Demand controlled ventilation: relevance of humidity based detection systems for the control of ventilation in the spaces occupied by persons

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ABSTRACT

Design of ventilation systems in Belgium is currently based on the Belgian Standard NBN D 50-001:1991. This regulation is more than 25 years old, and is not anymore suited to new technologies developed in the frame of increasing energy performance of buildings and its associated ventilation systems. This standard defines four classic ventilation systems, going from A (natural ventilation) to D (double-flux ventilation eventually with heat recovery). One of its main shortcomings is that it does not consider demand controlled ventilation (DCV) systems. For example, there are no requirement in the current standard on the type of detection appropriate for the living spaces. Carbon dioxide (CO_2) is usually considered as a good tracer for human occupation.

This paper presents the experimental and numerical investigation that have been performed in a pre-normative project whose objective is to evaluate the relevance of detection based on humidity for DCV systems in the living spaces.

Experimental measurement have been carried out in 26 dwellings in Belgium during more than 1 year. Temperature, humidity, CO_2 concentration have been monitored with a 5 minutes time step in 4 rooms and outside for each building. Measurement also took place in several meeting rooms in office buildings.

The analysis of the data showed no evident link between CO_2 concentration, usually considered as reliable indicator of human occupancy, and relative humidity. Same analysis has been performed with absolute variables (volume and mass concentrations). When considering the difference in absolute humidity between inside and outside, correlations are stronger. They are even stronger when looking at time derivatives of humidity and CO_2. On basis of this dataset, the direct correlation between CO_2 and RH does not seem sufficient to consider it as a relevant detection mean for DCV systems in living spaces. However, the analysis of the variations show that there is clearly a link between the two.

Next to experimental data analysis, DCV strategies have been evaluated through simulation with CONTAM software. The target was to compare RH based detection systems with CO_2 detection systems and constant flow systems. Various strategies and control algorithms have been tested. At equivalent air quality, direct control on the RH level does not achieve significant flow reduction compared to a constant flow ventilation. An alternative algorithm based on 24h moving average of RH shows significant flow reduction compared to constant flow or direct RH regulation while keeping high IAQ. This is only a theoretical demonstration, and should be demonstrated and/or fine-tuned in practice.

KEYWORDS

Demand Controlled Ventilation, Relative Humidity, Data Analysis, Multi-zones Simulation

1 INTRODUCTION

In the context of the global warming and the increasing energy performance of buildings, demand controlled ventilation (DCV) is becoming one of the most spread techniques to reduce the ventilation heat loss of the buildings, alone or combined with other techniques like heat recovery ventilation. It also decreases fans energy consumption in the case of mechanical ventilation.

Design of ventilation systems in Belgium for residential buildings is currently based on the Belgian Standard NBN D 50-001:1991 which is more than 25 years old and not anymore adapted to current technologies. While demand controlled ventilation is authorized in this standard, it does not give any indication on how to implement DCV. For example, there are no requirement in the current standard on the type of detection appropriate for the living spaces.

Carbon dioxide (CO_2) is usually considered as a good tracer for human occupation. This tracer is widely used for DCV in practice or in technical or research publication. Another common alternative is the presence detection. Relative Humidity (RH) is also often considered for DCV applications but in different ways depending on the country and/or the authors.

In Belgian practice and regulation [1], RH detection is mostly used for DCV of the so-called "humid-spaces" (bathroom, laundry, kitchen, etc.) and not for the living spaces. The practice in Netherlands is very similar to the one in Belgium, as [2] stays that "*RH is no appropriate indicator to assess the presence of people in living spaces … the moisture production of people it too small and the absorption capacity of materials too big … to adequately regulate in the presence of people*". On the contrary, RH based DCV in living spaces is widely used [4] and studied in various projects [5] in France.

The present work has been carried on in the frame of a pre-normative project whose objective is to develop the scientific background for a future revision of the Belgian Standard, including DCV aspects. The purpose of this paper is to analyze the relevance of RH based DCV to insure IAQ in the living spaces.

2 ON SITE MONITORING – DATA ANALYSIS

In the first part of this work, monitoring data of existing buildings has been analyzed to identify how strong is the link between moisture and CO_2, the latest being considered as a relevant indicator of human presence and human-related pollutants.

Monitoring data were available for 25 residential buildings and a few meeting rooms in office buildings.

2.1 Analysis of the residential buildings

The 25 residential buildings considered in this paper were part of the CALE ("Construire Avec L'Energie") program, a volunteer program aiming at energy efficiency of buildings that took place from 2004 in the Walloon Region (Belgium) before the first EPB regulations. Most of the buildings were equipped with double-flux heat-recovery ventilation systems.

For these buildings, measurements took place during almost two years in the living room, 2 or 3 sleeping rooms and outside at immediate proximity of the building. All measurements were carried out with Netatmo Weather Stations NWS01 with a frequency of 5 minutes. Measured variables were CO2 concentration (ppm), RH (%) and temperature (°C).

In the present analysis, we do not have any information on the control of the ventilation system and will only analyse raw measurement data. We computed the Pearson's correlation coefficient (linear correlation coefficient) for various variables combinations:

- CO_2 and RH
- CO_2 and moisture content
- CO_2 and additional moisture content compared to exterior
- CO_2 time derivative and RH time derivative

The data have been analysed for the living room and the main bedroom of each building on different periods (whole year or per season).

CO_2 vs. RH

Overall, the analysis of the measurement data has shown a weak correlation between CO_2 and RH. Figure 1 and Figure 2 show scatter plots for the living room of 2 out of the 25 buildings. If there is some correlation on the first one, the correlation is almost zero for the second one. A separate analysis for the winter (not presented in detail here) show that the coefficient correlation are generally slightly higher than on the whole year basis. The correlation coefficients have been computed for all 25 buildings, and the results are summarized in table Table 1.

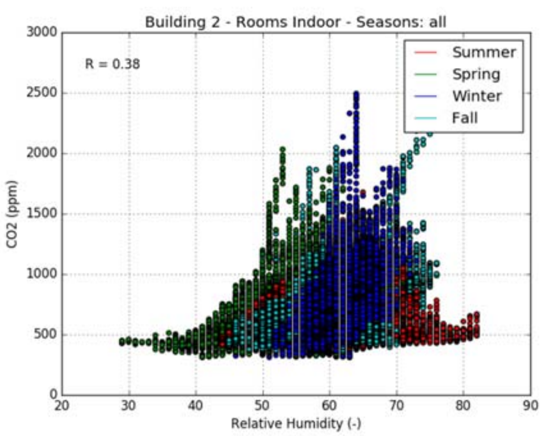

Figure 1: CO_2 vs. RH for living room of one of the residential buildings – A moderate linear trend is visible. While the maximum CO_2 levels are close for every season, the related RH are clearly different.

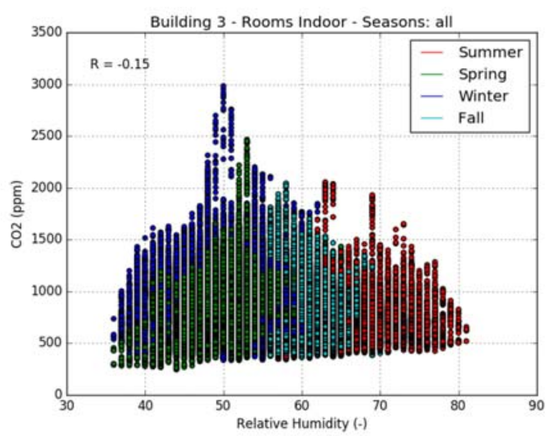

Figure 2: CO_2 vs. RH for living room of one of the residential buildings – The difference in RH values is clearly visible between the seasons, but there is not linear trend at all between the two variables.

CO_2 vs. Moisture content

As we try to correlate the concentration of two "pollutants" due to human presence, it is more meaningful to use absolute quantities (mass or volumes concentration) than RH (in %), which is impacted by the indoor temperature. As the temperature was also measured during the monitoring, the moisture content [g/kg] has been recomputed. An identical analysis as with the RH has been performed. Results are not presented in detail here, as the correlation coefficients are not very different from the ones from the previous section.

Table 1: Analysis of correlation (linear correlation coefficient) bewteen CO_2 and RH for 25 residential buildings. Altough there is a correlation for some of the buildings, the analysis of the 25 buildings show that the correlation is not obvious or even inexisting. Limiting to the winter period improves a little bit the correlation.

Correlation coefficient statistic	Living room – all year	Main bedroom – all year	Living room – winter	Main bedroom – winter
Average	0.05	0.09	0.07	0.20
Standard deviation	0.14	0.14	0.19	0.13
Maximum	0.38	0.36	0.43	0.54
Minimum	-0.15	-0.29	-0.27	0.01

CO_2 vs. additional moisture content compared to exterior

In the previous paragraph, the moisture has been used rather than RH to eliminate the effect of inside temperature. However, the absolute moisture content is strongly impacted by the exterior climate. On the contrary, the exterior CO_2 concentration is less variable. We tried to correlate the indoor CO_2 concentration with the difference in moisture between interior and exterior (in g/kg). Results of this analysis are summarized in Table 2. The average correlations were significanty higher than for CO_2 vs. RH correlations. However these correlation coefficients remained low (lower than 0.4) and variable (minimum values close to 0 or even negative values).

Table 2: Analysis of correlation (linear correlation coefficient) bewteen CO_2 and addiontal moisture for 25 residential buildings. Average correlation are significanty higher than for CO_2/RH, while still quite low in the absolue.

Correlation coefficient statistic	Living room – all year	Main bedroom – all year	Living room – winter	Main bedroom – winter
Average	0.32	0.39	0.33	0.28
Standard deviation	0.13	0.13	0.12	0.13
Maximum	0.54	0.57	0.59	0.52
Minimum	0.00	0.12	0.09	-0.04

CO_2 time derivative vs. RH or moisture time derivative

Previous example show that “variations” (between exterior and interior) of contaminants are more correlated than absolute values. In the same order of idea, a similar analysis was performed using time variations (derivatives) of CO_2/RH and CO_2/moisture content

Note that the derivatives had to be computed on smoothed signal for two main reasons:

- The noise in the measurement;
- The relatively weak variation of relative humidity combined with the accuracy of the RH measurement (0.01). This gives a stair step signal hardly usable as such to compute time derivatives.

The applied smoothing and the resulting derivatives are illustrated on a two days period in Figure 3 and Figure 4.

The scatter plots and correlation coefficients between the time derivatives are illustrated in Figure 5 and Figure 6, and results on the 25 buildings summarized in Table 3.
Using time derivatives of CO_2 and RH or moisture content showed significantly better correlations than using absolute values of CO_2 or humidity. The correlation coefficients were between 0.4 and 0.6 on average. However, the correlation remained poor in some cases as shown by the low minimum values in Table 3.

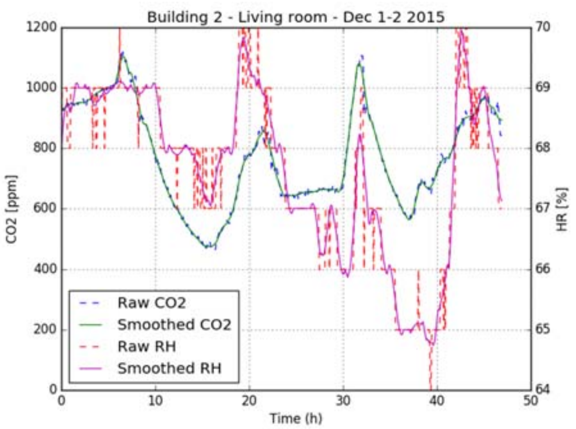

Figure 3: Example of smoothed time signal from raw data – CO_2 concentration on the left y-axis, RH (%) on the right y-axis. Measurement frequency of 5 minutes. Both signals have been smoothed using polynomial interpolation.

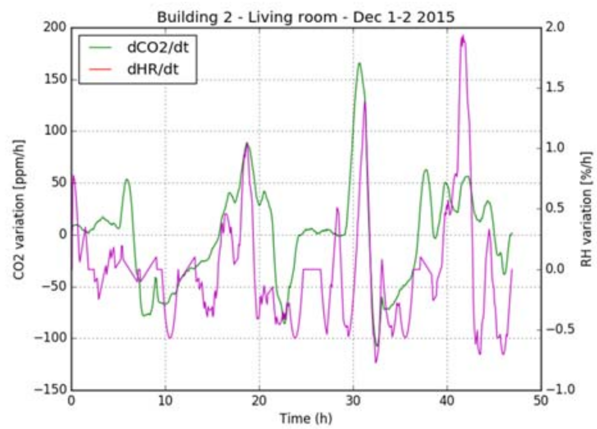

Figure 4: Time derivatives corresponding to Figure 3 smoothed signal.

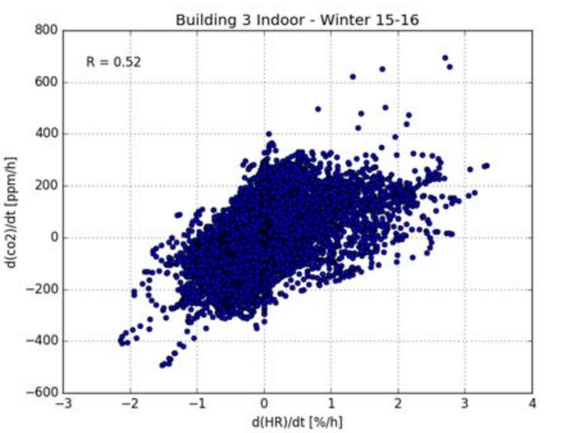

Figure 5: Correlation between CO_2 and RH time derivatives for one of the residential building on the 2015-2016 Winter months.

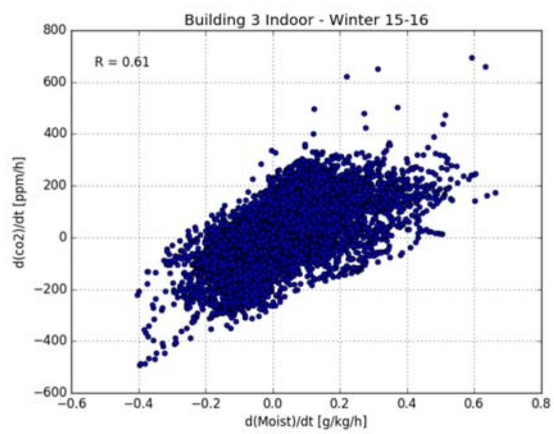

Figure 6: Correlation between CO_2 and Moisture content time derivatives for one of the residential building on the 2015-2016 Winter months.

Table 3: Analysis of correlation (linear correlation coefficient) bewteen CO_2 time derivative and RH or moisture (x) time derivatives for 25 residential buildings for the Winter 15-16 period (Dec, Jan, Feb). Average correlation bewteen 0.4 and 0.6, i.e. much higher than correlations between the absolute values.

Correlation coefficient statistic	Living room $\frac{d\,CO_2}{dt}$ vs $\frac{d\,HR}{dt}$	Main bedroom $\frac{d\,CO_2}{dt}$ vs $\frac{d\,HR}{dt}$	Living room $\frac{d\,CO_2}{dt}$ vs $\frac{d\,x}{dt}$	Main bedroom $\frac{d\,CO_2}{dt}$ vs $\frac{d\,x}{dt}$
Average	0.42	0.46	0.58	0.44
Standard deviation	0.15	0.13	0.10	0.16
Maximum	0.66	0.73	0.81	0.66
Minimum	0.05	0.20	0.35	-0.02

2.2 Analysis of meeting rooms in office buildings

The same path as for residential buildings has been followed for 4 meeting rooms located in two different office buildings in Brussels area. The results are presented only for one of the four (room "LOZ-4"), but the other rooms showed similar trends. The scatter plot for the 4 pairs of variables are given in Figure 7 to Figure 10 for a winter period. One can draw similar conclusions as for the residential buildings. Note that for the summer period (not presented here), little to no correlation is to be observed for any of the 4 data pairs.

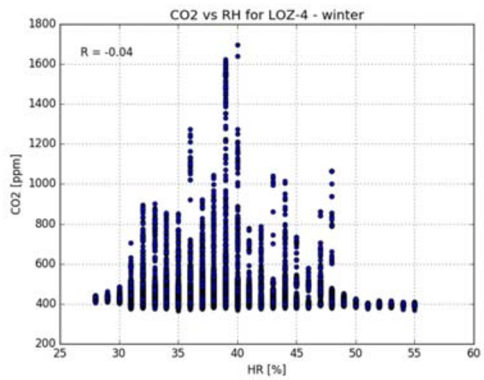

Figure 7: Room "LOZ-4" - CO_2 vs. HR for winter 2017-2018.

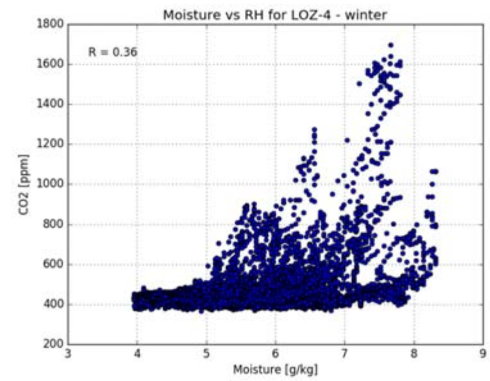

Figure 8: Room "LOZ-4" - CO_2 vs. moisture content for winter 2017-2018.

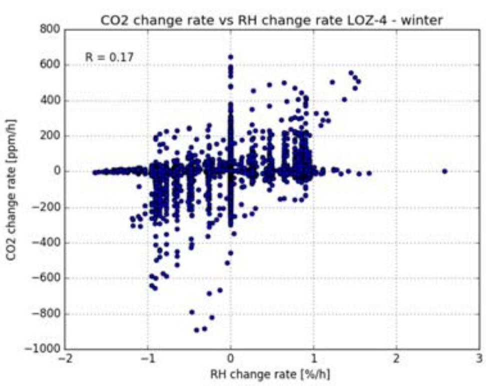

Figure 9: Room "LOZ-4" - CO_2 time derivative vs. HR time derivative for winter 2017-2018.

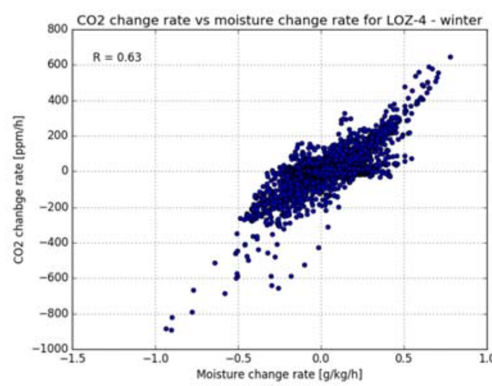

Figure 10: Room "LOZ-4" - CO_2 time derivative vs. moisture content time derivative for winter 2017-2018.

2.3 On site monitoring - Conclusion

From the data analysis of on-site monitoring in residential and office buildings, the conclusions is that RH level [%] only is not a reliable indicator of human presence in comparison to the CO_2 concentration as reference. The absolute values (moisture content, g/kg) seems slightly better correlated to the CO_2 reference, but the correlation remains very weak. Using the additional moisture content compared to exterior gave better results. The best correlations were found using time derivatives of RH or moisture content compared to CO_2. In the context of DCV, the question is how these parameters (additional moisture content compared to exterior, or time derivative of RH or moisture content) could be used to operate properly a ventilation system and how effective are these type of detection compared to CO_2 or presence detection.

3 MULTI-ZONE SIMULATIONS

3.1 Purpose of the simulations

In parallel to the on-site monitoring analysis, a multi-zone simulation model has been set-up with the CONTAM software to assess the performance of RH-based regulation strategies compared to other reference strategies to insure the IAQ in the living spaces.

3.2 Model and hypotheses

The reference model used is a single floor dwelling with 3 bedrooms, i.e. designed for 4 occupants. The considered system uses mechanical supply in living and sleeping rooms and mechanical extraction in service rooms. The analysis will focus on the living room and the main bedroom, where the air quality will mainly be affected by

- The local pollutant source and wall buffering;
- Outdoor climate;
- Ventilation flow rate and DCV strategy.

The pollutant emissions used for this analysis are listed in Table 4.

Table 4: Pollutant sources per person in the simulation model.

Pollutant	Pollutant emission – awake	Pollutant emission – asleep
CO_2 (l/h)	16	10
H_2O (g/h)	55	40

The reference occupancy profile used in this analysis is illustrated graphically in Figure 11. The weather file is the reference file from the Uccle (Brussels) meteorological station, and the considered period is the heating season (October to April included). The nominal flow are 100 m³/h for the living room and 50 m³/h for the bedroom (i.e. 25 m³/h per person).

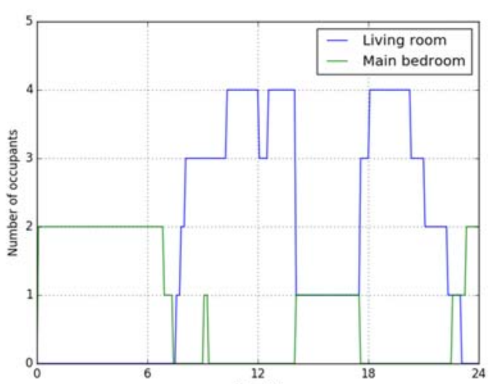

Figure 11: Reference occupancy profile used in living and main bedroom.

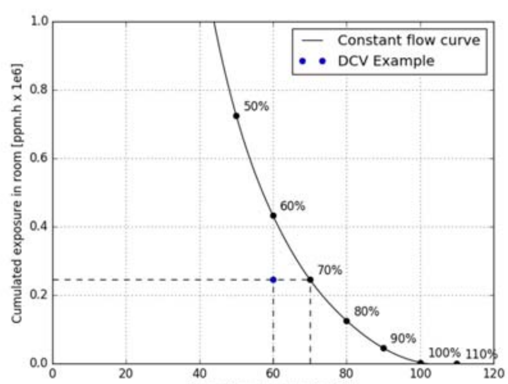

Figure 12: Comparison of DCV strategies with reference curve. In this example case, the DCV strategy (blue dot) gives IAQ equivalent to constant flow of 70% (of nominal), while the average flow over the period is only 60% of the nominal.

3.3 IAQ criteria and reference curve

The used IAQ criteria for the analysis is the cumulated CO_2 exposure above 1000 ppm (absolute using 400 ppm outside). Its mathematical expression is given in equation (1).

$$E = \int_t CO_2(t)[CO_2 > 1000] - 1000\, dt \quad (1)$$

The total exposure was computed for constant flow going from 50% to 100% of the nominal flow. The efficiency of each DCV strategy was evaluated by comparing the average flow of the DCV strategy over the whole period (i.e. proportional to ventilation loss) to the "constant flow" giving the same IAQ. The rationale is illustrated in Figure 12.

3.4 Types of controls

Various controls strategies were used in the analysis:

- CO2 proportional: linear flow variation from Q_{min} for CO_{2min} and Q_{max} for CO_{2max}
- RH proportional: linear flow variation from Q_{min} for RH_{min} to Q_{max} for RH_{max} (in 'living' spaces)
- Moving average: see below.

The 'moving average' control is defined by (detection in living space):

$$Qs(t) = K_p . RH(t) + C + K_{ma}\,(RH(t) - RH_{ma}) \quad (2)$$

With:

- K_p and C the constants of the proportional controller on RH (implicitly defined by minimum flow and RH thresholds)
- RH_{ma} the relative humidity averaged on the last 24 hours
- K_{ma} an arbitrary gain for the moving average term

This moving average term is expected:

- To change little or nothing when there is no occupancy since RH will stay close to RH_{ma};
- To add a steady state flow when humidity is higher than "normal", which is a sign that there is possibly an occupation;
- The "normal" is defined as the moving average on last 24 hours so that its evolution is slow but is adapted to the exterior climate with a time constant of 1 day.

The values used for the three types of controllers are given in Table 5, Table 6 and Table 7.

Table 5: Threshold and relative flow rate for CO_2 linear control in living spaces.

	Flow rates		CO_2 thresholds [ppm]	
Regulation	Q_{min}	Q_{max}	$CO_{2\,min}$	$CO_{2\,max}$
CO2-1	0.1	1.0	400	1000
CO2-2	0.1	1.0	400	900
CO2-3	0.3	1.0	400	800

Table 6: Threshold and relative flow rate for RH linear control in living spaces.

	Flow rates		RH thresholds	
Regulation	Q_{min}	Q_{max}	RH_{min}	RH_{max}
RH-1	0.1	1.0	0.5	0.9
RH-2	0.1	1.0	0.4	0.6
RH-3	0.3	1.0	0.4	0.6
RH-4	0.3	1.0	0.35	0.65
RH-5	0.5	1.0	0.35	0.65

Table 7: Threshold, relative flow rate and controller constant for the moving average control in living spaces.

	Flow rates		RH thresholds		K_{ma}
Regulation	Q_{min}	Q_{max}	RH_{min}	RH_{max}	
MA-1	0.3	1.0	0.35	0.7	10
MA-2	0.3	1.0	0.35	0.7	15
MA-3	0.5	1.0	0.35	0.7	10
MA-4	0.5	1.0	0.35	0.7	15
MA-5	0.3	1.0	0.35	0.7	25
MA-6	0.1	1.0	0.35	0.7	25

3.5 Results and discussion

Only living room results are presented, but the results are very similar for the main bedroom. Comparison of the different strategies for the reference occupancy are presented in Figure 7, Figure 8 and Figure 9. The best strategies in terms of IAQ of each type have been applied on a case with additional occupancy (with 5th occupant), see Figure 10. We draw the following conclusions:

- At equivalent IAQ, linear flow rate regulation based on RH detection give little flow rate reduction compared to constant flow rate ventilation. Furthermore, the resulting IAQ is not close to nominal flow or CO_2 reference;
- The proposed moving average technique gives significant improvement, and allow reaching better IAQ, close to the CO_2 reference.

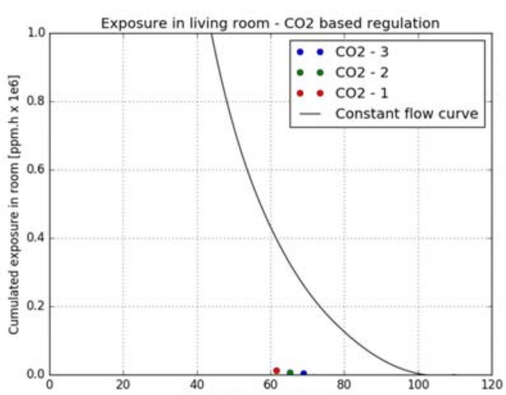

Figure 13: Results of CO_2 DCV strategies for reference occupancy profile.

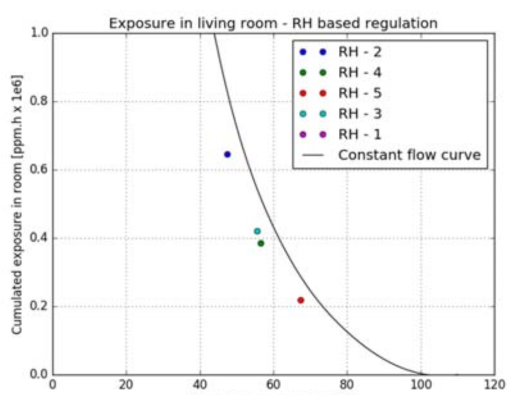

Figure 14: Results of RH DCV strategies for reference occupancy profile.

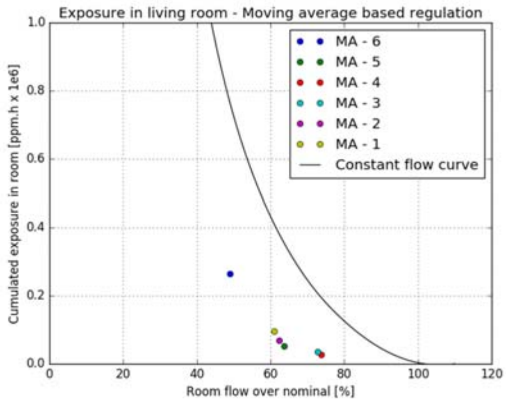

Figure 15: Results of moving average DCV strategies for reference occupancy profiles.

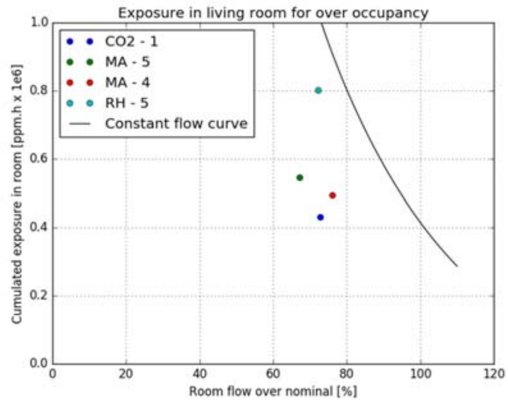

Figure 16: Results of several strategies for over-occupancy (5th person in the living room).

At this stage, it is important to recall that the purpose of the analysis was not to develop a new control strategy based on RH, but to verify if RH could be a relevant control parameter for DCV in living spaces. The answer is not straightforward. Linear control based on RH does not seem more efficient than constant flow regulation, while the alternative algorithm seems much better.

4 GENERAL DISCUSSION AND CONCLUSIONS

The target of this paper was to analyse the relevance of humidity-based regulation for the demand-controlled ventilation of living spaces in buildings.

From the on-site monitoring analysis performed on 25 residential buildings and a few meeting rooms, we tried to identify how humidity-based indicators are correlated with CO_2 concentration, generally accepted as a good indicator of occupancy. The conclusions of the data analysis are:

- Relative humidity alone is not a good indicator of human presence, as its correlation with CO_2 is generally very weak. Correlation of CO_2 with absolute humidity (moisture in g/kg) is barely better.
- When looking at humidity variations (in time) or differences (between inside and outside), the correlations with CO_2 are stronger. The clearest correlation is the one between CO_2 time derivative and absolute moisture time derivative.

The simulations performed with the CONTAM software reinforce these conclusions:

- Linear control of ventilation flow rate based on RH leads to worse IAQ than reference CO_2 control. At equivalent IAQ, the flow reduction is about a few percent compared to a constant flow rate regulation.
- An example control logic based on RH moving average gives flow rate reduction and IAQ close to the CO_2 reference. This control logic implicitly makes use of the stronger link between CO_2 and humidity variations emphasized in the data analysis.

The main conclusion is that RH as such seems to be a poor control variable for the detection of people using demand controlled ventilation, especially compared to CO_2. Alternative algorithms based on RH could have some potential, but it should be confirmed in practice since RH variations have small amplitude and the practical accuracy of sensors may limit the efficiency. Of course, these issues do not arise with a simulation model.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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