Exist'air: airtightness measurement campaign and ventilation evaluation in 117 pre-2005 French dwellings

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ABSTRACT

Between 2017 and 2018, the Centre for Studies and Expertise on Risks, the Environment, Mobility and Planning (Cerema) organized an airtightness measurement campaign in 117 multi-family collective and single-family French dwellings. These dwellings were built before 2005, that is, before the release in 2005 of the fifth French thermal regulation for new dwellings, that was the first to introduce specific requirements for airtightness. The aim of this campaign was to give a clear picture to the French Ministry of Sustainable Development of airtightness and ventilation performance of the existing building stock. To do so, the dwellings were selected to constitute a representative panel that represented the French residential building of the stock. First, a diagnostic protocol was defined to evaluate the state of deterioration of the building, the ventilation performance and the building airtightness. All this information and other details about the dwellings were compiled into a database to be processed.

Air change rates at 50 Pa (n_{50}) were very variable and ranged from 0.44 hr^{-1} to 13.7 hr^{-1}.

The results showed that some air leakages paths influenced the airtightness of the panel more than others. Some of them could not be observed before the airtightness measurement and were therefore not easily predictable. Results also highlighted the fact that some building characteristics were highly correlated to high air change rates. These characteristics were different between collective and single-family dwellings. Unfortunately, the size of the panel (67 houses and 50 apartments), compared with the number of characteristics, did not allow to propose some robust models for airtightness prediction. To address this issue, it was decided to expand the panel with a second airtightness measurement campaign in 2019.

In the same time, ventilation systems of these dwellings were recorded and their performance were qualitatively assessed without making any measurement. A lack of ventilation was detected in 84% of the houses and 64% of the apartments, either because the system installations were out of date, or because they were too incomplete or if not inexistent. Yet, when analysing the global air exchange rate, it appeared that it was sufficient in two-thirds of the dwellings, thanks to high air change rate that compensated the low ventilation performance. The good aeration habits of the inhabitants also limited the risk of condensation on and into the walls and poor indoor air quality.

Those results could be used to update the air change rates used in the French thermal regulation for the rehabilitation of existing buildings, which dated from 2007. In addition, this campaign helped to develop the "A+V+P-"indicator. This is a simple evaluation of the aeration, the ventilation and the airtightness of a dwelling, which could also be promoted by the Ministry to building contractors, as it gives a quick overview of the global air exchange before and after retrofitting.

KEYWORDS

Airtightness, air leakage, air change rate, ventilation, existing building stock.

1 INTRODUCTION

Existing buildings are not as airtight as new ones, even if airtightness value vary widely depending on the year of construction. Air leakages are also quite different as those found in new buildings.

(Stephen, 2000) studied the airtightness of 471 dwellings in the UK, built during the 20^{th} century. n_{50} values ranged from 7 to 14 h^{-1} and the average value was about 11,5 h^{-1}. Dwellings built between 1930 and 1960 were less airtight than those built before 1930, whereas the most recent dwellings were as airtight as those built at the beginning of the century. These results are due to the variability of building techniques and design, building materials and regulations, changing over the years (Barbisan & Altan, 2012).

(Sinnott & Dyer, 2013) analysed the airtightness of 28 Irish single-family dwellings built between 1944 and 2008. In average, the dwellings built before 1975 were more airtight than those built in the 80's and in 2008 (respectively: q_{50} = 7.5, 9.4 and 10.5 $m^3/h/m^2$). Main air leakages are located at the junction between walls and floors, trapdoors for attic access, windows and doors surrounds, ductworks (plumbing, electricity, etc.) passing through walls, floors or ceilings and mail boxes.

A database of 135 000 American single-family dwellings was analysed in (Chan, Joh, & Sherman, 2012). Unlike the two studies above, the authors showed that the oldest dwellings were the leakiest ones. They considered that the evolution of construction techniques made it possible to build more airtight buildings and that airtightness deteriorated over the years, especially if dwellings weren't retrofitted.

(McNeil, 2012) reached the same conclusion on 36 New Zealander single-family dwellings built before 2011 and explained also this result by the evolution of construction techniques: (Chan, Joh, & Sherman, 2012) no more floorboards or panels, seals at windows and doors, no more fireplaces, etc.

Retrofitting could be the solution to get all these dwellings airtight. Nevertheless (Földvary et al, 2017) and (Collignan et al, 2016) mentioned the risk of drastically lowering the global air change rate and, by this way, of affecting indoor air quality.

In France,

- available airtightness data of existing residential buildings do not well represent the French residential building stock;
- parameters such as building characteristics or retrofitting works already carried out are not available, so it is difficult to study the influence of these parameters on measured airtightness values;
- information about the airtightness and the ventilation of a dwelling is rare: therefore, the air change rate in French existing buildings is not clearly defined.

So the airtightness of existing buildings and the impact of retrofitting were never studied precisely in France. That is why the French Ministry of Sustainable Development commissioned the Exist'air measurement campaign about this topic to the Cerema.

2 METHOD

2.1 Selection of the representative panel

117 dwellings were selected to constitute a panel that represented the French residential building stock. (Bureau d'études POUGET Consultants, 2012) showed that the French residential building stock was composed of 55% of houses and 45% of apartments.

About 1/3 of the stock was built before 1948 (heritage buildings, built with traditional techniques and materials), 1/3 between 1949 and 1974 and 1/3 after 1975 (the year of the first French thermal regulation), as shown in Figure 1.

The Cerema sent a call for volunteers. Dwellings were selected in order to respect the composition of the global residential building stock. There were no criteria about the retrofitting works that had already been done.

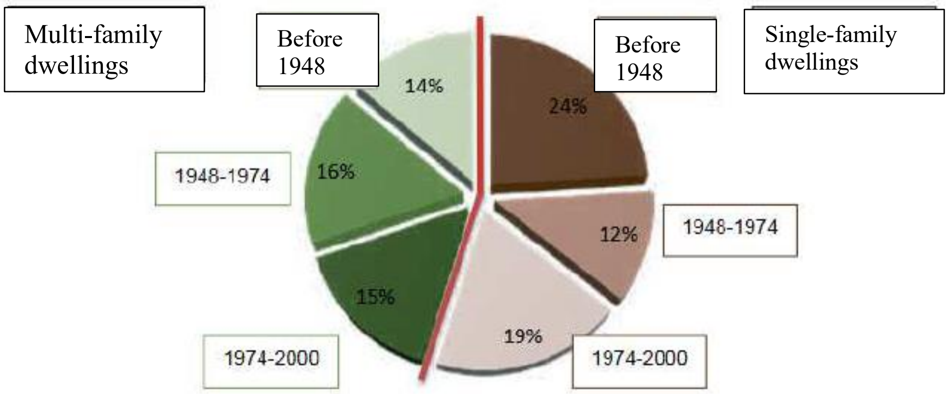

Figure 1: Composition of the French residential building stock (Bureau d'études POUGET Consultants, 2012)

2.2 Protocol for the in-situ campaign

A diagnostic protocol was defined to assess the state of deterioration of the building, the ventilation performance and the building airtightness.

2.2.1 Description of the characteristics of the dwellings

Information about dimensions and geographical context of the dwellings, composition of building elements like walls, floors and ceilings, nature and number of windows, doors and trapdoors, type of heating system and number of fireplaces were collected in a database. The state of deterioration of the building was evaluated by three possible levels for each element: good, intermediate or bad state.

The worst evaluation was always chosen. For walls, floors and ceilings, it depended on cracks, humidity, holes and aspect of finish.

For windows and doors, it depended on the state of deterioration of the seals, handle systems and aspect of the frame.

2.2.2 Evaluation of the ventilation systems

The evaluation method depended on the ventilation system:

- mechanical ventilation: evaluation of the state of deterioration of the extraction ventilator and ventilation network;
- natural ventilation: evaluation of the state of deterioration and number of vents and ductworks;
- no permanent air outlet (no mechanical or natural air outlet): there could however be air inlets.

Whatever the case, the method determined:

- if the dwelling had, at least, one air inlet in each dry room (living room, bedroom, desk, etc.), one air outlet in each damp room (kitchen, toilets, bathrooms, laundry, etc.);
- if it had 1 cm free cross-section under each inner door;
- if each inlet and outlet was clean;
- and if an airflow rate could be perceived each time.

A global score was determined for each dwelling, depending on the method. Table 1 presents the three possible scores.

Table 1: Evaluation of the ventilation score for each dwelling

Ventilation Score	Qualitative evaluation	Criteria
V3	Good ventilation	All rooms had an air inlet or an air outlet that was clean and an airflow rate was perceived each time. AND ventilation ductworks were well installed (no bend, no pinch and good connection to the ventilator) and in good state (no tear, no hole and good connection between two sections). AND exhaust air was rejected outside. AND ventilation system was independent of other systems and ran all the time. Some cross-section under inner doors could be narrower than 1cm.
V2	Medium ventilation	Some air inlets or air outlets were dirty or broken. OR there was an air inlet in a damp room or an air outlet in a dry room. OR ductworks were in bad state. OR exhaust air was rejected in the attic. OR ventilation system was not independent of other systems.
V1	Bad ventilation	Ventilator was not operating or not connected to the ventilation network. OR some air inlets or air outlets were missing. OR no airflow rate was perceived near an inlet or an outlet.

2.2.3 Airtightness measurement method

Airtightness was measured in accordance with (ISO 9972, 2015). Intentional openings in the building envelope were conditioned in accordance with method 3. These are detailed in Table 2.

Table 2: Conditions of intentional openings in the building envelope (method 3)

	Intentional openings	Conditions of intentional openings
Openings for natural ventilation	Air outlets: vents or ductworks	Sealed
	Air inlets: vents or inlets on windows or shutter casings	If the dwelling had at least one natural air outlet: sealed. If not: closed (if a closing device exists, open otherwise)
Openings for whole building mechanical ventilation	Air outlets: exhaust air openings	Sealed
	Air inlets: vents, supply air openings or inlets on windows or shutter casings	If the dwelling had at least one permanent mechanical air outlet: sealed. If not: closed (if a closing device exists, open otherwise)
Openings for mechanical ventilation (only intermittent use)	Air outlets: exhaust air openings	Closed (if a closing device exists, open otherwise)
	Air inlets: vents, supply air openings or inlets on windows or shutter casings	If the dwelling had at least one air outlet (natural ventilation or permanent mechanical ventilation): sealed. If not: closed (if a closing device exists, open otherwise)
Openings not intended for ventilation	Fireplaces and stoves	Closed (if a closing device exists, open otherwise)
	Boilers	Exhaust gas ductwork: closed (if a closing device exists, open otherwise) Air supply: open
	Kitchen hoods, tumble dryers, etc.	Open
	Water traps in plumbing systems	Filled with water or sealed
Windows, doors and trapdoors	-	Closed

In some cases, airtightness was measured with air inlets remained open.

2.3 Method for the analysis

The method employed in the Exist'air project is inspired from the one used in (Bramiana, Entrop, & Halman, 2016), which studied relationship between buildings characteristics and airtightness in Dutch dwellings.

2.3.1 Correlation between air leakages and dwellings characteristics

Some features as sliding windows, rolling shutter casings, trapdoors, false ceilings, kitchen hoods, etc. are deemed to be leaky. The frequency of air leakages on a feature (F, equation 1) provides guidance to project managers, when choosing to conserve or replace it.

$$F = \text{Number of dwellings with a given feature and with an air leakage on it} / \text{Number of dwellings with this feature} \quad (1)$$

It could be useful to get information about the risk of observing an air leakage by a simple evaluation of the state of deterioration of the building. The correlation between the state of deterioration of a building element (walls, floors, ceilings, windows, doors, trapdoors) and a type of air leakage was evaluated by the relative risk (RR, equation 2).

$$RR = \text{Frequency of air leakage on a building element in a bad state} / \text{Frequency of air leakage on a building element in a good or medium state} \quad (2)$$

A Fisher test was used to calculate the p-value of RR: if it is lower than 5%, the relative risk is significant, which means that the air leakage is correlated with the state of deterioration the building element.

2.3.2 Correlation between air leakages and airtightness values

Reducing important air leakages should be one of the objectives of project managers. To determine such leakages, a linear regression between the n_{50} and binary variables defined by the absence or the presence of an air leakage (equation 3) was calculated.

$$n_{50} = a*x + b + res \quad (3)$$

where:

- x is the binary variable;
- b is the mean value of n_{50} when x=0, i.e. when the air leakage is absent;
- a is the difference between the mean value of n_{50} when x=0 and the mean value of n_{50} when x=1;
- *res* is the residual; its distribution shall be normal to validate the linear regression.

A Student test was used to calculate the p-value of a. If a is positive and its p-value is lower than 5%, then the average value of n_{50} is significantly higher when the air leakage is present.

2.3.3 Correlation between airtightness values and dwellings characteristics

Information about dwellings characteristics that are associated with high n_{50} values can be useful for project managers when choosing an airtightness target. For this analysis, multi-family (49) and single-family (66) dwellings were studied separately. The database contained 42 variables, with many categorical variables, which was too extensive by comparison with the number of dwellings. First, an analysis of the correlations between variables was performed to get a set of independent variables. Then, for each numerical or binary variable, a linear regression as in equation (3) was calculated. For categorical variables, an ANOVA analysis was realised (equation 4).

$$n_{50} = a_1*x_1 + a_2*x_2 + a_3*x_3 + \ldots + b + res \quad (4)$$

where:

- b is the mean value of n_{50} when all x_i are null, i.e. when the dwelling is featured with all the reference categories (categories the most represented in the panel);
- x_i is a binary variable; x_i = 1 when the dwelling is featured with the category i;

- a_i is the coefficient associated to the variable x_i.

If a_i is positive with a p-value (Student test) lower than 5%, then n_{50} is significantly higher in dwellings featured with category *i* than the ones featured with the reference category.

2.3.4 Evaluation of the global air change rate

Global air change rate was qualitatively evaluated using an overall score:

- Score V+ (see §2.2.2)
- Score A+: frequency of aeration by opening windows: every day (A3), every week (A2), or rarely (A1)
- Score P-: depending on the n_{50} value (3) (values detailed in Table 3)

Table 3: Evaluation of the P- score for each dwelling

P- score	Impact of airtightness on global air change rate	n_{50} limit value
P3	The building was very leaky. Airflow rate participated highly to the global air change rate.	$n_{50} > 3\ h^{-1}$
P2	The building was quite airtight. Airflow rate participated significantly to the global air change rate.	$1{,}5\ h^{-1} < n_{50} < 3\ h^{-1}$
P1	The building was airtight. Airflow rate did not participate significantly to the global air change rate.	$n_{50} < 1{,}5\ h^{-1}$

n_{50} lower than 1,5 h^{-1} agrees with Minergie A and Minergie Passiv labels for retrofitting and with the German thermal regulation for retrofitted buildings with mechanical ventilation (Erhorn-Kluttig & Erhorn, 2012). n_{50} not higher than 3 h^{-1} agrees with German thermal regulation for retrofitted buildings with natural ventilation.

3 MAIN RESULTS AND DISCUSSION

3.1 Airtightness levels

Apartments were more airtight (n_{50} = 4.9 h^{-1}) than houses (n_{50} = 7.2 h^{-1}), Figure 2 (a) and the evolution over the periods of construction was similar, Figure 2 (b). Average values were much lower than n_{50} values presented in (McNeil, 2012) and (Stephen, 2000) at the same period of construction.

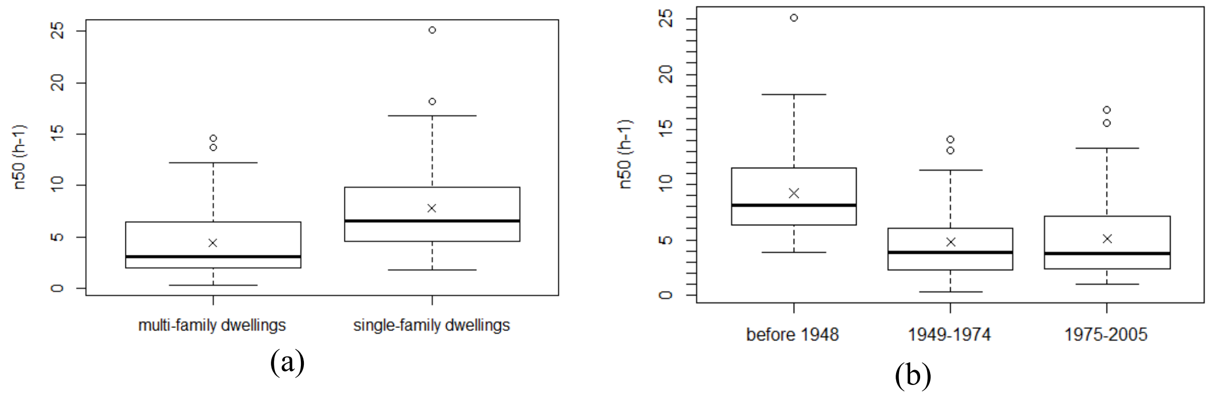

Figure 2: Airtightness of 117 dwellings depending on the type of building (a) and the period of construction (b)

When observing the nature of air leakages (Figure 3), the most frequent ones were due to missing or failing seals at windows (C2), ductworks crossings walls, floors and ceilings (D3) and electrical wall outlets (F3). These air leakages were present in more than 60 % of the panel.

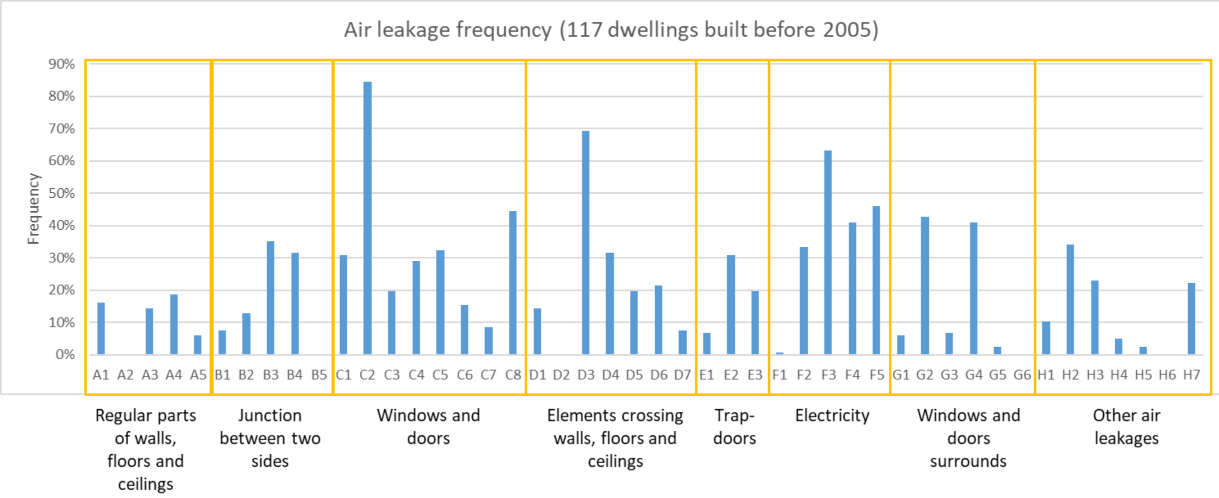

Figure 3: Air leakage frequency for 117 dwellings

3.2 Correlation between air leakages and dwellings characteristics

Data (detailed in Table 4) confirmed that false ceilings, sliding windows, shutter boxes, trapdoors, boilers, stoves, fireplaces and kitchen hoods were often leaky.

Table 4: Air leakages correlated with a dwelling characteristic

Air leakage types	Dwelling characteristics	Frequency or relative risk
Trapdoors	At least one trapdoor in the dwelling	F=91%
Air leakages on shutter casings	At least one shutter casing in the dwelling	F=86%
Leakage on a boiler or a stove	At least one boiler or stove	F=81%
Leakage on a kitchen hood	Presence of a kitchen hood	F=71%
Junction between suspended ceiling tiles	Ceilings were mainly suspended ceilings	F=66%
Air leakages on sliding windows	At least one sliding window in the dwelling	F=62%
Air outlets surrounds	Mechanical ventilation	F=15%
Junction between a floor or a wall and a staircase	Floors in a bad state	RR=4,7
Windows and doors surrounds	Bad state of windows and doors	RR=4,6
Junction between two walls	Walls in a bad state	RR=4
Little holes (fixing holes, etc.)	Ceilings, floors and walls in a bad state	RR=2,4 RR=3,6 RR=3,0
Various leakages on regular parts of walls and floors (cracks, junctions between floorboards or panels, etc.)	Ceilings in a bad state	RR=2,7
Junction between a wall and the floor	Floors in a bad state	RR=2,7

Unfortunately, the method to evaluate the state of deterioration of the building elements was not precise enough to predict air leakages on windows hinges, ductworks and electrical devices. Yet, those air leakages are common in existing dwellings (Figure 3).

3.3 Correlation between air leakages and airtightness values

Table 5 lists air leakages correlated with airtightness values.

If some types of air leakages were not often observed, they had yet an important effect on n_{50} value.

It highlights that several important air leakages were typically localised on the ceiling, which provides guidance to take special caution with this building element when retrofitting.

It also shows that predictable air leakages (see Table 4) had not always an important effect on n_{50}. Furthermore, some important air leakages were not detected by the evaluation of the state of deterioration of the building. It was the case for air leakages between building blocks, at the junction between a wall and a ceiling, between a beam and a wall or a ceiling and air leakages near light fittings.

Table 5: Air leakages correlated with airtightness values (n_{50})

Air leakage types	b (h^{-1})	a (h^{-1})	p-value of a (%)	Number of dwellings (presence of the air leakage)	Number of dwellings (absence of the air leakage)
Junction between building blocks	5,65	4,61	0,0%	17	98
Junction between suspended ceiling tiles	6,13	3,96	2,8%	6	109
Junction between a wall and a ceiling	5,47	2,77	0,1%	36	79
Junction between a beam and a wall	5,61	3,62	0,0%	23	92
Junction between a beam and a ceiling	5,67	3,04	0,2%	25	90
Surrounds of trapdoors to the attic	5,74	1,93	2,7%	35	80
Light fittings (recessed luminaires, surface-mounted fixtures, pendant-mounted fixtures)	5,59	1,60	4,7%	53	62
Junction between doors and walls	6,08	3,58	2,3%	8	107
Air inlet and air outlet that were not sealed during the airtightness test	5,83	2,32	1,7%	25	90

3.4 Correlation between airtightness values and dwelling characteristics

3.4.1 Single-family dwellings

As seen in Table 6, for the 66 houses of the panel, the nature and the type of insulation of walls and the type of insulation of ceilings were correlated with n_{50} values. The effect of ventilation system and specific equipment (as kitchen hoods) can be explained by the measurement method and the conditions of intentional openings in the building envelope.

Table 6: Houses characteristics correlated with airtightness values (n_{50})

Characteristic	Value	Coefficient (vol/h)	p-value (%)	Number of houses
Wall and outer materials	Blockwork with rendering (reference category)	6,18	0,0%	20
	Brickwork	3,27	2,8%	15
	Brickwork with rendering	0,98	51,9%	13
	Stone	2,73	10,2%	10
	Other	2,03	25,8%	8
Wall insulation	Insulated (reference category)	6,81	0,0%	48
	Non-insulated	3,56	0,2%	18
Ceiling insulation	Exterior insulation (reference category)	6,24	0,0%	29
	Interior insulation	2,74	2,0%	26
	No insulation	3,40	4,9%	8
	Unknown	-	-	3
Ventilation	Mechanical ventilation (reference category)	6,48	0,0%	38
	Natural ventilation	1,34	38,2%	7
	None	3,51	0,3%	21
Number of specific equipment (kitchen hoods, intermittent air outlets, etc.)	1 (reference category)	6,28	0,0%	33
	At least 2	3,30	3,0%	10
	None	2,86	1,3%	23

3.4.2 Multi-family dwellings

As seen in Table 7, for the 49 apartments of the panel, the structure of the building, the type of separation walls between apartments and the type of wall insulation were correlated with n_{50} values. The effect of ventilation system and open fires can be explained by the measurement method and the conditions of intentional openings in the building envelope.

Table 7: Apartments characteristics correlated with airtightness values (n_{50})

Characteristics	Values	Coefficients (vol/h)	p-value (%)	Number of apartments
Nature of separation walls	Load-bearing walls (reference category)	3,89	0,0%	43
	At least one lightweight partition wall	4,04	0,7%	6
Ventilation	Mechanical ventilation (reference category)	3,42	0,0%	35
	Natural ventilation	2,62	3,2%	9
	None	4,71	0,3%	5
Closed off open fire	None (reference category)	3,82	0,0%	42
	At least one	3,94	0,5%	7
Wall insulation	None or interior insulation (reference category)	5,43	0,0%	31
	Exterior insulation	-2,88	0,9%	15
	Unknown	-	-	3
Structure (walls, floors and ceilings)	Concrete (reference category)	2,13	0,1%	22
	Stone walls (whatever the floors type)	5,38	0,0%	11
	Other	3,21	0,1%	16

3.5 Evaluation of the global air change rate

Overall, dwellings were well aerated, bad ventilated and the air permeability contributed highly to the global air change rate (see Table 8). Lack of ventilation and bad-managed ventilations (V1) were more often observed in houses than in apartments.

Table 8: A+V+P- score for the whole dwellings panel (a) and V+ score depending on the building type (b)

(a) Score	3	2	1	(b) Score	V3	V2	V1
Aeration A+	83	18	1	Houses	7%	9%	84%
Ventilation V+	10	19	88	Apartments	10%	26%	64%
Permeability P-	88	21	8				

Only two dwellings were A3V3P1, i.e. the ideal configuration for a good air change rate with little energy consumption. 11 dwellings were quite airtight and correctly ventilated (V3P1, or V3P2, or V2P2). 57% of the dwellings were V1P3, which means air change rate was mainly provided by air leakages. In 22% of dwellings, ventilation was failing and building was quite airtight, but this lack of air change was often compensated by inhabitant good practice of aeration by opening windows.

4 CONCLUSIONS

In a panel of 117 dwellings built before 2005, airtightness measurement results were very variable and ranged from 0.44 h^{-1} to 13.7 h^{-1}. The analysis of correlation between n_{50} values and air leakages showed that several leakages at the ceilings influenced strongly the airtightness of existing buildings. Unfortunately, it seems impossible to anticipate those important leakages by a simple evaluation of the state of deterioration of the building. Furthermore, the analysis of the correlation between n_{50} and buildings characteristics highlighted that the type of walls and ceilings and their insulation were highly correlated to airtightness values.

The measurement method had also a strong influence on results (mainly because of the way to condition intentional openings in the building envelope). The size of the panel (67 houses and 50 apartments), compared with the number of parameters, did also not allow to propose some robust models for airtightness prediction. This limit argued for pursuing the measurement campaign in 2019.
In the same time, a lack of ventilation was detected in 84% of houses and 64% of apartments, either because installations were out of date, or because they were incomplete or inexistent. Nevertheless, the global air exchange rate was enough in two-thirds of the dwellings, thanks to high airtightness values that compensated low ventilation performance. The good aeration practices of the inhabitants limited also the risk of condensation and poor indoor air quality.
Those results should be used to improve the airtightness indicators of the French thermal regulation for existing buildings.

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6 REFERENCES

Barbisan, R., & Altan, H. (2012). Energy retrofit of the existing housing stock in England,. *33rd AIVC Conference.*

Bramiana, C., Entrop, A., & Halman, J. (2016). Relationship between building characteristics and airtightness of Dutch dwellings. *Energy Procedia 96*, 580-591.

Bureau d'études POUGET Consultants. (2012). *Programme Règles de l'Art Grenelle Environnement (RAGE) - Analyse détaillée du par résidentiel existant.*

Chan, W., Joh, J., & Sherman, M. (2012). Air leakage of US homes: regression analysis and improvements from retrofit. *33rd AIVC Conference.*

Collignan, B., Le Ponner, E., & Mandin, C. (2016). Relationship between indoor radon concentrations, thermal retrofit and dwelling characteristic. *Journal of environmental radioactivity*.

Erhorn-Kluttig, H., & Erhorn, H. (2012). Phylosophy and approaches for airtightness requirements in Germany. *AIVC International Workshop.*

Földvary, V., Bekö, G., Langer, S., Arrhenius, K., & Petras, D. (2017). Effect of energy renovation on indoor air quality in multifamily residential buildings in Slovakia. *Building and Environment*.

ISO 9972. (2015). *THermal performance of buildings - Determiantion of air permeability of buildings - Fan presurization method.*

McNeil, S. (2012). A survey of airtightness and ventilation rates in post 1994 NZ homes. *33rd AIVC Conference.*

Sinnott, D., & Dyer, M. (2013). Airtightness and ventilation of social housing in Ireland - a review of field measurements and occupant perspectives pre- and post-retrofit. *34th AIVC Conference.*

Stephen, R. (2000). *Airtightness in UK dwellings.* Building Research Establishment.