the F4 and F6 configuration. The operating times of the maximum airflows are fixed in the protocol (CCFAT, 2017).

3 METHODS

3.1 Numerical tools

A coupled TRNSys-CONTAM numerical simulation is used in this study. In order to match with the global assumptions of the protocol, some additional variables are computed in TRNSys which enables to generate sources flux in CONTAM. Since CONTAM does not consider some saturation phenomena, the main interest consists in taking into account some water vapour saturation in each zone with condensation/evaporation processes.

A detail description of the coupling and the added variables is available in (Faure, 2018).

3.2 Resilience to leakage distribution

The impact of external envelope leakage distribution is analysed through randomly distributed leakage while keeping constant the global building leakage value of 0.6m^3/h/m². One hundred simulations (runs) are realized with different leakage repartition. For each run, the default value of each leakage flow path is multiplied by a random coefficient so that the sum of leakage area is kept constant. Thus, for any coefficient above 1, some others are automatically below one. Figure 1 shows the cumulative distributions of all the coefficients for the hundred runs done in this study.

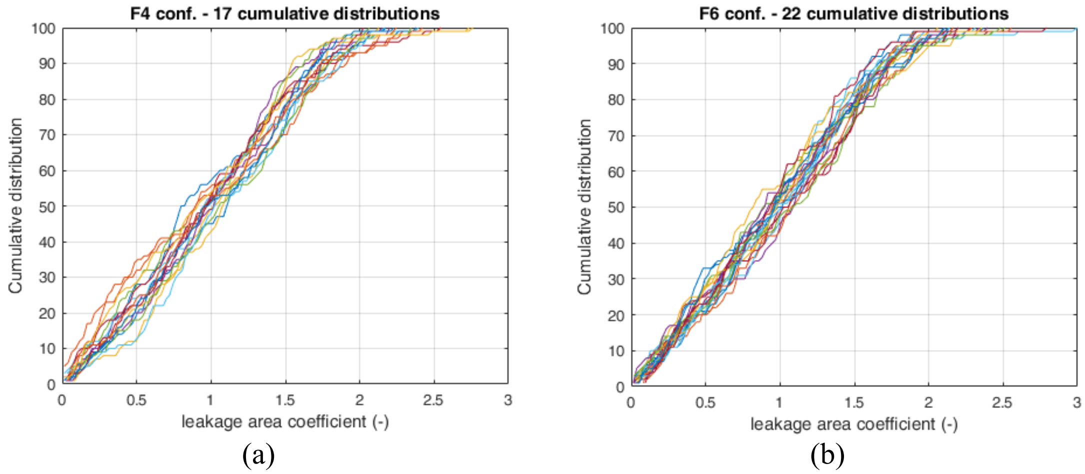


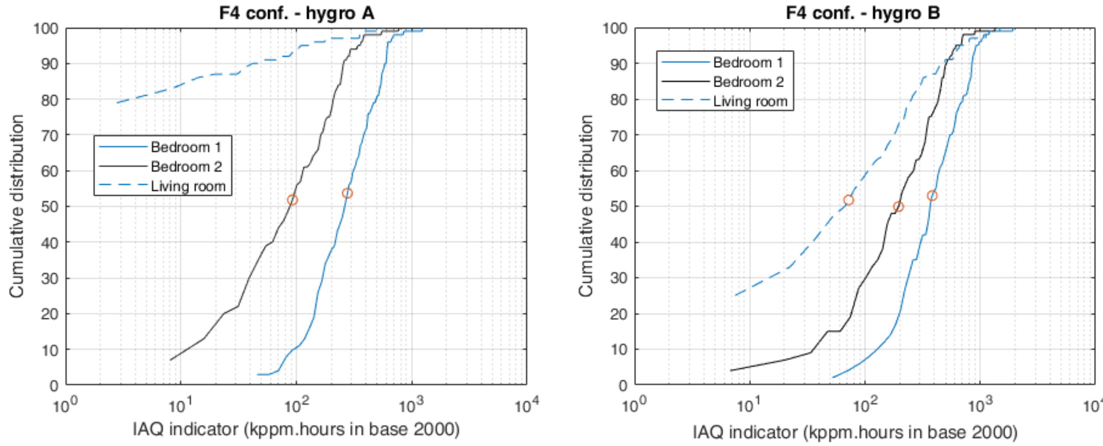
Figure 1: Cumulative distribution of the randomly generated coefficient of the different leakage flow paths for F4 configuration (a) and F6 configuration (b)

DCV strategies are evaluated using the same two indicators as the one used in the evaluation process: one concerning the occupant exposure (carbon dioxide cumulative exposure above a threshold concentration, taken at 2000ppm in this study) and one concerning the energy impact. A mean extracted airflow, when external temperature falls below 15°C, is computed. This value is taken as an input for the French thermal regulation. It is generally considered as the most important parameter for market choices. A last one is considered in the evaluation protocol for the purpose of mold development. Threshold values of time duration above relative humidity of 75% are defined for each zone type. This indicator is almost exclusively influenced by domestic activities and presents, thus, a very few sensitivity to leakage distribution. It is not presented in the following.

4 RESULTS

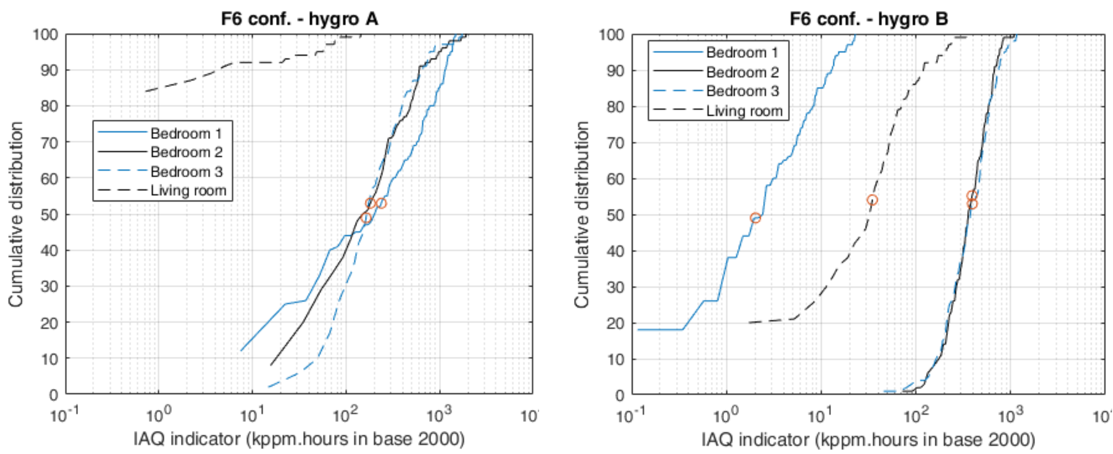
4.1 Impact on IAQ indicators

IAQ indicator cumulative distributions over the full runs are presented in Figure 2 for F4 configuration and in Figure 3 for F6 configuration. Only the zones presenting at least one run with none zero values are presented. Circle symbol on each distribution represents the reference case (evenly distributed leakage). If absent (hygro A – living room), the reference case gives 0. As mentioned, the IAQ indicator represents the cumulative integral of carbon dioxide concentrations above 2000ppm. Thus, as an example, 10 hours of exposure to 2100ppm would lead to 21kppm.hours. In accordance to the evaluation process, this indicator is computed from the 1st of October until the 20th of May.



(a) (b)

Figure 2: Cumulative distribution of the IAQ indicator for F4 conf. and DCV hygro A (a) and DCV hygro B (b)



(a) (b)

Figure 3: Cumulative distribution of the IAQ indicator for F6 conf. and DCV hygro A (a) and DCV hygro B (b)

If the IAQ indicator is above 0 for the reference case, both figure shows that it is systematically around the mid position of the cumulative distribution. The strong variability observed within each zone (slop of all curves) is representative of these DCV strategy's sensitivity to leakage distribution. Considering the evaluation process, the threshold value for such humidity based DCV strategies and configurations is 400kppm.hours per room. Which means, deriving from Figure 2 and 3, that for the same global envelope leakage, some leakage distributions would lead to reject that particular strategy. It is worth to recall that if one zone sees its IAQ indicator increase, some other will sees their IAQ indicator decrease. Table 2 presents the number of simulations with improper IAQ indicator within at least one zone.

Table 2: Number of simulations with improper IAQ indicator value in at least one zone

F4		F6	
Hygro A	**Hygro B**	**Hygro A**	**Hygro B**
29	53	63	51

The two configurations do not present the same sensitivity to leakage repartition and the effect of the two DCV strategies are inversed for both. The hygro A seems to be the most sensitive for F6 configuration but not for the F4 configuration, which shows the quite complex coupling between scenarios, configuration and effect of parameters. Aside from the influence of other parameters such as moisture buffering effect, local wind effect and, last but not least, occupancy and domestic activities, these outcomes show the too few resilience of single variable DCV strategies.

4.2 Impact on Energy indicator

The energy indicator impact is computed as a mean extracted airflow when external temperature gets below 15°C. The numerical model does not consider the fan curves. Extracted airflows are automatically ensured. Thus the variation between the different simulations comes from the humidity differences in bathrooms and kitchen (zones that has humidity based airflows). Since domestic activities and occupancy are strictly identical for all the runs, the local extracted airflows are almost identical. Table 3 shows the energy indicator for the default value and the maximum observed variation over the all runs.

Table 3: Energy indicator (m3/h) and maximum variation observed over the 100 simulations

F4		F6	
Hygro A	**Hygro B**	**Hygro A**	**Hygro B**
77.4+/-1%	61.8+/-2%	116.2+/-0.6%	92.4+/-1%

A maximum variation of 2% is identified for one case. The three others are identified at 1% or less. Modifying the numerical assumption by modelling the fan curves and air extraction network might not change these observations because of the quite flat pressure curves of the fans used.

4.3 Discussion

The global airflow network of a dwelling can be schematically presented as classical airflow network in industry like the one presented in Figure 4. Airflow inlets are positioned on each dry zone and air is extracted in all wet zones. The link between each zone is ensured by free left areas of closed doors. The envelope leakages are presented by the "Le" links to outside environment. This representation enables to visualize quite easily that some different leakage reparation will automatically lead to different airflows within each zone. As a simple example: increasing Le5 will lower the pressure in the hall and, as a consequence, will lower the global extracted airflow from the 4 dry zones.

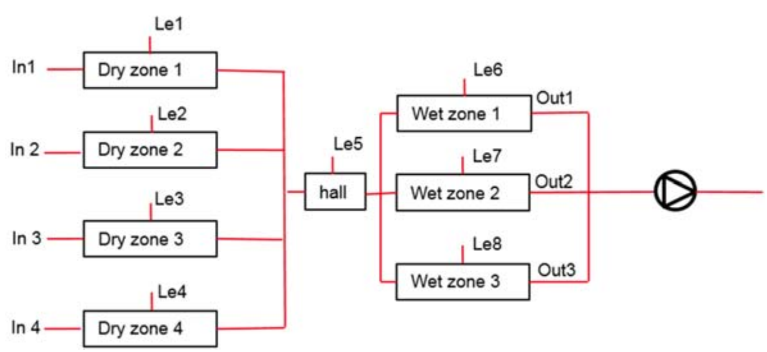


Figure 4: Schematic representation of the global dwelling airflow network

Thus, DCV strategies based on simple global extraction in wet rooms have few chances to reach the designed air changes rates in all the dry zones, since leakage distribution is impossible to control in real sites and is, for sure, not evenly distributed.

A way to ensure air change rates in any dry zone is to add extra outlet in each. Even if it might be trivial, some attention are needed to comply both energy and IAQ concerns. Aside from the fact that extracting airflow in dry room can lead to inversed airflow from wet rooms to dry rooms, introducing another sensor in DCV strategy also need extra IAQ indicators.
In the following section, such system is introduced with both numerical and experimental approaches.

5 DOUBLE SENSOR BASED DCV STRATEGY

5.1 Experimental results

A comparison is realized between single (relative humidity) and double (relative humidity and CO2) sensor based DCV strategies in an occupied single family dwelling (parts of COMEPOS project: www.comepos.fr). The update from the single to double sensor based strategy has been done by simply adding extra outlets in the three bedrooms without changing the modulations laws in the wet rooms nor the air inlets in the habitable rooms. The extra outlets ensured a minimum of $5m^3/h$ and a maximum of $30m^3/h$ with a linear increment between 1400 and 1800ppm. In this experiment no evaluation of potential inversed flow (inlets air through the dry room door) is realized nor the quantification of the energy impact of the extra outlets. Temperature, relative humidity and CO2 sensors are positioned in all the different zones. Figure 5 shows two different representations of the CO2 concentration in the main bedroom from mid-January 2017 to mid-May 2018. The double sensor based strategy has been installed at the beginning of June 2017.

Measurements are realized with another sensor than the one used by the DCV system. From the first graph, the maximum level of carbon dioxide reaches almost every day the sensor upper limits of 3500ppm in the first period and reaches a maximum of around 1800ppm during the last winter. From the second one (heat graph representation), the strong repeatability of occupancy can be identified. Further on, one can identify the wake up hour changes each weekend (small pics in the morning) as well as the winter/summer hour shifting. Two other bedrooms are occupied by young children and no significant changes were observed since even for the single DCV strategy, maximum carbon dioxide concentration were generally below 1500ppm.

Aside from the energy impact and from the air change rates reached in any zone, some control of carbon dioxide concentration and thus confinement of zone can be made through extra outlets in dry rooms. The energy impact might nevertheless be crippling for such systems, however some optimisations can be realized. Besides, as mentioned earlier, one or more extra IAQ indicators are needed in order to evaluate double sensor based DCV strategies correctly.

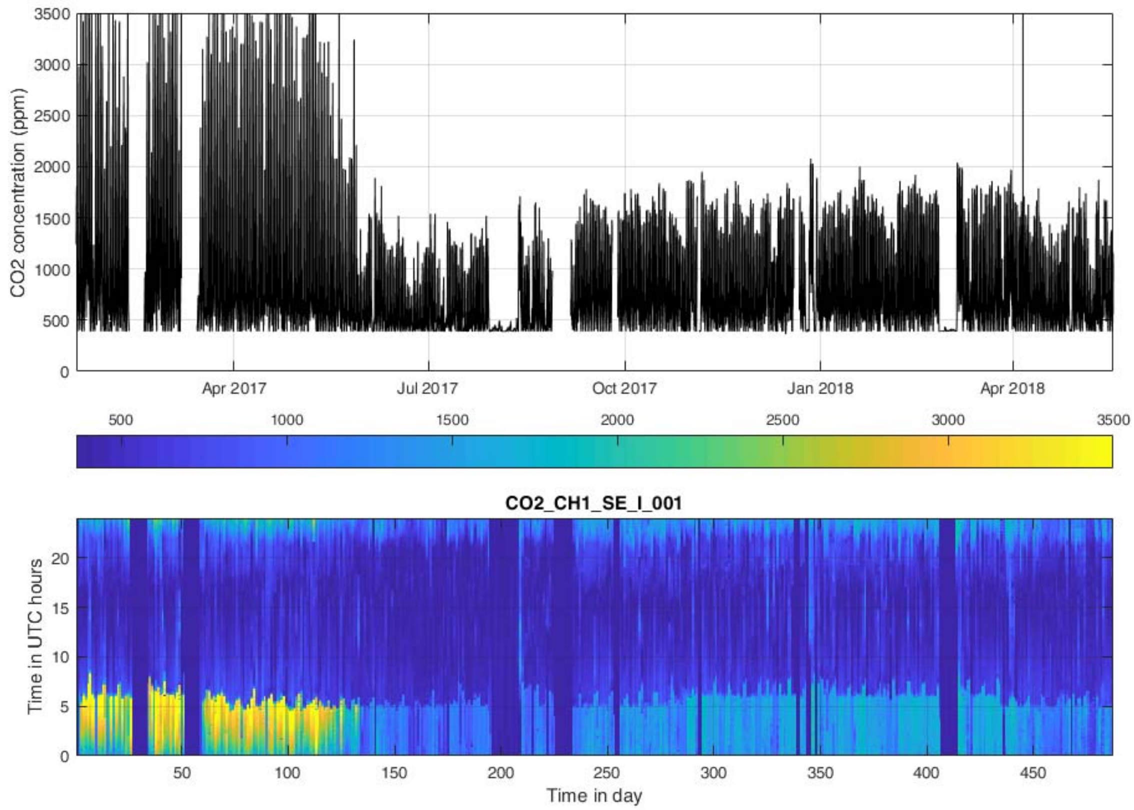


Figure 5: Carbon dioxide concentration in the parent's bed room in a temporal form (upper graph) and in a heat graph form (lower graph)

In the following, numerical simulations are realized and some extra indicators are proposed. In order to avoid strategies that would lead to non-acceptable IAQ, a similar indicator is taken based on 1200 ppm instead of 2000 ppm, as set out in the standard EN16798-1. In the same way, the inversed flow rates are quantified.

5.2 Numerical simulation

Such double sensor based DCV strategy has been modelled within MATHIS software (Demouge, 2011) with several modulation laws. Table 4 presents the modulation laws used for the different considered double sensor based cases: a hygro A strategy in the dwelling F4 and a hygro B strategy in the dwelling F2-F4-F6 (toilet apart from bathroom, except a bathroom with toilet in F6). As presented in table 1, the airflow range modulation is presented followed by the sensors (RH and CO_2) corresponding range.

Table 4: double sensor based DCV modulation laws

zone	**Case 1 Hygro A F4**	**Case 2 Hygro B F2**	**Case 3 Hyrgro B F4**	**Case 4 Hygro B F6**
		Air Outlets		
Kitchen	10-40/50-80	10-40/50-80	10-40/50-80	10-40/50-80
Bathroom	5-35/45-80	5-35/45-80	5-35/45-80	5-35/45-80
Toilet	5-30	5-15	5-30	5-30
Bedroom	2.5-15/800-1200	2.5-15/1700-2100	2.5-15/1000-1400	2.5-15/900-1300
		Air Inlets		
Living room	M45	6-45/46-61	6-45/46-61	6-45/46-61
Bedroom	M30			

Table 5 presents the results for all cases and the several indicators. Only the maximum value in all rooms is presented. These values were compared to standard single sensor based DCV as also simulated.

Table 5: Performance based indicators for DCV strategy

Case	**max IAQ 2000 ppm** (kppm.hour)	**max IAQ 1200 ppm** (kppm.hour)	**max inversed flow** (hour)	**max inversed flow 950 ppm** (kppm.hour.m³/h)	**Energy consumption** (m³/h)
Case 1	0	1745	2127	6	61.4
Case 2	45	2129	69	4	37.1
Case 3	1	2039	1384	30	57.1
Case 4	20	1949	1902	12	81.1

All cases were conform to the standard criteria of RH and cumulative exposure to CO_2-concentration (kppm.h in each room)) higher than 2,000 ppm, as set out in CCFAT (2017).
When considering the cumulative exposure to CO_2-concentration higher than 1,200 ppm, all cases showed values lower or similar to the single sensor based DCV systems.
Due to the extraction in the bedrooms, more hours during which inversion to the bedrooms occurred were found for the hygro A as well as for the hygro B system. However, the amount of CO_2 inversed to the bedrooms, expressed as the cumulative exposure to CO_2 was similar to standard systems without extraction in the bedrooms. Furthermore, no or negligible inversion was observed from wet rooms, where the risk on pollution is rather high. This indicates that the average air quality of the inversed flow could be similar for single and double sensor based DCV systems. Threshold values of these two extra indicators are to be defined with regards to existing systems available in the market. Research is still going on to define these indicators in order to be applicable for any single or double sensor based DCV systems.

6 CONCLUSIONS

Demand control ventilation strategy resilience is analysed through the envelope leakage distribution. Global building envelope leakage has great impact on energy consumption and targets values are systematically decreased in the several thermal regulations around the world. This leads to a more controlled ventilation system, but also in a more sensitive system to the leakage distribution. A set of 100 simulations is realized with constant global building envelope leakage value but with randomized distribution. The impact is observed to be very important on the IAQ indicator and close to negligible on the energy one. The envelope leakage distribution acts on the network equilibrium. Global flow paths across the entire dwelling are logically strongly influenced by the leakage distribution. As a result, and keeping all aside assumption constant, a single relative humidity sensor based DCV strategy, defined with evenly distributed leakage, would reject more than 50% of studied cases.
As an alternative, and to make DCV less sensitive to leakage distribution, a double based DCV strategy with extra outlets is analysed. IAQ efficiency is experimentally presented and a coupled IAQ and energy optimization is numerically demonstrated. Nevertheless, such system also requires some extra indicators in order to avoid undesired effects as the one observed for single sensors based DCV and to make a step forward in guaranteed performances in both fields of internal air quality and energy savings.

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