Assessing the performance of hybrid and natural ventilation systems: a review of existing methods

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ABSTRACT

Natural and Hybrid ventilation systems, by using exclusively or partially natural driving forces, help to reconcile building energy sobriety and good Indoor Air Quality (IAQ). However, in France, Building Regulations restrict the use of natural ventilation by imposing minimum airflows in buildings. Natural ventilation, whose driving forces are atmospheric conditions, has an efficiency depending on the climatic region. Concerning climatic regions where natural ventilation is not likely to provide sufficient airflow, the ventilation system may be featured with a mechanical assistance, which is called Hybrid ventilation systems. Hybrid ventilation systems, taking advantage from natural driving forces when the induced airflow is strong enough, and assisting it otherwise, allow using natural ventilation while verifying airflow requirements. The assessment of mechanical systems performance has already been questioned by the French protocol PROMEVENT. The absence of a similar protocol restricts the development of natural and hybrid ventilation systems. Such a protocol would widen the use of natural ventilation in favourable climatic regions and enable the improvement of the control strategy of hybrid ventilation systems. However, the plurality of openings, variable airflows, and unstable flow patterns make the measurement of the performance of natural and hybrid ventilation systems a challenging task. It represents the objective of the French research project VNAT.

This paper is issued from the first task of the VNAT project: the state of the art on the assessment of natural and hybrid ventilation systems. It presents a comprehensive review of existing studies and protocols regarding the measurement of airflow and Air Change Rate (ACR). It appears that direct measurement method of airflow may interfere with the flow pattern, which is troublesome for natural ventilation. Thus, the direct measurement is not likely to be representative. Indirect methods allow measuring Air Change Rate (ACR). They may be conventional tracer gas methods or occupant-generated CO_2 methods. Tracer gas methods are numerous and they are based on assumptions which can differ from a method to another. Two of them, called the constant injection and the concentration decay methods, are widely used to characterize the performance of ventilation systems thanks to their ease of implementation. The violation of assumptions leads to important measurement uncertainties. Occupant-generated CO_2 methods depend on the occupation rate and on the CO_2 emission rate, which induces uncertainties too. These measurement methods as well as tracer gas methods are compared regarding their accuracy and their limits. Modelling methods are also discussed.

Results from this paper will help to build a new protocol more suited to the assessment of the performance of hybrid and natural ventilation systems under real conditions.

KEYWORDS

Natural airflows, Modelling, Tracer gas methods, Occupant-generated CO_2

1 INTRODUCTION

The building sector is the most consuming sector of European countries, with a share of 42% of the final energy consumption. Natural and Hybrid ventilation systems, taking advantage of natural driving forces, allow to reconcile energy efficient buildings with an acceptable Interior Air Quality.

In France, building regulations impose general and permanent airflow rates in buildings. It promotes the use of mechanical ventilation systems in new buildings. Moreover, the protocol

PROMEVENT has improved the reliability of their performance evaluation's procedure, which eases the verification of the required hygienic airflows (Mouradian, 2017). Direct airflows or pressure measurements allow to assess the ability of a mechanical system to deliver standard-required fresh air.
Natural and Hybrid ventilation's implementation in new buildings is challenging, as specific procedures are required intending to prove that the system actually leads to the hygienic airflow rate prescribed by regulations. The problem is that it exists no protocol assessing accurately the performance of these kind of systems, such as the protocol PROMEVENT for mechanical ventilation. The diversity of openings, low pressure induced natural airflows, and fluctuating driving forces prevent from directly measure natural ventilation's performance thanks to conventional airflow meters. Under these conditions, the airflow meter could interfere with the unstable flow pattern, which would result in a non-reliable measurement. The other challenge regarding natural systems is that airflows are dependant from several parameters including the building geometry, openings configuration, and climatic conditions. Hybrid ventilation systems add the issue of the plurality of operating modes: pure natural, mixed, or pure mechanical. As a consequence, a measurement alone would only refer to a performance at a given state, which is non-representative of the global performance. Modelling methods seems to be required to allow the extrapolation of the global performance from measurements. Thus, the comprehensive review presented in this paper has two objectives: comparing the accuracy and applications' conditions of measurement methods used to characterize natural airflows, and comparing the suitability of modelling methods to account for natural and hybrid ventilation systems.
Concerning measurement methods, tracer gas methods are often used to characterize natural ventilation systems. They are indirect methods based on the concentration of a tracer gas, so they do not interfere with the flow pattern. However, they rely on assumptions whose violation results in an increase of uncertainty. Most critical assumptions are the homogeneity of the tracer gas in the enclosure and the invariant nature of airflow rates during the measurement. The latter restricts the number of suited tracer gas methods. Other measurement methods derived from tracer gas methods are occupant generated CO_2 methods. They often require to have access to the occupancy rate, as well as the emission rate. The emission rate, depending on people and activities, introduces another uncertainty source. Also, in most of the methods, the occupancy should not vary during a long time.
Regarding modelling methods, they are essentials to assess the performance of natural and hybrid ventilation systems to account for their numerous dependencies. Ventilation modelling methods may come from empirical models, network models or Computational Fluid Dynamics (CFD) models. However, models have to be experimentally validated. They are often validated thanks to measurement methods mentioned above, which may be unreliable regarding the studied case. Their suitability for natural and hybrid ventilation systems will be discussed in the present paper.

2 APPROACH

We made a comprehensive review of articles focused on the evaluation of methods intending to assess natural ventilation's performance. It includes articles that analyse the accuracy of tracer gas methods, of occupant-generated CO_2 methods, and of modelling methods.

This state of the art, realised in the context of the VNAT project's first task, aims at identifying methods assessing natural ventilation's performance, as well as their limits. A lot of articles have been tackling the issue of the accuracy of tracer gas methods since 1990. These methods are very interesting for the measurement of natural ventilation airflows, but they are characterized by important uncertainties. Occupant-generated CO_2 methods have been first considered in the 80s (Turiel 1980). A recent review paper on these methods has been found, especially used in school buildings applications (Batterman 2017). Their accuracy has also been questioned in several papers since the beginning of the 21st century. Finally, modelling methods also show a great interest, as the performance of natural and hybrid systems depend on several fluctuating parameters. Models only are able to consider this. Network models have been used for a long time, but CFD models are quite recent thanks to the increasing computational resources implemented on computers. Articles treating CFD models are mostly found from 2010.

3 DESCRIPTION OF MEASUREMENT METHODS

3.1 Tracer gas measurement methods

Tracer gas methods are widely used to characterize natural airflows. They have the double advantage not to interfere with the flow pattern and to take into account infiltration and exfiltration flows. Also, they account for the effective ventilation rather than the expected one (Nikolopoulos, 2012). They are based on the concentration of a tracer gas. Three main ways of injecting the gas within the zone are available: delivering it before the measurement, during the measurement at a constant flow rate, or during the measurement at a variable flow rate allowing to keep its concentration at a fixed target value. The first one, called tracer decay method, uses the decrease of the gas to obtain the mean Air Change Rate (ACR). The second one is called the constant injection method and get the airflow from an equilibrium of the concentration occurring after, at least, 3 air changes. The last one is called the constant concentration method and requires sophisticated servo-controlled air mass flow controller looped to a target concentration. Tracer gas methods are based on zonal assumptions including three requirements (Sherman, 1990):

- The tracer gas should be homogeneous in the entire zone;
- The zone should be isolated, with an exclusive exchange with the outdoor air;
- The outside air should be perfectly mixed within the zone, meaning that no shortcomings should occur.

As a consequence, performing tracer gas measurement in a building would assume the whole building to be a well-mixed single zone, with a homogeneous tracer gas. However, this is possible to perform tracer gas measurements in a multi-zone buildings by two means: either by using multiple gases which result in a matrix illustrating inter-zonal flows and outdoor air flow (Roulet, 1991), or by applying the constant concentration method while keeping each neighbouring room at the same concentration level. The last technique does not provide information about inter-zonal flows but inhibits its influence (Bekö, 2016). Multi-zonal tracer gas measurements are beyond the scope of this paper.

Tracer gas methods ensue from the mass balance equation (Sherman, 1990):

$$V \frac{d(C(t))}{dt} + Q * C(t) = E(t) \quad (1)$$

With V the volume, C(t) the concentration, Q the airflow and E the emission rate.

Then, Sherman proposed three techniques for resolving *equation (1),* with their specific assumptions (Sherman, 1990): the regression technique, the integral technique and the averaging technique. The regression and the integral techniques assume steady airflows whereas the averaging technique tolerates variable airflows. We saw above a first source of distinction between methods by ways of dosing the gas. The three resolution techniques result in another distinction inducing sub-methods. The standard ISO 12569 (ISO 12569, 2017) describe the application of each method and sub-method to measure airflow rates in a single zone.

Constant concentration method

The constant concentration method may be considered as the reference tracer gas method. Its servo-controlled mass flow controller allows to describe the evolution of the ACH during the measurement thanks to the evolution of the emission rate of the tracer gas. This is the only tracer gas method able to account for a dynamic airflow rate. As the concentration is assumed to remain constant, the resolution of the mass balance equation is immediate, and the airflow is obtained by the ratio of the emission rate by the target concentration value. It can theoretically be computed instantaneously but according to the response time of the system, it is recommended to average the equation on successive periods (Chao, 2004). Chao et al. prescribe to start the injection hours before the beginning of the test. This method requires sophisticated materials and trained staff. Its application is restrained to research projects (Bekö, 2016; Blomsterberg, 1999; Chao, 2004). It is often used to assess the accuracy of other tracer gas methods, considering the constant concentration method as the reference value.

Tracer decay method

As aforementioned, for the tracer decay method, the gas is released before the measurement. When the concentration reaches its expected value, the injection is stopped. It is common to use a mixing fan during the injection and a few minutes later to ensure the homogeneity of the tracer gas before the measurement, which is a requirement of the standard ISO 12569 (ISO 12569, 2017). Then, the exponential decrease of the gas provides the mean ACH between the first and the last measurement points. The tracer decay method is the most used tracer gas methods thanks to its ease of implementation and to the small amount of tracer gas required. Two results analyses are then available, based on different resolutions of *equation (1).* The two-points decay method is based on only two measurement points. It ensues from the averaging techniques. On the contrary, the multi-points method represents a least-squares regression, allowing to significantly smooth measurement errors.

Sherman gave the formula for the standard deviation of both methods, ensuing from the error propagation law (M. Sherman 1990). Cui et al. computed it with experimental data and found a difference in the standard deviation of both methods of about 6% (Cui, 2015). However, the least squares regression implies steady airflows, which is hardly suited to natural ventilation whereas the two-points method tolerates variable airflows. Two other sub-methods are possible: the pulse technique and the step-down exhaust concentration method. Because methods require either an identified inlet or outlet, these methods are less suited to natural ventilation systems.

Constant injection method

The constant injection method is also widely used but it requires an important amount of tracer gas. The gas is dosed at a constant flow rate. The constant injection method requires the tracer gas' emission to be homogeneous within the enclosure. A mixing fan should be avoided during the measurement, as it would affect the flow pattern. An important number of dosing points should be used. Just like the concentration decay method, different analysis resulting from different resolutions of *equation 1* are possible. The linear regression technique implies to wait for the equilibrium. The accumulation term of the mass balance equation tends to zero after 3 air changes, and the airflow becomes the ratio of the emission rate with the concentration. The averaging resolution technique induces the inverse concentration method and is suited to variable airflows (ISO 12569, 2017). It does not require to wait for the equilibrium of the concentration.

A passive method is derived from the constant injection method. It is called the Constant Injection Long-Term Sampling (CILTS) method. A liquid is evaporated at a relatively constant rate through a controlling membrane. They are commonly called "PFT" methods as gases used are PerFreons Tracer gases. The sampling technique may also be passive with absorption tubes, or with sampling bags. This method allows to measure the mean airflow rate during months in occupied houses, and showed a great interest in the literature (Bekö, 2016; Blomsterberg, 1999; Okuyam, 2009).

3.2 Occupant-generated CO_2 methods

Occupant-generated CO_2 methods are very interesting because they do not require the injection of any tracer gases, taking advantage of a gas directly produced by people. Turiel et Rudy were of the firsts to identify the potential of occupant-generated CO_2 (Turiel, 1980). Batterman recently presented a review of existing occupant-generated CO_2 methods (Batterman, 2017). He identified 4 main methods relying on tracer gas methods' principles: the concentration decay, the built-up method, the steady-state method, and the transient mass balance equation method. The main problem arising from these methods is the uncertainty in the estimation of the emission rates which depends on each individuals, occupancy, activity, gender. The approximation, which is often made concerning emission rates, introduces significant errors. Persily et de Jonge proposed an update of the emission rate formula, which had not been revised since 1980 (Persily, 2017). They included, among others, the influence of the gender and of the age. In this respect, it has recently been proven that the old formula overestimated males' emission rate by 15% and females' emission rate by 25%.

Concentration decay

The concentration decay is based on the same principle than the tracer decay method. The measurement begins when occupants leave the studied zone. It has the advantage to be independent from the emission rate. However, it requires a significant rise in CO_2 levels in the enclosure. Thus, this method is often used in classrooms or offices (Roulet, 2002). The occupancy in those buildings are convenient with period hosting a huge and constant number of occupants, and period where everybody leaves the building like during breaks or at the end of the day. The increase of CO_2 must be in the order of several hundred in order to be far enough from typical CO_2 measurement errors (Batterman, 2017).

Steady-state method

The steady-state method is the regression constant injection method. The occupancy should not change during the measurement which has to last at least 3 air changes. This represents a significant obstacle to the method as the equilibrium is very hard to achieve (Batterman, 2017). The airflow is often over-estimated with this method.

Build-up method

The build-up method requires a step-up in the occupancy. The occupancy should not vary after the beginning of the measurement. These two requirements are similar to the steady-state method. However, it uses the transient increase of the CO_2 concentration and not the steady-state. As a consequence, the measurement requires less time than the steady-state method. A non-linear regression is required, often performed thanks to softwares. Bekö et al. used principally this method to assess the airflow of 500 children bedrooms (Bekö, 2010). Hou et al. also used this technique to investigate almost 400 child bedrooms in northern China (Hou et al. 2018a).

Transient mass balance equation method

The transient mass balance equation uses computer programs performing a non-linear fit. The occupancy can change but must be recorded as it represents input of the model. The emission rate as well as the airflow rate is deduced from the model. Coley et Besteiner performed it in classrooms (Coley, 2002). The main advantage of this method is that it does not require a fixed occupancy, once the evolution of the number of occupant is recorded (Batterman, 2017). However, the airflow rate should be constant during the fitting. If not, the model has to be computed on successive periods, in which the airflow rate is constant.

4 DESCRIPTION OF MODELLING METHODS

4.1 Empirical and Analytical modelling methods

Empirical and analytical models are based on the assumption that the whole building is homogeneous and surrounded by an envelope, on which balance equations may be realized. They aim at characterizing the openings behaviour. The envelope is decomposed of elements that account for energetic transfers, such as walls and roofs, and other elements that allow the air transfer, such as air inlets or windows. Then, the flow crossing openings is characterized by laws connecting pressure and airflows such as $Q = C * (\Delta P)^n$. The most used empirical model is the following (Wullens, 2015):

$$Q = A.C_d.\sqrt{\frac{2.\Delta P}{\rho}} \quad (2)$$

With A the effective area, C_d the discharge coefficient, ΔP the pressure difference across the opening, and ρ the density.

These models are used on standards to compute airflows within buildings (ISO 16798-7 2017) (ISO 16798-7, 2017). They are convenient because they can quickly account for the order of magnitude of airflows. It is suited to energetic considerations to assess the heat losses by the air renewing. They require to measure wind speed and direction, outdoor and indoor temperatures, and ideally pressure coefficients. However, the amount of assumptions required to close the system impacts their accuracy (Omrani, 2017). The assumed homogeneity of the whole building introduces other sources of uncertainty. Nevertheless, authors keep trying to improve models, especially for single-sided ventilation and cross-ventilation, in which accurate wind effects are difficult to assess (Larsen, 2016). Caciolo et al. developed a new empirical correlation to characterize the flow crossing a window located leeward (Caciolo, 2013).

4.2 Network modelling methods

Network models consists in dividing the building into zones where each state variable is homogeneous. Zones may be rooms or floors. Mass balance equations are resolved within each zones and they are connected to each other thanks to pressure/airflow laws, or by different models such as wide openings models (Wullens, 2015). Several softwares include multizone network models, such as MATHYS (Demouge, 2017), developed by the french Building's Scientific and Technical Center (CSTB), COMIS, or CONTAM. These models are very convenient as their lightweight allows to simulate during 1 year, describing the evolution of each state values. However, homogeneous zonal assumptions may introduce uncertainties and they cannot give any information about the flow pattern. The assumed pressure field homogeneity is often withdrawn on last versions on softwares aforementioned (Wullens 2015).

Other network models with finer meshes may be realised. They may be called "zonal models". They rely on the resolution of mass and energy balance equations on each zones.

4.3 Computational Fluid Dynamics methods

CFD modelling is the most used modelling method to characterize natural airflows. It consists in discretizing the building volume and resolving Navier-Stokes equations on each sub-volume. Thus, they account for the flow pattern within the building, which makes a huge difference with other models. The other main difference is that wind effects are better treated. Two CFD approaches are in use: the Reynolds Averaged Navier Stokes (RANS) and Large Eddy Simulations (LES). RANS methods average wind pressure and temperatures to reduce the computational cost. An approximation is then realised by adding a turbulence models intending to keep the dynamic nature of physical mechanisms. Several models are used in the literature and the choice of one of them is often complicated. LES methods reduce the computational cost by ignoring small length scales thanks to low pass filters. The meshing is coarser than RANS models.

CFD models rely on several assumptions about the domain, the mesh, boundaries, solver parameters and the mesh sensitivity (van Hooff, 2017). Thus, they need to be experimentally validated. According to Omrani et al., CFD models can be used through two main approaches (Omrani, 2017). The first one is the association of CFD models with measurements. Measurements would allow to validate the model, and to visualize the data computed by the simulation. Once validated, CFD models are very useful to test different parameters, assessing for example the influence of openings types, locations and sizes. The second approach would be to couple CFD models with network models. First, CFD models would accurately compute boundary conditions by modelling the surrounding of the building of interest. Computed boundary conditions can be implemented in the multi-zone models thanks to adequate interface. Then, multi-zone models compute airflows of each room and it saves a huge computational cost (Wullens 2015). It remains a lot of work to do for those coupled models and we will not further analyse them in the present paper.

5 RESULTS & DISCUSSION

5.1 Tracer gas measurement uncertainties

Tracer gas measurement methods are subject to several studies, which tackle the issue of their accuracy. These methods are very promising for the characterization of natural airflows as they do not interfere with the flow pattern. However, they rely on assumptions which induce several sources of uncertainties. Table 1 compile the synthesis of tracer gas methods with their estimated accuracy and their limits.

Concerning the decay method, the homogeneity assumption is assumed to be the most critical as spatial differences in the concentration may be as large as 10% (Cui, 2015). Van Buggenhout et al. found a deviation of the ACH about 86% for one of the sensors, situated near the inlet (Van Buggenhout, 2009). Several studies indicate that the best sampling locations are near the outlet (Cui, 2015; Van Buggenhout, 2009), ensuring a deviation below 10%. However, the outlet is not systematically clearly identified in natural ventilation. Okuyama et Onishi developed a method intending to reduce the influence of inhomogeneity (Okuyama et Onishi 2012). They performed a sinusoidal injection at the inlet. Another issue in the decay method is the choice between the 2 points and the multi-points decay method. As mentioned above, with steady airflows the multi-points method should be around 6% more accurate (Cui et al. 2015). However, unlike the 2 points method, it does not tolerate variable airflow. Remion et al. showed that a linear variation of 10% of the airflow during the multi-points decay measurement increases the deviation by 3% in controlled conditions (Remion et al. 2018). Anyway, due to its greater accuracy, the multi-points method is often preferred, even to characterize fluctuation airflows (Cui, 2014.; Caciolo, 2010; Gough, 2018). Chao et al. found an overestimation of the multi-points decay method with variable airflows, against the constant concentration method, of 10 to 15% (Chao, 2004). Under steady airflows, Sandberd et Blomqvist found a difference between both methods of 6% (Sandberg, 1985).

The Constant Injection Long Term Sampling technique was investigated by Sherman et al. (Sherman, 2014). Under ideal conditions, an accuracy of 15% could be expected. On in-situ buildings, with a trained staff, the accuracy decreases to 20 – 25%, mainly because of the variation in parameters, such as the airflow rate, the emission rate or the sampling rate.

Carrihlo et al. developed a method based on the daily CO_2 cycle (Dias Carrilho, 2015). It provided values within 10% of the reference value measured by the occupant-generated CO_2 decay.

5.2 Occupant-generated CO_2 measurement uncertainties

Table 1 also includes the analysis of occupant-CO2 generated tracer gas methods. Batterman et al. realised a comprehensive review of occupant-generated CO_2 methods applied in school buildings (Batterman, 2017). His conclusion is that the transient mass balance method is very convenient as it is flexible with respect to occupancy. Coley et al. compared the accuracy of this method with the tracer decay measurement performed with SF_6. They found for closed windows configuration a deviation of 15% between both methods whereas the deviation increases to 40% with opened windows. Differences are justified by interzonal flows which influence the CO_2 measurement as its concentration is higher in buildings than outdoor. Santamouris et al. also reported an accuracy of 15% for the transient mass balance analysis (Santamouris, 2008). Another advantage of the transient mass balance equation method is that this is the only occupant-generated CO_2 method that can account for a fluctuating airflow rate.

When the occupancy does not change, authors often prefer the build-up method rather than the steady-state method because of the significantly reduced required time (Hou, 2018; Bekö, 2010; Bekö, 2016). Bekö et al. tried each method depending on the occupancy in 500 Danish rooms but often retained only the build-up method. The decay method would require a significant charge in CO_2 concentration, which is difficult to obtain with a small occupancy. They estimated the inaccuracy due to interzonal flows thanks to CONTAM, a building simulation software, around 30%. In a later paper, Bekö et al. compared the build-up method with constant concentration method and found that the occupant-generated CO_2 method resulted in airflow rates twice as large as those measured by the tracer gas method. Hou et al. investigated Chinese rooms and reported that the build-up method’s accuracy has been estimated by Stavova, in a thesis project, around 15% in controlled conditions (Hou et al. 2018b).

Lu et al. proposed an improvement of the occupant-generated CO_2 decay method by applying the Maximum Likelihood Estimation (MLE) to the decay. It is assumed to be more powerful and to give results faster, which would allow to apply the method without huge rise in CO_2 concentration levels (Lu, 2010).

Table 1: Limits of main natural ventilation's performance measurement methods

Tracer gas methods							
Method	**Sub-method**	**Fluctuating ACH**	**Accuracy**	**Measure-ment time**	**Cost**	**Other limits**	**References**
Concentration decay	Multi-points	No	10 - 25%	-	-	- Volume < 500 m^3	*(Caciolo, 2011); (Sandberg, 1985); (Chao, 2014)*
	2 points	Yes	15 - 30%		-		*(Cui, 2015); (Sherman, 1990)*
Constant injection	Steady-state	No	NA	+	+	- Important amount of TG - The dosing of the gas should be homogeneous	
	Inverse concentration	Yes	NA	-	+		*(Allab, 2017)*
	Long term	Yes	20 - 100%	++	--		(Sherman, 2014); (Lunden, 2012)
Constant concentration		Yes*	3 – 9%	[1]	++	- Sophisticated equipment	*(Bekö, 2016); (Chao, 2014); (Blomsterberg, 1999); (Sandberg, 1985)*
Occupant-generate CO_2 tracer gas methods							
Build-up		No	15 - 100%	-	--	- No change in occupancy - Need emission rate	*(Hou, 2018); (Bekö, 2010); (Bekö, 2016)*
Concentration decay		No	10 - 25%	-	--	- Require a huge CO_2 charge	*(Turiel, 1980); (Roulet, 2002)*
Steady-state		No	10 – 30%	++	--	- No change in occupancy - Need emission rate	*(Batterman, 2017); (Santamouris, 2008)*
Transient mass balance equation		Yes	15 - 40%	*	--	- Need the occupancy - Need the emission rate	*(Batterman, 2017); (Santamouris, 2008)*

** Not only tolerates variable airflow but also provides its evolution. [1]By choice of the experimenter.*

5.3 Comparison of modelling methods

Omrani et al. performed a comparison of each modelling methods (Omrani, 2017). As many authors agree on, empirical formulas are very convenient as they provide a fast estimation of general airflows in buildings. However, the whole building's homogeneity assumption, and the averaging of the wind introduced in empirical models may cause huge uncertainties. Several studies compared empirical models with tracer gas measurements, especially for single-sided ventilation and cross-ventilation (Gough,2018; Caciolo, 2013; Cui, 2014).Cui et al. found a difference for cross-ventilation between empirical models and tracer decay method between 45% and 60% depending on correlations (Cui, 2014). Gough et al. deduced directly airflows thanks to pressure taps sensors installed across openings (Gough, 2018). Comparison with tracer decays showed a weak correlation with a coefficient R^2 <0,17. Caciolo et al. found differences between empirical models and tracer decay measurement for single-sided ventilation above 25% for every models they tried (Caciolo, 2010).

Network models are also often validated by means of tracer gases. Belleri et al. used PFT methods to validate a multi-zone model (Belleri, 2014). When windows are closed, the model shows a good agreement with the measurement (5%). However, open windows lead to large deviations between both methods. As for empirical formulas, network models cannot accurately predict the effect of wind. Blomsterberg compared a COMIS network model with constant concentration tracer gas measurement (Blomsterberg, 1999). He found a difference of 1% for a single-family house and 20% for an apartment. Results from buildings with several floors may be less realistic because standard pressure coefficients are involved in the simulation. However, there is a significant spatial discrepancy of pressure coefficients on façades, especially for high-rise buildings. Accurate pressure coefficients can only be obtained in wind tunnels. Zhai et al. compared different network models and found no significant differences between models as they often rely on same physical principles (Zhai, 2015). They seem to work efficiently for simple geometries without open windows. However, they cannot accurately account for wind effects.

CFD models are supposed to give best results as they theoretically resolve every issues mentioned in this paragraph: they do not assume any homogeneity of building zones, they take into account the fluctuating wind, they compute pressure coefficients and they determine the flow pattern inside the building. However, they require such an amount of assumptions, that the validation is even more required than for other models. These assumptions are different than for previous models as they are made by the modeler and not by the modelling software. Validation methods are more diversified than for other models as CFD outputs give a lot more information. Validation may be done by means of tracer gas (Nikolopoulos, 2012), by measurement of state parameters (Elshafei, 2017), by direct measurement of airflow in an opening (van Hooff, 2017), and finally by Particle Image Velocimetry (PIV) measurement in an opening (Bangalee, 2013). The higher accuracy of CFD models is induced by way more sophisticated models requiring a huge computational time, even more for LES models which last between 80 and 100 times longer than RANS models (van Hooff, 2017). Van Hooff et al. also compared the accuracy of RANS and LES models and found that all results where within 8,6% of the reference value.

CFD models are the most accurate and give the more information which is very useful to treat the air distribution's function of ventilation systems but they require significant computational resources. Also, caution have to be given to CFD results as modelling choices may introduce significant impacts. The validation is challenging but crucial. Network models may be convenient compromises between computational cost and accuracy. However, they hardly account for wind effects. Empirical and analytical methods are convenient for quick single-zones airflow's estimation. Finally, models' validation is very challenging for natural ventilation systems for the moment because of the lack of an accurate natural airflow's measurement method, as seen in 5.1 and 5.2.

6 CONCLUSION

A comprehensive review has been done on articles treating the assessment of natural and hybrid ventilation's performance. Two main methods were identified to characterize natural airflows, including tracer gas methods and occupant-generated CO_2 methods. Modelling methods characterizing natural ventilation systems, as a whole, were also analysed.

Regarding the in-situ measurement of natural airflows, tracer gas methods seem to be promising but only a few are suited to variable airflows. Moreover, they are characterized by important uncertainties because of the violation of assumptions, the required homogeneity of the tracer gas, and measurement uncertainties. The constant concentration method would be ideal as it provides the evolution of the ACH, but its implementation on in-situ buildings in a reasonable cost is nearly impossible. Occupant-generated CO_2 methods take the advantage of tracer gas principles, but have the great benefit not to require any dosing instruments or gases. However, neither the emission rate has to be accurately determined, which is challenging, nor the rise in CO_2 concentration levels has to be significant, meaning a long or important occupancy preceding the measurement. Moreover, 3 out of 4 occupant-generated CO_2 methods require strict conditions concerning the occupancy.

To account for the dependency of natural and hybrid ventilation systems, modelling methods are essential but their validation is very complicated as no measurement methods provide accurate ACH results. Network models are convenient for simple geometries but are hardly suited to account for wind effects. CFD models may be more accurate, but rely on several modeller-made assumptions, which increases the importance of the validation. They may be validated by other means than tracer gases, but often in wind-tunnel with reduced-scales buildings. Also, they require a huge computational cost, which restrains their use for research projects.

Finally, the development of a protocol assessing the global performance of natural and hybrid ventilation systems could come from the coupled measurement/modelling approach, which is the aim of the french VNAT project. It intends to overcome the difficulty to measure natural airflow while allowing to extrapolate the performance's assessment from measurements of indicators chosen thanks to a sensitivity analysis.

7 ACKNOWLEDGEMENTS

This work is supported by the French ministry of building construction. Being part of the VNAT project, it is also supported by ADEME, the French environment and energy management agency.

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