Review and analysis of existing diagnostic methods for characterizing air transfers in existing homes

Imane Mannan[1], Adeline Mélois[1], Bassam Moujalled[1], Luke Smith[2], Christopher Wood[3], Xiaofeng Zheng[3]

1 Cerema, BPE Research Team 46 rue Saint Théobald F-38081, L'Isle d'Abeau, France

**Corresponding author: e-mail address imane.mannan@cerema.fr*

3 Architecture, Climate and Environment Research Group, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

2 Build Test Solutions Ltd., Building 8, The Royal Ordnance Depot NN7 4PS, UK

ABSTRACT

Buildings energy renovation is a major priority in most European countries in order to achieve a fully decarbonized building stock by 2050. In France, 7 million homes are poorly insulated and 14% of French people feel cold in their homes. The government has thus implemented an ambitious plan to scale up energy-efficient renovations of buildings to achieve carbon neutrality by 2050 while also pursuing a social objective of combating energy precarity.

More and more energy audits are being carried out, and the diagnostic method will be overhauled in 2024. These audits are often the only diagnostic work carried out prior to energy renovation, which must be done on a massive scale and quickly if the government's targets are to be met. Yet, existing homes feature a wide range of ventilation systems (non-existent, natural, mechanical) and levels of envelope air permeability. Overlooking these essential parameters in the energy renovation process, which are vital for ensuring good indoor air quality, could result in a proliferation of under-ventilated dwellings.

Air change rate in dwellings have an impact on both their energy performance and indoor air quality, particularly through the air infiltration of dwellings and the ventilation airflow. Methods currently exist for characterizing and assessing these factors using in situ measurements. However, these methods are often time-consuming to perform, and there are constraints on their widespread use during housing renovations. The most commonly used methods to characterize building air permeability and natural airflow rate are the blower door and tracer gas, respectively.

Recently, alternative methods for measuring building airtightness such as the Pulse method have been developed. This paper aims to investigate the existing measurement methods and devices for in-situ diagnostic of air change rate (air permeability of the envelope and natural ventilation airflow) in existing French and English dwellings.

This paper presents a review of the various existing methods for measuring building air permeability and natural airflow rate, and analyses the advantages and disadvantages of their use in existing occupied dwellings based on the reliability of the measured parameters and practical constraints.

KEYWORDS

Airtightness, blower door, pulse, tracer gas

1 INTRODUCTION

Buildings energy renovation is a major priority in most European countries in order to achieve a fully decarbonized building stock by 2050. In France, 7 million homes are poorly insulated and 14% of French people are cold in their homes. The government has thus implemented an ambitious plan to scale up energy-efficient renovations of buildings to achieve carbon neutrality by 2050 while also pursuing a social objective of combating energy precarity. In 2017, the UK government set out a target to improve the rating of all fuel-poor homes to band C by 2030, and an aspiration for as many homes as possible to band C by 2035.

Thus, more and more energy audits are being carried out, but they are often the only diagnostic work carried out prior to energy renovation, which must be done on a massive scale and quickly. Yet, existing homes exhibit a wide range of ventilation systems (non-existent, natural, mechanical, hybrid, etc.) and envelope air permeability levels. Overlooking these essential parameters in the energy renovation process, which are vital for ensuring good indoor air quality, could result in a proliferation of under-ventilated dwellings. Indeed, air transfers in dwellings have an impact on both their energy performance and indoor air quality, particularly through the air permeability of dwellings and the air change rate. Methods currently exist for characterizing and assessing these factors using in situ measurements. However, these methods are often time-consuming, and there are constraints on their widespread use during housing renovations. The most commonly used methods to characterize building air permeability and natural airflow rate are the blower door and tracer gas, respectively. Recently, alternative methods such as the Pulse method have been developed and is authorized in regulatory context in the UK. This paper aims to investigate the existing measurement methods and devices for in-situ diagnostic of air transfers (air permeability of the envelope and air change rate) in existing French and UK dwellings. In this paper, we first describe the current context regarding ventilation in existing dwellings in France and the UK. Then, we present the different tools we are studying for the development of a new protocol adapted to these dwellings, and the first results of comparison between the three tools we have used in laboratory conditions and in an office building.

1.1 French context

Since the late 60s, France has seen a huge growth in the energy efficiency of the new residential buildings after implementing successive thermal regulations. In the meantime, with the coming into force of the ventilation regulations, with the decree of 1969 (JO 1969) and then the decree of 1982 (JO 1982), the use of controlled mechanical ventilation systems has become mandatory in housing and has led to a progressive abandonment of natural ventilation (Moujalled et al. 2022). On January 2022, France had replaced the last thermal regulation, RT2012, with the new energy and environmental regulation for all new construction RE2020, which is more ambitious and more demanding for the construction sector. This regulatory framework has been made in order to ensure good indoor air quality by allowing occupants to have reliable and efficient mechanical ventilation systems, with the introduction of the mandatory inspection of the ventilation systems for dwellings. Nevertheless, all these regulations only apply for new buildings.

In French old dwellings, air change rate is most of the time ensured by the leaks located on the envelope, with sometimes also natural ventilation and rarely mechanical ventilation. Yet, when

it comes to energy renovation that often leads to more airtight buildings, ventilation rates and air permeability levels are always neglected, which raises many questions about indoor air quality levels post the renovation process. This is why we are studying the use of existing diagnostic tools dedicated to airflow measurements in order to propose a method to evaluate the need for new mechanical ventilation systems in these dwellings that are being retrofitted.
Since 1982, all new dwellings have to comply with the same regulation regarding ventilation. This regulation requires that the air must be able to circulate freely from the air inlets located in the main rooms, all the way to the air outlets in the service rooms, at least in kitchens, bathrooms or showers and toilets, made by vertical ducts or natural exhaust with natural draft or mechanical devices. The airflow rate extracted by the ventilation system in each room depends on the number of the main rooms in dwellings. These exhaust airflow are defined in Table 1 (JO 1982).

Table 1: Airflow rates to be extracted which can be achieved simultaneously or not (JO 1982)

	Minimum Exhaust Airflow rate (m3/h)						
Number of main rooms	Global minimum	Kitchen (basic)	Kitchen (peak)	Bathroom with or without toilet	Other bathrooms	Toilet: First one	Toilet: Others
1	35	20	75	15	15	15	15
2	60	30	90	15	15	15	15
3	75	45	105	30	15	15	15
4	90	45	120	30	15	30	15
5	105	45	135	30	15	30	15
6	120	45	135	30	15	30	15
7	135	45	135	30	15	30	15

1.2 British context

In England, properties are required to comply with the Part F Regulation (UK Government 2022), which guides ventilation within buildings. The minimum whole dwelling ventilation rates in the habitable rooms should respect the values presented in Table 2.

Table 2: Minimum whole dwelling ventilation rates determined by the number of bedrooms

Number of bedrooms	Minimum ventilation rate by number of bedrooms (m^3/h)
1	68.4
2	90
3	111.6
4	133.2
5	154.8

Exhaust outlets should be located properly, in places where the re-entry of exhaust air into the building, or into nearby ones would be minimized. For each additional bedroom, 6l/s must be added to the values of the table 2 (UK Government 2022) .

In contrast to France, when a building is being assessed for retrofit, property owners in England are provided with a guide (IAA 2021), to help them determine whether their existing ventilation is adequate, if it requires modest intervention or more advanced and extensive ventilation work. The guide includes a methodology to identify the need to improve the ventilation strategy in case of renovation (Figure 1). This methodology includes air permeability measurements.

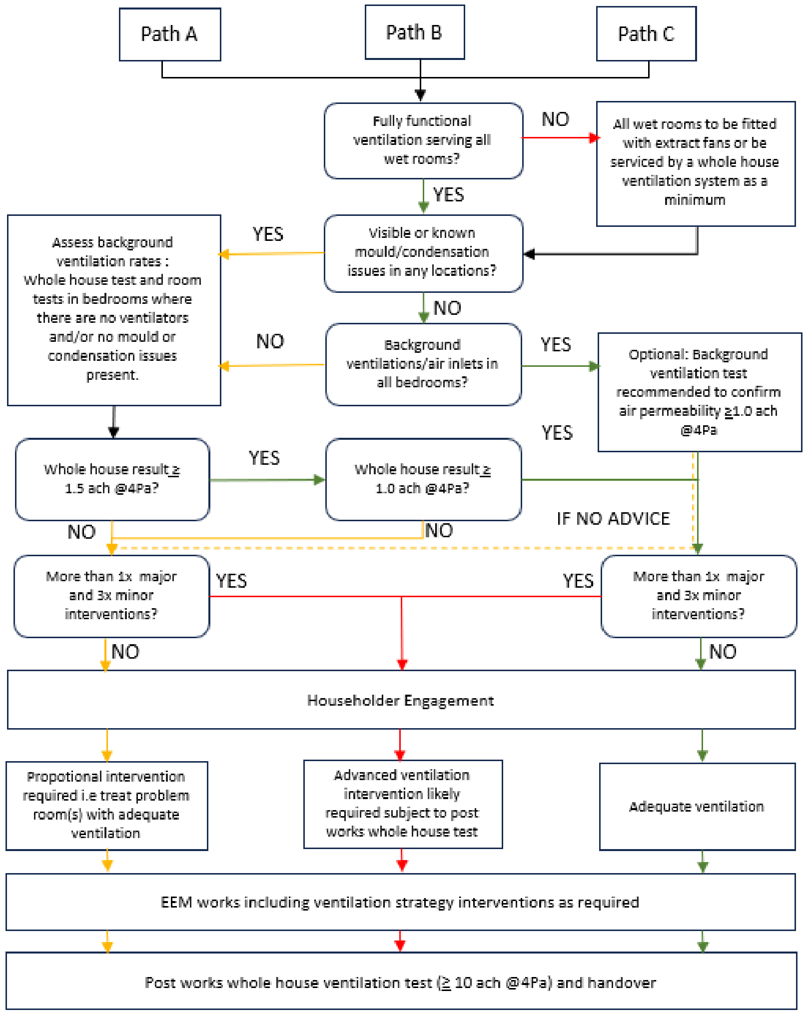

Figure 1: Ventilation assessment matrix (IAA 2021)

2 MEASUREMENT METHODS

We investigate in this paper the use of existing measurement methods and devices for in-situ diagnostic of air transfers (air permeability of the envelope and air change rate) in order to develop a new protocol adapted to existing dwellings before retrofitting. Thus, we present in this section the methods and tools we have considered.

2.1 Measurement of envelope airtightness

Building airtightness is mostly characterized by two indicators; air permeability, which is described as the amount of air per hour per square meter that moves through the building's envelope, and air changes per hour (ACH) which is how many times per hour the volume of air is replaced within a building.
The fan pressurization test is the most commonly used method to measure air permeability; by creating a range of high-pressure differences (10-100 Pa) between the inside and the outside of the building and the corresponding airflow through the measurement device is simultaneously determined. The main shortcoming of this method is how it is affected by outdoor conditions, ISO 9972 (ISO 2015) claims that the overall uncertainty for tests in accordance with this standard can be calculated and is estimated to be under 10% for calm conditions and to reach 20% in windy conditions. An additional source of uncertainties is the extrapolation of air

permeability to 4 Pa; which is a more suitable pressure for infiltration under normal operating conditions.
Alternatively, the novel Pulse method is attracting considerable interest due to the testing that is being conducted under low pressure levels. By rapidly releasing bursts of air (pulses) into the tested building, thereby creating an instant pressure rise that quickly reaches "quasi-steady" condition, Pulse determines the building air leakage in the range of 1-10 Pa and reports it at 4 Pa without extrapolation (Hsu 2021). Another strength of Pulse lies in how quick it is, which drives the uncertainties generated by the wind to become less significant.

2.2 Measurement of natural airflow rate

When characterizing natural airflow rate, tracer gas is widely used and it is considered to be the most reliable method that allows testing in natural conditions. In this context, the tracer gas method will be used as a reference when using both the Blower door and Pulse to determine whether the ventilation rates are sufficient in buildings with natural ventilation systems post energy renovation or not.
Tracer gas methods that derive benefit from metabolic CO_2 are generating considerable interest, since they do not require any gas injection, and are consequently less expensive and less harmful to the environment. The decay method consists of using the observed decays of metabolic CO_2 concentration, when the occupants leave the building, and using it as an indicator of indoor air quality within the tested area. In order to use this method effectively, we focused on the maximum recorded CO_2 concentration at 6pm, so that we can have the most important decay, which in our case corresponds to 26/03/2024.
In order to determine the air change rate with this approach, two methods were used. The first method can be modeled by the equation 1 (Asadi, Costa, and Gameiro da Silva 2011).

$$C(t) - C_{equi} = (C_0 - C_{equi}) * e^{-\lambda t} \tag{1}$$

where:

- $C(t)$ is the concentration of the pollutant at time t [ppm];
- C_{equi} is the asymptotic value of the concentration when equilibrium is reached [ppm];
- C_0 is the initial concentration value [ppm];
- λ is the infiltration rate of the indoor compartment [vol.h-1].

The second method uses multiple points, making the results more accurate (Remion 2020)

$$N_n = \frac{\sum t_i * \sum \ln(C_i - C_{ext}) - n * \sum t_i * \ln(C_i - C_{ext})}{n * \sum t_i\text{^}2 - (\sum t_i)\text{^}2} \tag{2}$$

- N is the ventilation rate [vol.h-1];
- Ci is the concentration at t_i [ppm];
- C_{ext} is the external concentration [ppm];
- t_i is the time [h].

In Table 3, we give a first evaluation of advantages and disadvantages for the different methods we consider.

Table 3: First comparison of different considered methods

	Blower door	Pulse	Metabolic CO_2 decay	Injected CO_2 decay
Time of installation	+++	+	+	++
Time of measurement	++	+	++++	+++
Possible with occupancy	Yes	Yes	Yes	Not in all rooms

Direct result of air change rate	No	No	Yes	Yes
Accuracy	?	?	+	+++

3 METHOD

3.1 Tests in laboratory

It is of interest to investigate the ability of Pulse to generate similar results for multiple tests, especially when it comes to how accurate this measuring device can be when it is used to test naturally ventilated buildings. With a total surface area of 37.2 m^2 and a volume of 14.5 m^3, a sheltered chamber at Build test solutions (Pulse supplier) was tested using Pulse with 3 different leakage profiles and n exponents (Figure 2):

- Moderately airtight dwelling (Configuration 1);
- Average building (Configuration 2);
- Leaky building (Configuration 3).

When testing the chamber, two types of Pulse were used; the default production Pulse MK2 (Figure 3) and another version of Pulse; MK3 (Figure 4) which is not yet commercialized.

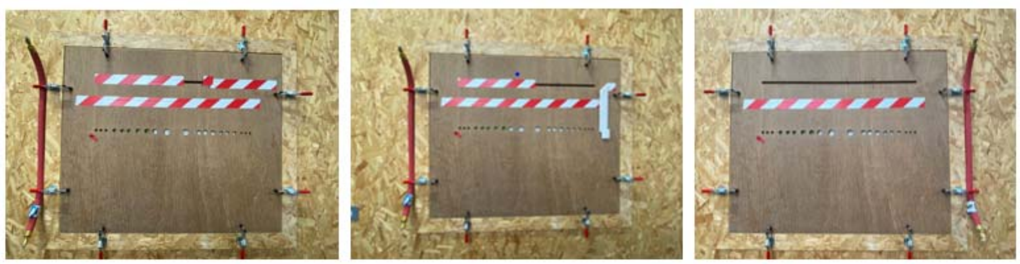

Figure 2: Configuration 1, 2 and 3

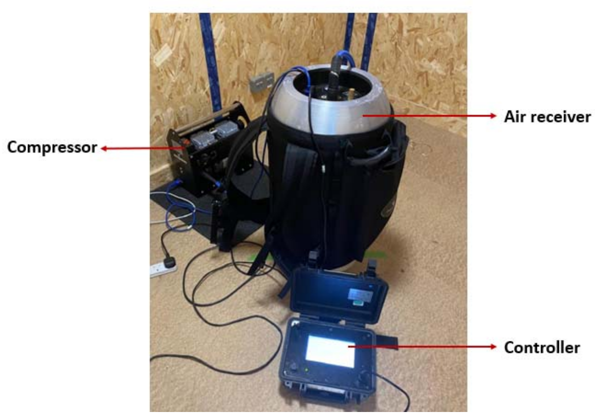

Figure 3 : Default Production pulse (MK2)

Figure 4 : Pulse MK2 controller, MK3 Air receiver

5 combinations of parameters for each device have been tested, including different durations of valve opening, different pressure inside the tank and different number of steps (Table 4).

Table 4: Parameters combinations for Pulse tests in laboratory

	Default Production pulse (MK2)			Pulse MK2 controller, MK3 Air receiver		
	Valve opening duration (s)	Number of steps	Tank pressure (bar)	Valve opening duration (s)	Number of steps	Tank pressure (bar)
C1	1.5	2	1	1.5	1	0.5

	1.5	1	0.5	1.5	2	0.8
	1.5	3	1, 1.5	1.5	3	0.8
	3	1	0.8	3	1	0.8
	3	2	1	3	2	1.5
	1.5	2	2	1.5	1	0.6
	1.5	3	0.8	1.5	2	2
C2	1.5	1	0.6	1.5	3	0.8
	3	1	0.9	3	1	0.9
	3	2	1	3	2	1
	1.5			1.5	1	1.4
	3			1.5	2	3, 2.5
C3				1.5	3	3.5
				3	1	1.7
				3	2	3.5

The same chamber at BTS was tested using the blower door with the same 3 configurations. During our Blower door tests, one of the challenges that we faced was the door frame from the blower door not getting adjusted to the actual door frame of the test chamber. The gaps were sealed with tape, but even after that, it was obvious that many openings were left uncovered.

Figure 5: Sealed gaps while using the blower door

3.2 Tests in office space

To get a better understanding of how occupants metabolic CO_2 is used as a tracer gas, the office area at Build test solutions was tested and both infiltration rate and air change rate were determined using both Pulse, and the decay method. Figure 5 shows the tested area, our focus is only on places that are mostly occupied, i.e. the office/kitchen area. Regarding the decay method, the used CO_2 data collected from the CO_2 sensors covered the period from 7:30pm to 4:30am on the 26th of March 2024. 3 Pulse tests were conducted, with the fan of the ventilation system on, covered, and then off.

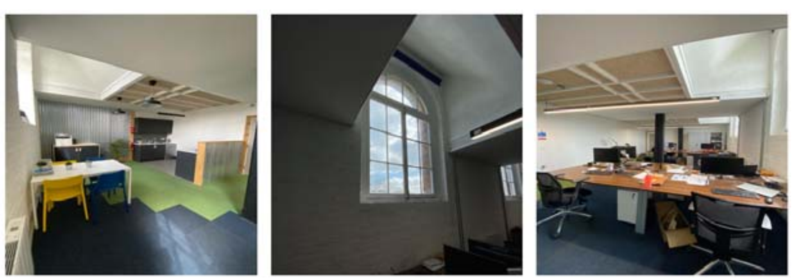

Figure 5: Office/kitchen area at BTS

4 RESULTS

4.1 Laboratory results

Figure 6, Figure 7 and Figure 8 present the results for the different combinations of parameters for each of the three configurations of the laboratory with Pulse. First, we consider the distribution of the values we have measured. For all three configurations, the median and mean values of Air Permeability at 4 Pa given by Pulse are quite similar, the distribution can thus be considered symmetric. When the mean values of the standard deviation of each test type are compared, it is clear how the results given by the MK2 and the ones given by the MK3 do not differ much, the MK2 mean standard deviation value only exceeds the MK3 one by approximately 5.5%.

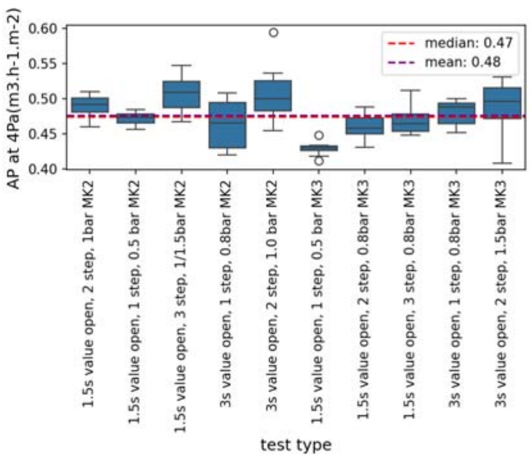

Figure 6: Air permeability at 4Pa using Pulse (Configuration 1)

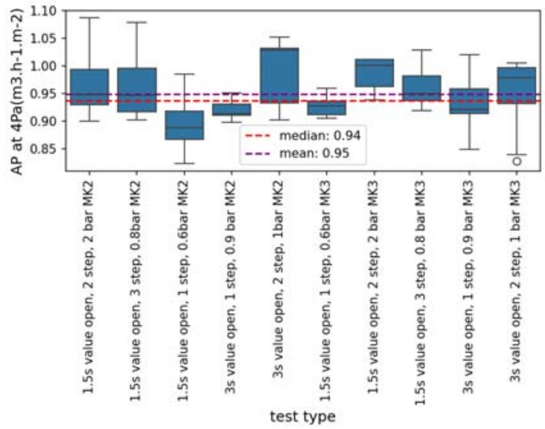

Figure 7: Air permeability at 4Pa using Pulse (Configuration 2)

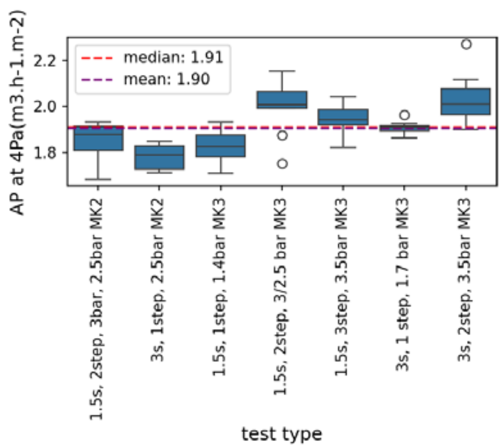

Figure 8: Air permeability at 4Pa using Pulse (Configuration 3)

Then we compared these results with the ones we have obtained with the blower door tests: Table 3 compares the results of air permeability at 4 Pa using the blower door and Pulse. The air permeability appears to be higher when measured by the Blower door. The contrast between our results can be explained by the gaps we failed to completely seal, and the windy conditions that day.

Table 3: Values of Air permeability at 4Pa using the Blower door and Pulse for the 3 configurations

	Air permeability at 4Pa (m3/h/m2)		
Test type	Config 1	Config 2	Config 3
Blower door (Pressurization)	0.87	1.82	2.52
Blower door (Depressurization)	1	1.50	2.84
Pulse test	0.48	0.95	1.90

4.2 Office space results

Figure 9 shows the result of the application of the CO_2 decay method to evaluate the infiltration rate in the office space. In the office/kitchen area we get 3.22 air changes per day which makes it 0.13 air changes per hour when applying the 2 points decay method. The same result was obtained when using the multi-points method.

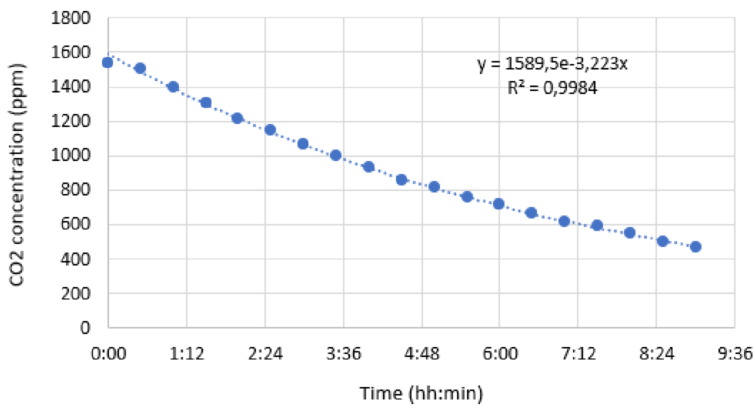

Figure 9: Infiltration rate using the 2 points method

In the UK, for high pressure airtightness testing at 50Pa, the divide by 20 rule is applied to get the infiltration rate by directly dividing the air permeability by 20. The proposed value for N if the ratio uses low-pressure airtightness measurements (4 Pa) is 7.9, The standard error is approximately ±0.5 (Vega Pasos 2020).

Tests using Pulse were conducted in the office space, with the mechanical ventilation system on (Fan On), with it off (Fan Off) and with the ventilation duct covered (Fan covered).

The results of air permeability given by Pulse were divided by 7.9 to get the infiltration-air leakage rate (Table 4).

Table 4: Evaluation of infiltration-air leakage rate with Pulse and the CO_2 decay method

	AP @4Pa	Infiltration rate or air change rate (/h)
Pulse Fan On	1.83	0.23
Pulse Fan covered	1.74	0.22
Pulse Fan Off	1.81	0.23
Decay 2 points	-	0.13
Decay multipoints	-	0.13

As expected, the highest value of air permeability given by Pulse is the one with the fan on, followed by the one given when the fan was off, and then the one when the fan was covered. Although our results differ slightly, it is worth noting that the divide by 7.9 rule is not yet widely used. Therefore, in the upcoming study, we will also be investigating its accuracy. Another limitation of this study is that the tested building is not a typical domestic building, with no controlled CO_2 conditions (only metabolic CO_2 with a starting concentration level around 1600ppm with a drop of 1000ppm, in addition to only 2 CO_2 sensors being used).

5 CONCLUSION AND PERSPECTIVES

In this paper, we presented the very first result of our investigation of existing measurement methods and devices for in-situ diagnostic of air transfers (air permeability of the envelope and air change rate) in order to develop a new protocol to evaluate the airflow through natural ventilation system in existing dwellings. We presented two approaches: one included tests in a laboratory and one in an office space. From laboratory results and office space tests, we have seen significant differences between the results from the methods we have tested. Thus, we identified the need to complete the study with new tests in order to better define the link between Blower door results, Pulse results and CO_2 decay method results.

A follow-up study will be carried out in 3 old dwellings with natural ventilation systems, in the city of Lyon, France. Our main target will be to verify if the ventilation ensured by the natural ventilation ducts is enough after the building's renovation or not, using the fan pressurization method, Pulse and tracer gas. Airflow measurements will be conducted with the ducts sealed in order to determine the airflow that is passing through the leaks on the envelope and then with the ducts uncovered, which will enable us to get the airflow rate through the natural ventilation ducts and determine how effective they are. Other laboratory tests will be performed in a new facility near Lyon, with a perfectly known envelope airtightness and different openings that have been perfectly characterized.

6 REFERENCES

Asadi, Ehsan, J. J. Costa, and Manuel Gameiro da Silva. 2011. "Indoor Air Quality Audit Implementation in a Hotel Building in Portugal." *Building and Environment* 46 (8): 1617–23. https://doi.org/10.1016/j.buildenv.2011.01.027.

Cooper, Edward, Xiaofeng Zheng, Christopher Wood, Mark Gillot, David Tetlow, Saffa Riffat, and Lia De Simon. 2016. "Field Trialling of a Pulse Airtightness Tester in a Range of UK Homes." *International Journal of Ventilation* 18 (1): 1–18. https://doi.org/10.1080/14733315.2016.1252155.

Hsu, Yun-Sheng. 2021. "The Impact of Wind on the Building Airtightness Measurement Using the Pulse Technique." Thesis, University of Nottingham.

IAA. 2021. "Best Practice Guide - Background Ventilation Assessment of Existing Buildings." Insulation Assurance Authority.

ISO. 2015. "EN ISO 9972: Thermal Performance of Buildings - Determination of Air Permeability of Buildings - Fan Pressurization Method." ISO.

JO. 1969. "Arrêté Du 22 Octobre 1969 Relatif à l'aération Des Logements."

———. 1982. "Arrêté du 24 mars 1982 consolidée relatif à l'aération des logements : aération générale ou permanente."

Moujalled, Bassam, Adeline Mélois, Valérie Leprince, and Gaëlle Guyot. 2022. "French Building Airtightness Database after 10 Years of Operation: Statistical Analyses of about 500,000 Measurements." In . Rotterdam, The Netherlands.

Remion, Gabriel. 2020. "Mesure in Situ Des Performances Aérauliques d'un Système de Ventilation Naturelle Par Conduit." Thèse de Doctorat, Vaulx-en-Velin, France: Université de Lyon.

UK Government. 2022. "Ventilation: Approved Document F."

Vega Pasos, Alan Emmanuel. 2020. "Air Infiltration Modelling Based on Low-Pressure Airtightness Measurements." Thesis, University of Nottingham.