Long-term durability of humidity-based demand-controlled ventilation: results of a ten years monitoring in residential buildings

Elsa Jardinier*[1], François Parsy[1], Gaëlle Guyot[2], and Stéphane Berthin[1]

1 AERECO SA
62 rue de Lamirault – Collégien
77615 Marne la Vallée Cedex, France
elsa.jardinier@aereco.com

2 CEREMA Direction Centre-Est
46, rue Saint Théobald
F-38080, L'Isle d'Abeau, France

ABSTRACT

In-situ performance of mechanical humidity-based mechanical exhaust ventilation (RH-MEV) is characterized in this study. This ventilation system includes fully-mechanical air inlets in the dry rooms and exhaust units in the wet rooms: the extensions and retractions of a hygroscopic fabric modify their cross-sections upon hygrometric changes in their environment without the need for motors or electronic sensors.
This demand-controlled ventilation (DCV) system was invented 35 years ago; it is now widely used in Europe, and the first ventilation system in new French residential buildings.

A large-scale monitoring on thirty new occupied apartments in two residential buildings, equipped with this system, was held from 2007 to 2009. The equipment included indoor air quality (IAQ) sensors in different rooms of each dwelling (temperature, humidity, and CO_2), as well as pressure and volume flow sensors for monitoring the ventilation system. Recordings were performed every minute over two years. This former study showed:

- The good IAQ in terms of CO_2 and humidity provided by the ventilation system, despite the over-occupation of some apartments. These results showed the system's appropriate reaction to human occupation resulting from a good correlation between CO_2 and airflows.
- The statistical real-field savings on heat losses of 30 % in average compared to constant airflows from the French regulation.
- The good agreement of the heat loss measurements with the simulation models used for the French DCV technical agreements.

Ten years later the acquisition system is turned back on with the intention to assess the ventilation system behaviour/performance after a prolonged in-situ functioning period. We present in this article the results of a preliminary study:

- At start-up, more than 80 % of the metrology is still in working conditions.
- Using this rough data, the average in-situ drift of the hygroscopic devices after 9 years of operation is estimated below ± 1.5 %RH and is lower than the announced accuracy of the electronical humidity sensors at installation (± 1.8 %RH).
- The observed drift of volume flows on some of the exhaust units is typical of an absence of maintenance.
- The battery of the presence-based toilet exhaust is often (90 %) discharged.

These first promising results will be followed by a thorough IAQ and performance study which shall include:

- The collection of the ventilation devices for a full quality control before and after the recommended maintenance.
- The collection of the metrology sensors for re-calibration and drift-correction on the measurements.
- A new set-up for each apartment including pollutant (VOC, particle matter) sensors to follow the latest interests of IAQ research.

KEYWORDS

Demand-controlled ventilation (DCV), humidity-controlled mechanical exhaust ventilation (RH-MEV), indoor air quality (IAQ) energy, monitoring, residential

1 INTRODUCTION

In Europe, several countries enable and/or promote the use of demand-controlled ventilation (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, Guyot, Walker and Sherman 2018). Pushed by the international movement toward nearly-zero energy buildings, this 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 2014) – are moving towards a generalization of low-pressure systems, DCV systems and balanced heat recovery systems by 2018. With DCV, the indoor air quality (IAQ) for the building and its occupants is guaranteed, as ensured by European countries agreement procedures or certifications (Guyot, Sherman, et al. 2017).

Historically born 35 years ago in a context of energetic crisis, humidity-controlled mechanical exhaust ventilation (RH-MEV) was designed to protect the buildings from condensation induced by tighter building constructions and lower indoor temperatures, while limiting the heat losses due to ventilation. RH-MEV is a DCV system adjusting the airflows according to the estimated needs of the building and its occupants, with a direct relative humidity (RH) measurement in both the wet and dry rooms. The extensions and retractions of a hygroscopic fabric modify the cross-section of inlets and outlets upon hygrometric changes in their environment without the need for motors or electronic sensors.

Relative humidity has direct incidences not only on buildings sanitary quality but also on comfort and health of the occupants. This parameter is used to assess the ventilation needs, as humidity is directly correlated to occupancy and occupant activities, produced by breathing, cooking, showering, or clothes washing and drying. When no activity or occupancy is detected, minimum airflows are maintained, as required by the French regulation for correct dilution of pollutants not linked to occupancy – such as volatile organic compounds (VOC).

Several on-field studies were performed (Savin, Berthin and Jardinier 2016) in the last 25 years, proving and improving the above-mentioned performances of the RH-MEV systems.

In this paper, the studied ventilation system includes fully-mechanical air inlets in the dry rooms and exhaust units in the wet rooms, except in the toilets equipped with an occupancy sensor. Energy savings have been estimated about 30 to 50 % of the heating energy compared to constant airflows MEV (Savin and Bernard 2009).

Its simple and reliable components and principle of operation allow its robustness, low cost and ease of installation. This last aspect is of tremendous importance, knowing that non-compliance to ventilation systems installation rules are observed in 50 to 65% of the controlled dwellings (ADEME 2016).

As a result, and pushed by the energy performance regulation, this system has been the most widely installed in new French dwellings in the past 10 years (Bailly, G.Guyot and Leprince 2016).

We present a 10 years follow-up study on a large-scale monitoring on thirty new occupied apartments in two residential buildings equipped with this RH-MEV system, which extended from 2007 to 2009 in Paris and Lyon, France. The equipment included IAQ sensors in

different rooms of each dwelling (temperature, humidity, and CO_2), as well as pressure and volume flow sensors for monitoring the ventilation system.
In the first part of this article, we describe the studied RH-MEV system and its components. We then present the main results of the initial 2007 to 2009 project. We finally introduce the 10-years follow-up study, starting by some preliminary results, followed by the perspectives for the study that will be held over the next two years.

2 MECHANICAL EXHAUST HUMIDITY-CONTROLLED VENTILATION

2.1 System and working principle

Mechanical exhaust ventilation (MEV) is based on the sweeping principle (see figure 1.a): an exhaust fan ensures an under-pressure in the dwelling, allowing the outdoor air to come in through air inlets (figure 1.b) situated in the “dry” rooms (bedrooms and living room) and go out through exhaust units located in the service or “wet” rooms (kitchen, bathroom, toilets).

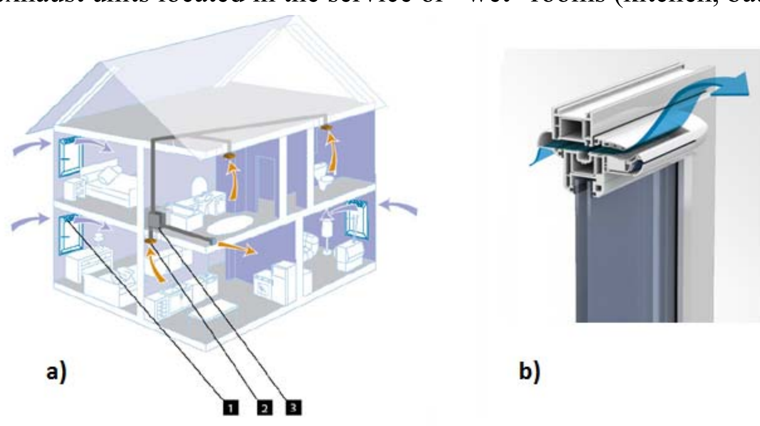

Figure 1: a) Sweeping principle and MEV components: 1. Air inlet, 2. Exhaust unit, 3. Fan. b) Example of an air inlet

In the humidity-controlled MEV (RH-MEV) system described here, both the exhaust units and air inlets are humidity sensitive. The unit aperture is controlled by a humidity sensor: if the air is dry enough, its opening area is minimum, so that the airflow is at its minimum. When a pollution episode – such as cooking or showering – occurs, or for prolonged occupation, the humidity rises in the room and is detected by the unit sensor. As a result, the opening area gets wider, according to the humidity level, and the volume of air passing through the room is increased, removing and diluting the pollutants.
The fan is pressure-constant: the airflow directly depends on the exhaust unit opening area.
Exhaust units and air inlets have different hygroscopic behaviours and are adapted to the kind of pollution they need to remove – high humidity events in the wet rooms and mainly breathing in the dry rooms.
A typical exhaust unit hygroscopic curve envelope is presented on figure 2.a. The humidity and airflow ranges are wide in order to respond to high humidity peaks during cooking or shower events as well as lower humidity levels due to occupancy.

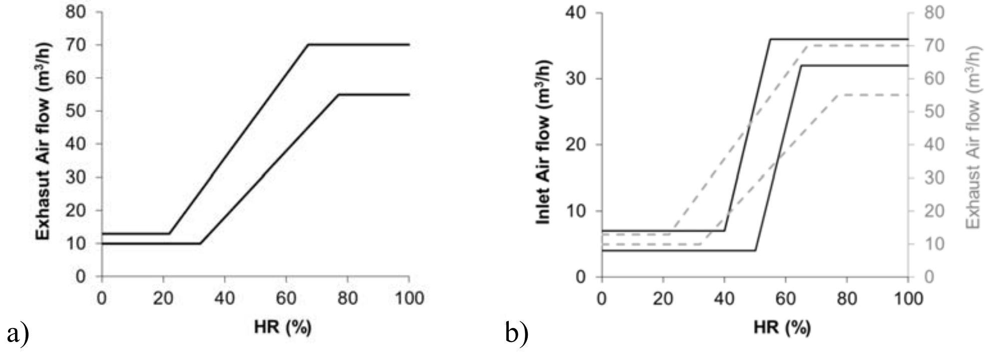

Figure 2 : a) Exhaust unit hygroscopic curve envelope. The airflow increases with relative humidity. Every type of exhaust unit is designed to have particular RH and airflow ranges to be as close as possible to the typical needs of the room. b) Inlet hygroscopic curve envelope (black curve). The airflow increases with humidity. The previous exhaust unit curve has been added in dotted grey to show the slightly steeper curve of the inlet, with adapted RH and airflow ranges: lower humidity and airflow ranges in a dry room than in a wet room.

Air inlets (see a typical envelope on figure 2.b), exhibit higher sensitivity to small changes of relative humidity on lower ranges, such as the one brought by human breathing. As a result, in an occupied room, the inlet aperture widens-up in response to rising humidity, increasing the proportion of the total airflow passing through it. In the meantime, in an unoccupied room, the opening area remains minimum, reducing the airflow passing through the air-inlet.

As a result, air is distributed according to the occupation needs.

In addition, the humidity-charged air travels through the dwelling towards the humidity-controlled exhaust units, which gets more opened, increasing the total airflow.

More details are given in (Savin and M.Jardinier 2009).

As far as the humidity sensor is concerned, several techniques have been experimented. Among them, nylon-based mechanical sensor and actuator is massively used due to its proved reliability (Savin, Berthin and Jardinier 2016). It is presented hereafter.

2.2 Hygroscopic components

The hygroscopic component we are presenting here is both a sensor and an actuator, taking advantage of the hygroscopic properties of the nylon-strips it is made of. The sensor detects humidity changes: when humidity increases, the nylon strips elongate while they shorten for decreasing humidity. Attached to a spring, the sensor mechanically actuates a shutter, defining the free opening area of the ventilation terminal (air inlet or exhaust unit), as seen on the hygroscopic curves previously presented. The components are designed so that the nylon strips are kept away from the airflow and therefore protected from grease and dirt.

Figure 3 : Hygroscopic nylon strips sensor and actuator in an exhaust unit

This mechanical sensor and actuator works with no electrical energy and does not require any wiring or battery. This not only ensures its robustness and reliability by limiting the risk of failure and drift but also reduces the risk of wrong installation of ventilation terminals.

The 2007-2009 large-scale monitoring we present below is one of the studies that have shown the efficiency of the RH-MEV systems based on hygroscopic nylon strips. Its context, execution and main results are reported in the next part of this article.

3 2007-2009 MONITORING

3.1 Context and objectives

The initial study (Savin and Bernard 2009) involved the main French RH-MEV manufacturer and distributors, in collaboration with public and private laboratories. It was held in three phases. The aims of the first phase was to formalize a quality approach to improve the performances of the buildings in terms of permeability and ducts installation. It was adopted in the second phase on two new residential buildings, as early on as the construction phase.

The third part consisted in a large-scale monitoring on thirty new occupied apartments (1 to 4 bedrooms) in the aforementioned buildings (see table 1), equipped with RH-MEV system. The aim was an on-field evaluation of the RH-MEV components and systems in terms of energetic performance and indoor air quality, over two heating seasons (2007-2009). The ventilation terminals were instrumented, and the buildings were equipped during the construction phase.

Table 1 : Characteristics of the instrumented buildings

Site	Height	Type of dwellings	Permeability	Monitored
Paris	8 floors	1 to 5 main rooms	I4 = 1.07 m3/h/m² @ 4 Pa n50 = 1.51 ACH @ 50 Pa	19 dwellings
Lyon	6 floors	2 to 5 main rooms	I4 = 0.64 m3/h/m² @ 4 Pa n50 = 0.94 ACH @ 50 Pa	10 dwellings

3.2 Instrumentation and metrology

The dwellings and ventilation terminals were instrumented as follows:

- In the living room and one or two bedrooms, sensors units including electronical CO_2, relative humidity and temperature sensors were installed.
- In the kitchens and bathrooms, sensors units including electronical relative humidity and temperature sensors were installed. In two dwellings CO_2 was recorded as well.
- In the toilets, presence infrared (PIR) sensors controlling the exhaust units were monitored.
- Every exhaust unit was equipped with a pressure sensor in ducts, as well as a hall-effect sensor to monitor its aperture. Measuring the aperture and the pressure allowed to compute the airflow passing through the unit.
- Every air inlet was equipped with hall-effect sensors to monitor its aperture.

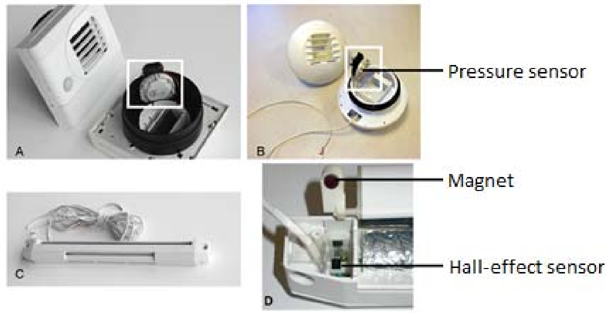

Figure 4 : Instrumented ventilation terminals. (A and B) Exhaust units are instrumented with aperture (hall effect) and pressure sensors (+ PIR for in the toilets). (C and D) Air inlets are instrumented with aperture sensors.

- Outdoor conditions (temperature, humidity, CO2 and wind speed and direction) were monitored.

Every sensor (except CO_2, only checked) and ventilation units were laboratory-calibrated before their onsite installation.

3.3 Main results

3.3.1 Indoor Air Quality (IAQ)

- CO_2 measurements in all dwellings have shown that the indoor air quality was ensured in rooms with low occupancies as well as in rooms with high occupancies, with very few hours above 1500 ppm in the worst cases, as observed on figure 5.a. This emphasizes the ability of RH-MEV to respond to the real needs even if this need is far from the design occupation: even in over-occupied dwellings, the IAQ is still ensured by RH-MEV.

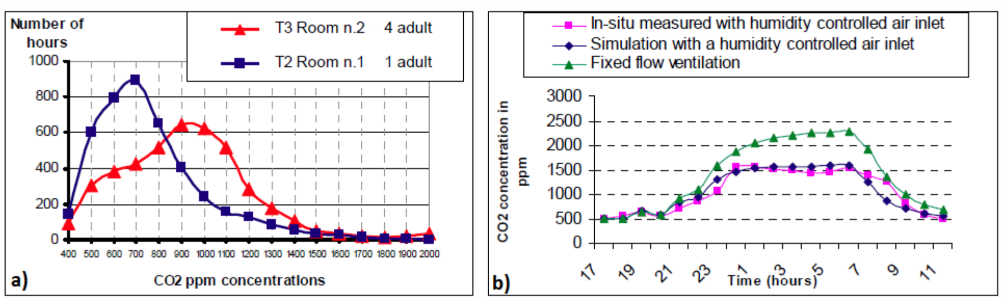

Figure 5 : a) Repartition in hours of the CO_2 level for two room occupations. b) Time evolution of CO_2 concentration for measured hygroscopic air inlet, simulated hygroscopic air inlet and simulated constant air-flow (18 m^3/h at 10 Pa) air inlet, in a 35 m² room occupied by 4 teenagers.

- Measurements together with simulation results showed that RH-MEV, thanks to the air inlet opening in response to humidity, performed better than constant air-flow system, by ventilating above the regulatory constant airflow when needed. See figure 5.b for an over-occupied room.
- Humidity results were very satisfactory, showing that most dwellings presented a null condensation risk, except in one case where a drying machine was installed in the toilets.

3.3.2 Energy impact

- The measured airflow savings compared to the French regulatory constant airflow reference were of about 30 %, most dwellings being over-occupied. Extrapolating the results to the statistical average French occupancy for each type of dwellings, the estimated heat losses savings rise to 50 %.
- The measured fan consumption reduction allowed by RH-MEV was of 35 % in the Lyon site and 50 % in the Paris site.
- The good agreement between the French regulation computation results and the in-situ measurement results validated the good energetic prevision of the SIREN software.

3.3.3 In-situ operation of the humidity-controlled ventilation components

- All humidity-controlled exhaust units were working (in-situ) in their tolerance envelope, following the laboratory nominal curve, as presented on figure 6 for a kitchen exhaust unit. The month discrepancies are explained by the lower indoor relative humidity in winter when outdoor air is dryer. The exhaust units are therefore statistically less opened in winter than in summer, without being detrimental to their dynamics and fast response to humidity changes. This design allows to have a sufficient IAQ inside the dwellings in winter while contributing to energy savings.

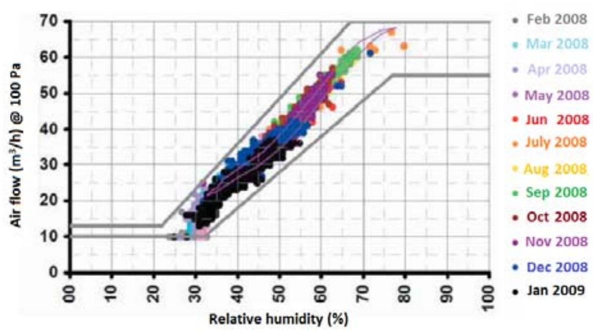

Figure 6 : Representative example of a hygroscopic curve of a kitchen exhaust unit. Fine line: laboratory measurements. Bold line: tolerance envelope. Points: in-situ measurements.

- All air-inlets were working in their tolerance envelopes, slightly shifting towards lower humidity as temperature decreased. This allows the air inlet to work on its whole air-flows range even in winter when outdoor humidity is lower, ensuring its role of air distribution (maximum airflows in highly-occupied rooms, minimum in unoccupied ones).

3.3.4 Occupant behaviour

- A one-month breakdown of the fan in the Lyon building allowed to observe a strong rise of CO_2 concentration (above 1900 ppm most of the time), as well as an important increase of the condensation risks. The occupants did not feel this confinement increase, showing that occupants are unaware of the IAQ in their dwellings and confirming the major role of an automatic DCV.

4 10 YEARS FOLLOW-UP STUDY

4.1 Context and objectives

The sensors and instrumented ventilation units were never removed from the apartments. This offers the rare opportunity to turn the large-scale monitoring back on, in order to assess the performance of RH-MEV systems and components after more than ten years of in-situ operation. Several aspects will be studied, among which:

- Determining if the hygroscopic components drifted and, if they did, by which extend,
- Identifying the maintenance issues,
- Determining the impact of dwelling use on indoor air quality.

4.2 Preliminary results

The preliminary results presented here should be taken with care. The aim of this first phase was to turn acquisition systems back on, in order to identify the number of responding sensors and get some first data to decide whether the study was feasible and of interest.

The system was turned back on in April 2017. 106 sensors over 112 responded, showing that both the sensors and ventilation units were still in place and wired. When the power supply was turned off, 80 % of the sensors were still communicating. The weather stations however were off. Data was recorded from April to July 2017, as the power supply was over-heating and had to be resized. One must note here that no maintenance was made on the sensors so that the data is not laboratory certified.

4.2.1 Sensors

All communicating sensors give coherent results, although their absolute values are not laboratory certified.

The Hall-effect sensors suffer from periodic perturbations. An electromagnetic compatibility problem is suspected as these sensors are analogic. A Fourier-transform post-treatment was implemented to remove the noisy data from the analysis.

4.2.2 Hygroscopic ventilation units

Air inlets

Because of the noise on the Hall-effect sensors, the air inlets response was difficult to evaluate and analyse. Among the 38 Hall-effect sensors: 4 did not response or were too noisy. 26 over 34 communicating air inlets had coherent dynamics, with usual estimated airflow and response to relative humidity. The issues with the remaining air inlets and their supposed explanations can be found below:

Table 2: Air inlets issues (8 over 38) and probable explanations

Issue	Number	Possible explanation
Blocked aperture (Minimum or maximum)	4	Occupant intervention to maximise or minimize the airflows Unhooked actuator
Incoherent range (Aperture over maximum)	2	Unhooked Hall-effect sensor
Low dynamics	2	Occupant intervention to minimize airflows Misplaced Hall-effect sensor

These preliminary results and explanations have to be confirmed on site.

Exhaust units

The 19 instrumented toilets exhaust units are presence-controlled. Among them, 4 suffered from electrical perturbation issues, and 14 had their batteries discharged. It has to be noted here that these instrumented units have a higher power consumption than usual presence-controlled units due to the reading of the PIR sensor data.

The hygroscopic behaviour of the kitchen and bathroom exhaust units were investigated. The estimated airflows (measured apertures under 100 Pa) were plotted versus the measured RH, together with their tolerance envelopes. The Hall-effect sensors noise was filtered, as well as fast RH transitions. Indeed, for rapid humidity increases – typically cooking or shower events – the nylon strips need a few minutes to elongate and open the shutter, which is their normal functioning behaviour. The electronical humidity sensor however senses the changes immediately. As a result, an average of 5 % of the points are irrelevant. The example of figure 7 is representative of the 38 communicating exhaust units.

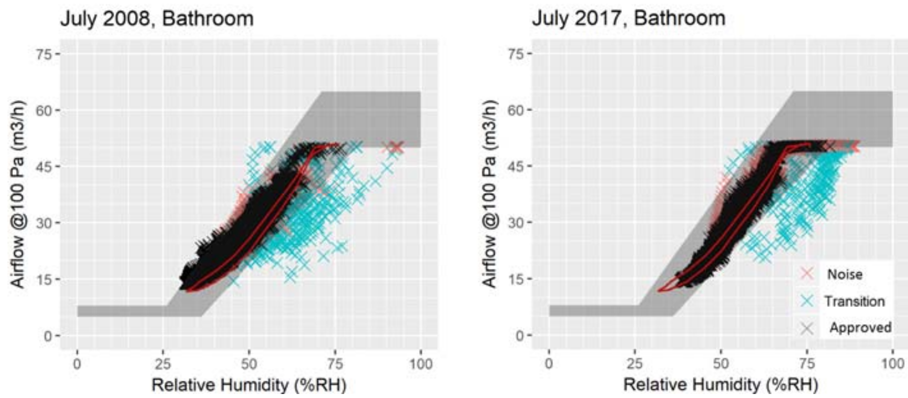

Figure 7: Hygroscopic curves and envelope of a bathroom exhaust unit in July 2008 (left) and July 2017 (right). Noise (red crosses) and fast transitions (blue crosses) are filtered to keep only the relevant points (black crosses). The red curve was laboratory plotted in 2008.

- As far as kitchen exhaust units are concerned and let aside the Hall-effect sensors issues, 13 over 14 hygroscopic curves were inside their tolerance envelopes. The remaining one was blocked at the boost airflow, either by the occupant or because of a component defect.
- Among the 23 communicating bathroom exhaust units, 19 hygroscopic curves were inside their tolerance envelopes. 1 was blocked in opened position, 2 showed erratic behaviour which could be due to a Hall-effect sensor issue, and 3 exhibited behaviours typical to high clogging of the exhaust canal (airflow reduction at high humidity, see figure 8.b)

In order to evaluate the drift of the hygroscopic components, we compared data from July 2008 and July 2017 (figure 7). We assumed that the airflows did not drift and computed the mean humidity rates for each airflow. Some of the curves displayed obviously blocked shutters, as seen on two examples on figure 8. From our previous experience (Berthin and Parsy 2018) these behaviours are usually due to dust clogging and are reversible by simple cleaning and maintenance. Such curves were excluded from the computation.

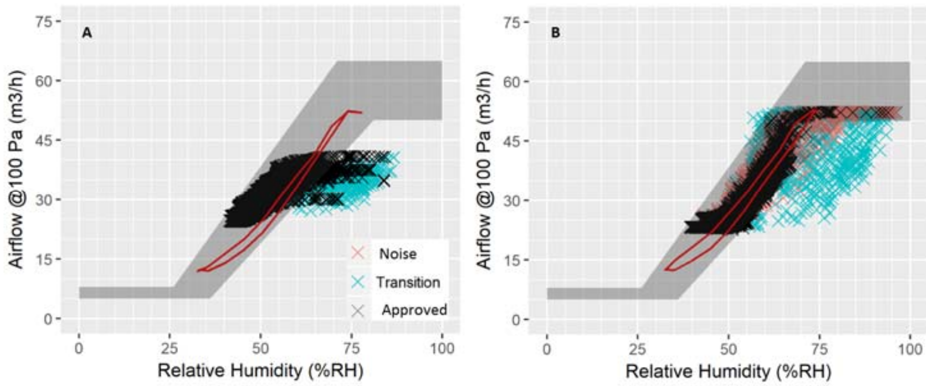

Figure 8: Probably dust-clogged bathroom exhaust units. A) The maximum airflows are never reached (blocked below 40 m^3/h), B) The minimum airflows are never reached (blocked above 22 m^3/h), the curve still fits in its tolerance envelope.

- A 1,5 % RH average drift was computed over 21 curves between July 2008 and July 2017 (giving less than 0,2 % RH drift/year). This value is lower than the 1,8 % accuracy given by the RH electronic sensors (Sensirion SHT75) at their installation. Laboratory measurements would allow to get a finer evaluation of this very low drift.

4.3 Next steps

The preliminary results have shown that most of the in-situ instrumentation was operational – with 80 % of the sensors communicating – and that data could be collected. The first data analysis has proved that coherent results could be obtained and shown the feasibility of a rigorous study of the installed RH-MEV ventilation systems and components after ten years of operation. The hygroscopic behaviour of the air inlets and exhaust units were checked, giving very encouraging results. Maintenance and sensors issues were presumed and should be verified on-site. Furthermore, a re-calibration of all the sensors should be made. Therefore, with the agreement of the Paris and Lyon social housing offices, a 10 years follow-up study will be held by the CEREMA, together with the manufacturers of the installed RH-MEV systems. It will be divided into three phases that we develop below.

4.3.1 Phase 0

The aim of the first phase, that ought to be held from September 2018 to May 2019, is to get a first full winter analysis of the systems after 10 years of operation, with as low disturbance as possible for the occupants.

The power alimentation will be resized, and new weather stations will be installed on the roof terraces. In addition, the batteries of the toilets presence-controlled exhaust units will be changed.

To avoid any heavy intervention in the dwellings, the metrology will not be re-calibrated before data collection.

4.3.2 Phase 1

The second phase, planned from May 2019 to September 2019, has three main objectives:

- Qualifying the hygroscopic components after 10 years of operation, before and after maintenance of the grid and air channel of the unit
- Checking the metrology and recalibrate the sensors,
- Using the re-calibration of the sensors to post-treat the Phase 0 data.

To fulfil those objectives, the instrumented ventilation terminals as well as the sensor units will be collected from the dwellings to be laboratory tested and recalibrated. The ventilation units will first be tested as collected and then cleaned to differentiate the potential drift of the hygroscopic components from the effect of the maintenance of the grid and ventilation channel.

4.3.3 Phase 2

The last phase, planned from September 2019 to May 2020, aims at making an in-situ QAI and energetic performance monitoring of RH-MEV systems after 10 years of operation, with certified metrology and normally maintained ventilation units. To do so, a full winter data collection with the maintained instrumented ventilation units (keeping the 10 years old hygroscopic nylon strips without any recalibration) and recalibrated sensors will be held. New sensors such as particulate matter (PM1; PM2.5), or VOCs sensors could be added to further investigate the air quality inside the dwellings. An occupation and behaviour survey will be made with the occupants in order to get finer data analysis.

5 CONCLUSIONS

Mechanical humidity-controlled mechanical extract ventilation (HR-MEV) systems and components were introduced in the first part of this article. The initial 2007-2009 large-scale monitoring, aiming at characterizing HR-MEV in 30 occupied dwellings of 2 residential buildings, was then presented, as well as its main results, showing:

- The good IAQ in terms of CO_2 and humidity provided by the ventilation system, despite the over-occupation of some apartments. These results showed the system's appropriate reaction to human occupation resulting from a good correlation between CO_2 and airflows.
- The statistical real-field savings on heat losses of 30 to 50 % in average compared to constant airflows from the French regulation.
- The good agreement of the heat loss and IAQ measurements with the simulation models used for the French DCV technical agreements.

Ten years later the building is re-visited, and the monitoring system is turned back on with the intention to assess the IAQ and the ventilation system behaviour/performance after a prolonged in-situ functioning period. The results of a preliminary study were presented showing that:

- At start-up, more than 80 % of the metrology is still in working conditions, although not laboratory certified,
- Using this rough data, respectively 26 over the 34 communicating air inlets have coherent aperture response to humidity and 32 over 37 communicating exhaust units are inside their tolerances. The average in-situ drift of the hygroscopic devices after 9 years of operation is estimated below ± 1.5 %RH. This value is lower than the announced accuracy of the electronical humidity sensors at installation (± 1.8 %RH).
- The observed drift of volume flows on some of the exhaust units is characteristic of an absence of maintenance.
- The battery of the presence-based toilet exhaust is often (90 %) discharged.

These first promising results need to be confirmed by a thorough study which shall include:

- The collection of the ventilation devices for a full quality control before and after the recommended cleaning.
- The collection of the metrology sensors for re-calibration and drift-correction on the measurements.
- A new set-up for each apartment including particle sensors to follow the latest interests of IAQ research.

6 ACKNOWLEDGEMENTS

The contribution of Cerema is funded by the French Ministries in charge of sustainable development, transport and urban planning. The sole responsibility for the content of this publication lies with the authors.

7 REFERENCES

ADEME. "VIA-Qualité Guide pratique à destination des constructeurs de maisons individuelles." 2016.

Bailly, A., G.Guyot, and V. Leprince. "Analyse of about 90 000 Airtightness Measurements Performed in France on Residential and Non-Residential Buidings from 12008 to 2014." *Proceedings IAQ 2016 Defining Indoor Air Quality : Policy, Standars and Best Practices. AHSRAE - AIVC.* Alexandria, 2016.

Berthin, S., and F. Parsy. "Feedback on installation, maintenance, and aging of mechanical humidity-controlled exhaust units." *AIVC.* Antibes Juan-Les-Pins, 2018.

Borsboom, W. "Quality and compliance on building ventilation and airtightness in the Dutch context." 2015.

European Parliament, the Council. "Directive 253/2014 with regard to codesign requirements for ventilation units." 2014.

Guyot, G., I.S. Walker, and M.H. Sherman. "Performance based approaches in standards and regulations for smart ventilation in residential buildings: a summary review." *Int. J. Vent. 0*, 2018: 1-17.

Guyot, G., M.H. Sherman, I.S. Walker, and J.D. Clark. "Residential smart ventilation : a review." 2017.

Kunkel, S., E. Kontonasiou, A. Arcipowska, A. Bogdan, and F. Mariottini. "Indoor air quality, thermal comfort and daylight - Analysis of residential building regulations in eight EU member states." *Build. Perform. Inst. Eur. BPIE 100*, 2015.

Savin, J-L., and A-M. Bernard. ""Performance" project : Improvement of the ventilation and building air tightness performance in occupied dwellings in France." *AIVC.* Berlin, 2009.

Savin, J-L., and J. Laverge. "Demand-controlled ventilation: An outline of assessment methods and simulation tools." *32nd AIVC conference "Towards Optimal Airtightness Performance".* Brussels, 2011.

Savin, J-L., and M.Jardinier. "Humidity Controlled Exhaust Ventilation in Moderate Climate." *AIVC - Ventilation Information Paper n° 31.* 2009.

Savin, J-L., S. Berthin, and M. Jardinier. "Demand-controlled ventilation. 20 years of in-situ monitoring in the residential field." *AIVC.* Alexandria, 2016.