AIRTIGHTNESS OF 12 NON RESIDENTIAL LARGE BUILDINGS RESULTS FROM FIELD MEASUREMENT STUDIES

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ABSTRACT

We investigate the airtightness of 12 French non-residential buildings, by means of experimental fan-depressurization tests. For this study, 12 recent large (volume > 500 m^3) buildings have been chosen according to the construction structure and the activity. Four categories of buildings have been selected : hotels, schools, offices and polyvalent halls. We assessed the air leakage rate of each building, with a fan-depressurization equipment, following the recommendations of the international norm project ISO 9972. The airtightness of the sole envelope is measured by sealing intentionally the openings provided to the buildings for natural or mechanical ventilation. Meanwhile quantifying air leakage rates, we also observe the locations of air leakage paths using a smoke detection method and infrared thermography. We assess the ratio of the air leakage rates weighted by intrinsic dimensions of each construction, namely : the *unheated* surfaces and the heated volume. We analyze the infiltration air exchange contributions according to the types of constructions, and we compare the results to the requirements applicable in France since June 2001 for the Thermal Regulation 2000.

KEY WORDS

Field measurements ; Infiltration ; Airtightness ; Building Envelope ; Large non residential Buildings; 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

BACKGROUND

Recent studies on residential buildings' airtightness have shown that several types of problems can arise from uncontrolled leakages in buildings (e.g., higher energy cost, thermal comfort and health of occupants, building components and equipment preservation). Although, these impacts have been recognized as of key importance and studied for smaller volume buildings such as dwellings, we lack of knowledge on the performances of non residential and large buildings. Indeed, less than 30 on-site measurement results for these categories of buildings are available in France.

Moreover, France and other European countries have decided to explicitly account for the leakage index I_{DP} [m^3/h/m²] in their mandatory thermal regulations (such as the French regulation RT2000 applicable since June 2001). The leakage index I_{DP} is defined as the infiltration airflow rate at ΔP_0 weighted by *whole building* specific envelope areas. For example, RT2000 considers the surfaces exposed to unheated and outside spaces, considered as the most susceptible to promote air leakage infiltrations. If several works have experimentally studied the airtightness performances of small constructions (V < 500 m²), by means of commercially available tehcnical equipements, for larger volume buildings, airtightness measurement dedicated tools are scarce and tests are difficult to be widely performed, mainly for economical and for practical reasons. For example, in France, only one equipement is available. The cost of a depressurization test with such a tool exceeds 6 000 €.

Yet, since RT2000 considers *whole building* performances, there is an urgent need to better charaterize the airtightness of large buildings and, therefore, to develop experimental techniques for measuring the airtightness of whole large buildings.

OBJECTIVES

The objective of this paper is to study the airthightness performance of a sample of 12 non residential large French buildings, less than 5 year old. We aim at characterizing air leakage flows and the most frequent infiltration locations, as well as assessing the airtightness building performances to compare them to the French requirements of RT2000.

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), see ref. [1].

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

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 Eq. (2), where the airtightness parameters (Ki, ni) refer to each envelope surface Si.

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

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.

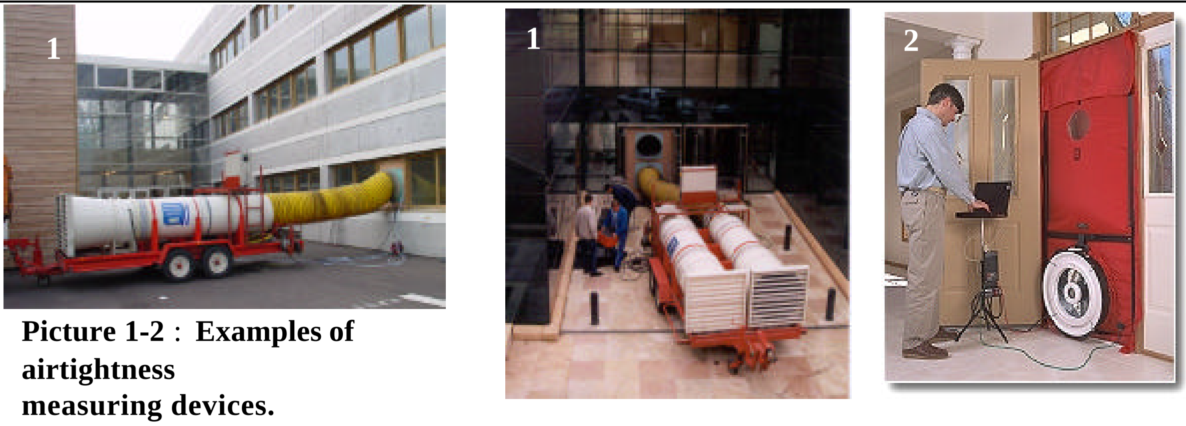
Airtightness indicators

To compare building infiltration performances among themselves, one needs to assess the (measured or theoretical) infiltration air flowrate at a reference pressure ΔP_0 weighted by a construction intrinsic dimension. 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, since it can be compared to intentional ventilation airflow rates. It is equal to the ratio of the air leakage flowrate at ΔP, divided by the heated volume of the building. 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 this study, and in accordance with RT2000, we considered the specific *unheated surfaces*, defined as the *« surfaces that separate the indoor heated volume from the outdoor air and indoor unheated air, excluding the floor »*. For RT2000, airflow rates are assessed at 4 Pa. Moreover, from Eq. (1), 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 Eq. (3).

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

Leakage Measuring Techniques

To date, the only reliable manner to determine the airtightness of a building consists in measuring its infiltration airflow rate. A standardized method, using a fan-depressurization technique (generally known as the «bloower-door » method), is commonly used by many countries and follows the procedure described in the international norm ISO 9972, see ref. [2]. The *« blower-door »* technique is particularly adapted to measure the air leakages in small or airtight buildings. For larger constructions and / or leaky constructions, the building depressurization usually becomes impossible, due to the power limitation of the commercially available fans. For these buildings, CETE Lyon has developped an equipment, unique in France, that measures infiltration airflow rates up to 65 000 m^3/h. One should know that this 5 meter long equipment is towed by a truck to the operation site (see Figure 1).



Picture 1-2 : Examples of airtightness measuring devices.

1) CETE Lyon's Large Building equipment

2) Blowerdoor™ equipment

EXPERIMENTAL METHOD

Selection and classification of buildings

The airtightness of 12 French large non-residential buildings have been measured between November 200 and July 2001, using CETE Lyon's Large Building equipment. The buildings were chosen to be less than 5 year old. They were classified according to the activity (hotels, education, offices and polyvalent halls) and to the type of construction structure (metal/timber frame or concrete/masonry structures). Besides, infrared thermography (IRTh) inspections have been coupled to the depressurization tests in 9 buildings in order to assess air infiltration locations.

Name	Location (zip code)	Ref.*	IRTh	S m^2	V m^3	V/S m^3 / m^2	Construction technique
Foyer CAT	St Nabord (88)	**H1**	·	800	2695	3,4	Timber frame
Etap Hotel	Anthony (92)	**H2**		520	660	1,3	Masonry
Hôtel Parada	Paray le Monial (71)	**H3**	•	717	2871	4,0	Masonry
Etang du puits	Cerdon (45)	**H4**		682	1115	1,6	Timber frame
Ecole	Mouthe (25)	**E1**	•	1736	4287	2,5	Timber frame
Collège Joliot-Curie	Bron (69)	**E2**	•	1602	4862	3,0	Masonry
Ecole	Grézieu (69)	**E3**	•	2045	4563	2,2	Masonry
Lycée Militaire	Autun (71)	**E4**	•	2473	7426	3,0	Metal frame
ONF	Vesoul (70)	**B1**	•	878	1809	2,1	Timber frame
CMR	Autun (71)	**B2**	•	685	1688	2,5	Masonry
Salle municipale	Coisevaux (70)	**SP1**		814	1702	2,1	Timber frame
Cosec	Sancé (71)	**SP2**	•	1245	3306	2,7	Masonry

Table 1 : Characteristics of buildings.
(* letter H relates to hotels, E to education buildings, B to offices and SP to polyvalent halls).

Experimental protocol and data collection

The protocol described in the international norm ISO 9972 was followed for depressurization tests. The equipment characteristics and the experimental operating mode are extensively described elsewhere, see ref. [3] [4]. At least two depressurization tests were performed in each building. The airflow rate through the fan (i.e., the infiltration airflow rate) was determined at stationary increasing steps of approximately 10 Pa. Measurements were performed in the range 10-60 Pa for the differential pressure between inside and outside.

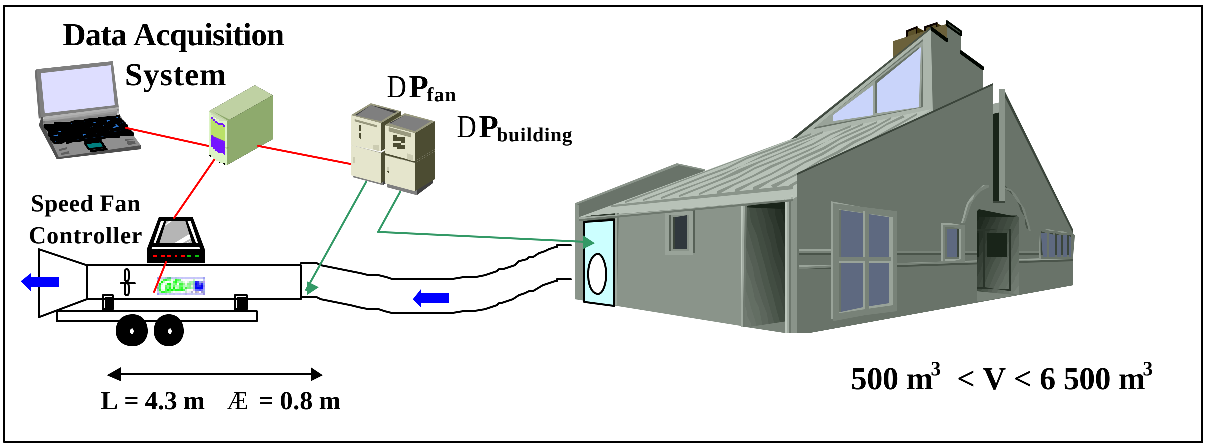


Figure 1 : Equipment and experimental protocol for measuring airtightness of large buildings.

The building airtightness parameters (n, K) were determined by linear regression (for more than 7 points, and $r^2 > 0.90$) of the collected data $\{\Delta P_{building}, Q\}$. The Eq. (1) was solved to assess the infiltration airflow rate at 10 Pa and 4 Pa, and the corresponding τ_{10} and I_4 were determined.

Prior to the depressurization tests, the openings provided to the buildings for natural or mechanical ventilation were intentionally sealed with duct tape. A first depressurization of the building at approximately 50 Pa enabled visual inspections and determination of air infiltration locations accross the building envelope, either by smoke detection method or by infrared thermography.

RESULTS

Qualitative results : air leakage locations

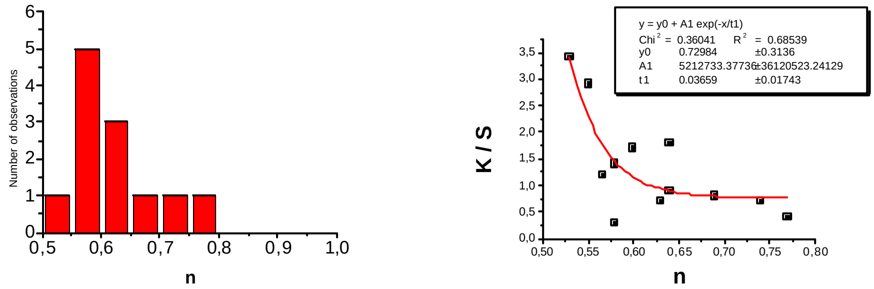
The air leakage pathways were carefully investigated under the test depressurization conditions, by using visual smoke detection techniques and infrared thermography. The observations have been reported for each building and were classified according to the occurrence of different air leakage pathway types. The most frequent locations observed for infiltration are similar to the locations already observed in an earlier measurement campaign on 70 recent French dwellings, see ref [5]. These locations were namely the bonding between window frames and walls, the outlets of electrical equipments and the bonding between floors and walls. The main difference with the locations observed in dwellings were the technical equipments set in the ceilings, such as electrical, lighting or ventilation devices, that appeared to cause important infiltration air leakage flowrates.

Building characteristics and Airtightness parameters

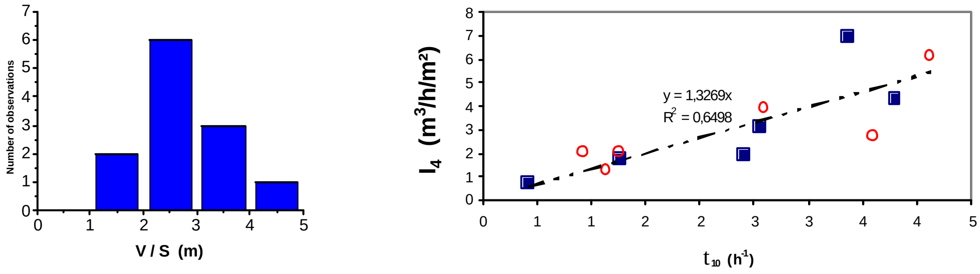
The leakage parameter K and the flow exponent n of Eq. (1) were assessed for the 12 buildings following the depressurization technique. The collected results show a median value of the flow exponential n equal to 0.615, with 75 % of the values in the range [0.55-0.65]. The commonly average value found in the literature is 2/3, and refers generally to small volume buildings. This result shows that airflow pathways in larger buildings seem to be mainly caused by turbulent airflow patterns created by larger orifices than those encountered in smaller buildings.

The ratio of the leakage parameter K divided by the specific unheated surfaces S shows a significant decrease with the flow exponent n from Eq. (1), see Figure 2 b). This trend is consistent with theoretical considerations found in the literature, that correlate large values of K (i.e., important leakage airflow rates) with the presence of large orifices in the building envelope, causing turbulent airflows ($0.5 < n < 0.6$). On the contrary, lower values of K (i.e., lower infiltration airflow rates) happen to be correlated with larger values of n ($n > 0.7$, laminar flows caused by micro-cracks).

The building factor shape ratios V/S are observed to vary in the range [1-5], with an accumulation of values in the range [2-3] (V/S median = 2.5 m), see Figure 2 c) . According to Eq. (3) , and given the low spread of the n values and the good linear fit between V and S ($V = 2.66 \times S$, $r^2 = 0.8825$), the indicators τ_{10} and I_4 appear to be well correlated for larger buildings, see Figure 2 d). This remark leads us to analyze building airtightness performances through the measured values of I_4.



a) Histogram of measured n **b) Exponential decay (n, K/S)**



c) Histogram of V / S **d) Correlation between t_{10} and I_4**

Figure 2 : Building characteristics and airtightness measured parameters

	Mean	SD	Size	Median
n	0.63	0.075	12	0.615
K	1290	684.3	12	1197
V / S	2.52	0.765	12	2.5

Airtightness indicators and potentials to improve building airtightness

Although earlier studies have shown that metal and timber frame buildings happen to be more sensitive to infiltrations, no influence of the construction struture type was found on the airtightness indicator I_4 among the 12 building sample. Two main reasons explain this result. First, the size of the sample prevents us from drawing any significative trend. Second, if one considers the French RT2000 airtightness requirements as average values, the airtightness performances measured here appear to be globally extremely low : only 2 buildings out of 12 would comply with the airtightness default value of RT2000 (see Figure 3). Indeed, for the assessment of the RT2000 C coefficient (C is the building energy consumption coefficient, kWh), the French regulations give two possibilities to building engineers for their calculations. They can either select the airtightness default value (I_4^{def} = 1.7 $m^3/h/m^2$ for non-residential and non-industrial buildings) as the input for the assessment of C or choose a lower value (i.e., more airtight) and be subsequently submitted to an on-site control to confirm this value. For RT2000, the building coefficient C is assessed in order to be compared to the

Reference coefficient C_{ref}, that is determined as a function of reference values (the airtightness reference value is $I_4^{ref} = 1.2$ m^3/h/m² for non-residential and non-industrial buildings).

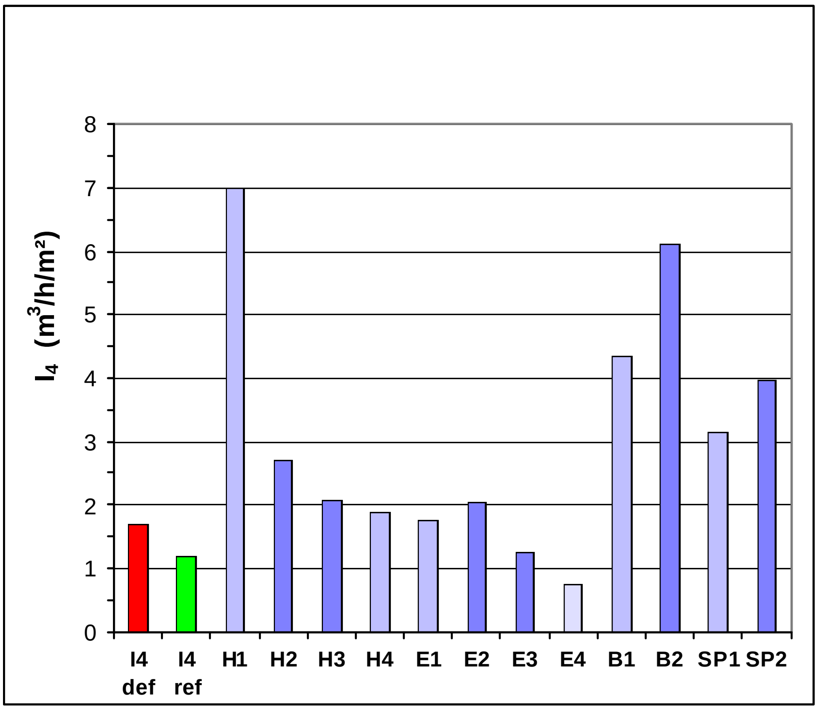


Figure 3 : Comparisons of I_4 results (RT2000 default and reference values are respectively presented in dark and light grey)

On the contrary to building structures, the building activities seem to show different levels for airtightness performances : hotels (except for building H1) and educational buildings appear to be less sensitive to air infiltrations than office buildings and polyvalent halls do. We explain this trend by the fact that the latter buildings have technical ceilings much less airtight than dwellings or hotel bedrooms can have : as we could note, this type of ceilings are very sensitive to air leakage infiltrations.

In the light of the results concerning the type of infiltration orifices encountered in large buildings, we studied the influence of the airflow exponent n (i.e., wether the airflow is laminar, intermediate or turbulent) on the value of the I_4 indicator. Figure 4 shows an exponential decay between n and I_4, that would cause a decrease of I_4 by a factor of approximately 2 if n increases from n = 0.55 (turbulent airflows caused by large orifices) to n = 0.65 (median value of n found in the literature). Thus, the potentials to reduce airtightness rates (i.e., down to the RT2000 levels) appear to be important if one can *improve* the envelope of large buildings to the level of smaller buildings, namely by eliminating the orifices caused by the crossing of technical equipments (electrical, lighting, ventilation, etc..) across the walls and ceilings.

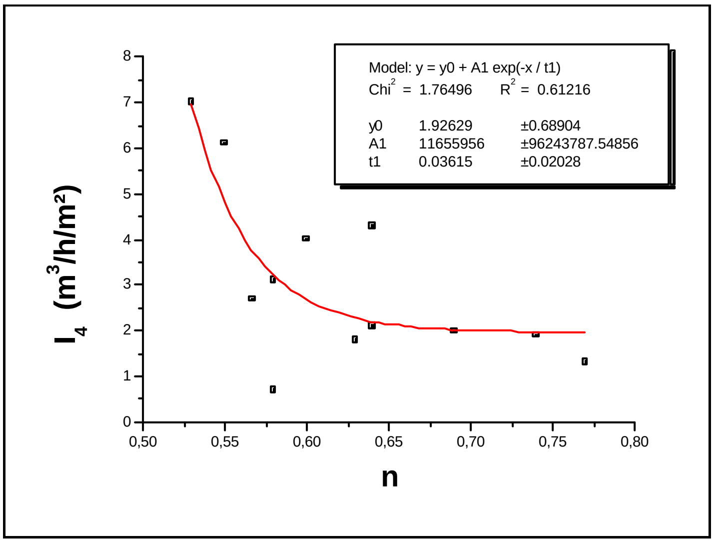


Figure 4 : Exponential decay of (n, I_4)

CONCLUSION

In the light of our qualitative and quantitave results, we show the significant impact that infiltration can have on large and non-residential buildings. From our sample, the airtightness performance of masonry/concrete and timber/metal frame buildings appear to be very low as compared to the RT2000 levels. Due to the importance of air leakages, no influence of the construction type could be shown on the airtightness performances. We could also observe that the level of performance appear to be influenced by the nature of the envelope leakage orifices, that seem to be larger than those encountered in smaller buildings (e.g., dwellings). Potentials to reduce the infiltration leakage levels appear to be be important. Such efforts will help to improve heating, ventilation and air conditionning issues that affect significantly building energy efficiency and indoor air quality.

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