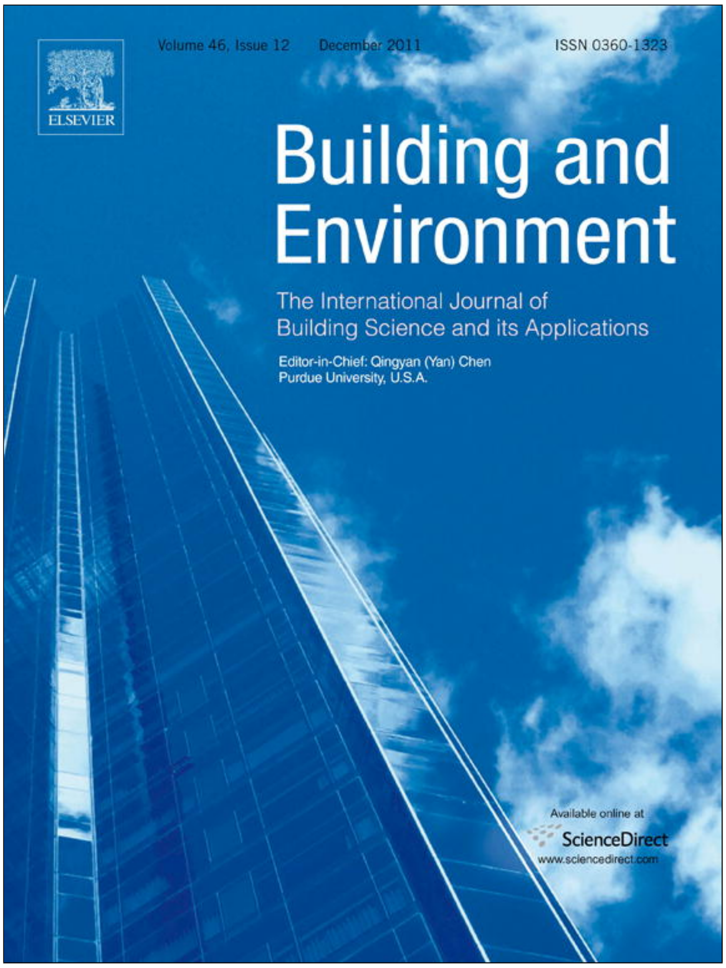
Volume 46, Issue 12
December 2011
ISSN 0360-1323
ELSEVIER
Building and Environment
The International Journal of Building Science and its Applications
Editor-in-Chief: Qingyan (Yan) Chen
Purdue University, U.S.A.
Available online at
ScienceDirect
www.sciencedirect.com

Building and Environment 46 (2011) 2480–2489

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Air permeability measurements of dwellings and building components in Portugal

M. Pinto [a,*], J. Viegas [b], V.P. de Freitas [c]

[a] *School of Technology, Viseu Polytechnic Institute, Campus de Repeses, Viseu 3504 510, Portugal*
[b] *National Laboratory of Civil Engineering, Av. do Brasil 101, Lisboa 1700 066, Portugal*
[c] *Building Physics Laboratory, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, Porto 4200 465, Portugal*

ARTICLE INFO

Article history:
Received 26 November 2010
Received in revised form
4 May 2011
Accepted 2 June 2011

Keywords:
Air permeability
Air flow
Dwellings
Building components
Ventilation systems
ACH_{50}

ABSTRACT

Ventilation represents a significant part of heat loss in winter, leading to the need to minimize airflow. However, it is absolutely necessary to ensure indoor air quality and the safety of the users and to control the risk of condensation. Ventilation is responsible on average for 30%–40% of energy consumption in air conditioning in Western European buildings. There is great variability in air change rates (ACH [h^{-1}]) from country to country and the minimum value takes into account comfort, sensory and hygrothermal criteria. In Portugal improvements have been made in the air permeability of window frames, but despite the improvements also made in installing mechanical extraction ventilation devices in kitchens and toilets, these often do not guarantee the minimum number of air change rates required.

Air permeability tests were recently carried out in five flats with identical construction characteristics, in the same building, with the aim of characterizing the air permeability of buildings and components, in Portugal. These data are particularly useful for improving the design of building components (e.g., windows and roller shutter boxes) and to perform simulations with reliable data.

1. Introduction

Ventilation systems play a major role in defining hygrothermal conditions of comfort and air quality inside buildings. They are absolutely necessary for removing pollutants and moisture produced by the use of buildings and to ensure the oxygen levels required for human metabolism and efficient work of combustion devices. According to studies published in Europe, ventilation represents approximately 30%–40% of the energy consumed for heating buildings and in Portugal the variation may be from 30% to 80% [1,2].

Quantifying infiltration through cracks and joints is difficult or even impossible. It is difficult to identify and characterize all the cracks in a building. In order to overcome this difficulty, building components (e.g., window or door) are often tested *in situ* or in a laboratory. In Portugal, the air permeability of windows, doors and self-adjustable inlets has rarely been tested [3].

The air permeability coefficients of different components and construction elements (e.g. windows, doors, walls, floors, ceilings, joints between elements and chimneys) may be found in the specialized literature and in current international standards or regulations [4,5].

Various quantitative methods can be used to assess the air permeability of components [6]. The simplest one just uses a ventilator to establish, step by step, a pressure difference between the interior of a compartment and the exterior. The test is carried out twice; in the first time the air flow rate blown into the compartment is measured for every pressure step; for the second time the joints of the windows are made impermeable with an adhesive tape and the air flow rate blown into the compartment is recorded again. The air permeability of the window is thus given by the flow rate difference between tests for every pressure step. This is called the indirect method. A "Blower door" can be used for this test and it implies that one of the building doors should be replaced by an adjustable door fitted with a reversible fan whose characteristics (q, Δp) must be known beforehand.

Furthermore, another application of this method is to predict average air infiltration rates (ACH). The average local climate should first be characterized in terms of wind and temperature. Afterward it is usually assumed that [7]:

$$ACH_{\text{annual average}} = \frac{ACH_{50}}{N} \qquad (1)$$

At European level several studies [8–11] show that air permeability strongly depends on the type of building. On average, terraced

---

[*] Corresponding author. Tel.: +351 232 480 500; fax: +351 232 424 651.
E-mail address: mpinto@estv.ipv.pt (M. Pinto).

0360-1323/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2011.06.009

Nomenclature

A	area of opening perpendicular to air flow, [m^2]
ACH	air change rate, [h^{-1}]
w	width of an exhaust device/door/window, [m]
C	leakage coefficient, [m^3 h^{-1} m^{-2} Pa^{-n}] or [m^3 h^{-1} m $^{-1}$·Pa^{-n}] or [m^3 h^{-1} Pa^{-n}]
h	height of an exhaust device/door/window, [m]
N	constant, which depends on the local climate, type and location of the building, [-]
n	air flow exponent, [-]
q	air flow rate, [m^3/h]
Greek symbols	
Δp	pressure difference, [Pa]
ζ	pressure loss coefficient, [-]
Subscripts	
infilt	infiltration
syst	system
annual average	average annual air change rate
50	air change rate at 50 Pa

houses are less permeable than semi-detached or detached houses, but more permeable than flats.

The document CEN/TR 14788: 2006 [12] also gives ACH_{50} limits as a function of the type of the ventilation system and the shielding of the dwelling in order to achieve $q_{\text{infilt}} < 0.25 \cdot q_{\text{syst}}$.

So, in order to optimize energy efficiency in accordance with the European Directive on Energy Performance of Buildings (EPBD - 2002/91/CE) [13], the air permeability of buildings has to be assessed and the components which play the most important part in that air permeability must be identified. Given the difficulty in finding published data on the overall air permeability in dwellings (ACH_{50}) with similar construction characteristics and similar components (e.g. air permeability of interior doors) to Portuguese housing stock in Mediterranean countries [4,14], a wide-ranging experimental campaign was carried out with tests performed in five flats with identical construction characteristics and building components.

These data are particularly useful for improving the design of building components (e.g., windows and roller shutter boxes) and to perform reliable simulations.

2. Methodology of pressure tests

2.1. Principle

The pressure test consists of applying a known pressure differential between the two sides of a crack, construction element or building. The volume of air flow rate is measured and plotted in function of the pressure (q, Δp).

The pressurization and depressurization curves can be defined as:

$$q = C\Delta p^n \tag{2}$$

where the air flow exponent, n, characterizes the flow regime and varies between 0.5 for turbulent flow and 1.0 for laminar flow [15]. For a significant international sample of dwellings, an average value of n equal to 0.66 was obtained [14].

2.2. Procedures and standards for determining ACH_{50}

The measurement range is typically between 10 Pa and 60 Pa with increments of between 5 Pa and 10 Pa and a minimum of 5 measurement points [16,17]. Flow rates are not measured for outside/inside pressure differences below 10 Pa, in order to minimize the influence created by the wind and by thermal differentials during the tests (for normal climate conditions, pressure induced by the combined effect of temperature differences and wind is in the range of ±10 Pa) [6]. It is also recommended that the windows and doors of adjacent flats are open [18] so that the pressure difference between the exterior and the flat under study is as uniform as possible.

As mentioned above, the tests are influenced by external weather conditions so they should only be carried out when the product of the difference between the exterior and interior air temperature by the height of the building is not higher than 200 m °C [16] or not higher than 500 m K [17] (the test criteria vary according to the standard). Test conditions are most favorable when the wind speed is between 0 m/s and 2 m/s and the exterior air temperature is between 5 °C and 35 °C [16].

2.3. Uncertainty

For standard equipment, uncertainty in determining the various parameters that may be obtained with this test are below 15% in most cases [17]. Uncertainty in determining values for C and n may be obtained by the methods described in various documents [17], likewise the uncertainty of flow rate measurements [15].

3. Test results - experimental characterization of building components and ventilation devices

3.1. Description of the building and ventilation system tested

A four-story multifamily building located in the neighborhood of Porto was chosen (Fig. 1). The flats had a ceiling height of approximately 2.5 m.

The natural ventilation system proposed by the designer had the following characteristics and locations (Fig. 2):

- air self-adjustable inlet device located above the roller shutter box at an approximate height of 2 m; one self-regulated air inlet per room (the characteristic air flow rate is 30 m^3/h at the pressure difference of 20 Pa) and two in the living-room (Fig. 3); this is a so-called “module 30” air inlet;
- air fixed inlet device on the external kitchen door (with an adjoining balcony) installed in the lower portion of the door; its overall size is 55 × 16.5 cm^2 (an effective area of 247.5 cm^2);
- extraction from toilet with a fixed plastic “current” outlet positioned approximately 2.1 m above the floor (gross area of 15 × 15 cm^2 and effective area of approximately 26 cm^2) and a static ventilator (cowl) at the end of the duct on the roof (Fig. 4).

The elements that are not a direct part of the ventilation system, but influence it nonetheless, had the following characteristics:

- particleboard bedroom doors with rubber weather strips in the top and side joints and a bottom gap of an average height of 0.4 cm when the door is closed;
- particleboard kitchen and bathroom doors with rubber weather strips in the top and side joints and a bottom gap of an average height of 0.8 cm;

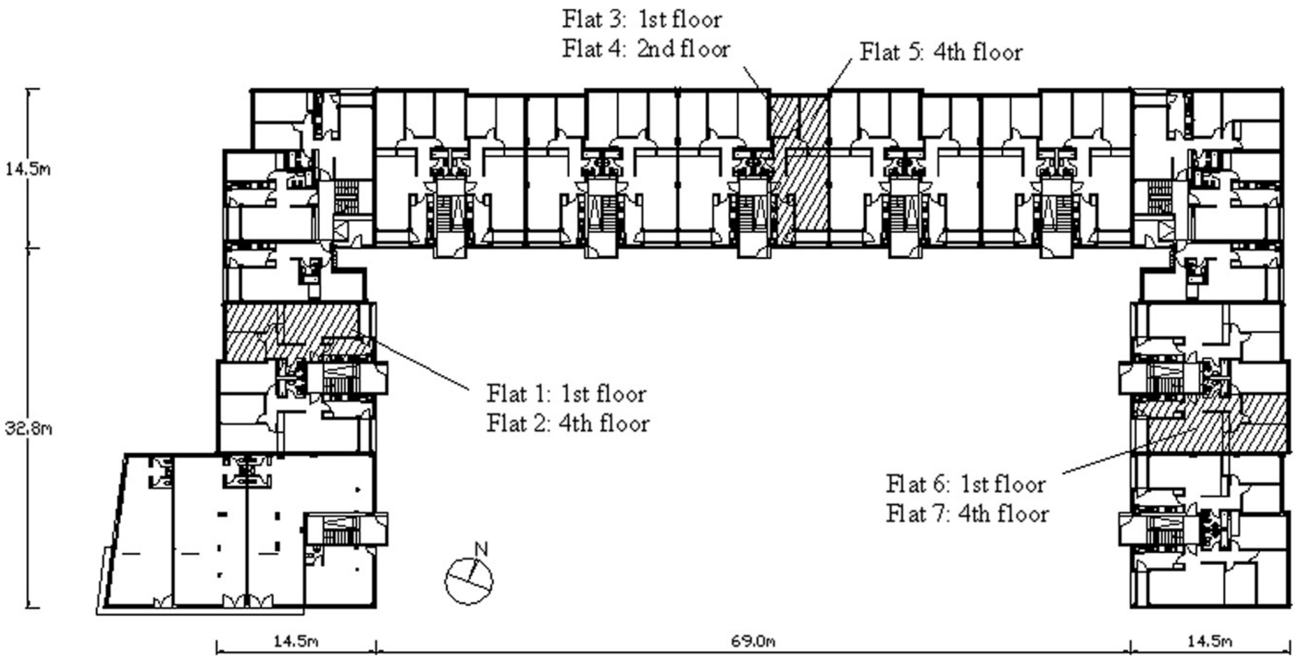

Fig. 1. Residential building containing the flats tested.

- main entrance door of solid wood with rubber weather strips in the top and side joints and threshold lowered by 1 cm on the inside;
- expanded polystyrene (EPS) roller shutter box with a horizontal particleboard lid in the bedrooms and living room;
- sliding single-glazed windows with air permeability of class 2 according to EN 1026: 2000.

The tests were performed in five flats (flats 1 and 3: 1st floor; flats 2 and 5: 4th floor; flat 2: 2nd floor). The volumes of the flats were approximately 160 m^3 (see Fig. 2). Fig. 2 shows the flat type and the location of the ventilation system inlets.

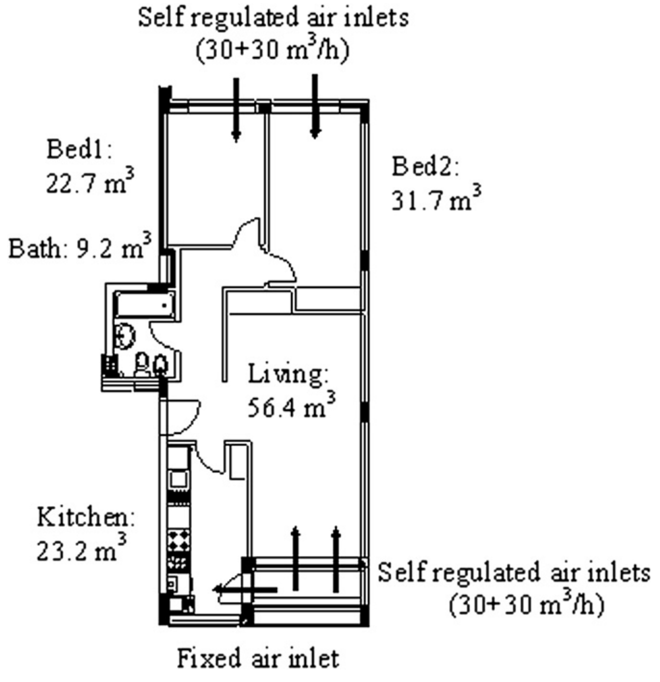

Fig. 2. Two bedroom flat. Volumes of the rooms and air inlets.

3.2. Experiments

The aim of the experimental campaign was to characterize the installed ventilation devices and building components, both in the laboratory (National Laboratory of Civil Engineering - LNEC) and *in situ*. A comparative analysis of the results (including some test results obtained by the manufacturers) was carried out.

The *in situ* tests lasted from February to March 2006 and were carried out using a blowing door (Minneapolis Blower Door model). The air permeability of the components was determined by the indirect method.

In the results presented below, in the case of depressurization the air is flowing from the outside to inside the flat.

During all the tests carried out *in situ*, the weather conditions were measured (wind speed and direction, air temperature and relative humidity) at the roof of the building, as well as the

Fig. 3. Self-regulated inlets fitted above the windows.

Fig. 4. Static ventilators on the bathroom ducts.

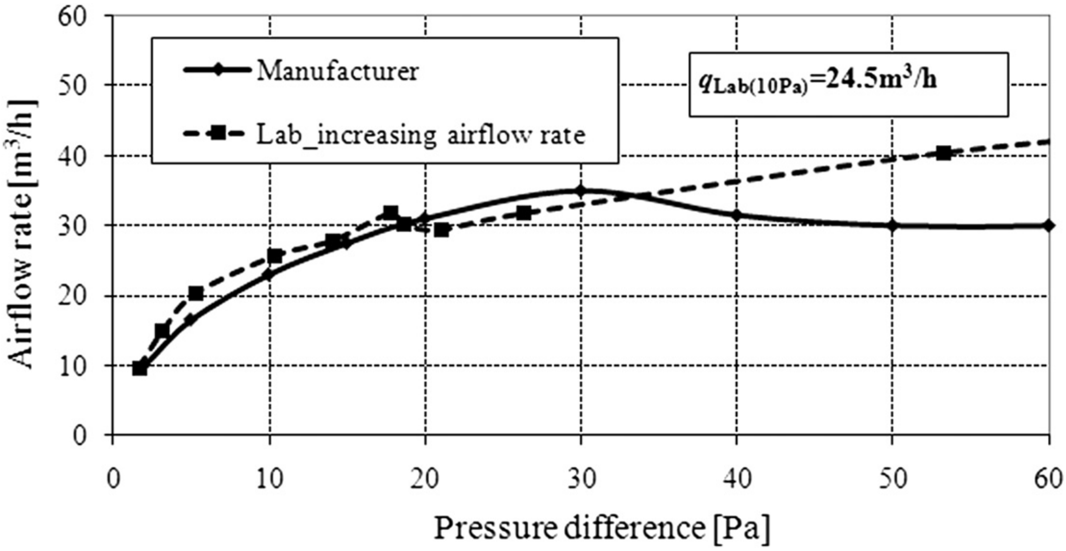

Fig. 5. Aerodynamic performance of the self-regulated air inlet.

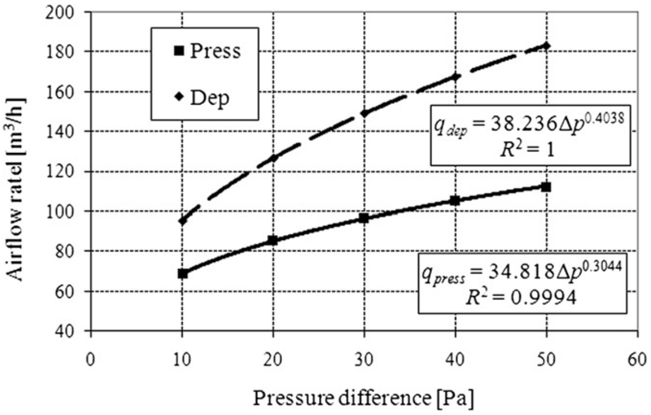

Fig. 6. Aerodynamic performance of the self-regulated air inlets (7th March 2006).

temperature and relative humidity inside the flats under study (from an indoor measuring point).

The following building components and ventilation devices were tested:

- self-regulated air inlets;
- current window (in the bedrooms);
- bathroom exhaust device;
- static ventilator (cowl);
- roller shutter boxes;
- interior and exterior doors.

3.2.1. *Aerodynamic performance of the self-regulated air inlet*

Fig. 5 shows the aerodynamic performance of the "module" 30 self-regulated air inlet - French made. These inlets must conform to the requirements set out in standard NF E 51-732: 2005 [19].

From the comparative analysis of the results presented by the manufacturer and the laboratory test results, it may be concluded that at low pressure (0–20 Pa), which is more common in natural ventilation or mechanical ventilation systems, the flow rates are quite close since the opening essentially behaves like a constant section opening. Moving toward the highest range of pressures, where the effect of the self-regulating membrane is sensitive, a different performance is found between manufacturer tests and laboratory tests. A difference between flow rates at high pressures may therefore result from a malfunctioning of the regulating membrane.

The *in situ* air permeability of the self-regulated air inlets was determined for the group of 4 inlets (Fig. 6) installed in the flat, which, in the case of depressurizing the flats (air intake), should reach approximately 98 m^3/h (24.5 m^3/h × 4) for a pressure difference of 10 Pa (Fig. 5).

All the results obtained from the *in situ* air permeability tests of the inlets can be found in Table 1.

Table 1
Aerodynamic performance of the self-regulated air inlets (group of 4).

Flat	Test date	Test	Air permeability [m³/h]	Flow rate for 10 Pa [m³/h]
4	7th March 2006	Pressure	$q = 34.818\Delta p^{0.3044}$	70.2
4	7th March 2006	Depressurization	$q = 38.236\Delta p^{0.4038}$	96.9[a]
5	14th March 2006	Pressure	$q = 32.382\Delta p^{0.3460}$	71.8
5	14th March 2006	Depressurization	$q = 27.925\Delta p^{0.4752}$	83.4

[a] For one air inlet is 24.2 m^3/h.

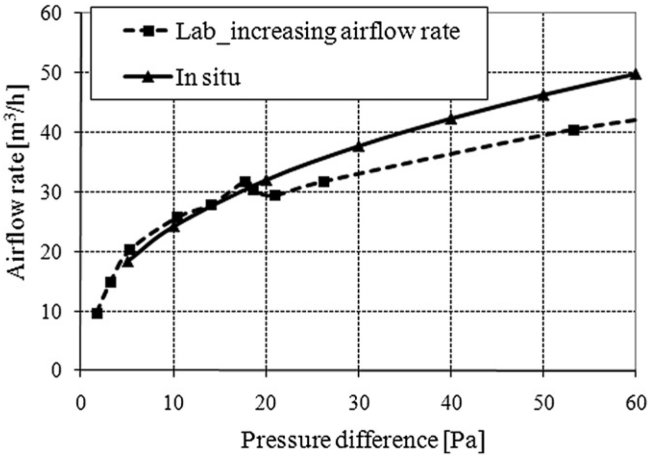

Fig. 7. Comparative analysis of the aerodynamic performance of a self-regulated air inlet (depressurization, comparison for 7th March 2006).

Table 1 shows some variability in the results. This may be explained by fluctuating wind speed. When the under depressurization is 10 Pa the air flow rate is slightly below the expected rate.

The comparative analysis between the tests carried out *in situ* and those carried out in the laboratory in Fig. 7 shows that these values are close at pressures below 20 Pa. Nevertheless, there is still some discrepancy in the results at higher pressures, showing that a malfunction of the self-regulating membrane occurs also in *in situ* measurements.

3.2.2. *Air permeability of the current window*

The European standards EN 1026: 2000 [20] and EN 12207: 1999 [5] were followed in the laboratory tests (conducted on the window manufacturer's prototype). The window had the following characteristics: total area of 1.80(w) × 1.00(h) m^2; length of the moveable external joint of 6.60 m; thickness of the simple window glass pane of 4 mm.

Under European standard EN 12207: 1999 [5], the window's air permeability belongs to class 2 (the best class obtained among the pressure and depressurization partial tests). The equations obtained as a function of the air permeability trials (adjusted results for standard conditions of 20 °C and 101.3 kPa) are summarized in Table 2. The accuracy required in accordance with the international test standard EN 1026: 2000 is 10% [20].

Compared with the Initial Type Tests carried out under the responsibility of the window assembly designer ("system house"), the tests carried out on the window manufacturer's prototype showed a significant increase in air permeability (over 100% for 10 Pa), thereby lowering the air permeability class from 3–4 to 2. These results show the mismatch between the best assembly practice developed by the assembly designer and the real assembly practice of the window manufacturer (Fig. 8).

The air permeability test results obtained *in situ* for the windows, both together and separately, are found in Table 3. The

Table 2
Air permeability of the current window (window manufacturer).

Test	Flow rate as a function of total area [m³/h m²]	Flow rate for 10 Pa [m³/h m²]	Flow rate as a function of the length of the movable joint [m³/h m]	Flow rate for 10 Pa [m³/h m]
Pressure	$q = 0.8538\Delta p^{0.5801}$	3.2	$q = 0.2329\Delta p^{0.5801}$	0.9
Depressurization	$q = 0.1975\Delta p^{0.8485}$	1.4	$q = 0.0489\Delta p^{0.8485}$	0.3

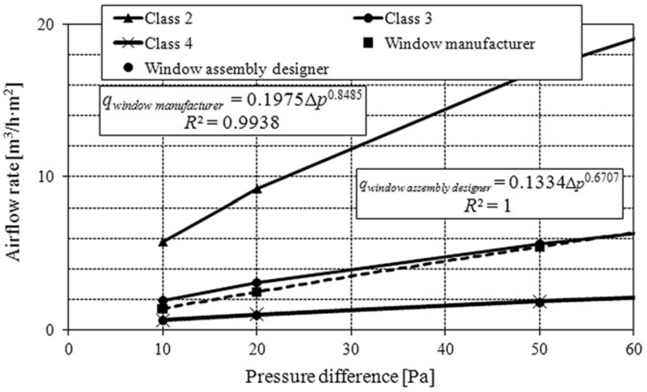

Fig. 8. Comparative analysis of the air permeability tests carried out by window assembly designer and window manufacturer (air permeability per unit of area - depressurization).

size of the windows was as follows: living room window area of $2.70(w) \times 2.00(h)$ m^2, kitchen window area of $1.80(w) \times 1.10(h)$ m^2 and bedrooms window area of $1.80(w) \times 1.00(h)$ m^2 (total area of 10.98 m^2). Considering the similarity of test methods, the pressure and the flow rate determined *in situ* may be compared with the pressure and the flow rate determined in the laboratory. Care should be taken when interpreting laboratory tests because the outer face of the window is placed inside the test rig; therefore, pressure inside this test rig corresponds to a flow from outside to inside the compartment, which is comparable to depressurization site tests. In these tests, the air permeability (flow rate) would be expected to be lower for the pressure test (air flowing out of the flat) because some windows (kitchen outside door) are of the type single side-hung casement, opening inwards; therefore, a higher pressure inside the flat compresses the casement against the joint, reducing the gaps and thus the air permeability. However, this was only found to be the case for the test held on 8th February 2006.

A comparative analysis per unit of area between the bedroom window laboratory test and the *in situ* living room window test is shown in Fig. 9. Given the discrepancy of results, mainly at high pressures, it may be concluded that the extrapolation of tests to larger windows as mentioned in [21] is not recommended. In this case an overestimation of approximately 200% is obtained for 600 Pa (this pressure is under the range of the standard EN 12207: 1999 [5], but having in mind the comparisons of test results, here the air permeability is only presented up to 60 Pa).

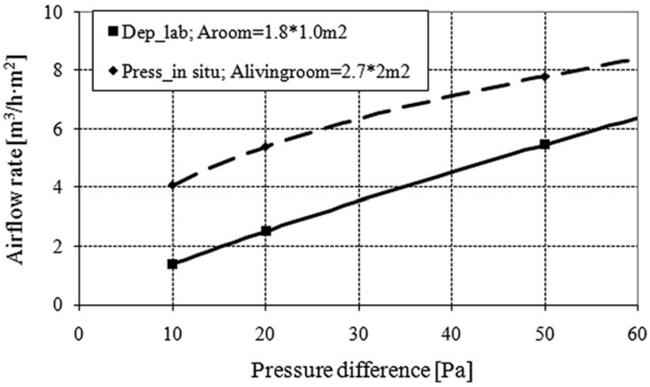

Fig. 9. Comparative analysis of the air permeability for laboratory test of bedroom window and the *in situ* test of living room window (comparison for 7th March 2006).

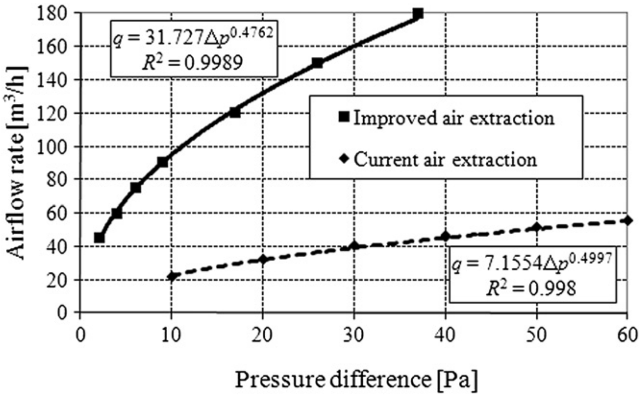

Fig. 10. Aerodynamic performance of the bathroom exhaust device.

Table 3
Air permeability of the windows.

Flat	Test date	Test	Air permeability [m^3/h]	Flow rate for 10 Pa [m^3/h]	Flow rate for 10 Pa [m^3/(h m^2)]
1	8th February 2006	Pressure (Global)	$q = 4.333\Delta p^{0.7488}$	24.3	2.21
1	8th February 2006	Depressurization (Global)	$q = 10.324\Delta p^{0.4989}$	32.6	2.97
3	21st February 2006	Pressure (Global)	$q = 7.576\Delta p^{0.4917}$	23.5	2.14
3	21st February 2006	Depressurization (Global)	$q = 1.100\Delta p^{1.0015}$	11.0	1.00
4	7th March 2006	Pressure (living room window)	$q = 7.734\Delta p^{0.4028}$	19.6	3.63

3.2.3. Aerodynamic performance of the bathroom exhaust device

The tests were carried out in accordance with standard NP EN 13141-1: 2006 and the respective aerodynamic performance is shown in Fig. 10. The accuracy obtained is smaller than 5% of the measured value [22].

The extraction pressure loss coefficient of the exhaust device ($\zeta = 2 \times \Delta p/1.2 \times [A/(q/3600)]^2$) is 2.8, which is equivalent to a pressure drop of 40 Pa for 45 m^3/h. This figure greatly exceeds the pressure loss recommended by NP 1037-1: 2002 [23], 3 Pa, thus implying a drastic reduction in bathroom air flow extraction rates in Portugal today, where the use of this type of device is common.

In the flats with improved ventilation systems, an aluminum exhaust device with the following size was used: exterior = $196(b) \times 150(h)$ mm^2, interior: $\phi 120$ mm. The manufacturer's aerodynamic performance rating is shown in Fig. 10.

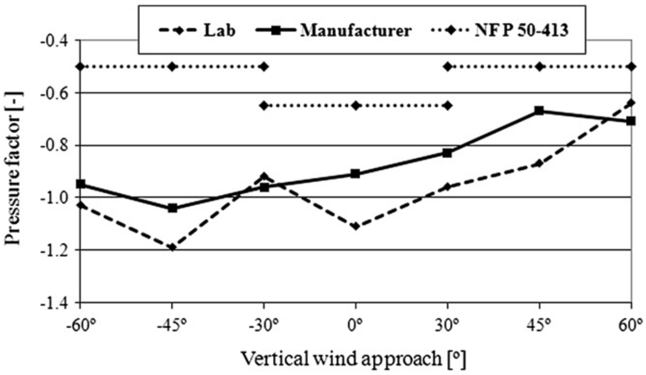

Fig. 11. Comparative analysis of the pressure factor of the static ventilator.

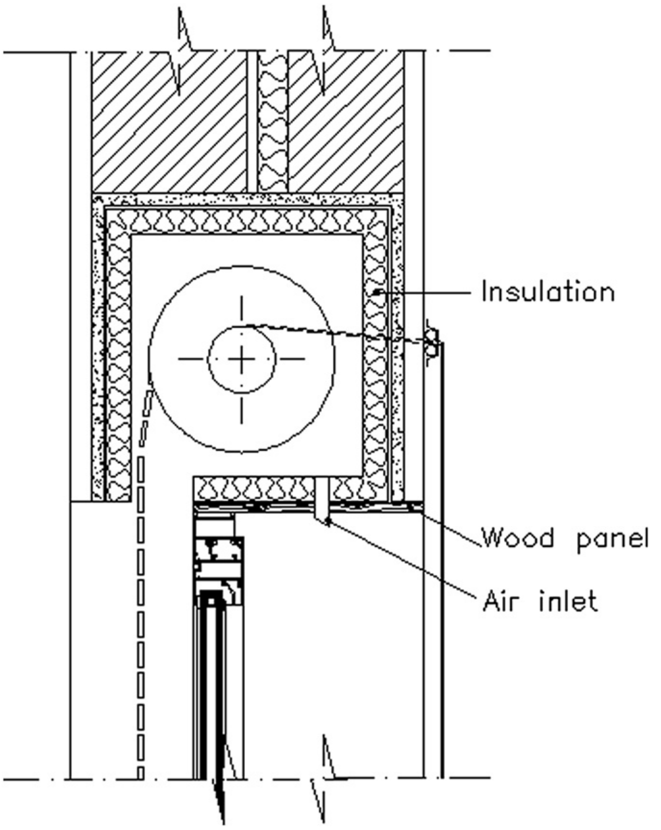

Fig. 12. Typical detail of a roller shutter box in Portugal.

Table 4
Roller shutter box air permeability.

Flat	Test date	Test	Air permeability [m^3/h]	Flow rate for 10 Pa [m^3/h]
1	8th February 2006	Pressure	$q = 107.044\Delta p^{0.3695}$	251.6
1	8th February 2006	Depressurization	$q = 81.117\Delta p^{0.5127}$	264.1
3	21st February 2006	Depressurization	$q = 99.602\Delta p^{0.4458}$	278.0

The extraction pressure loss coefficient of this device is 0.77, which is equivalent to a pressure drop of 2 Pa for 45 m^3/h. So, it does not surpass the pressure loss recommended by NP 1037-1: 2002 [23].

3.2.4. *Pressure loss and pressure factor of the static ventilator (cowl)*

The static ventilator was tested in the laboratory in accordance with standard prEN 13141-5: 1998. The wind tunnel test took place at LNEC. The determined parameters were the pressure loss coefficient ($\zeta = 1.5$; the nominal value claimed by the manufacturer is $\zeta = 1.51$) and the pressure factor.

Table 5
Air permeability of the interior doors of the flat (bedrooms and kitchen).

Flat	Test date	Test	Flow rate as a function of the length of the moveable joint [m^3/h m]	Flow rate for 10 Pa [m^3/h]	
		3 doors	1 door	1 door	3 doors
4	7th March 2006	Pressure	$q = 3.974\Delta p^{0.4931}$	68.0	204.1
4	7th March 2006	Depressurization	$q = 4.739\Delta p^{0.3943}$	64.6	193.9
5	14th March 2006	Pressure	$q = 1.744\Delta p^{0.7399}$	52.7	158.1
7	14th March 2006	Depressurization	$q = 2.374\Delta p^{0.6024}$	52.3	156.8

Table 6
Air permeability of the flat's main entrance door.

Flat	Test date	Test	Flow rate as a function of the length of the moveable joint[a] [m^3/h m]	Flow rate for 10 Pa [m^3/h]
5	14th March 2006	Pressure	$q = 0.792\Delta p^{0.8547}$	30.6
5	14th March 2006	Depressurization	$q = 6.038\Delta p^{0.5402}$	113.1

[a] Length of the moveable joint: 5.40 m.

The static ventilator's performance obtained by the manufacturer was graded in accordance with standard NF P 50-413: 1993 (this standard was recently withdrawn; its content is now in DTU 24.2.P1-1: 2006 [24]). This document grouped the static ventilators in 2 classes. Class B (Good), the classification obtained by this ventilator, had the following specifications:

- pressure loss coefficient, ζ, less than 2;
- pressure factor less than -0.65 for wind directions of ±30° with respect to the horizontal axis;
- pressure factor less than -0.50 for wind directions in ranges $[-60°; -30°]$ or $[+30°; +60°]$;
- pressure factor less than 0 for other wind directions.

Fig. 11 shows the comparative analysis for the two tests, from which it is possible to conclude that the ventilator is of class B. However, the results obtained in the laboratory give lower (better) values for the pressure factor.

3.2.5. *Air permeability of the roller shutter boxes*

Fig. 12 shows a typical detail of a roller shutter box in Portugal. The roller shutter boxes were not tested in the laboratory since their performance in terms of air permeability depends, to a great extent, on their installation. Only the *in situ* test results are presented (Table 4). As shown in Section 4, the air permeability of the overall roller shutter box is higher than that of the window.

To reduce the air permeability of the roller shutter box, the following recommendations on the design should be retained:

- to seal the whole fixed joint between the walls, windows and the roller shutters with, for example, mastic;
- to improve the connection between the frame of the roller shutter box and the horizontal particleboard (that encloses the box) with a "male-female" joint.

3.2.6. *Air permeability of the doors*

The performance of the doors is detailed in the tables below. The size of the doors was as follows: area of interior doors $0.75(w) \times 2.00(h)$ m^2, area of kitchen external door

Table 7
Air permeability of the external kitchen door.

Flat	Test date	Test	Flow rate as a function of the length of the moveable joint[a] [m^3/h·m]	Flow rate for 10 Pa [m^3/h]
1	8th February 2006	Pressure	$q = 0.538\Delta p^{0.6660}$	13.4
1	8th February 2006	Depressurization	$q = 1.016\Delta p^{0.7314}$	29.4
4	7th March 2006	Pressure	$q = 0.819\Delta p^{0.6586}$	20.0

[a] Length of the moveable joint: 5.36 m.

Table 8
- Comparative analysis of the various sources of the results.

	Manufacturer - base value	Laboratory	*In situ*
Self-regulated air inlet	q for 10 Pa = 23.2 m^3/h (Fig. 5) q for 50 Pa = 36.0 m^3/h (Fig. 5)	q for 10 Pa = 24.5 m^3/h (Fig. 5) q for 50 Pa = 52.6 m^3/h (Fig. 5)	q for 10 Pa = 24.2 m^3/h (Fig. 6; Table 1) q for 50 Pa = 46.4 m^3/h (Fig. 6; Table 1)
Static Ventilator	Pressure factor for 0° = −0.91 (Fig. 11) Pressure loss = 1.51	Pressure factor for 0° = −1.11 (Fig. 11) Pressure loss = 1.5	– –
	Window assembly designer - base value	Window manufacturer - Laboratory	Window manufacturer - *In situ*
Window	q for 10 Pa (depressurization) = 0.6 m^3/h m^2 (Fig. 8)	q for 10 Pa (depressurization) = 1.4 m^3/h m^2 (Fig. 8; Table 2)	q for 10 Pa (depressurization) = 2.0 m^3/h m^2 (Table 3, Average)

0.80(w) × 2.00(h) m^2 and area of main entrance door (flat exterior) 0.90(w) × 1.80(h) m^2. For the interior doors, the depressurization test indicates that air flow tends to close the door.

Table 5 shows that the air permeability does not vary significantly as a function of the flow direction (higher flow rates would be expected in the direction in which the door casement opens - pressure). This result may be explained by the low air permeability of the door, which means that the air flows essentially through the bottom gap.

As mentioned above, the interior doors of bedrooms and living rooms are sealed with rubber weather stripping on the sides and at the top. The air permeability figures obtained for the interior doors are lower than those presented in the Portuguese literature [25], which highlights the need for air transfer devices, especially in bathroom and kitchen compartment doors.

In accordance with NP 1037-1: 2002 [23], the air permeability of the main entrance door should not exceed 12 m^3/(h m^2) for a pressure difference of 100 Pa, which, in this case, would be 19.4 m^3/h. Table 6 shows that this is greatly exceeded (392.4 m^3/h in depressurization). This door had seals like the ones described above.

The air permeability of the external kitchen door also greatly exceeds the recommended value in NP 1037-1: 2002 [23] (158.1 m^3/h in depressurization; Table 7).

In both situations, the high air permeability is probably due to the existence of an unusually large gap at the bottom. This stresses the need to apply weather strips also in the lower horizontal opening joint. For the external doors of both the kitchen and the flat, the depressurization test indicates that air flow tends to open the door.

A comparative analysis of the various sources of the test results is presented in Table 8. For the self-regulated air inlet, a comparative analysis between the tests carried out *in situ*, in the laboratory and those carried out by the manufacturer shows some results discrepancy, namely at higher pressure differences. These differences are due to a malfunction of the self-regulated membrane. This fact raises some doubts about the reliability of such membranes in normal use. If so, a degraded aerodynamic performance may be expected in buildings ventilation. For the static ventilator, better results were obtained in the laboratory, but this difference is considered to be of the magnitude of the test uncertainty; therefore, it is considered insignificant. It can be concluded that the window made by the window manufacturer (when tested both in laboratory and *in situ*) had higher air permeability than the Initial Type Test results presented by the window assembly designer. This also shows the deterioration in the quality of window installation carried out by the window manufacturer from the laboratory to the working site.

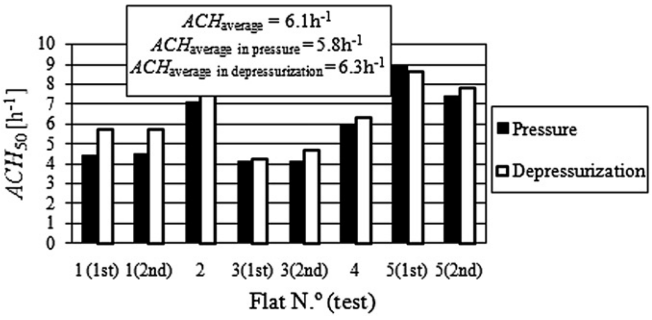

Fig. 13. Overall air permeability of flats.

4. Test results – overall air permeability of the flats

As far as possible, the determination of the overall air permeability of the flats followed the standard EN 13829: 2000 [17]. The weather conditions did not influence the test results. According to this standard, the uncertainty of the obtained results, particularly ACH_{50}, is in general below 15%. All the results were adjusted to the standard conditions of 293 K and 101.3 kPa, in accordance with standard ASTM E 779: 2003 [16].

The overall air permeability test of the flats was carried out in accordance with method B of EN 13829: 2000 [17] (for this test all air inlets and outlets that belong to the ventilation system were closed with a self-adhesive tape in order to measure just the air permeability of the flat envelope), equivalent to method B of ISO 9972: 2006 (see Fig. 13).

From Fig. 13 it is possible to conclude that the value of the overall air permeability (ACH_{50}) in each studied flat is similar for the pressure and depressurization tests. Flats 1 and 3, on the lowest level, are also found to have lower air permeability than flats 2 and 5, which are on a higher level (4th floor). There is a variation in the ACH_{50} between 4.4 and 9 h^{-1} with an average of 6.1. These results are in line with those already presented in the Portuguese literature (variation between 2 and 8 h^{-1} [3]). In additional tests, the air permeability measured between flats was negligible. In accordance with standard EN ISO 13790: 2004 [26] for multifamily buildings, the results obtained are at the high level of air permeability.

The air permeability of the roller shutter boxes, windows, main entrance door of the flat and kitchen external door, for a pressure

Table 9
Air permeability of the components - depressurization.

Component	Test date	Flat	Flow rate for 50 Pa [m^3/h]
Roller shutter boxes	8th and 21st Feb. 2006 (Table 4; Average)	1 and 3	586.3
Windows	8th and 21st Feb. 2006 (Table 3; Average)	1 and 3	64.0
Main entrance door	14th March 2006 (Table 6)	5	269.8
Kitchen external door	8th Feb. 2006 (Table 7)	1	95.2
		Total air flow rate [m^3/h]	1015.3
		ACH_{50} [h^{-1}]	6.3

difference of 50 Pa, previously measured and presented in Section 3, are summed and presented in Table 9. The obtained flow rate corresponds to a $ACH_{50} = 6.3$, that is equal to the average ACH_{50} obtained at the overall air permeability tests presented in Fig. 13. This agreement shows that these building components have the most influence in the overall air permeability of the flat. It shows also that these measurements are reliable, because similar results are obtained by following two different test methods (measurement of overall air permeability of the flat, versus individual measurement of the air permeability of each of the building components).

5. Conclusions

In this paper tests of air permeability of every building component and tests of the overall flat air permeability were carried out. With respect to the individual characterization of the components, the following may be concluded:

- In general, there is some discrepancy between the test results from different sources. In the case of the self-regulated air inlet (Figs. 5 and 7), the test results of the aerodynamic characteristics presented by the manufacturer and those obtained in the laboratory and *in situ* tests do not agree for higher pressure differences (which, in the case of natural ventilation, is not too important because the pressure differences are usually small). This is due to malfunction of the self-regulating membrane.
- The example of the bedroom window also shows that the real window has higher air permeability than Initial Type Test results presented by the window assembly designer (in this case by 200% - Fig. 8). This shows the deterioration in the quality of window installation carried out by the window manufacturer because the construction rules issued by the window assembly designer are not completely followed. Recommendations should be issued in order that window manufacturers fully follow the technical instructions prepared by the window assembly designer.
- The high air permeability of the kitchen external door and main entrance door, confirmed the expectations (Table 9): faulty configuration of the bottom horizontal joint. In light of the requirements set out in NP 1037-1: 2002 [23] this is one of the components which should be given the most attention at the design and execution stages.
- The low air permeability of the interior doors (Table 5) as compared to the values cited in the Portuguese literature highlights the potential restriction of air flow inherent to a ventilation system and shows that bigger gaps indoor joints or ventilation air transfer devices are needed in order to avoid ventilation restriction.
- The high pressure drop characteristic for a “current” exhaust air terminal device installed in the bathroom exhaust duct (Fig. 10) shows the importance of proper component selection.
- The data obtained from the roller shutter box confirm that this is the component making the greatest percentage contribution to the overall air permeability in flats (Tables 4 and 9). It also highlights the need to improve their performance, along with that of external doors.

As regarding to the overall air permeability of the flats, the following may be concluded

- Although the flats tested were of the same size, with the same components and apparently with the same construction processes, the overall air permeability shows wide variation. This is probably due to the variation of the dimension of the gaps surrounding the roller shutter boxes and the gaps in the lower opening joint of the external doors (altogether these correspond to more than 90% of the overall air permeability of the flat, according to Table 9), that strongly depends on the local installation work. Nevertheless, the average value is similar to that shown in the Portuguese literature. The overall flat air permeability should be reduced by improving the quality of roller shutter boxes and external doors manufacturing and installation.
- Good agreement between the air permeability obtained in the individual component test (Table 9) and the overall air permeability (Fig. 13), can be concluded and indicate the reliability of the results.

Acknowledgments

The authors wish to thank Dr. João Delgado, Department of Civil Engineering Faculty of Engineering - University of Porto for his valuable suggestions during the preparation of this manuscript and the National Laboratory of Civil Engineering for the experimental support.

This research was supported by Fundação para a Ciência e Tecnologia (Research Project POCTI/ECM/45555/2002).

References

[1] Ferreira M, Corvacho H, Alexandre J. Natural ventilation of residential buildings in Portuguese winter climatic conditions. Prague, Czech Republic: Proceedings of 25th AIVC Conference; 2004.
[2] Ferreira, P. Hybrid ventilation systems in buildings. Energy analysis resulting from implementing innovative ventilation systems (in Portuguese). Master's Thesis, Porto, Portugal: Faculty of Engineering – University of Porto; 2006.
[3] Pinto A. Recommendations for air permeability limits of the envelope. Lisbon, Portugal: Proceedings of Seminar on the Application of Natural and Mixed Ventilation; 2007.
[4] Orme M, Leksmono N. Ventilation modelling data guide, 5. Brussels, Belgium: AIVC Guide; 2002. Annex 5-AIVC, IEA-ECBCS.
[5] CEN. Windows and doors. Air permeability. Classification. EN 12207. Brussels, Belgium: European Committee for Standardization; 1999.
[6] Roulet C, Vandaele L. Air flow patterns within buildings. Measurement techniques. Technical Note 34. Annex 5-AIVC. Coventry, Great Britain: IEA-ECBCS; 1991.
[7] Silva A. Characterization of average annual infiltration in Portuguese buildings by the pressurization method (in Portuguese). Master's Thesis, Porto, Portugal: Faculty of Engineering – University of Porto; 1991.
[8] Bossaer A, Demeester J, Wouters P, Vandermarke B, Vangroenweghe W. Airtightness performance in new Belgian dwellings. Oslo, Norway: Proceedings of 19th AIVC Conference; 1998.
[9] Litvak A, Guillot K, Kilberger M, Boze D. Airtightness of french dwellings. Results from field measurements studies. Hague, Netherlands: Proceedings of 21st AIVC Conference; 2000.
[10] Andréws L, Matthieu F, François C. Envelope and ductwork airtightness data in Portugal: field practice, regulatory approach, energy implications, and progress needed. Fulda, Germany: Proceedings of 1st European Blowerdoor Symposium; 2006
[11] Sfakianaki A, Pavlou K, Assimakopoulos M, Santamouris M, Livada I, Karkoulias N, et al. Air-tightness measurements of forty residential houses in Athens, Greece. Helsinki, Finland: Proceedings of Clima 2007 conference; 2007.
[12] CEN. Ventilation for buildings. Design and dimensioning of residential ventilation systems. CEN/TR 14788. Brussels, Belgium: European Committee for Standardization; 2006.
[13] European Directive on Energy Performance of Buildings (EPBD – 2002/91/CE).
[14] Orme M, Liddament M, Wilsom A. An analysis and data summary of the AIVC's numerical database. Technical note 44. Annex 5-AIVC. Coventry, Great Britain: IEA-ECBCS; 1998.
[15] Etheridge D, Sandberg M. Building ventilation. Theory and measurement. Chichester, England: John Wiley & Sons; 1996.
[16] ASTM. Standard test method for determining air leakage rate by fan pressurization. E 779–03. West Conshohocken, USA. Am Soc for Test Mater; 2003.
[17] CEN. Thermal performance of buildings. Determination of air permeability of buildings. Fan pressurization method. EN 13829. Brussels, Belgium: European Committee for Standardization; 2000.
[18] Flanders S. Fan pressurization measurements by four protocols. Palm Springs, USA: Proceedings of 16th AIVC Conference; 1995.
[19] AFNOR. Composants de ventilation mécanique contrôlée. Entrées d'air en façade. Caractéristiques et aptitude à la fonction. NF E 51–732. Paris, Portugal: Association Française de Normalisation; 2005.
[20] CEN. Windows and doors. Air permeability. Test method. EN 1026. Brussels, Belgium: European Committee for Standardization; 2000.

[21] Pinto A. Experimental qualification of a window frame at the housing block in Areias, Gondomar. Frame prototype trial (in Portuguese). Projecto POCTI/ECM/45555/2002. Edifícios – Nota Técnica 01/2005 – NCI. Lisbon, Portugal: National Laboratory of Civil Engineering; 2005.
[22] Pinto A. Testing building components. Instrument calibration for measuring air flow (in Portuguese). Relatório 26/01-NCCp. Lisbon, Portugal: National Laboratory of Civil Engineering; 2001.
[23] IPQ. Ventilation and combustion products evacuation from places with gas-burning appliances. Part 1: dwellings. Natural ventilation (in Portuguese). NP 1037–1. Monte da Caparica, Portugal: Instituto Português da Qualidade; 2002.
[24] CSTB. Travaux de bâtiment. Travaux de fumisterie – systèmes d'évacuation des produits de combustion desservant un ou des appareils. Partie 1: cahier des clauses techniques – règles générales, DTU 24.1 P1. Paris, Portugal: Centre Scientifique et Technique du Batiment; 2006.
[25] Viegas J, Silva F, Pinto A, Matias L. Ventilation of dwellings: requirements and experiments. Coimbra, Portugal: Proceedings of XXX IAHS World Congress on Housing; 2002.
[26] CEN. Energy performance of buildings. Calculation of energy use for space heating and cooling. EN ISO 13790. Brussels, Belgium: European Committee for Standardization; 2004.