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Smart Ventilation Performance Durability Assessment: Preliminary Results from a Long-Term Residential Monitoring of Humidity-based Demand-Controlled Ventilation

Gaëlle Guyot, PhD

Stéphane Berthin, Eng

Sandrine Charrier, Eng

Elsa Jardinier,PhD

Elise Hallemans, PhD

Marc Legrée, Eng

François Parsy, PhD

Emmanuel Roux, Eng

ABSTRACT

Humidity-based DCV systems have been widely used in France for 35 years and are considered as a reference system, including for low-energy residential buildings. The on-going Performance 2 project delivers the preliminary results of a thirteen-year monitoring in thirty social housing apartments.

The initial project was a large-scale monitoring on thirty new occupied apartments equipped with this DCV system, which extended from 2007 to 2009. 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. Recordings were performed every minute over two years. This former study showed: The good IAQ in terms of CO_2 and humidity, a good correlation between CO_2 and airflows, savings on heat losses of 30 % in average compared to regulatory constant airflows.

Thirteen years later the building is re-visited, and the monitoring system is turned back on with the intention to assess the ventilation system performance after a prolonged in-situ functioning period.

In this article, we analyse the literature in order to discuss the choice of humidity as a relevant parameter to control ventilation, and we present the results from the first heating period.

These first promising results will be followed by: the collection of the ventilation devices for laboratory tests and a new set-up for each apartment including TVOC, formaldehyde and particle sensors to follow the latest interests of IAQ research.

In the context of the increasing awareness about smart ventilation, these feedbacks highlight as a crucial issue, the durability of the ventilation systems and its components (including the sensors) and their robustness to a lack of maintenance or even a bad use by occupants.

INTRODUCTION

General context towards demand controlled ventilation

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, demand-controlled ventilation (DCV) systems and balanced heat recovery systems by 2018. Performance-based approaches generally guaranty the indoor air quality (IAQ) and the energy performance of DCV systems, through agreement procedures or certifications (Guyot,

G. Guyot is a researcher at Cerema, research projet-team BPE, France, and research fellow at LOCIE, Univ Savoie Mont Blanc, France**. E. Jardinier, F. Parsy, M. Legrée and S.Berthin** are engineers at Aereco SA, France, **E. Hallemans, E. Roux, and S. Charrier** are engineers at Cerema, France

Sherman, et al. 2017). In Europe, several countries already enable and/or promote 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, Guyot, Walker and Sherman 2018). Humidity-controlled mechanical extract ventilation (RH-MEV) systems have been widely used in France for 39 years. Most of the new residential buildings complying with RT 2012 energy performance regulation, are equipped with such systems (Mélois et al., 2019). They are also considered today as a reference system.

Technological context: presentation of the reference humidity based DCV system

Humidity-based mechanical exhaust ventilation (RHMEV), further described in (Jardinier et al., 2018), is based on the sweeping principle: an exhaust fan ensures an under-pressure in the dwelling, allowing the outdoor air to come in through air inlets 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). 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 mechanical humidity sensor and actuator. If the air is dry enough, the unit's 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. 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.

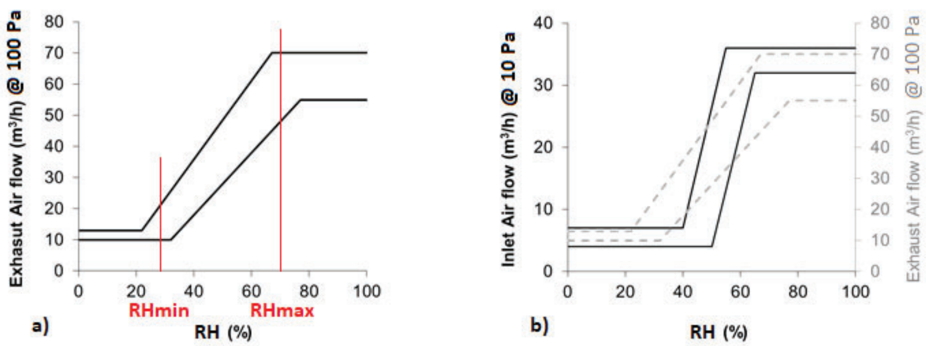

Figure 1 : a) Exhaust unit hygroscopic curve envelope. b) Inlet hygroscopic curve envelope (black curve).

A RH-MEV unit is defined by its hygroscopic curve (Figure 1): for RH < RHmin, the airflow is minimum. For $RH_{min} < RH < RH_{max}$, the airflow varies more or less linearly, for $RH > RH_{max}$, the airflow is maximum. Air inlets (see a typical envelope on figure 1.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. In addition, the humidity-charged air travels through the dwelling towards the humidity-controlled exhaust units, which become more opened, increasing the total airflow. Several on-field and laboratory studies were performed (Savin, Berthin and Jardinier 2016, Berthin and Parsy 2018) in the last 25 years, proving and improving the performances of the RH-MEV systems. Energy savings have been estimated about 30% to 50 % of the heating energy compared to constant airflows exhaust-only ventilation (Savin and Bernard 2009). Its simple and reliable components and principle of operation allow its robustness (Berthin and Parsy 2018), low cost and ease of installation.

In 2019, the "Performance 2" project was launched in three phases in order to (1) get a first full winter analysis of the system after 13 years of in-situ operation, with the installed sensors (non-recalibrated) and no major intervention, (2) collect the ventilation units and sensors for laboratory testing before and after cleaning and maintenance, (3) reinstall the cleaned and maintained ventilation units (hygroscopic components unchanged) with new calibrated sensors.

In this article, we first analyse the literature in order to discuss the choice of humidity as a relevant parameter to control ventilation. After recalling the main conclusions of the Performance project (2007-2009), we finally present the results of the first (1) phase of the Performance 2 project.

Is humidity a relevant parameter to control ventilation?

This research firstly set out to answer the related question of whether relative humidity can be representative of other parameters, such as occupant-related emissions. A literature review (Guyot et al., 2017) showed that there was actually no consensus about this issue. The moisture buffering effect and the dependence of relative humidity on temperature and air moisture content reduces the relationship between moisture and occupancy. As a result, several studies (Anon, 1983; Barthez and Soupault, 1984; Sheltair scientific Ltd., 1988; Parekh and Riley, 1991) show a poor relationship between relative humidity and the occupant load in a room. (Fisk and De Almeida, 1998) confirmed that other residential pollutants are not correlated with humidity. A two-week monitoring study of a house reported by (Mansson, 1993) showed no correlation between the value given by an RH sensor and a mixed gas sensor in the living room. (Pecceu et al., 2018) have been carrying out measurements in 26 dwellings in Belgium over more than 1 year and concluded that there was not direct correlation between CO_2 and relative humidity. However, they observed a clear link between both when they analysed their variations.

In contrast, during the Performance project, (Bernard, 2009) highlighted a strong correlation between CO_2 concentrations and the relative humidity levels measured in 31 apartments over the duration of more than two complete heating seasons. To quantify this correlation, the authors plotted the average degree of opening of humidity-controlled air inlets against CO_2 concentrations between 300 ppm and 2000 ppm and observed a clear correlation between degree of inlet opening and concentration of CO_2 in bedrooms.

These results confirm previous ones from 26 apartments equipped with humidity-controlled ventilation in France, Belgium, and the Netherlands (Mansson, 1993). (Moffat et al., 1991) observed in one house that CO_2 levels and relative humidity tend to track each other, but that CO_2 peaks occurred three hours later. This was confirmed by research by (Parekh and Riley, 1991). (Raatschen and Trepte, 1987) showed that, in a three-occupant living-room, air change rates necessary to remove moisture are higher than those necessary to keep CO_2 concentrations below 1000 ppm. They also showed that in an unoccupied bathroom the hourly air change rate needed to remove moisture was higher than the one needed to remove formaldehyde; the opposite was observed in the living room. In residential buildings, Raatschen and Trepte conclude that the need for ventilation in occupied rooms is dominated by moisture; in unoccupied rooms the need to ventilate for formaldehyde control is more important and must be considered when setting minimum airflows.

The correlation between absolute humidity and CO_2 might be stronger than the correlation between relative humidity and CO_2; however, it has a lag time due to sorption characteristics of the building materials and furniture in the home (Moffat et al., 1991; Savin and Jardinier, 2009).

In conclusion, the relevance of using RH as a parameter for controlling ventilation is mainly dependant on strategy and environment, just as for any other type of controlling parameter. Indeed, key parameters as climate, type of controls imposed by a DCV system, level of airflows, moisture buffering effect, influence the correlations. Similarly, and although less controlled, CO_2 sensors accuracy also depends on environmental parameters such as temperature or barometric pressure.

In France, over the last 39 years, the RH-MEV systems performances have been observed and experienced at large scale. Moreover, relative humidity has direct incidences not only on health but also on buildings damage risks as well as indirect health risks due to mold growth, so there is a direct interest of this mode of controlling ventilation. Furthermore, humidity is not only generated by human breathing but also by most human activities generating other pollutants emissions such as cooking, showering, cleaning, clothe washing and drying, making it an important parameter to monitor for ventilation.

Performance Project and prior results

The Performance project included a large-scale monitoring on thirty new occupied apartments in two buildings, respectively situated in Lyon and Paris in France, and equipped with RH-MEV system. The dwellings were equipped with low-cost CO_2, RH and temperature electronic sensors. Ventilation terminals were instrumented with magnetic field sensors (Hall effect)and magnets, for measuring aperture and in-duct pressure sensors. Every sensor

(except CO_2, only checked) and ventilation units were laboratory-calibrated before their onsite installation. The main results from these two years of operation demonstrated a good IAQ (CO_2 and RH) and heat losses savings close to 50%, despite the over-occupation of some apartments and have been further described in (Jardinier et al., 2018).
A first data analysis in 2017 (Jardinier et al., 2018) proved that coherent results could be obtained from the installed metrology and showed the feasibility of a rigorous study of the installed RH-MEV ventilation systems and components after thirteen years of operation. The next paragraphs focus on the first phase of this "Performance 2" project.

RESULTS FOR THE FIRST FULL WINTER ANALYSIS

Interventions

As planned after the 2017 diagnosis, the power supply was resized (Phenix QUINT4-PS 1AC/12DC/15) to get rid of the observed electromagnetic perturbation; the weather stations were replaced (new sensors, not calibrated); new 9V batteries were installed in the presence-based toilet exhaust units or given to the occupants for installation. In addition, the sensor units (CO_2, T/HR) that did not communicate anymore were changed (7/90, old and non-recalibrated sensors). As a result, 100% of the installed sensors in the 15 participating apartments were communicating. To avoid any heavy intervention in the dwellings, the metrology was not re-calibrated before data collection.

Results

The results presented here should be taken with care as no maintenance was made on the sensors and ventilation units so that the data is not laboratory certified. Furthermore, except from a few apartments where interventions were made, we had no information on the environment and state of maintenance of the products. This information was carried out during the phase of collection of the ventilation and sensor units and will be analysed in another article.

Hygroscopic air inlets
As the pressure difference at the air inlets is unknown, plotting their onsite hygroscopic curves is difficult. Among the 31 Hall-effect sensors, 23 (74%) had coherent dynamics for both estimated opening area and response to relative humidity. Among the remaining sensors, 5 had coherent responses to humidity but were not in the right range of opening areas, and the last 3 were most of the time blocked to minimum airflow. The issues and their supposed explanations can be found in table 1. These preliminary results and explanations will be confirmed on the second phase of this study and presented in a later article.

Table 1: Air inlets issues (8 over 31) and probable explanations

Issue	Quantity	Possible explanation
Aperture blocked at low airflows	3	Occupant intervention to minimize the airflows Unhooked actuator Drifted hall effect sensor or magnet
Incoherent range (Aperture over maximum)	1	Corresponding living room opened to the kitchen Drifted hall effect sensor or magnet
Low dynamics	4	Occupant intervention to minimize airflows (tape 3 inlets at least) Misplaced Hall-effect sensor Drifted hall effect sensor or magnet

In order to answer the question of pertinence of using hygroscopic air inlets in the habitable spaces as a proxy for presence, it is interesting to investigate closely the daily dynamics of indoor relative humidity, CO_2 and estimated opening area of the air inlet. The graphs below are for one bedroom air inlet but are representative of the 23 air inlets with normal ranges of indoor relative humidity and opening area.
We studied the same air inlet in a bedroom during four days chosen in two different weeks with different average outdoor relative humidity (brought to 21°C) levels, computed from our weather station. In the chosen week of

February (figure 2.left), the mean outdoor $RH_{21°C}$ was about 45 % (among the highest in the monitored period) while in the week of January (Figure 2.right), it was about 30 %, among the lowest outdoor RH of the monitored period.

First, we can observe on both figures, that indoor RH and CO_2 levels have similar dynamics: the occupants breathing peaks and high plates at night can clearly be observed on both parameters. The range of humidity and CO_2 variations are different between the two weeks and some peaks of one parameter are not found for the other one, especially at higher outdoor humidity.

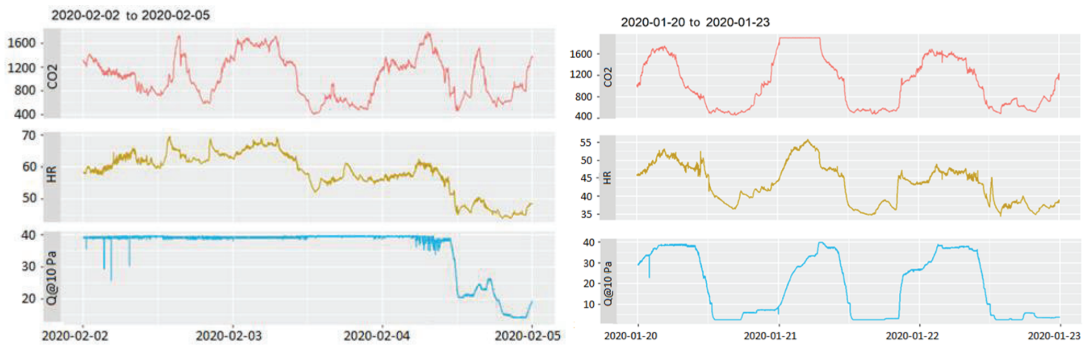

Figure 2: CO_2 (ppm), indoor RH (%) and air inlet estimated opening area (cm²) dynamics at high outdoor relative humidity (left, $RH_{21°C}$ ~ 45%) and low outdoor humidity (right) in a bedroom. The spikes seem to be perturbations on the hall effect sensor.

As observed on figure 2.left, at high outdoor RH, indoor RH is, most of the time, higher than the RH_{max} of the air inlet, so that it remains at maximum opening area. This is transparent for energy losses as inlets play a role in the distribution of airflows and not on actual flowrates.As far as IAQ is concerned, the distribution among rooms is not optimal as every room has an opened air inlet. However, less air passes through the leaks and more through the inlets, where the need is. Furthermore, at high outdoor humidity, the exhaust airflow is usually higher so that more air flows into the habitable spaces.

At lower outdoor relative humidity (figure 2.right), the dynamics of the air inlet perfectly follows the one of CO_2 and indoor relative humidity: the total airflow is distributed according to the need. When indoor relative humidity reduces towards the minimum design airflow of the air inlet, and RH emissions due to breathing are low, CO_2 peaks can be missed. This is particularly the case in living rooms, where the behaviour illustrated on figure 3 can be observed.

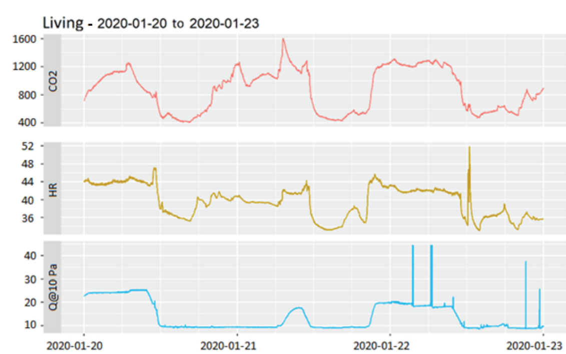

Figure 3 : CO_2 (ppm), indoor RH (%) and air inlet area (cm²) dynamics at low outdoor RH ($RH_{21°C}$ ~ 30%). Situation in a living room at low indoor RH. Spikes probably due to hall-effect sensor perturbations.

The absolute CO_2 levels mostly remain below 2000 ppm, following the French regulation: the French technical agreement (CCFAT, 2015) computes the cumulative exposure concentration higher than 2000 ppm, which should not be higher than 400 $kppm.h_{2000ppm}$ in each room over the heating period. This indicator will be computed after laboratory recalibration of the sensors, if a sufficiently trustworthy recalibration law can be obtained. The values over 2000 ppm (saturation value of the sensors) could be extrapolated.

Although more related to the next section on exhaust units, it is important to recall that the hygroscopic curves (humidity range and airflows) can be adapted for all units, so that other standards can be met, or to adapt to other meteorological environments. For instance, if the weather is particularly wet (respectively dry), the range of reaction to humidity of all units can be appropriately shifted toward higher (receptively lower) values. If a 1200 ppm limit is set by a local regulation, the minimum and maximum airflows will be adjusted accordingly, at a cost in terms of heating losses. Within certain limits, RH-MEV can be adapted to local regulations. A perspective of this study is to make multi-zone simulations (previously validated with the monitored data), to account for other environments or requirements.

Hygroscopic exhaust units

The hygroscopic behaviour of the kitchen and bathroom exhaust units were investigated. The estimated airflows at 100 Pa, based on aperture estimation and pressure measurement, were plotted versus the measured RH, together with their tolerance envelopes. Again, sensors were not recalibrated, so that uncertainties add up on absolute values. The dynamics remain interesting.

The fast RH transitions were filtered. Indeed, for rapid humidity increases – typically cooking or shower events – the nylon strips of the hygroscopic sensor and actuator need up to 15 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. Figure 4 is representative of the 38 communicating exhaust units.

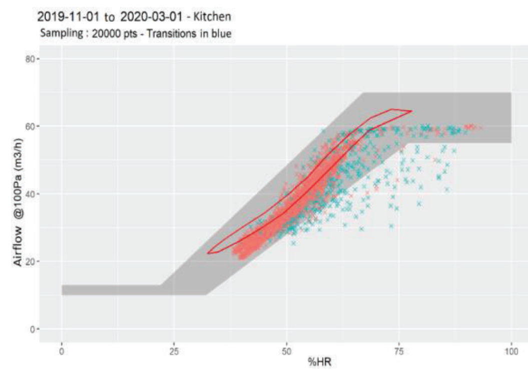

Figure 4 : Hygroscopic curve and envelope of a kitchen exhaust unit. Fast transitions (blue crosses) are filtered to keep only the relevant points (red). The red curve was plotted on a laboratory test-bench in 2007.

- As far as kitchen exhaust units are concerned, 12 over 15 hygroscopic curves were inside their tolerance envelopes. Two had airflows above the maximum possible airflow, which could be explained by a drift of the hall-effect sensor or an alteration of the shutters. The remaining one was an old unit, kept in uncontrolled conditions, used to replace the one that had been removed by the occupant. Although in their envelope, 2 units presented negative airflows (hall-effect sensor defect) and one had a limited maximum airflow, typical of high clogging.
- Among the 23 communicating bathroom exhaust units, 22 hygroscopic curves were inside their tolerance envelopes. The remaining one seemed to have defective electronic RH sensor (vertical curve). Although in their envelope, 6 units presented maximum or minimum airflow limitations, that are typical of highly clogged units. 4 exhibited erratic behaviour probably due to electronic sensor drift.

These results allow to conclude with high probability that on at least 90% of the products, the hygroscopic sensor and actuator still reacts to humidity and with dynamics similar to the ones measured on installation.

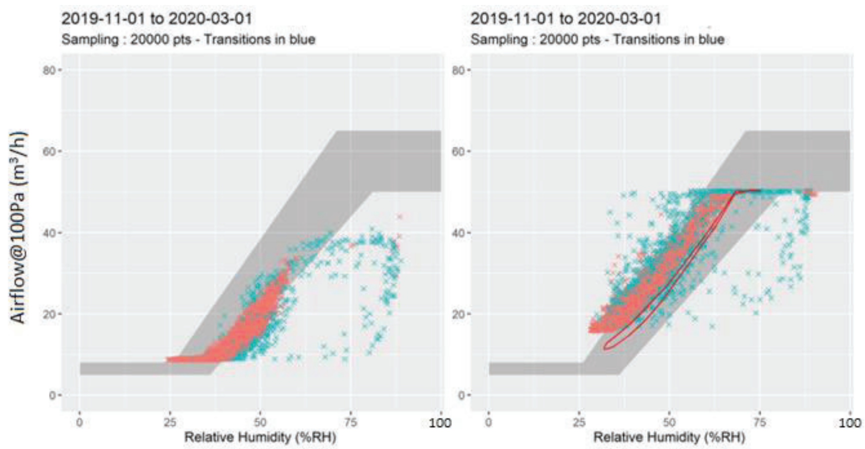

Figure 5: Probably degraded bathroom exhaust units. left: maximum airflows are never reached (blocked below 40 m^3/h), right: minimum airflows are never reached (blocked above 18 m^3/h).

Some of the curves displayed obviously blocked shutters, as seen on two examples on figure 5. From our previous experience (Berthin and Parsy 2018) these behaviours are usually due to dust clogging and are reversible by simple cleaning and maintenance. However, a modification of the shutter case through the years could be in cause and these assumptions will be checked on laboratory test benches.

Presence controlled toilet exhaust units

12 over the 15 (80%) presence-controlled exhaust units performed correctly with the maximum air flow in presence of occupants and minimum airflow during absence periods. The remaining 4 exhaust units were blocked at Qmin (2/4) or Qmax (2/4) and seemed to have deficient presence sensors, no battery, or been blocked by the occupant.

CONCLUSIONS AND NEXT PHASES

In the Performance 2 project, we aim to produce knowledge and recommendations based on both the durability of the sensors and components being part of smart ventilation strategies, and on the robustness of these ventilation systems to a lack of maintenance and cleaning, as experienced in many buildings. In this article, a literature review showed that the relevance of using RH as a parameter for controlling ventilation in dry rooms is mainly dependant on strategy and environment, just as for any other type of controlling parameter (CO_2, COV, …). Key parameters as climate, type of controls imposed by a DCV system, level of airflows, moisture buffering effect, influence the correlations.

Secondly, we presented the results of the first on-site monitoring study after 13 years of in situ operation. We mostly checked the dynamics of the measured parameters, as the absolute values should be taken with care. At this stage, we can conclude that:

- At least 74 % of air inlets' hygroscopic actuators react to humidity. The reason why the remaining air inlets do not react correctly will be investigated. They could be related to poor maintenance of the unit or metrology issue. The estimated aperture is correlated to CO_2, particularly at high CO_2 concentrations, in the bedrooms, when most needed.
- At least 90 % of exhaust units' hygroscopic actuators still react to humidity. The range of reaction is close to the one measured at installation. The remaining exhaust units are thought to suffer from maintenance problems or metrology issues.
- 80 % of presence-controlled units correctly reacted to presence. The remaining ones were probably modified by the occupants.

These results are preliminary results that confirm the interest of the "Performance 2" project. Both the metrology (electronic RH, T, CO_2, Hall effect and pressure sensors) and ventilation units should be verified on laboratory test benches. This is the aim of the on-going second phase of this project, which will result in recommendations toward design and maintenance of smart ventilation systems.

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