APPLICATION OF BLOWER DOOR MEASUREMENTS IN THE EVALUATION OF WORKMANSHIP INFLUENCE IN AIRTIGHTNESS

Nuno M. M. Ramos[*1], Vasco P. de Freitas[1], Pedro F. Pereira[1], António Curado[2] and Alexandre Machado[1]

1 Building Physics Laboratory, Faculty of Engineering, University of Porto
Rua Dr. Roberto Frias, 4200 465 Porto
Portugal
**Corresponding author: nmmr@fe.up.pt*

2 Polytechnic Institute of Viana do Castelo - School of Technology and Management
Avenida do Atlântico, s/n, 4900-348 Viana do Castelo
Portugal

ABSTRACT

A large social housing retrofitting program was implemented in Porto, Portugal, a mild climate region. One of the features of that program was the upgrade of windows and ventilation systems. An increased airtightness was expected and mechanical extraction on kitchens and bathrooms was implemented. This work analyses the changes in building airtightness that resulted from that renovation.

A large sample of identical dwellings was analysed using the blower door test. This analysis was performed in a set of dwellings that were identical and also identically renovated. As two different contractors were involved in the renovation of specific sub sets of those dwellings, the opportunity to use the blower door test as an indicator of workmanship quality was created.

The results of this work therefore include not only the airtightness of the renovated buildings but also the variability of ACH_{50} values for each subset of dwellings, allowing for conclusions on the workmanship effect. The analysis of the adequacy of the resulting airtightness is also performed, regarding the specific climate conditions and the typical user behaviour of the dwellings. Finally, the user modifications also proved to be of high importance to the found airtightness.

KEYWORDS

Airtightness; Workmanship; Variability

1 INTRODUCTION

Workmanship quality is frequently referred as a key aspect for building airtightness (Kalamees, 2007), (Sherman, 2004), (Hens, 2011) and (Sinnott and Dyer, 2012). This paper studies that influence and tries to quantify it based on blower door measurements performed in two sets of dwellings, of identical features, renovated by two different contractors. The objective is to define if airtightness measurements allows for the comparison of different teams workmanship and which parameters are relevant for that evaluation. The authors believe that not only the average ACH_{50} is important but also the variability found in identical interventions by the same contractor.

The paper starts with a literature review intended to identify the airtightness variation ranges found in other studies that can be used as reference. The case study and measurement procedure is presented. The results of the measurement campaign are analysed, supporting the final conclusions.

2 LITERATURE REVIEW

Many experimental studies on building airtightness, using the fan pressurization method, have been carried out in international context. Several of those studies pointed out the relevance of workmanship quality to building airtightness.

According to (Fernández-Agüera et al., 2011), despite the study had been carried out on the same types of building, which share construction processes and external variables, the results of the tests vary greatly. The authors appoint the manual processes used during construction as causes for those variances.

These variances were also detected by (Chan et al., 2005) who analysed near 70000 dwelling and denoted considerable fluctuations in the airtightness of dwelling with, apparently the same characteristics. This studied also denoted that the dwellings with bigger floor areas have smaller normalized leakage. Their explanation for this phenomenon is that larger (more expensive) homes are likely to have tighter envelopes because they are better built.

According to (Johnston and Miles-Shenton, 2009), a study carried out in seven United Kingdom dwelling, three equal dwellings in terms of construction type, built form and internal floor area, have shown airtightness results with a considerable variance. They identified the main air leakage paths as being: gaps around service penetrations through the external walls, floors and ceiling; poorly fitted and draught sealed doors, windows and loft hatch; junction between door/window frame and plasterboard drylining; and gaps between the upper floor and the external walls.

(Kalamees, 2007) studied 32 detached dwellings in Estonia. In this study the author compares the ones that were built under professional supervision and the ones built without professional supervision since it's not rare in Estonia for a house owner to build a detached house on his own, with the help of some friends or a couple of workers without professional supervision. It was found that the airtightness of the dwellings without professional supervision are significantly worse.

In a study carry out by (Pan, 2010), where the airtightness of 287 dwellings were determinate by means of a blower door, the data were collected from three house building companies in the UK. The 3 companies were independent from each other but associated in a national development group where shared some technical and managerial knowledge of the group in relation to energy efficiency design and construction. Through this, they minimise any skewed analysis which might be generated from including test results from other companies which may be associated with drastically different management context. Although the author highlights the ambiguous concept of management context (workmanship), they denoted that the analysis reveals significant difference between the airtightness of dwellings built in the three companies.

Air tightness of 28 buildings in Ireland was studied by (Sinnott and Dyer, 2012). The study grouped the dwellings in the main categories by their construction's year. Some of the oldest ones were partial or total retrofitted although, the most recent ones, newer than 2008, don't have any refurbishment. Furthermore, the newest houses are all equal to each other. The results showed that the airtightness of these houses have considerable differences. The authors made some surveys and used smoke pencil tests, in addition to common leakage paths, identified the critical leakage pathways related to poor workmanship.

The authors of (Pinto et al., 2011) studied the airtightness of 5 similar dwellings near Porto, Portugal. The 5 dwellings were part of the same building and have 2 different typologies at different stories. The results showed that the difference between them were not negligible. The authors appointed the cause as probably being 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 that strongly depends on the local installation work.

The airtightness of a dwelling were studied by (Roberts et al., 2005) at seven stages after which a pressure test were undertaken, giving an indication of the relative importance of each step in terms of airtightness. Although the different stages showed the influence of the application of some layers, they also denoted that workmanship in other vital areas that contribute to airtightness may not be as meticulous.

In the report (Sherman, 2004), the authors review over 100 of the most important international publications until 2004. That report cites a study by Shaw and Jones (1979) measured the airtightness of eleven Canadian schools. They conclude that the poor workmanship and sealing were observed to be the cause of high air leakage. The report (Sherman, 2004) conclude that in light of the fact that many of the air leakage problems are caused by poor designs and workmanship, practical guidelines for designers, contractors, and developers have been made available by various agencies. They also conclude that it is not atypical to see log-normal distributions with the standard deviation being equal to the mean. They appointed the large variation as being attributable to variations in workmanship, variations in structure use and maintenance and variations in renovation and repair activities. They finalized saying that many studies have addressed the effectiveness of air barriers and building materials to minimize leakage, but it is often the quality of workmanship and careful design that are the determining factors in achieving desirable air tightness.

According to (Hens, 2011) the results of the ACH_{50} in 14 dwellings of an estate in Belgium, showed a significant variance. According to the author, one of the main reasons for that is the lazy workmanship at the contractor’s side.

From the literature review, it’s possible to not only conclude on the relevance of workmanship to airtightness but also to initiate a discussion on the typical variance that can be found on measurements performed in comparable situations. The information available on ACH_{50} and q_{50} values results on the coefficient of variation (COV) presented in Table 1. It can be observed that even for identical dwellings, the COV can go up to 30% and up to 60%, on similar houses.

Table 1: Airtightness variance found in international studies

Study	Mean ACH_{50} (h^{-1})	Mean q_{50} ($m^3/h\cdot m^2$)	COV (%)	Observations
(Johnston and Miles-Shenton, 2009)	-	8.45	11.5	3 similar dwellings
(Kalamees, 2007)	3.5	-	68.5	23 houses built under professional supervision
(Kalamees, 2007)	8.4		44.0	9 houses built without professional supervision
(Sinnott and Dyer, 2012)	11.0	-	21.9	7 identical dwellings built in 2008
(Pinto et al., 2011)	6.2	-	32.0	3 identical dwellings
(Hens, 2011)	9.3	-	66.0	14 similar dwellings from the same neighbourhood

3 CASE STUDY AND METHODS

3.1 Studied buildings

A large social housing retrofitting program was implemented in Porto, Portugal. The interventions included the upgrade of windows and ventilation systems. One of the renovated neighborhoods was chosen as case study for this work. The neighbourhood has 4 detached buildings with similar typologies. The renovation work was performed in 2009 and 2010 by two different companies, based on the same design project for all buildings.

Figure 1: Location and image of the retrofitted buildings.

The neighbourhood has a total of 179 dwellings, including the following typologies: 19 T1 dwellings, 31 T2, 72 T3, 56 T4 and 1 T5.

The dimensions of the types subject to test and the number and total area of windows is presented in Table 2.

Table 2: Dimensions of the Studied Dwellings

Typology	**Volume (m^3)**	**Net floor Area (m^2)**	**Exterior Walls Area (m^2)**	**Windows Area (m^2)**
T1	100	40	44.3	9.4
T3	160	64	36.8	12.1
T4 – A	185	74	57.5	13.4
T4 – B	185	74	46.8	13.4

The tested dwellings geometry is presented in figures 3, 4 and 5.

Natural ventilation was adopted with improvement of the air admission points, and continuous mechanical extraction was applied in the kitchens. The users, however, shut down that extraction during most of the day. A mechanical fan was installed in the bathrooms, to be turned on when the facility is used. In the main compartments self-regulating air vents were installed. The laundry had a fixed air inlet of 1x30 cm^2. Some modifications of the initial settings of the ventilation system were performed by the users, which are outlined in Table 3. If one is to interpret these dwellings as having a purpose provided natural ventilation system, than the ACH_{50} could range between 4 h^{-1} and 8 h^{-1} (Liddament, M., 1996).

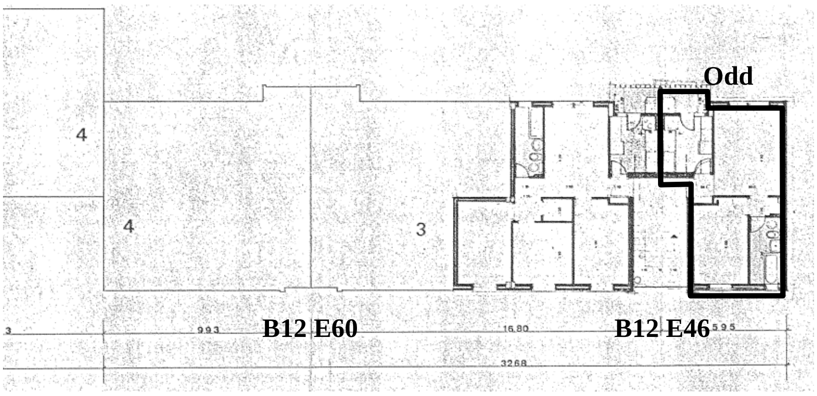

Figure 2: Plan view of building 12.

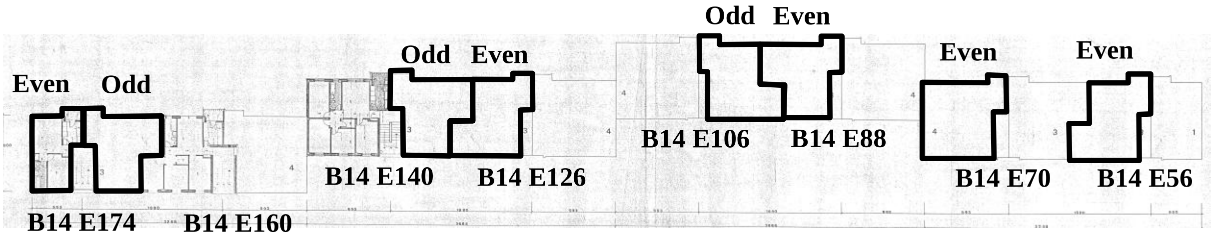

Figure 3: Plan view of building 14.

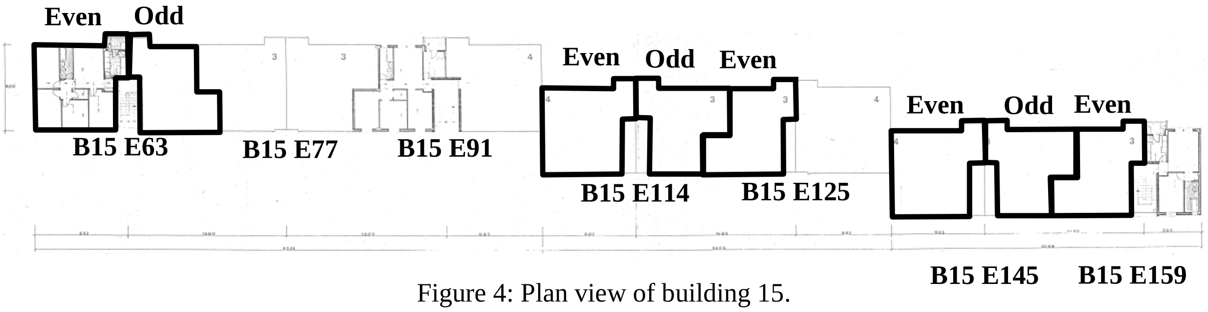

Figure 4: Plan view of building 15.

3.2 Measurement methods

The air permeability measurements were carried out using the Retrotec 1000 blower door model. The standard EN:13829-2001 was applied in the tests, following method A described in the standard. In each dwelling, both pressurization and depressurization tests were performed. The in situ measurements were done in four days of two consecutive days during spring, with average temperature ranging from 13.5 ºC to 21.0 ºC. The wind velocity during tests varied between 1.2 m/s and 2.4 m/s.

4 RESULTS AND DISCUSSION

4.1 Results

The values obtained in the tests of pressurization and depressurization were averaged and are presented in Table 3, Figure 5 and Figure 6. Table 3 also includes the description of modifications performed by the users. The dwellings without modifications are shaded in Figure 5 and Figure 6. Along with ACH_{50} values, the resulting q_{50} is presented. Two values were calculated: (A) including only vertical envelope elements and (B) including also ceiling area for dwellings located on the top floor. The hypothesis (B), although suggested by standards, should not be considered. In this type of construction, with a concrete slab in the ceiling of the top floor, no leaks should be expected there. By considering it one would erroneously conclude that the envelope of the dwellings B12 / E46 / H11 and B12 / E46 / H41 was quite different and that’s not so.

Table 3: Measured Dwellings

Dwelling (Building / Entrance / Door)	**Typologies**	**q_{50} (A) ($m^3/h\cdot m^2$)**	**q_{50} (B) ($m^3/h\cdot m^2$)**	**ACH_{50} (h^{-1})**	**Modifications performed by the building users**
B12 / E46 / H11	T1	28.43	28.43	12.65	No modification observed
B12 / E46 / H41	T1	29.01	15.24	12.85	No modification observed
B14 / E56 / H22	T3	19.59	19.59	4.53	Laundry opening sealed
B14 / E56 / H42	T3	19.15	6.98	4.41	Laundry opening sealed
B14 / E70 / H22	T4-B	20.79	20.79	5.34	No modification observed
B14 / E88 / H12	T3	27.84	27.84	6.44	No modification observed
B14 / E88 / H22	T3	26.70	26.70	6.18	No modification observed
B14 / E88 / H32	T3	14.50	14.50	3.35	Self-regulating devices and laundry openings sealed
B14 / E88 / H42	T3	22.85	8.32	5.26	Self-regulating devices sealed
B14 / E106 / H11	T3	31.33	31.33	7.25	No modification observed
B14 / E126 / H12	T3	28.47	28.47	6.58	No modification observed
B14 / E140 / H41	T3	29.66	10.81	6.82	No modification observed
B14 / E174 / H11	T3	35.85	35.85	8.30	No modification observed
B14 / E174 / H22	T1	16.67	16.67	7.38	No modification observed
B14 / E174 / H42	T1	20.45	10.75	9.06	No modification observed
B15 / E63 / H22	T4-A	15.82	15.82	4.92	No modification observed
B15 / E63 / H42	T4-A	16.34	7.14	5.08	No modification observed
B15 / E63 / H41	T3	21.11	7.69	4.86	Self-regulating devices sealed
B15 / E114 / H32	T4-B	31.68	31.68	7.96	No modification observed
B15 / E114 / H41	T3	13.37	4.87	3.08	Self-regulating devices and laundry openings sealed
B15 / E114 / H42	T4-B	16.91	6.55	4.28	Laundry opening sealed
B15 / E125 / H42	T3	44.16	16.11	10.16	No modification observed
B15 / E145 / H21	T3	43.31	43.31	10.02	No modification observed
B15 / E145 / H32	T4-B	28.04	28.04	7.09	No modification observed
B15 / E159 / H12	T3	41.67	41.67	9.64	No modification observed

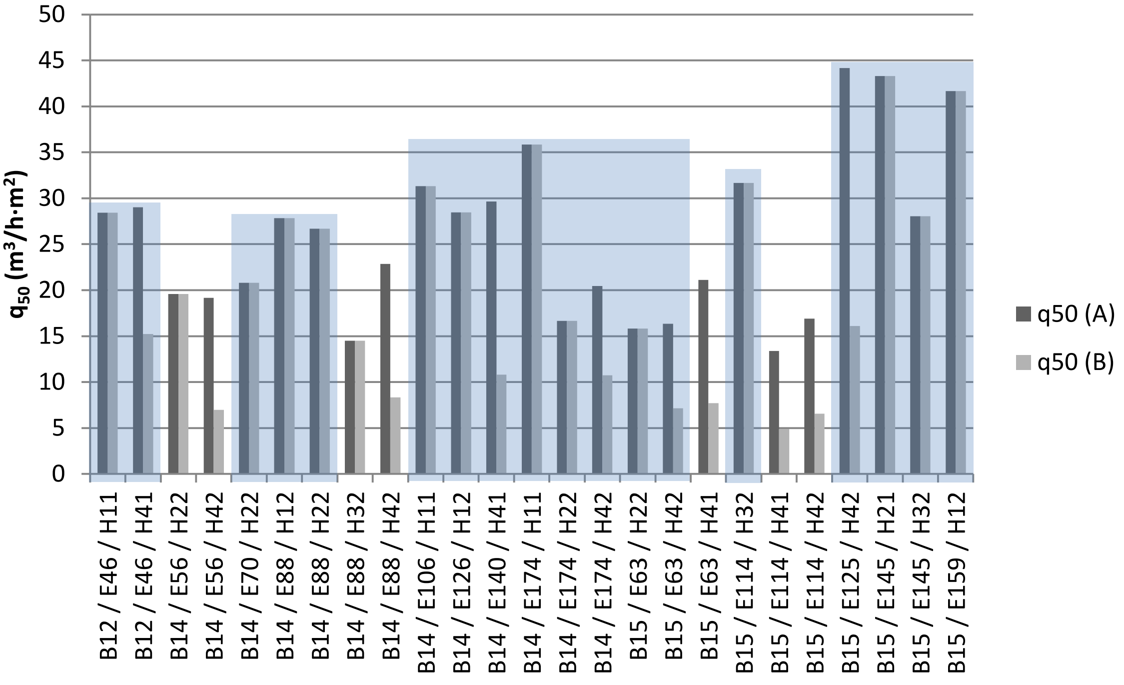

Figure 5: Values of q_{50} (A) and q_{50} (B).

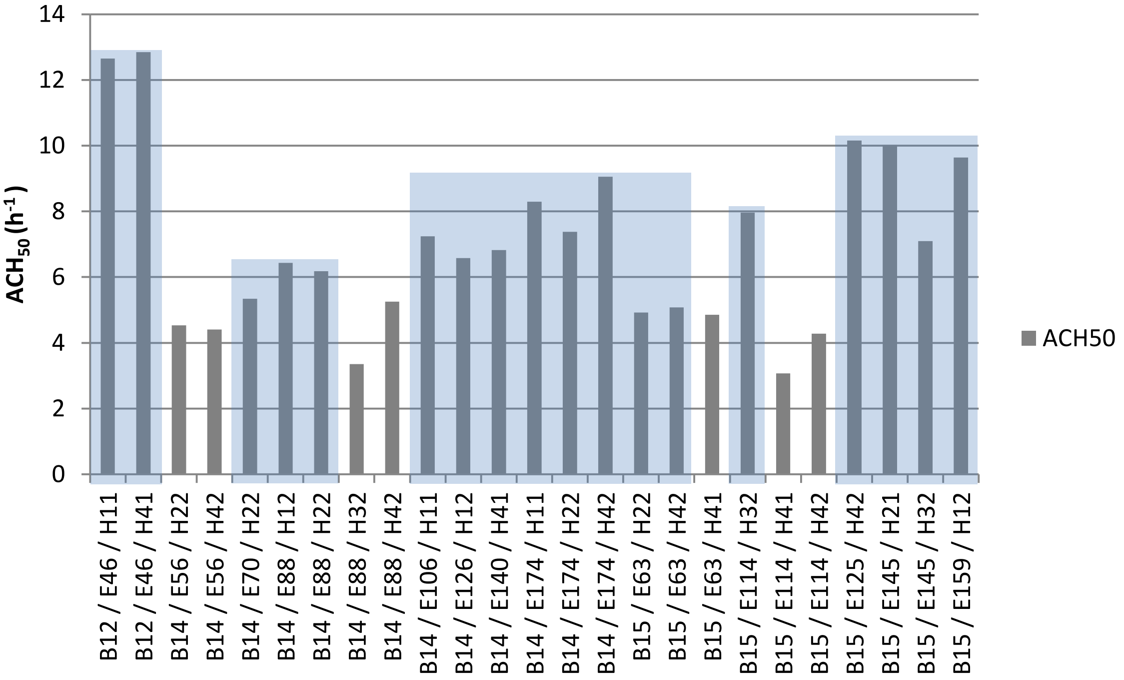

Figure 6: Values of ACH_{50}.

4.2 Discussion

The statistical analysis of the measured data is presented in Table 4, including mean and coefficient of variation (COV) of the measured ACH_{50} and q_{50} (A) values.

Table 4: Statistics of q_{50} (A) and ACH_{50}

Type of dwellings		**Specimens**	**q_{50} (A)**		ACH_{50}	
			mean ($m^3/h \cdot m^2$)	**COV (%)**	**mean** h^{-1}	**COV (%)**
All dwellings		25	25.75	35	6.94	38
All dwellings	T1	4	23.64	26	10.48	26
	T3	15	27.97	35	6.46	36
	T4 (A and B)	6	21.60	31	5.78	25
All dwellings without modifications	T1	4	23.64	26	10.48	26
	T3	9	34.33	21	7.93	21
	T4 (A and B)	5	22.53	31	6.08	22
Modified dwellings	T3	6	18.43	32	4.24	32
All dwellings without modifications by contractor	T1 - B12 (C1)	2	28.72	1	12.75	1
	T1 - B14 (C2)	2	18.56	14	8.22	14
	T3 - B14 (C2)	6	29.98	11	6.93	11
	T3 - B15 (C1)	3	43.05	3	9.94	3
	T4 (A and B) - B14 (C2)	1	20.79	-	5.34	-
	T4 (A and B) - B15 (C1)	4	22.97	35	6.26	24

The statistics presented in Table 4 support the following observations:

- The sample including all 25 measured dwellings presented a mean value of ACH_{50} = 6,9 h^{-1} and COV = 38%, Both values are in line with literature references for this type of buildings (see Table 1);

- Measurements in buildings with no modifications by the users, and separated by contractor, show that the mean ACH_{50} decreases from T1 to T4. That is not so for the q_{50} values;
- Comparing the performance of both contractors, the mean ACH_{50} by dwelling type was always lower for contractor C2, indicating better workmanship. No additional gain was introduced, in this case, with the analysis of q_{50} which could be expected given the type of construction of these buildings, where permeability is more linked to singularities than overall envelope behaviour;
- The variability of ACH_{50} dropped to a COV = 11% when considering the best contractor and the 6 T3 dwellings, the combination with the largest number of specimens;
- The modified T3 dwellings presented a mean ACH_{50} of 4.2 h^{-1}, indicating that the users tried to reduce infiltrations to its lowest value. This can be easily explained by the fact that they try to use heating the least as possible due to their low income. This value is still in the range suggested for this type of dwellings (see section 3.1) but very near its lower boundary, indicating that in some cases the ventilation rates may not be sufficient.

5 CONCLUSIONS

The main conclusions of this work are the following:

- Literature often defines workmanship as being responsible for insufficient building airtightness;
- The work by two different contractors was compared based on blower door tests, allowing to find differences of up to 50% increased ACH50 mean values in identical typologies. Based on that it’s possible to say that contractor C2 was better than C1.
- A COV = 11 % was found for a sample of 6 identical dwellings retrofitted by the best contractor. A high COV could also be an indicator of poor workmanship, but in this case there was not enough data to support that.
- User action can have an important effect on building airtightness. In this case of social housing where heating is reduced to an absolute minimum, the users acted on air inlets in several apartments, reducing ACH50 mean values to almost 50% of the initial values. This action is not necessarily good as it may result in poor ventilation.

6 REFERENCES

CEN, Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method (EN 13829-2001),

CHAN, W, R,, NAZAROFF, W, W,, PRICE, P, N,, SOHN, M, D, & GADGIL, A, J, 2005, Analyzing a database of residential air leakage in the United States, *Atmospheric Environment*, 39**,** 3445-3455,

FERNÁNDEZ-AGÜERA, J,, SENDRA, J, J, & DOMÍNGUEZ, S, Protocols for measuring the airtightness of multi-dwelling units in Southern Europe, 2011 Bologna, 98-105,

HENS, H, 2011, Dwelling air-tightness in a 55 years old estate, *9th Nordic Symposium on Building Physics - NSB 2011*, 1 of 3**,** 47 to 54,

JOHNSTON, D, & MILES-SHENTON, D, Airtightness of UK dwellings, 2009 Nottingham, 271-280,

KALAMEES, T, 2007, Air tightness and air leakages of new lightweight single-family detached houses in Estonia, *Building and Environment*, 42**,** 2369-2377,

LIDDAMENT M., 1996, A Guide to Energy Efficient Ventilation, AIVC, 254,

PAN, W, 2010, Relationships between air-tightness and its influencing factors of post-2006 new-build dwellings in the UK, *Building and Environment*, 45**,** 2387-2399,

PINTO, M,, VIEGAS, J, & DE FREITAS, V, P, 2011, Air permeability measurements of dwellings and building components in Portugal, *Building and Environment,* 46**,** 2480-2489,

ROBERTS, D,, JOHNSTON, D, & ISLE, J, A, 2005, A novel approach to achieving airtightness in drylined load-bearing masonry dwellings, *Building Services Engineering Research and Technology*, 26**,** 63-69,

SHERMAN, M, C,, C, 2004, Building Airtightness: Research and Practice, *In:* LABORATORY, L, B, N, (ed,) *REPORT N,º LBNL-53356,*

SINNOTT, D, & DYER, M, 2012, Air-tightness field data for dwellings in Ireland, *Building and Environment*, 51**,** 269-275,