Airtightness of French dwellings
Results from field measurement studies

Andrés LITVAK [1]* - Karine GUILLOT [1] - Marc KILBERGER [1] - Didier BOZE [2]

[1] CETE de Lyon - DVT/HTC
46, rue St Théobald BP 128
38081 L'ISLE d'ABEAU Cedex - FRANCE

[2] CETE de Lyon - Laboratoire Régional d'Autun
Boulevard de l'Industrie, Z.I. de Saint Andoche BP 141
71406 Autun Cedex - FRANCE

* *corresponding author :* tel : int/ 33 4 74 27 51 67 fax : int/ 33 4 74 27 52 52
e-mail : andres.litvak@equipement.gouv.fr

ABSTRACT

A field measurement study of the airtightness of 73 - less than 5 year old - French dwellings was led between 1999 and 2000. Buildings have been selected and classified according to the construction structure, the thermal insulation and the occupancy mode. Using a fan-depressurization technique, we assessed the air leakage rate of each dwelling with two depressurization tests. Meanwhile quantifying air leakage rates, we observed qualitatively the most frequent locations of air leakage paths using a smoke detection method and infrared thermography. We assessed the ratio of the air leakage rate weighted by intrinsic dimensions of each construction, namely : the *unheated* surfaces and the heated volume. From our results, we compare the performances of the different types of dwellings and we assess the impact of the envelope airtightness on the building ventilation efficiency. We show that thermal performances of buildings can be dramatically affected according to the dwelling construction characteristics. Finally, we discuss the potentials for reducing indoor air infiltration with a view to improve the indoor air quality and the energy efficiency of buildings.

KEY WORDS

Field measurements ; Infiltration ; Airtightness ; Building Envelope ; Dwellings; Thermal Regulations; Energy Efficieny; Indoor Air Quality

LIST OF SYMBOLS

ΔP	[Pa]	Differential pressure between indoor and outdoor
Q	[m^3/h]	Airflow rate
S	[m^2]	Envelope unheated surface area
V	[m^3]	Heated volume
K	[m^3/h/Pa^n]	Leakage parameter
n	[-]	Flow exponent
τ_{10}	[h^{-1}]	Infiltration airchange rate under 10 Pa
I_4	[m^3/h/m^2]	Leakage indes under 4 Pa
η	[-]	Ventilation efficiency
DD_{18}	[°C·day]	Degree days (base = 18°C)

BACKGROUND

Recent studies on buildings airtightness have shown that several types of problems can arise from uncontrolled leakages in buildings, namely higher energy cost, thermal comfort and health of occupants or material degradation resulting in building components and equipment damage. Although these impacts have been recognized as of key importance, work is still needed to better charaterize the airtightness of buildings.

Since building airtightness performances can play a significant part in *indoor air quality* (IAQ) and *energy efficiency* (EE) related issues, many European and North American countries have recently decided to explicitly require airtightness mandatory levels for their buildings. For example, the next French New Thermal Regulation (NRT), applicable in 2001, will require airtightness levels according to the type of building (single-family dwellings, multi-family dwellings, non residential or large volume buildings) [4]. These levels were selected as a function of the actual knowledge of the French building performances, namely through the results of field measurement campaigns led in France in the 80s [1], [2] and in the 90s [10] and throughout the expertise gained with numerical modelling. As a matter of fact, during the last two decades, modelling efforts have led to improve our knowledge on infiltration mechanisms and on the impact of building airtightness on IAQ and EE. A recent review of literature has listed numerical models for air infiltration and ventilation calculations [13]. Simplified models, that consider buildings as monozone volumes, allow the assessment of the whole building airtightness with much lower numerical efforts. However for these models as well as for more detailed multizone models, building intrinsic data (e.g. building characteristics, weather, site topography, etc...) are needed for inputs of the numerical codes. Yet such data is very often impossible to assess without field measurement campaigns.

OBJECTIVES

The objective of this study is to quantify the actual performance of French dwellings in terms of the envelope airtightness, with a view to compare the observed levels with the requirements ot the NRT. In this work, we aim at establishing a classification among buildings based on different construction types. For that, we analyzed 73 measurements of the airtightness of less than 5 year-old French dwellings, performed by the CETE de Lyon between 1999 and 2000.
The work presented here is part of a 18 month study that aims at improving our knowledge of the actual thermal performances of French dwellings in terms of ventilation and airtightness impacts. The overall results of the study are reported elsewhere [5]. A companion paper in the proceedings of the 21st AIVC conference presents the results related to ventilation performances of the same dwelling sample [6].

THEORY

Leakage modelling

The modelling of airflow patterns through cracks of the building envelope follows from the theory of Fluid Mechanics adapted to single elementary orifices. The early works on hydronamics of pipes allowed to assess the airflow rates through elementary holes, given by **(1)**. It is demonstrated that the flow coefficient n in **(1)** varies in the range [0.5-1.0] (a laminar airflow pattern corresponds to n = 1.0, whereas a turbulent airflow pattern corresponds to n = 0.5), [15].

$$\mathbf{Q = K \cdot \Delta P^{n}} \qquad \textbf{(1)}$$

The modelling of airflow patterns through elementary orifices was adapted from **(1)** to the cracks and holes of the building envelope as a whole, under conditions that consider : 1) the air as the fluid of the flow, 2) pressure differentials in the range [0 : ±100 Pa] and 3) orifice diameters larger than their respective length. Hence, for an entire building, the airtightness governing equation assessing the total infiltration airflow rate is given by **(2)**.

$$\mathbf{Q_{building} = \sum_i (K_i \cdot \Delta P^{n_i})} \qquad \textbf{(2)}$$

In general, the infiltration airflow rate of a building is assessed following the classic form of **(1)** (the parameters K and n representing the airtightness and flow coefficient of the *whole* building). The equation **(1)**, relative to a whole building, enables to qualify the airtightness quality of the walls : namely, if $0.7 \leq n \leq 1.0$, the construction can be considered as having no major infiltration pathways (the value of K allowing to quantify the airtightness of the construction). On the contrary, the presence of one or more large openings within the walls is characterized by $0.5 \leq n \leq 0.6$. As a matter of fact, the value of n = 2/3 is commonly accepted in the literature as representative of the average flow coefficient observed accross buildings' envelopes.

Airtightness indicators

To compare building infiltration performances among themselves, one needs to assess the ratio of the (measured or theoretical) infiltration air flowrate assessed at a refence pressure ΔP_0 weighted by an intrinsic dimension of the construction. Several dimensions are used in the literature : the envelope surface, the heated volume, the unheated walls surface, etc...

The infiltration airchange rate $\tau_{\Delta P}$ [h^{-1}] is a commonly used indicator to compare the airtightness of buildings. It is equal to the ratio of the air leakage flowrate at ΔP, divided by the heated volume of the building. On the other hand, for their specific requirements, some European countries have decided to consider the leakage index $I_{\Delta P}$ [$m^3/h/m^2$], defined as the infiltration airflow rate at ΔP_0 weighted by envelope surface areas the most susceptible to promote the infiltration of air leakages. For our study, and in accordance with NRT objectives, we considered the specific *unheated surfaces*, defined as the *« surfaces that separate the indoor heated volume from the outdoor air and indoor unheated air »*.

It is possible to link τ_{10} and I_4 , if one knows the flow coefficient n and the ratio V/S of the building. The relationship between both indicators leads to **(3)**.

$$I_4 = 0.4^{n} \times \frac{V}{S} \times \tau_{10} \qquad \textbf{(3)}$$

To date, the most reliable manner to determine the airtightness of a building consists in measuring its infiltration airflow rate. A standardized method, using a fan-depressurization technique (known as the « bloower-door » method), is commonly used by many countries and follows the procedure described in the international norm ISO 9972 [7]. The *« blower-door »* technique is particularly adapted to measure the air leakages in small buildings. For larger constructions and/or extremely leaky buildings, the building depressurization usually becomes impossible, due to the power limitation of the fan. For this reason, tests involving multi-family buildings were performed only on single dwellings in our study.

Estimation of energy impact of infiltration

Since thermal insulation of buildings is becoming more and more efficient, the energy relative impact of infiltration will necessarily increase. As explained in a recent literature review [12], the *heating degree-day* concept has been extended to incorporate both effects of air infiltration and latent heat changes. Average specific infiltration rates are used to account for ventilation. Using this concept, a study on the residential ventilation and energy characteristics in the United States [14] estimated the energy savings or penalties associated with tightnening or loosening the building envelope while still providing ventialtion for adequate indoor air quality. This study showed that for a typical US dwelling the cost-effective saving potentials is about 38 GJ - the average annual ventilation energy use being approximately 61 GJ.

METHOD

Selection and classification of dwellings

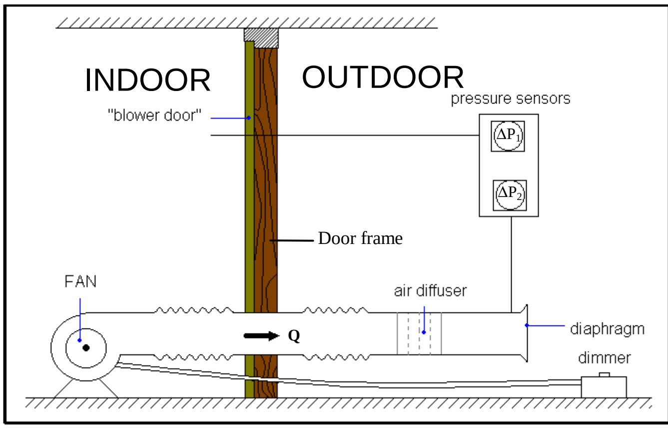
The airtightness of 73 French dwellings have been measured between June 1999 and May 2000, using the same fan-depressurization equipment (the « blower-door » technique) and following the protocol described in the international norm ISO 9972. The buildings were chosen to be less than 5 year old. They were classified according to the type of construction, namely by the occupancy mode (multi- or single- family), by the thermal insulation (inner, outter or integrated to the walls) and by the type of structure (metal/timber frame or concrete/masonry structures). Dwellings were selected by pairs; therefore, 35 residential constructions were selected in total, with 2 dwellings per site (for one case we tested 5 dwellings instead of 2).

One should note that in order to have samples with a minimum statistical significance, we had to account for dwellings with different construction structures for a given thermal insulation. Here, the groups Cr and Ie respectively include 4 (out of 8) and 7 (out of 11) metal or timber frame dwellings.

Type	Reference	Number of dwellings
multi- family / inner thermal insulation	Ci	14
multi- family / integrated thermal insulation	Cr	8
multi- family / outter thermal insulation	Ce	8
single- family / outter thermal insulation	Ie	11
single- family / integrated thermal insulation	Ir	8
single- family / inner thermal insulation	Ii	12
single- family / metal or timber frame	Ib	12

Experimental protocol and data collection

Before each depressurization test, the openings provided to the dwelling for natural or mechanical ventilation were intentionally sealed with duct tape. A first depressurization of the dwelling enabled to inspect visually, either by smoke detection method or by infrared thermography, the potentials for air infiltration accross the enveloppe. For each test, the speed of the fan was increased by stationary steps of 10 Pa in order to depressurize progressively the dwelling, until a maximum generally close to 70 Pa. The experimental protocol is exhaustively described elsewhere, [9].



The equipment is mainly composed of 4 elements :

- the variable speed fan, that depressurizes the building
- the « blower door », a fake-door which has a flexible structure that allows to adapt it to the door-frame of the dwelling, and through which the fan extracts the air from the building
- the pressure sensor, that measures the pressure difference
- a flowmeter system, that determines the airflow rate through the fan that depressurizes the building

Figure 1 Description of the experimental protocol

Two consecutive depressurization tests were carried out. In a first test, the airtightness of the sole envelope was measured by sealing intentionally the openings provided to the dwelling for natural or mechanical ventilation. In a second test, the test was repeated with the inlet air ventilation openings unsealed. During the depressurization tests, the pressure difference ΔP_1 (between indoor and outdoor) and ΔP_2 (at the diaphragm) were recorded at each stationary step. The airflow rate through the fan (i.e., the infiltration airflow rate) was determined by **(4)**. Finally, the parameters (n, K) were determined by linear regresion (for more than 7 points, and $r^2 > 0.99$) of the collected data $\{\Delta P_1, Q\}$. Then, **(1)** was solved to assess the infiltration airflow rate at 10 Pa and 4 Pa, and the corresponding τ_{10} and I_4.

$$\mathbf{Q} = \mathbf{k} \times \sqrt{\Delta \mathbf{P}_2} \qquad \textbf{(4)}$$

RESULTS

Qualitative results : air leakage locations

The most frequent air leakage pathways were carefully investigated under the test depressurization conditions, by using visual smoke detection techniques or infrared thermography. The observations have been reported for each building and were classified according to the occurrence of different air leakage pathway types [5]. The most frequent locations observed for infiltration are the indoor chests of shutters (in 82% of dwellings with shutters), the bonding between window frames and walls (77%), the electrical outlets (in 73% of the dwellings) and the bonding between floors and walls (56%). No significant link was found between the construction type and occupancy mode and the infiltration locations reported here.

Airtightness parameter K and airflow exponent n

The leakage parameter K and the flow exponent n of **(1)** were assessed for 68 dwellings following the depressurization technique. The airtightness of 5 dwellings could not be determined due to the fan power limitations, since the maximum depressure achieved for these dwellings was less than 20 Pa. Four dwellings among the latter shown air leakage flow rates that we considered to be greater than 5 h^{-1} for τ_{10} (and 4 $m^3/h/m^2$ for I_4), by experimental estimates from one-point measurements under 10 Pa (although the uncertainty is high for a single point measurement, the assumption of having $\tau_{10} >> 5\ h^{-1}$ and $I_4 >> 4\ m^3/h/m^2$ was found to be reasonable for these dwellings, due to the extremely low measured ΔP levels). For the last dwelling, the leakage air flow rate was also too high to be measured from an extrapolation to 10 Pa of **(1)**. However, since for this dwelling the maximum measured ΔP was about 20 Pa, we proceeded to a single point measurement at 10 Pa of the leakage airflow rate, that we approximated to be the Q_{10} value.

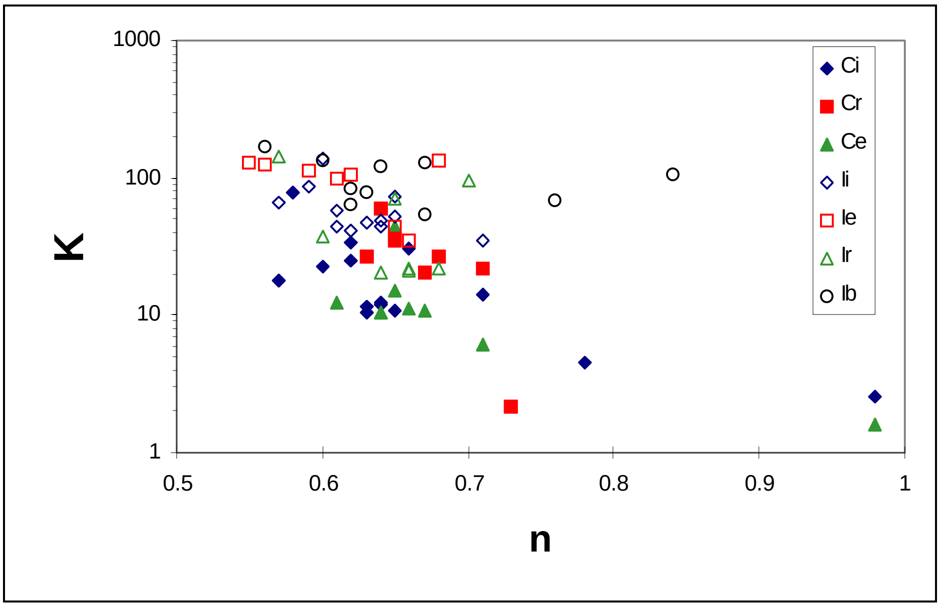


Figure 2 K as a function of n. Blank patterns represent single family dwellings. Filled patterns represent multi-family dwellings.

The results collected for this field measurement campaign are in good agreement with the data published in the literature concerning the theoretical flow modeling of building airtightness. Namely, the median flow exponential found here is equal to 0.65, see Figure 5, while the commonly average value found in the literature is 2/3.

Although, from our results, the leakage parameter K does not show a significant correlation with the flow exponent n, see **(1)**, for multi-family dwellings K appears to approximately decrease exponentially with n, see Figure 2. This figure shows also for all dwellings an accumulation of values of $n < 0.7$ and $K > 10\ m^3/h/Pa^n$.

Airtightness indicators

The factor shape ratios V/S for the multi family sample vary in the range [1 ; 5], while this range is much narrower [0.8 ; 2] for the single family sample, see Figure 4. This observation leads us to suggest that a linear correlation between τ_{10} and I_4 is difficult to obtain for multi-family dwellings, when one considers the sample median values of V/S and n in **(3)**. As a matter of fact, the lack of acceptable correlation between τ_{10} and I_4 (see Figure 2) obliged us to consider both indicators separetely for all construction types.

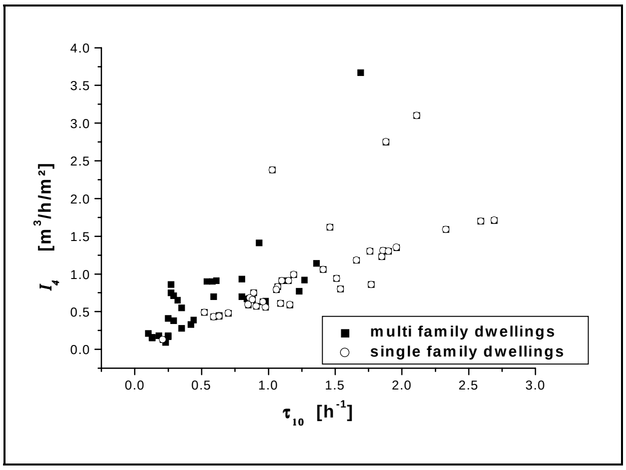


Figure 3 Correlation between τ_{10} and I_4

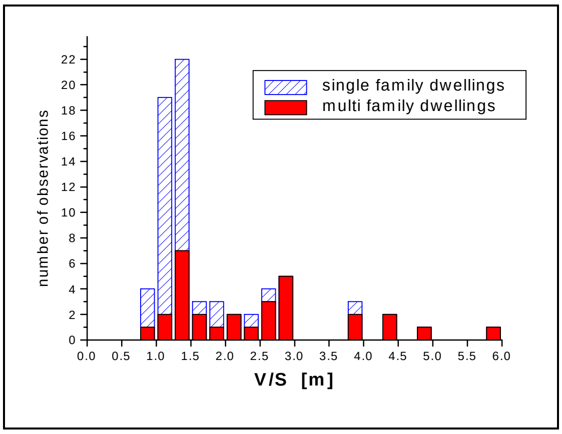


Figure 4 Histograms of shape factors (V/S) (median values : multi fam. = 2.22 m ; single fam. = 1.25 ; total = 1.37 m)

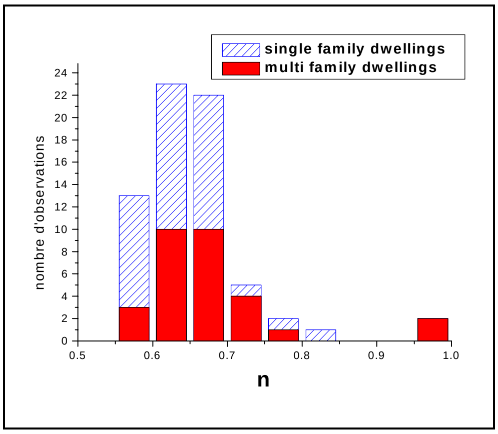


Figure 5 Histograms of n (median values = 0.65)

Figure 6, Figure 7 and Figure 8 show the range and median values of τ_{10} and I_4 as a function of construction types. From these results, we show that :

- τ_{10} and I_4 have similar trends as a function of construction types : namely, single-family and metal/timber frame dwellings appear to be much less airtight than their complementary type do;
- no significant trend for thermal insulation types, due to the bias caused by the simultaneous presence of concrete/masonry and metal/timber frame dwellings in the same type;

- among the different construction types, variations of performances are larger when expressed with τ_{10} instead of I_4 (i.e., the range of τ_{10} median values is much wider than the one relative to I_4 median values).
- if one considers the NRT requirement for dwelling airtightness of 0.8 m^3/h/m² at 4 Pa as a reference, only 52% of the dwellings of our sample would comply with the future regulation; besides, only 39% of the single family dwellings would be eligible, against 70% for the multi family dwellings.

Type of dwelling	τ_{10} [h^{-1}] (number of dwellings)	I_4 [m³/h^{-1}/m²] (number of dwellings)
Ci	0.3 (14 dw.)	0.6 (14 dw.)
Cr	0.7 (8 dw.)	0.9 (8 dw.)
Ce	0.3 (8 dw.)	0.3 (8 dw.)
Total (multi family dw.)	**0.4 (30 dw.)**	**0.7 (30 dw.)**
Ie*	1.8 (11 dw.)	1.3 (9 dw.)
Ir	0.7 (8 dw.)	0.6 (8 dw.)
Ii	1.1 (12 dw.)	0.8 (12 dw.)
Ib*	1.8 (12 dw.)	1.6 (12 dw.)
Total (single family dw.)	**1.4 (43 dw.)**	**0.9 (41 dw.)**
TOTAL	**1.0 (73 dw.)**	**0.8 (71 dw.)**

Figure 6 Airtightness performance of buildings as a function of construction types.
* Two dwellings of this construction type have τ_{10} >> 5 h^{-1} and I_4 >> 4 m^3/h/m².

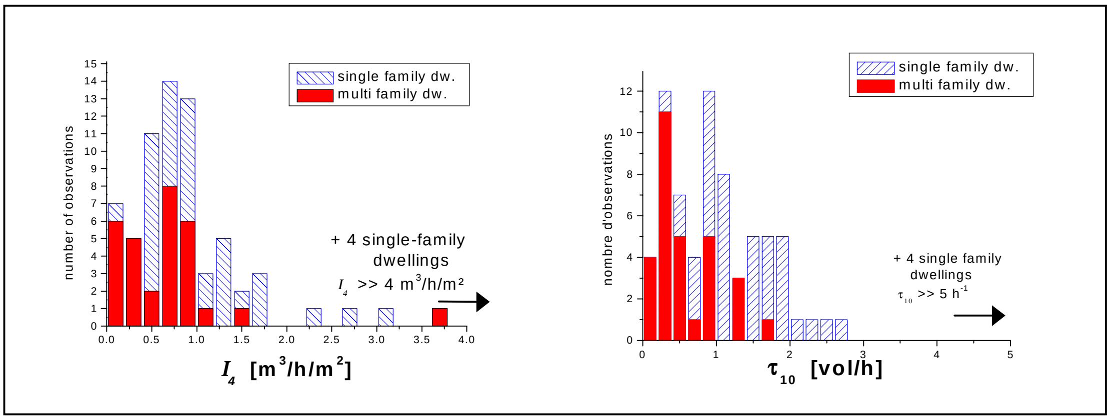


Figure 7 Airtightness performance of buildings as a function of construction types.

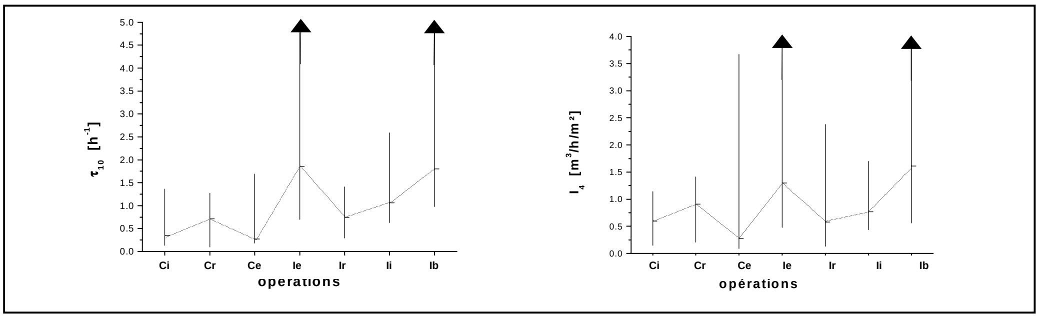


Figure 8 Range and median values of airtightness indicators as a function of construction types.

Impact of airtightness on ventilation

We analyzed the impact of building airtightness on the ventilation efficiency by dividing the incoming airflow rate through the ventilation inlets under 10 Pa by the total incoming airflow rate under 10 Pa (i.e., originating from the ventilation inlets and the envelope leakage defects), see (5).

$$\eta_{10\,Pa} = \frac{\mathbf{K}_1}{\mathbf{K}_2} 10^{n_1 - n_2} \qquad \textbf{(5)}$$

where the indexes 1 and 2 refer to the two depressurization tests, respectively the sole envelope depressurization test and the global (ventilation inlets + enveloppe) test. Among the 44 dwellings for which η was assessed, we show that :

- for the multi-family dwellings (21 cases) : at least 1/3 of the incoming air systematically originates from the enveloppe leakage defects (the η_{10} median value is 50%)
- for the single-family dwellings (23 cases) : at least 2/3 of the incoming air systematically originates from the enveloppe leakage defects (the η_{10} median value is 80%)

DISCUSSION

From Figure 2 and Figure 5, we see that a large majority of dwellings (63 out of 68) have a flow exponent n in the range [0.6:0.7]. These values suggest the presence of large orifices in the enveloppe of the concerned buildings, causing large turbulent infiltration airflow rates. Only 5 dwellings show a value of n > 0.75, which allows us to suggest that their envelope does not have important leakage defects (i.e., large orifices). Three single family dwellings show n > 0.7 and large values of K ≈ 100 $m^3/h/Pa^n$; we explain this phenomom by the presence of numerous sharp orifices or micro-cracks in the latter dwellings envelope, that can create important laminar airflow rates. On the contrary, the multi-family dwellings for which n > 0.75 reveal excellent airtightness performances for these dwellings (K < 10 $m^3/h/Pa^n$). Appart from the occupancy mode, we found no significant trend between (K,n) values and the structure or thermal insulation types.

The above analysis of the flow exponent and leakage parameter results give valuable information concerning the construction quality of the dwellings. In other words, it allows us to draw primary conclusions concerning the types of envelope leakage defects as a function of the construction characterisitics (i.e., the occupancy mode).

Furthermore, the analysis of the infiltration performances throughout the indicators values also showed that some construction types are more likely to be airtight than others. One should note that experimental results are obtained under calm weather conditions (namely, for wind speeds < 2 m/s). For these conditions, the dwelling outdoor surfaces are not exposed to any (de)pressurization force except the force supplied from indoors by the fan. Yet, normal weather conditions include outdoor positive or negative pressures (induced by the wind on outdoor surfaces). This remarks led us to suggest that τ_{10} is more adapted to quantify the performances of the building under the stationary depressurization test conditions, whereas I_4 is the best index characterizing the building airtightness under normal weather conditions. The results of Figure 6 show that the significant difference of performance from one construction type to another is lessened when using I_4 instead of τ_{10}.

In order to assess cost-effective strategies of ventilation and airtightness measures, it is essential to assess the annual energy cost of infitration among dwellings. With a view to gain knowledge on the impact of airtightness on building annual energy requirements, many researchers have pointed the need to correlate the one-time pressurization test results with the annual infiltration rate. Yet, translating blower door measurements into an average infiltration rate still remains a very difficult task. The rate of air infiltration constantly varies, while the pressurization test is typically a single measurement. The modelling efforts undertaken to assess the annual infiltration rates as a function of the depresurization tests results are mainly based on empirical methods. Numerous experimental tests have shown that the approximate air infiltration rate is of the order of 1/20 of the measured air change rate at 50 Pa [8]. This simple *"Q_{50}/20 rule of thumb"* yields surprisingly reasonable average infiltration estimates, even though it ignores many details of the infiltration process, such as the stack effect, the site topography and the wind exposure. It is demonstrated that a simplified correction factor that accounts for these effects when assessing the values of the infiltration airchange rate can overestimate infiltration by a factor of 2 or underestimate it by a factor of about 3 as compared to the Q_{50}/20 value [11]. Although other more powerful models are reported in the literature, we rejected them since they require specific inputs that are not compatible with the data collected for our sample.

We compared the annual infiltration heating demand E_{leak} of 18 dwellings of our sample, see **(6)**, assessed from the *"Q_{50}/20 rule of thumb"*, to the theorical level E_{req} as required by the present French thermal regulation [3], see **(7)**.

$$\mathbf{E_{leak} = Q_{50}/20 \times DD \times 0.34 \times 24 \times 10^{-3} \quad (kWh)} \tag{6}$$

$$\mathbf{E_{req} = 0.34 \times Qs \times DD \quad (kWh)} \tag{7}$$

where Qs is the infiltration airflow rate caused by the sole envelope leakage defects and assessed according to building and site characteristics [3]. Figure 9 shows that even if we account for the overall range of variations of E_{leak} - due to the over and underestimation of the infiltration airflow rate - the theoretical annual infiltration heating demand assessed from the French thermal regulations is almost systematically much lower than the energy demand assessed from measurement results ($0 < E_{req}/E_{leak} < 0.5$).

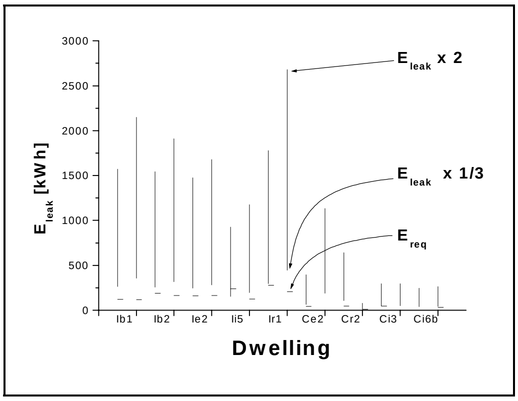


Figure 9 Comparison of the annual infiltration heating energy demands : measurements and theory.

CONCLUSION

In the light of our qualitative and quantitave results, we show the significant impact that infiltration can have on dwelling ventilation and therefore on issues such as building energy efficiency and indoor air quality. From our sample, the airtightness of single-dwellings and/or timber/metal frame buildings appear to be much less important than the performance of multi-family dwellings and/or masonry/concrete buildings. Plus, due to the strong influence of the occupancy mode and construction structure on infiltration, the thermal insulation characteristics could not be analyzed as a major factor of infiltration. Last, according to the wide range of observed performances among the different constructive types of our classification, the unique requirement level applicable for the NRT appears to be inadapted. Future work is needed to better characterise the performance of French dwellings, especially with the view to develop modelling tools capable to assist in the prediction of the annual infiltration airflow rates of the residential buildings.

ACKNOWLEDGEMENTS

This work was supported by the *Département Bâtiment et Collectivités*, of the *Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME)*, under contract n° 99.04.010. The authors wish to thank E. Balas, P. Berger, S. Marconnet and F. Sémenta (CETE de Lyon), Agnès Ougier-Simonin (INSA LYON) and Anne-Laure Destombe (ENTPE) for their valuable contribution to air leakage measurements and data analysis.

REFERENCES

[1] CETE de Lyon "Perméabilité à l'air des logements neufs - H2E85". Plan Construction - Direction de la Construction , pp. **:** 220.

[2] CETE de Lyon, "Eléments de synthèse concernant la perméabilité à l'air dans les logements." Colloque RENEX , 1985: , pp. : 42.

[3] CSTB "Règles de calcul ThG - R.E.E.F. (Réf. AFNOR DTU P 50-704)." Paris, 1991.

[4] DGUHC. "Nouvelle Réglementation Thermique des bâtiments (NRT) - Eléments d'information". Ministère de l'Equipement , Paris (F), 1998.

[5] Guillot, K.and A. Litvak "Field measurement results of airtghtness and ventilation of 70 dwellings". CETE de LYON , pp. **:** 42.

[6] Guillot, K.et al. "Ventilation performances in French dwellings : results from field observations and measurements." 21st AIVC Conference The Hague (NL), 2000:

[7] ISO9972 . "Thermal insulation - Determiantion of building airtightness - Fan pressurization method". Organisation Internationale de Normalisation , Genève (CH), 1996.

[8] Liddament, M. W. "A guide to Energy Efficient Ventilation". International Energy Agency , pp. **:** 255., 1986

[9] Litvak, A. . "Building airtightness : state of the art and review of practice". CETE de LYON , 2000, pp. **:** 89.

[10] Litvak, A.et al. "Field measurement results of the airthghtness of 64 french dwellings." ROOMVENT2000 Reading (U.K.), July 2000 , Vol. 2, pp. :1093-1098.

[11] Meir, A. "Infiltration : just ACH50 divided by 20?" Home Energy January/February 1994 (http://hem.dis.anl.gov/eehem/94/940111.html), 1994: , pp. : 1-6.

[12] Orme, M. "Energy impact of ventilation Estimates for the service and residential sectors."
AIVC, Coventry (U.K.), 1998: , pp. : 43.

[13] Orme, M. "Applicable models for air infiltration and ventilation calculations." AIVC, Coventry (UK), 1999: , pp. : 66.

[14] Sherman, M. and N. Matson . "Residential ventilation and energy characteristics". L.B.N.L. , report n°39036, 1996, pp. **:** 25.

[15] Sherman, M. H. . "Air infiltration in buildings". PhD Thesis , Lawrence Berkeley Laboratory report n°10712, 1980 , pp. **:** 217.