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The energy impact of infiltration: a study on buildings located in north central Spain

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Abstract Improving the energy efficiency of the thermal conditioning of buildings is an international priority. Along this line, there have been major advances in the insulation of enclosures and the equipping of facilities. The need for building ventilation has an enormous impact on the environmental energy consumption evaluation. Filtration resulting from imperfections in enclosures and partitions always accompanies narrow ventilation flow, increasing the unabated consumption of energy. The present research study establishes an evaluation procedure for this excess energy consumption via an experimental study carried out in various buildings located in the north and central part of Spain. The procedure, commonly called the *Blower Door Test*, is based on standards EN 13829 and ISO 9972. The work is composed of the following sections: a description of the air entry processes in buildings, an experimental study and calculation of the airtightness of enclosures, a discussion of the energetic effects of infiltration and conclusions.

Keywords Air leakage · Airtightness · Fan pressurization · Leakage area · Ventilation

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Introduction

The need to introduce energy-saving measures, both for environmental and economic reasons, altered significantly the principles of architectural design in force since the International Style: if previously energy demands were satisfied by mechanical systems with high consumption, the evolution of project management and regulations promoted the use of insulation to protect buildings from the outdoor environment.

In this framework appears the Energy Performance of Buildings Directive of the European Union, and even though the Member States have progressed unevenly along the guidelines of this Directive, all of them have in common the fact of identifying the requirements to reduce the energy consumption in domestic indoor heating, which contributes significantly to emissions of carbon dioxide and has a high potential of energy savings.

From an energetic point of view, the building can be considered like a thermodynamic system continuously affected by multiple and varied physical influences and limited by an architectonical envelope through which energy and mass are dynamically exchanged. Thus and broadly speaking, the energy consumption in winter demand depends on the needs to cover the resultant between the internal and solar gains and the losses through the envelope.

The energy-saving strategies seek to minimize the thermal losses through the envelope (passive measures) and, likewise, to improve building systems' efficiency and implementing renewable energies (active measures).

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There are two sorts of losses through the building enclosure. The first corresponds to heat transfer losses, determined by building design, thermal conductivity and thickness of the building materials of the architectural envelopes. The second type belongs to ventilation losses, including infiltration, determined by airtightness of the building enclosure. The thermal and airtightness characteristics are inherent properties of design and execution quality of the building envelope.

Both losses should be considered when aiming at decreasing the energy consumption of dwellings. However, problems arise when the standards, such as those existing in the Mediterranean countries like Spain (Código Técnico de la Edificación 2009), only establish requirements for the first type (heat transfer losses), minimizing the importance of quantifying infiltration by including it in the air exchange rate of the system itself. Even many models that simulate the energy behaviour of buildings assume that a "practically airtight" architectural enclosure is achieved by assuming that air leakage only results from the window frames (Código Técnico de la Edificación 2013).

However, under certain environmental conditions, air will penetrate uncontrollably through points where construction elements converge, with magnitudes that vary according to the solutions adopted in each building. Consequently, the infiltration causes problems of over-ventilation, entry of contaminants or odours, discomfort and unnecessary waste of energy (which is difficult to quantify).

The improvement of the energy performance, resulting from minimizing the heat transfer losses, is raising the energy impact of ventilation losses, increasing up to 9 % of the primary energy consumption in buildings (Axley 2001). A non-negligible quantity of energy loss that is a result of air leakage should be added to this percentage.

Logically, the contribution of air has a much more significant effect on the heating demand of buildings located in cold climates. Particularly, in residential buildings in cold climates, infiltration is responsible for approximately 25 % of the heating demand and 3 % of the cooling demand (Kalamees 2007): for example, simulations carried out in Finland show that by increasing the air exchange rate, n_{50}, from 1 to 10 L/h, the consumption of heat energy increases from 4 to 21 % (Jokisalu and Kurnitski 2002).

For cooling needs of dwellings located in regions with temperate climates, where buildings are characterized by having large holes in their facades, there is a cultural tradition of using natural ventilation to achieve cooling, air exchange and comfort. However, the potential for natural ventilation has dwindled because of the alteration of urban temperatures due to the heat-island phenomenon and the drastic reduction in wind velocity due to urban canyons. As a consequence, buildings with conditioning systems whose performance is highly dependent on possible rates of infiltration have proliferated in these cities (Sfakianaki et al. 2008).

The present article studies the impact of enclosure permeability in countries with temperate climates based on the analysis of a series of real case studies in residential buildings located in central and northern Spain. The process includes in situ tests and the use of energy performance simulation tools to predict the demand of each building and to quantify the supplementary energy required due to the degree of permeability of the built enclosure.

The importance lies in that residential buildings represent approximately 70 % of the housing stock in Spain (de la Energía IDAE 2011) and are responsible for almost 10 % of the national primary energy consumption per year (de la Energía IDAE 2011; Eurostat. Final energy consumption, by sector, corresponding to 2011). According to the European Union directives concerning energy efficiency and the required implementation of the 20/20/20 objectives (Unión Europea. La eficiencia energética en el horizonte de 2020), it is necessary to perform research studies to move towards energy efficiency improvements in buildings, given that there are great possibilities in this field to reduce consumption. According to some estimates, reductions as great as 30 % are possible (WFF/Adena. Retos y oportunidades de financiación para la rehabilitación energética de viviendas en España. Madrid: Informe 2012; Comisión 2008). These studies found that the incidence of infiltration is significant, therefore warranting greater emphasis in terms of regulations and raising professional awareness.

The entrance of air into buildings

The entry of outdoor air to the interior of a building is based on a pressure differential. To quantify the flow rate, it is necessary to quantify three unknowns: the pressure gradient, the aperture of admission and the pressure drop that occurs upon crossing the said aperture.

The pressure gradient is the result of the combined effect of two simultaneous processes: forced convection, which is either of natural origin, i.e. wind, or artificial, i.e. mechanical ventilators, and natural convection, which is due to the density differential produced by the effect of different temperatures on both sides of the enclosure. This flow is virtually independent of the possible movement of indoor air; therefore, practically all of the studied models assume that indoor air is at rest (static equilibrium) (Etheridge and Sandberg 1996).

The other variables are associated with the air movement through the enclosure. By superpositioning these effects, the controlled processes of air entry via specific openings (ventilation) and its chaotic and uncontrolled entry through interstices (infiltration) can be distinguished. In both cases, the incoming airflow is turbulent, with a variable magnitude that influences the load loss of the process.

After calculating the effective real air exchange rate in buildings, it is necessary to consider two superimposed phenomena: ventilation plus infiltration. The ventilation term is easily obtained from the dimensions of the system. However, for infiltration, the randomness of the environmental variables (the pressure gradient) involves a nonlinear phenomenon in which an exact calculation is not possible but can only be simplified and approximated. The only term whose value can be reliably obtained is the airtightness of the enclosure via the fan pressurization technique.

The pressurization test assesses the airtightness of the building, which is expressed via a series of objective parameters obtained from the relationship between the flow rate that traverses the enclosure and different pressure gradient intervals (Fig. 1). This relationship is fitted to a power law that has the following form (Reiher et al. 1932):

$$Q_{\Delta \mathrm{P}} = C_{\mathrm{L}} \cdot (\Delta P)^{n} \quad (1)$$

where

- $Q_{\Delta P}$ is the filtration flow rate (m^3/h)
- ΔP is the pressure difference (Pa)
- C_L is the power law coefficient ($m^3/h \cdot Pa^n$)
- n is the power law exponent

The coefficient C_L depends on the filtration area. The exponent n depends on the resistance of the filtration openings to the passage of air, and it represents the three-dimensional geometry of the filtration openings (height, width and depth) and the physics of air transport (Sherman and Chan 2006; Roberson 2004). Its limiting values are as follows:

- $n=0.5$ (the flow is proportional to the square root of the pressure drop). This is the case of large, direct openings with short development where friction forces can be ignored, which is understood as a nozzle and turbulent flow.
- $n=1.0$ (the flow is proportional to the pressure drop). This is the case in which the air traverses a trajectory long enough to acquire laminar flow.

Experimentally, the exponent n usually has an intermediate value, normally $n \approx 0.65$, during both pressurization and depressurization (Orme et al. 1994). Consequently, the flow is neither fully turbulent nor dominated by laminar characteristics. Thus, if the value of n is close to the limits, it is possible to deduce interesting information about the physical nature of the dominant filtration points.

From the power law (Eq. 1), several parameters can be determined, allowing for the comparison of the results in different buildings (CEN 2000; ISO 2006) (Table 1):where

- V is the internal volume (m^3), defined as the space subject to measurement within the building and which is the same zone with respect to acclimatization and ventilation.
- A_E is the area of the architectural enclosure (m^2) or the boundary that separates the internal volume, subject to testing, from the exterior environment or other bordering interior space.
- A_F is the usable floor space in the internal volume to be tested.

Based on such previous studies, several European countries have studied the status of their real estate by constructing experimental housing during the first decade of the twenty-first century and strengthening the standards regarding the airtightness of enclosures. In addition, the calculation of the infiltration flow rate has become critical for the correct characterization of the energy performance of buildings (Europe's Buildings under the Microscope 2011).

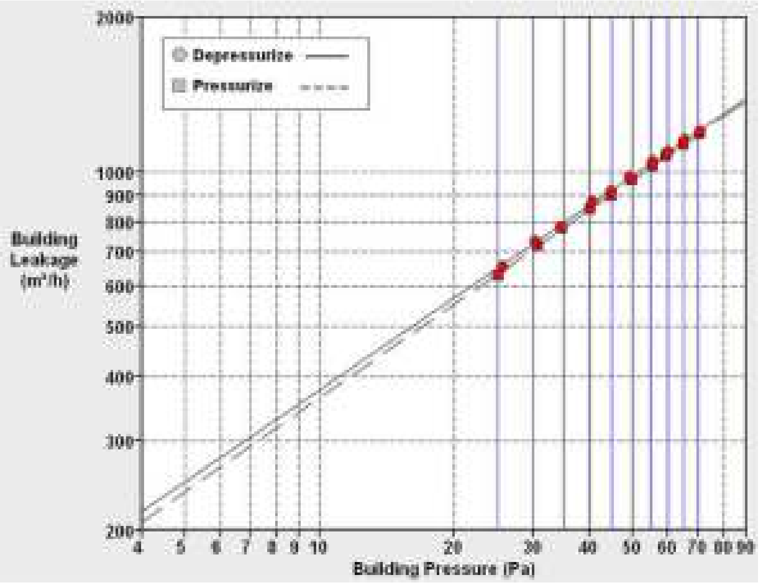


Fig. 1 Relationship between building leakage and pressure

Experimental study of enclosure airtightness

Description of the buildings

The present work collectively analyses pressurization tests carried out in 13 dwellings located in residential blocks in the centre and north of Spain (Table 2). Geographically, the tests are clearly located in two different climatic zones: the oceanic zone and the Mediterranean zone (Fig. 2).

The buildings in Basauri and Sondika, bordering Bilbao, are exposed to a mesothermal climate, which is moderate in terms of temperature and with high precipitation rates; this is also referred to as a wet temperate climate without a dry season. This climate is characterized by air masses whose temperatures decrease upon contact with temperate ocean waters, resulting in less acute thermal oscillations and, therefore, mild winters and cool summers.

The buildings in Vitoria are in a transition zone between the oceanic climate and the Mediterranean climate of the interior. However, Atlantic characteristics predominate, although there is less precipitation.

Valladolid clearly experiences a continental Mediterranean climate, which is characterized by very extreme temperatures. The winters are long and very cold, and the summers are very hot but with large daily oscillations. In all months, precipitation is scarce.

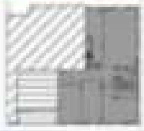
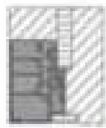
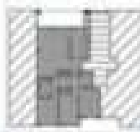
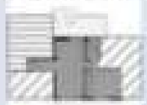
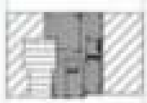
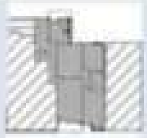
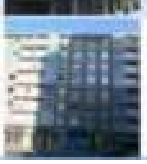
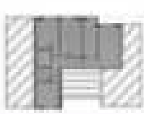
These climatic characteristics indicate that the focus of the energy demands of air conditioning should be on the coldest months. During summer, the mild temperatures in the oceanic zone do not represent an important thermal load and it is possible to take advantage of natural nocturnal cooling in the continental zone.

In terms of construction definitions of the tested dwellings, all of them have the same technical solutions (concrete structures, factory-made enclosures, standard openings, etc.), but they are affected by the three levels of regulatory frameworks of increasing requirements: projects prior to 1979, which lacked any energy regulations, post-1979 projects regulated by the NBE-CT-79 Thermal Conditions in Buildings and projects since 2006 regulated by the new Spanish Building Code (CTE), which include the energy efficiency directives driven by the European Union.

Table 1 Parameters that define the airtightness

Parameter		Equation	Unit
Q_{50}	Average filtration flow rate needed to obtain ΔP (at 50 Pa)	$C_L\,(50)^n$	m^3/h
n_{50}	Air change rate (at 50 Pa)	Q_{50}/V	h^{-1}
q_{50}	Permeability of enclosures to air (at 50 Pa)	Q_{50}/A_E	$m^3/(h \cdot m^2)$
w_{50}	Normalized filtration rate according to the usable surface (at 50 Pa)	Q_{50}/A_F	$m^3/(h \cdot m^2)$

Table 2 The characteristics of the tested dwellings

Dwelling number	Image	Location	Year	Orientation	Floor scheme (Test zone / Adjacent dwellings / Common spaces / Exterior space)	Total number of floors	Height tested floor	V (m^3)	A_F (m^2)	A_E (m^2)
1		Basauri (Vizcaya)	2012			5	2nd	195.9	81.6	279.1
2		Vitoria (Álava)	2012			8	3rd	199.9	84.6	296.2
3		Sondika (Vizcaya)	2012			4	2nd	192.8	73.9	247.5
4		Vitoria (Álava)	2011			9	2nd	160.1	67.0	231.5
5 6 7		Vitoria (Álava)	2011			10	1st 8th 9th	221.6 227.2 227.2	87.6 89.8 89.8	309.8 323.1 323.1
8		Valladolid (Valladolid)	2006			8	8th	107.3	42.9	170.8
9 10 11		Valladolid (Valladolid)	2002			10	2nd 5th 10th	218.7	90.0	291.5
12		Valladolid (Valladolid)	1979			7	3rd	216.0	87.7	356.2
13		Valladolid (Valladolid)	1973			8	5th	184.24	75.21	258.2

Test methodology

All tests were carried out according to European Norm 13829 (CEN 2000), which in turn entirely adopts the International Standard 9972 (ISO 2006). The procedure, commonly called the *Blower Door Test*, creates a stationary pressure differential in the interior of a zone to be tested with respect to the exterior atmosphere, and the

Fig. 2 Distribution of the climatic zones in Spain (IGN Instituto Geográfico Nacional 2008; Instituto para la Diversificación y Ahorro de la Energía IDAE 2010)

air flow circulates through a fan in a range of certain pressures that are measured.

The pressure gradient chosen by convention is 50 Pa because it is sufficiently low that the fans can test the volume of air contained in the majority of dwellings and is sufficiently high that conditioning is not required because of the climatological influences (up to wind speeds less than 6 m/s) (de Gids 1981). However, the flow rate at 50 Pa is not a representative value that would permit direct extrapolation to air exchanges caused by environmental conditions, given that the real average gradient between the faces of enclosures range between 1 and 4 Pa. It is not possible to reliably experimentally measure the airflow at such low and variable natural pressures.

The preparation of the internal volume to be tested is performed according to method B of the standard EN 13892 (CEN 2000), used to measure the airtightness of the building envelope: any intentional opening in the building enclosure should be closed or sealed. Before starting the test, it is useful to detect the infiltration foci to document and facilitate subsequent sealing. The process consists of creating an increased depressurization during a period of time to allow for flow stabilization and the thermal action of the infiltrated air over the entry points. The simplest method for locating air leakage is the use of infrared thermography (Fig. 3).

Finally, the results of the tests are subjected to an error analysis: with standard equipment, uncertainty in determining the different parameters that may be obtained with each test are below 15 % in all cases (CEN 2000; D'Ambrosio et al. 2012; Pinto et al. 2011).

Tests in multi-storey residential buildings

Throughout the study, the typology of the target building must be clearly distinguished by the relationship of the tested zone with its external environment. The pressurization test is particularly well adapted for studying the building as a whole, with its sole total volume contained by the architectural enclosure: In this case, the external environment is responsible for all air leakages, as occurs in isolated single-family dwellings and individual buildings. However, in general, this method is not applicable to whole residential buildings by the magnitude of the internal volume under test, which is too large for available fans.

In semi-detached or attached dwellings and those belonging to residential buildings, the tested zone has part of its enclosure in common with other adjacent areas that are different from the exterior space, such as other housings, public areas, vertical communication elements, commercial establishments, etc. This requires addressing the difficulty of clearly distinguishing air leakages that come from the outside from those that come from the adjacent premises, implying that there are air inlets with different environmental conditions. The result will be determined by the characteristics of the existing partitions between the various locations for the vertical development of the building enclosure and the interconnections necessary for the common facilities.

Different pressurization methods have been described for the measurement of inter-zonal and exterior filtrations in residential buildings (Sheltair Scientific

Fig. 3 The use of thermography to locate air leakages

1987), although a consensus has not been reached regarding a common methodology (DePani 1999). The most common are *detached unit method* (DePani 1999), *pressure equalization method* (DePani 1999), *method of equal zone-to-zone pressures* (Modera et al. 1986), *pressure-drop method* (Nylund 1981; Love 1986), *open-door methods* (Blasnik and Fitzgerald 1992) and *whole building method* (DePani 1999). Among these methods, the most reliable is the pressure equalization method (DePani 1999) since it is an approximation that requires that the adjacent zones are subjected to the same pressurization process as the test zone: given that the interzonal flows are theoretically eliminated (as there are no gradients), the detected infiltrations are those occurring through the external enclosure. However, the technical difficulty limits its application.

This difficulty made it advisable to perform the tests using the detached unit method, which is discussed in this article. In this method, the dwelling integrated in the building is assimilated to an isolated dwelling: The dividing walls and horizontal partitions are considered to be part of the exterior housing. So, the test is performed by opening the windows and doors of the adjacent zones such that their pressure is similar to the atmospheric pressure. The intrinsic nature of the approximation, which assumes that all air leakage comes from the exterior space, requires adopting the most unfavourable approach towards the energy incidence.

Experimental studies, carried out using a similar approach but based on the pressure equalization method, suggest that the infiltration flow rate coming exclusively from the exterior accounts for an average of 20 % of infiltration (this additional flow rate comes from annexed rooms), with significant differences depending on the location of the dwelling in the building (The New River Center for Energy Research and Training (NRCERT) 2012; Proskiw 2007; Finch et al. 2009). For this reason, an adequate strategy for characterizing an entire building would be to test the greatest number of possible housing units (up to 20 % of the total dwellings (Bichof et al. 2012) and up to 20 % of the building's exterior wall area (Air Tightness Testing and Measurement Association ATTMA 2007)), where it is advisable to study at minimum an attic apartment, the dwelling with the lowest ceiling and an intermediate apartment (Fig. 4) (Walther and Rosenthal 2009).

Finally, it should be mentioned that another alternative is to use tracer gases. However, a significant margin of error results from the inevitable duration of the tests, over the course of which the final environmental conditions vary with respect to those at the beginning of the process (resulting in changes in the average filtration flow rates).

Airtightness results

Independent of the distinctiveness of each dwelling, the results clearly indicate that the construction characteristics imposed over the time by the different standards have influenced the presence of infiltration (Table 3). In the case of Spain, buildings built 50 years ago were designed under an absence of regulations regarding energy losses. These buildings were usually built with high-mass enclosures without thermal insulation, and frames were mounted with low thermal features having a high level of air permeability. In the 1970s, issues related to indoor comfort conditions in homes began to appear and the demanded expenses to reach these suitable levels, improving the average energy demand. Since then, in many cases, these buildings have experienced a major improvement, when the building owners have solved the existing deficiencies by replacing and

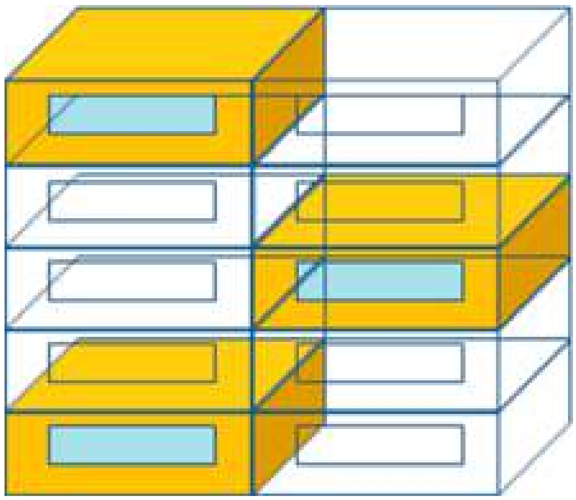


Fig. 4 Recommendations for testing dwellings in buildings

upgrading the frames, sealing the detected air leakages, placing thermal insulation in the walls and replacing systems by others with higher efficiency.

The first regulation regarding energy in Spain is CT-79, which was a result of the energy crisis of the 1970s: the use of thermal insulation in the architectural envelope became necessary, and the quality of the frames improved, establishing the minimum requirements for thermal resistance and airtightness in both elements. However, there was no regulation regarding infiltration and there was even a design awareness of executing permeable enclosures in order to cover the absence of an indoor ventilation system and to prevent superficial condensations.

The current Spanish Building Code or CTE, enforced since 2006 and written according to the Energy Performance of Buildings Directive, has limited the energy consumption of buildings, depending on the climatic zone and the predicted use of the building. The regulations promote an increase in thermal resistance of the architectural enclosure and quantify the energy demand for conditioning the ventilation air (mandatory for the first time in Spain). The use of infiltration is considered only for exterior frames. However, generally, the improvement in building constructive systems has successfully increased the airtightness level of the architectural envelope, even when there are no regulations limiting this problem.

Consequently, the experimental tests show that the best airtightness levels belong to the most recent buildings, followed by those buildings constructed before 1970, in the cases in which they have been renovated by their owners. The buildings constructed between these two periods involve mediocre performances, but these shortcomings are not so evident that the inexperienced owner is self-convinced of the advantages of investments in this field (and the possible fast return of this investment).

Table 3 Results of the performed tests

Dwelling	Location	Year	Applicable standard	Q_{50} (m^3/h)	n_{50} (h^{-1})	$n_{50\ \mathrm{corrected}}$ n_{50}—20 % (h^{-1})	q_{50} (m^3/h·m^2)	w_{50} (m^3/h·m^2)
1	Basauri (Vizcaya)	2012	CTE	1,143	5.83	4.67	4.10	14.01
2	Vitoria (lava)	2012	CTE	711	3.56	2.85	2.40	8.40
3	Sondika (Vizcaya)	2012	CTE	975	5.06	4.05	3.94	13.19
4	Vitoria (lava)	2011	CTE	411	2.57	2.05	1.78	6.13
5	Vitoria (lava)	2011	NBE-NT-79	1,683	7.59	6.08	5.43	19.21
6				1,498	6.59	5.27	4.64	16.68
7				1,647	7.25	5.80	5.10	18.34
8	Valladolid (Valladolid)	2006	NBE-NT-79	1,441	13.43	10.74	8.44	33.59
9	Valladolid (Valladolid)	2002	NBE-NT-79	1,653	7.13	5.70	5.35	17.32
10				1,527	6.98	5.58	5.24	16.97
11				1,559	7.56	6.05	5.67	18.37
12	Valladolid (Valladolid)	1979	–	698	3.23	2.59	1.96	7.96
13	Valladolid (Valladolid)	1973	–	857	4.65	3.72	3.32	11.39

Analysis with respect to other UE countries

An analysis of the trend in countries of Central and Northern Europe shows that their normative horizon is focused on adopting in the future the values required by the Passivhaus standard (n_{50}≤0.6 to 1.0 h^{-1}).

Direct comparison of the existing national standards along European countries is not possible due to the absence of agreement on the best descriptor for evaluating the airtightness of the envelope. Table 4 shows a summary of the airtightness requirements for dwellings in air change rate (h^{-1}), at 50 Pa, n_{50}, where it is possible to confirm that countries of the European Union located in temperate climates (Italy, Spain, Portugal, Greece, Cyprus and Malta) do not have the same concern about it (to adapt the different parameters, the assumptions presented by Limb 2001 were used, considering a typical volume of 300 m^3 and a surface area of 250 m^2 and expressing the obtained values of n_{50} with brackets).

Traditionally, the buildings of the twentieth century in the Mediterranean countries are characterized by the utilization of heavy systems based on reinforced

Table 4 Summary of the airtightness requirements for dwellings in air change rate

		Average n_{50} (h^{-1})
Passivhaus standard		≤0.6–1.0
Austria (depending on Lănder)	(Dwellings with natural ventilation)	≤3.0
	(Dwellings with ventilation systems)	≤1.0–1.5
Bulgaria	Floor multi-dwelling (high/med/low)	<2/2–5/>5
	Floor, single flats (high/med/low)	<4/4–10/>10
Czech Republic—CSN 73 0540-2	(Dwellings with natural ventilation)	≤4.5
	(Dwellings with ventilation systems)	≤1.5
	(Dwellings with heat recovery)	≤1.0
Denmark—EN13829	Residential	(≤4.5)
Finland—FIN3 Building Code D3 2012		(≤3.3)
France—RT 2012	(Isolated dwellings)	(≤2.7)
	(Enclosures within buildings)	(≤4.4)
Germany—EnEV 2009	(Dwellings with natural ventilation)	≤3.0
	(Dwellings with ventilation systems)	≤1.5
Latvia	(Dwellings with natural ventilation)	≤3.0
	(Dwellings with ventilation systems)	≤1.0–1.5
Lithuania	(Dwellings)	(≤2.5)
Netherlands—NEN 2687	(Dwellings with natural ventilation and mechanical exhaust)	(≤4.0–6.4)
	(Dwellings with mechanical supply)	(≤2.0–3.1)
Norway—NS 3031:2007	(New buildings)	≤1.5
	(Small buildings)	≤2.5
Slovakia	(Dwellings with high quality windows)	≤2.0
	(Dwellings with normal windows)	≤4.0
Slovenia	(Dwellings with natural ventilation)	≤3.0
	(Dwellings with ventilation systems)	≤2.0
UK—Building Regulations Part L1A 2010		(≤8.3)
Spain	Minimum of airtightness in window frames (depending on climatic zones)	
Greece	Not regulated in building codes	
Italy	Not regulated in building codes	
Portugal	Not regulated in building codes	
Cyprus	Not regulated in building codes	
Malta	Not regulated in building codes	

concrete and masonry. Before the emergence of the first implementation of regulations due to the oil crisis of 1973, this building solution was virtually unchanged throughout the area of these countries; thereafter, it was necessary to add thermal insulation in those climatic zones with higher energy demands.

This similar policy allows to compare these test results with others published by different European researchers (Fig. 5). In general, the few available data for the Mediterranean area show higher values than results obtained in Central and Northern Europe.

The results are in line with the widespread thought in the south of the advantages of air-permeable buildings, but natural ventilation is required only where there is no ventilation system in the dwelling. Since a few years ago in the Mediterranean countries, it is necessary to install a ventilation system, infiltration in new buildings should be reduced to a minimum (like in tested dwellings 1 to 4).

When buildings use natural ventilation for improving indoor air quality (like in dwellings 5 to 13), intentional openings in the enclosure were present (exterior exhaust and vents in bathrooms and kitchens). In these cases, the inlet flow rate from these openings is not considered when measuring the airtightness level and the tests have been carried out according to method B of EN 13829 (which establishes the requirement of closing or sealing of any intentional opening).

The problem could arise in dwellings that use infiltration as the unique system for improving indoor air quality. In these cases, old buildings renovated by their owners may be exposed to problems of poor indoor air quality and presence of condensation on the walls if the air exchange is insufficient (the European project HELTH has estimated that in these dwellings is needed a q_{50} value between 5 and 15 m^3/h·m^2—n_{50} between 4.2 and 12.5 h^{-1}, with the assumptions (Limb 2001)—to ensure a sufficient air exchange rate, and if the coefficient q_{50} is lower than 5 m^3/h·m^2—n_{50} lower than 4.2 h^{-1}—it is necessary to install an additional system of mechanical ventilation (Eskola 2013)).

The energy effects of infiltration

Estimating infiltration via permeability tests

In many European countries, the energy performance regulations take into account envelope airtightness in their calculation method (Sherman 1987). It is known that the Blower Door Test with 50 Pa is very appropriate for measuring the airtightness of architectural enclosures. However, the flow rate at 50 Ps is a representative value for the direct extrapolation of the "real" infiltration flow rates, which evidently hinders the estimation of the energetic performance of buildings.

In order to calculate the annual rate of infiltration, it is necessary to develop a model of the driving forces (wind, indoor-outdoor temperature differences and mechanical ventilation systems) and their interaction with the building. Thus, the pressures can be calculated

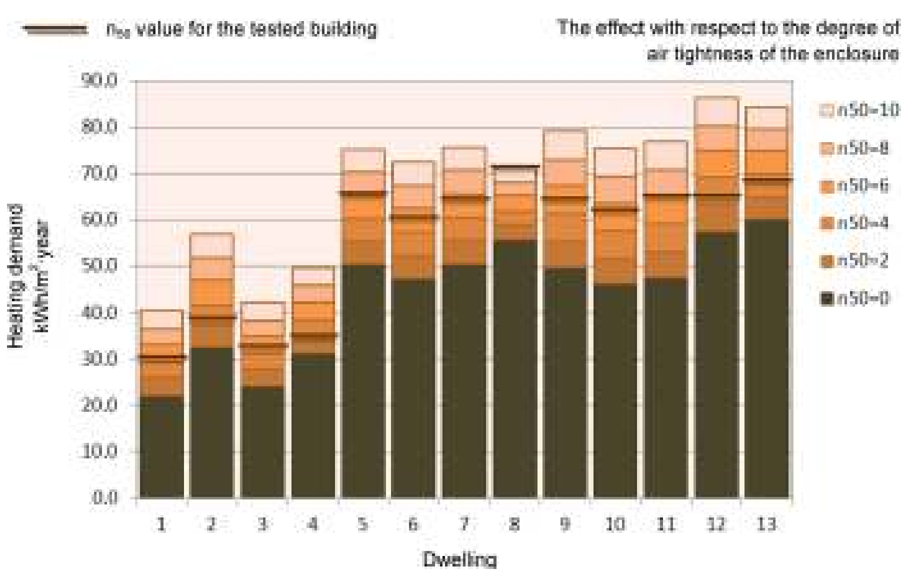


Fig. 5 Effect of different airtightness on the heating energy

separately and then combined by quadratic superposition (Sherman 1987). In this article, the research is conducted by using computer simulation software: the infiltration modelling started with geometry creation for the buildings in DesignBuilder. The building geometries were prepared and set up for the airflow network modelling to analyse dependence of air flow on wind pressure, buoyancy and stack effects in EnergyPlus.

Results of the energy effects

The results (Fig. 6) are in agreement with other similar individual results in Vitoria (Meiss and Feijó-Muñoz 2013), Sweden (Sikander et al. 2007) and France (Código Técnico de la Edificación 2009). Those studies showed that the wasted energy due to the permeability of the enclosures varies in winter between 2 and 5 kWh/m^2·year for each unit above n_{50}.

Likewise, studies in Belgium and Germany estimated that the permeability of the enclosures accounts for approximately 10 % of the energetic performance of the building (Carrié and Rosenthal 2008); therefore, the improvement predicted by the airtightness would be similar to that which would be obtained with the installation of solar collectors to satisfy all thermal needs of the building (Carrié and Rosenthal 2008). Similar studies developed in Sweden confirm that the energy losses attributable to infiltration can exceed those caused by transmission through the enclosures (Sandberg et al. 2007).

The results (Table 5) show that infiltration represents between 10.5 and 27.4 % of winter energy demand in buildings built under the current Spanish Building Code, between 21.9 and 27.0 % in buildings subject to CT-79 and between 11.3 and 13.0 % in old buildings without energy regulation (but restored by their owners) following the principles aforementioned.

The characteristics of the climate in central and northern Spain cause the heating season to extend between the months of October to May (Ministerio de Fomento 2014): In these 8 months, the presence of infiltration is an unnecessary waste of energy. According to the energy simulation carried out in the tested buildings, improving each unit over n_{50} represents between 1.7 and 2.5 kWh/m^2·year in CTE buildings, between 1.5 and 3.1 kWh/m^2·year in the CT-79 buildings and between 2.4 and 3.0 kWh/m^2·year in old buildings without energy regulation. If the analysis is based on the climate zone, in Basauri and Sondika, each unit over n_{50} represents between 1.7 and 2.0 kWh/m^2·year; in Vitoria, between 1.8 and 2.5 kWh/m^2·year and in Valladolid, between 1.4 and 3.0 kWh/m2·year.

In summer months, from June to September, natural ventilation itself is a useful energy resource; at

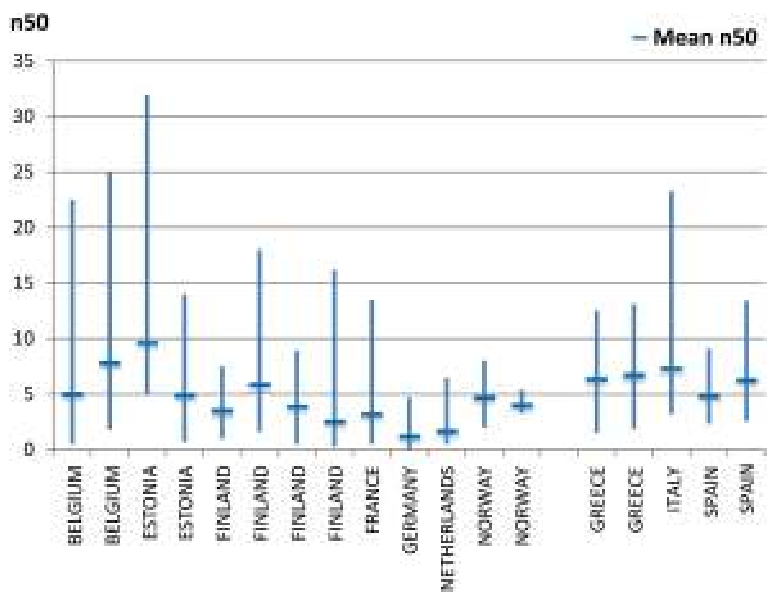


Fig. 6 Comparison of test results with others published by different European researchers (Papaglastra et al. 2008; Bossaer et al. 1998; Jõgioja and Jõgioja 2000; Axley 2001; Polvinen et al. 1983; Kauppinen 2001; Korpi et al. 2004; Brunsell and Uvslokk 1980; Granum and Haugen 1986; Jokisalu and Kurnitski 2002; D'Ambrosio et al 2012; Sordo-Barreda 2013)

Table 5 Infiltration represents between 10.5 and 27.4 % of winter energy demand in buildings built under the current Spanish Building Code

Dwelling	Location	Winter demand (kWh/m^2)	Summer demand (kWh/m^2)	Incidence of infiltration during winter demand	Incidence of infiltration during winter demand
1	Basauri (Biscay)	30.76	2.75	27.4 %	No
2	Vitoria (Alava)	38.96	3.81	16.1 %	No
3	Sondika (Biscay)	33.26	3.02	26.9 %	No
4	Vitoria (Alava)	35.19	3.64	10.5 %	No
5	Vitoria (Alava)	65.56	5.21	23.1 %	No
6		60.54	4.68	21.9 %	No
7		65.11	5.17	22.3 %	No
8	Valladolid (Valladolid)	72.32	33.11	22.8 %	<1 %
9	Valladolid (Valladolid)	66.40	3.10	25.0 %	<1 %
10		62.44	4.32	26.0 %	<1 %
11		65.25	5.36	27.0 %	<1 %
12	Valladolid (Valladolid)	65.01	1.82	11.3 %	<1 %
13	Valladolid (Valladolid)	69.16	12.22	13.0 %	<1 %

night, natural cooling is used since zones of central and northern Spain are characterized by their high thermal amplitude. For this reason, the presence of infiltration apparently represents an overall energy benefit; however, this reasoning ignores the discomfort caused by the uncontrolled entry of hot air during daytime.

Therefore, it will be interesting to investigate the impact of the different degrees of infiltration on the same building, in terms of the energy demand for the winter season. In this way, the importance of recognizing and repairing the current filtration routes in existing buildings can be seen. This approach would be complete if, as mentioned above, the project is complemented by incorporating on-demand ventilation systems with energy recovery.

Conclusions

From the results and discussion of the present study, it can be concluded that there is very little information available regarding infiltration measurements of buildings in the Mediterranean region (Sfakianaki et al. 2008; D'Ambrosio et al. 2012; Pinto et al. 2011; Gantioler 2006; Hakan Tanribilir et al. 1990) and it can be initially observed that the problem is undervalued both at the regulatory level and the professional level.

The obtained results show that the energetic importance of infiltration has increased (relatively) simultaneously with the reduction of the heat transfer losses through the architectural envelope, to the point where greater investments in insulation do not result in a significant energetic improvement or in the return on investment. In contrast, the results for investment in building airtightness demonstrate translatable energy savings in terms of the short-term economic benefits and the benefits to the environment, as is the case of the Passivhaus standard.

It is also noteworthy that infiltration with n_{50} rates $>6\ h^{-1}$ (Kurnitski et al. 2005) yields uncomfortable fluctuating temperatures in rooms, and a greater airtightness improves safety by restricting the spread of smoke during a fire (Marchant 2000). For these reasons, it appears clear that the time has come to implement a rigorous study of infiltration in building complexes located in Spain and the Mediterranean countries by incorporating this concept in future reforms to the current regulation.

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