Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 96 (2016) 580 – 591

Energy Procedia

SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep, 5-7 October 2016, Tallinn and Helsinki

Relationships between building characteristics and airtightness of Dutch dwellings

C.N. Bramiana [A], A.G. Entrop [A*], J.I.M. Halman [A]

[A] *University of Twente, Fac. of Engineering Technology, Dept. of Construction Management & Engineering, P.O. Box 217, 7500 AE, Enschede, The Netherlands*

Abstract

Building airtightness is an important parameter to improve the energy efficiency of buildings. By means of a literature study, as well as the use of empirical data on the specific leakage of more than 300 dwellings, this paper provides insights in the relationships between building airtightness and eight individual variables. A total leakage construct was one of the adopted variables to distinguish cases. Correlational analyses, as well as ANOVA tests show that year of construction, total leakage, roof type, construction method and construction typology have significant relationships with building airtightness, but regression analysis suggests that only the year of construction and the total leakage influence the airtightness. Two-way ANOVA tests show that both have a significant interaction on building airtightness, in terms of specific leakage rate. Considering that the year of construction is related to multiple other variables influencing the airtightness of a building and the number of individual leakages and their sizes can only be assessed after completion, both variables cannot yet help us to estimate the specific air leakage of an object in advance.

Peer-review under responsibility of the organizing committee of the SBE16 Tallinn and Helsinki Conference.

Keywords: Building airtightness; Specific leakage rate; Air leakage; Building characteristics, Dwellings

1. Introduction

Airtightness is considered as an important element in improving the energy efficiency of buildings, as well as their comfort. In terms of an air permeability level, building airtightness has been included in building regulations in multiple countries. European legislation on the energy performance of buildings (Energy Performance Building Directive – EPBD) states that member states must calculate the energy efficiency of a building in their countries [1]. The ripple effect of this, for example, is evident in the Dutch Building Code [2], which among others requires residential buildings to comply with a certain level of energy performance and a given limit of total airflow. The term “airtightness” pertains to the intensity of the uncontrolled airflow through the building envelope as a result of pressure differences between interior and exterior air [3]. An improved building airtightness leads to lower air infiltration, reducing the cooling load and heat losses of buildings [4]. Multiple scholars have reflected on the importance of building airtightness with regards to energy efficiency [5, 6], thermal comfort and indoor air quality [7–10]. Ensuring a certain minimum level of building airtightness is also essential for the effectiveness of air-to-air heat recovery installed in ventilation systems [11, 12], affecting again the building’s energy efficiency.

---

[*] Corresponding author. Tel.: +31(0)53-489-6860; fax: +31(0)53-489-2511.
E-mail address: a.g.entrop@utwente.nl

1876-6102
Peer-review under responsibility of the organizing committee of the SBE16 Tallinn and Helsinki Conference.
doi:10.1016/j.egypro.2016.09.103

However, when designing buildings it is still unclear what leakage can be expected. To ensure that a maximum uncontrolled air flow or minimum airtightness are met, only after completion a blower door test can be conducted to measure the air flow leaking into or out of the assigned building. Many studies have attempted to predict airtightness prior to a blower door test, even though, Relander [13] concluded that no such model can substantially replace the blower door test. However, predicting airtightness is a fruitful effort to achieve a desired level of building airtightness, especially in the case of Dutch regulations, that require a certain value of q_{v10} or w_{10} to calculate the Energy Performance Coefficient (EPC).

Therefore, this research aims at finding the relationships of building airtightness and characteristics related to the design or construction process of the building, which further can contribute at developing a model that can estimate building airtightness on the basis of characteristics. A literature study was conducted 1) to explore what definitions on infiltration, airtightness and unwanted ventilation are in use; 2) to find what factors influencing the airtightnes are already known and 3) to get insights into how do these factors influence the building. The empirical material for our study was derived from a database that contains blower door test reports of more than 300 Dutch dwellings. However, using the original blower door test reports we were also able to add data to the database by means of observed air leakages as captured by (infrared) pictures.

This paper proceeds as follows. Section 2 addresses our theoretical framework in which airtightness is being defined, air leakage measurements are being explained and variables influencing building airtightness are listed. Section 3 provides the research methodology. Section 4 presents the results, while Section 5 continues on the analysis of the data by means of correlation analysis, analysis of variance and regression analysis. Section 6 provides the discussion, before we finish with a conclusion in Section 7 and recommendations in Section 8.

Nomenclature

V_m	Measured air flow rate	m^3/h
V_{env}	Air flow rate via building envelope	m^3/h
V_L	Air leakage rate	m^3/h
V_{50}	Air leakage rate at 50 Pa	m^3/h
C_{env}	Air flow coefficient	$m^3/(h\cdot Pa_n)$
C_L	Air leakage coefficient	$m^3/(h\cdot Pa_n)$
p	Pressure	Pa
Δp	Induced pressure difference	Pa
n	Air flow exponent	-
A_E	Envelope area	m^2
A_F	Floor area	m^2
v	Internal building volume	m^3
N_{50}	Air change rate at 50 Pa	h^{-1}
Q_{50}	Air permeability at 50 Pa	$dm^3/(s\cdot m^2)$
w_{50}	Specific leakage at 50 Pa	$dm^3/(s\cdot m_2)$

2. Theoretical framework

This section introduces difference terms used to address building airtightness and variables related to building airtightness.

2.1. Defining building airtightness

There are three quantities commonly used to express the airtightness of a building, namely in relation to its 1) envelope area, 2) building volume or 3) floor area [10, 19, 20]. Their usage depends on the context by means of regulation, location or purpose. Consequently and in line with NEN-EN 13829 [16], there are three different terms in use to address building airtightness.

Most studies seem to use the term *air permeability* ($m^3/h\cdot m^2$) as the target of their research [4, 8, 16, 19, 23, 24]. Air permeability is the capability of a surface to let air pass through – in this case, the capability of the building envelope itself. The lower the air permeability is, the more airtight a building is. Normalization on the basis of envelope area is particularly useful if one wants to define the quality of the envelope as a uniform “fabric” [10]. The terms air permeability and airtightness are sometimes interchangeably used, but they are actually reciprocal.

When the building volume is known and used to normalize measurement data, the result is normally expressed in air changes per hour at the reference pressure. This is the so called *air change rate* (h^{-1}). The air change rate is the second most common airtightness metric reported in the literature [7, 21, 22]. Since infiltration and ventilation rates are often quoted in air changes per hour, the air change rate is by many regarded as a convenient expression for this phenomenon.

A *specific leakage rate* ($m^3/h\cdot m^2$) at a certain pressure difference related to floor area, can be compared to the other two normalizations relatively easy be determined. One needs to take only two dimensions into account instead of three. Since the amount of usable living space hoovers around the floor area, these two are sometimes even being considered as equal, when assessing the specific leakage rate [10].

2.2. Measuring air leakage

In order to determine the airtightness of a building, a standardized test is carried out to measure the amount of air passing through the building envelope at a certain pressure difference. The most common method is a pressurization test, which uses a blower door. This method is based on the mechanical pressurization or depressurization of (a part of) a building, using a blower door mounted in the frame of the front or back door of the building. During pressurization opening for ventilation are sealed and all other doors and windows part of the thermal shell are closed. As expressed by Eq. 1, the occurring air leakage is quantified as the airflow V in m^3/h (or dm^3/s) passing through the building envelope and related to a pressure difference ΔP expressed in Pa (Pascal). The air leakage coefficient C is a function of the size of building openings, and the pressure exponent n has a range of 0.5 to 1.0. An exponent of 0.5 denotes fully turbulent and an exponent of 1.0 represents laminar flow. Often the flow exponent can set at 0.65 [10]. Commonly, the airflow is denoted with the reference pressure as a sub-script (e.g. V_{50} or V_{25}). A reference pressure of 50 Pa is often used, but other existing reference pressures are e.g. 1 Pa, 4 Pa, 10 Pa, 25 Pa, and 75 Pa [10].

$$V_L = C_L \cdot \Delta P^n \tag{1}$$

2.3. Variables involved in estimating building airtightness

Former studies carried out with the aim to develop models predicting building airtightness can be divided into two categories: ‘experimental’ and ‘correlational’ [8]. ‘Experimental’ research is carried out under controlled experimental conditions with the purpose of measuring the causal effects of independent variables on dependent ones, while ‘correlational’ research is carried out under statistical control with the purpose of understanding the correlation between variables.

Table 1 Summary of predictors of building airtightness from past studies

Country	Average permeability	Influencing variables	N	Method of analysis	Ref.
United Kingdom	Q_{50} 5.97 $m^3/(h \cdot m^2)$	Construction type Type of residential building Management context	287	Multi linear regression	[8]
United States		Year of construction Climate zone Floor area House height Type of foundation Location of ventilation system Energy class of family house	134.000	Multi linear regression	[14]
Finland	N_{50} 3.70 ACH	Annual infiltration rate	1	Sensitivity analysis simulated building	[7]
Greece	N50 6.79 ACH	Total length of window frames	20	Regression	[21]
Estonia	Q_{50} 4.2 $m^3/(h \cdot m^2)$	Number of storeys, Workmanship quality and supervision, Construction method (built in site or prefab) Ventilation system	32	Experimental analysis	[18]
Spain and France		Year of construction Construction type Number of storeys Floor area	251	Multi linear regression	[20]
Ireland	Q_{50} 9.1 $m^3/(h \cdot m^2)$	Year of construction Design detail Retrofitting	28	Experimental study	[17]
Portugal		Quality of workmanship	5	Experimental study	[19]
Croatia	Q_{50} 0.76 – 19.64 ACH	Opaque part of building envelope, its material and structure Transparent part of building envelope, its material and structure	58	Neural network prediction	[3]

Experimental studies were carried out using building simulation and test specimens, which were e.g. located in Portugal [19], Ireland [17] and Italy [22]. ‘Correlational’ research employed regression methods, which can be found in some studies carried out in Finland [7], the UK [8], the US [14], Catalonia [20], Greece [21] and Estonia [18]. A recent study used neural networks and was conducted in Croatia by Krstic et al. [3]. These studies also had the aim to develop a model to predict the building airtightness prior to a blower door test. Relander, Holøs and Thue [13] distinguish three categories in estimating building airtightness: 1) estimations based on multiple regressions, 2) estimations based on the rough characteristics of a building and 3) estimations based on the leakage and geometry of a building.

Literature provides a plethora of variables influencing airtightness. Chan, Joh & Sherman [14], Alev et al. [9], Montoya et al. [20], Sinott & Dryer [17] consider 'year of construction' as one of the variables in estimating building airtightness. Structural and non-structural building characteristics have also been noted as variables to be considered. Structural building characteristics include variables such as dwelling type [8], construction type [20], type of foundation [14] and construction method [18]. Non-structural building characteristics are floor area [14], house height [14] and number of storeys [18], ventilation system [19, 23], insulation type [20] and even the management context [8].

Furthermore, the quality of workmanship seems, according to multiple scholars, to play an important role in achieving building airtightness, because it corresponds directly to possible leakage paths [16, 23, 24]. Parameters related to workmanship being mentioned are construction methods, details of joints, and the opaqueness of the building envelope. Leakage paths on joints can be found at window to wall interfaces [23], as well as at connections to the structural floor [24], the joints between basement wall and wooden frame wall [25], between wall and roof [26], and in roof joints [27]. A select group of variables found in our literature study (see Table 1) is going to be the independent variables. We will test them for significance and analyse them using our database of blower door test results in the following sections.

3. Research Method

3.1. Data collection

Airtightness measurements were gathered from several organizations that run blower door tests in Dutch houses. These organizations responded to our call to hand in blower door test reports. Because the blower door tests were conducted by different organizations, some variety in reports was found. However, due to the existence of national protocols on blower door test reports –e.g. NEN 2686 [28], NEN-EN 13829 [16] and NEN-EN-ISO 9972 [29]—we were able to analyse the collected reports relatively easily. Given the protocols, all reports need to indicate the following essential elements: the value of q_{v10} or w_{10}, the airflow leakage at multiple pressure differences, the flow coefficient and the pressure exponent.

Even though, Q_{50} and N_{50} are the most commonly used in many countries, the Netherlands use q_{v10} which equivalent to w_{10} the specific leakage rate at 10 Pa difference. Furthermore, the national Building Code mentions that the permitted total air flow rate, being the sum of air flow due to infiltration and ventilation, of a building of 500 m^3 is not allowed to exceed 0.2 m^3/h. The specific leakage rate is a form of input to calculate the EPC of a house. The relation between q_{v10} and N_{50} depends on the flow coefficient (n) and can be divided by about 25 to 30. An airflow (q_{v10}) of about 113 dm^3/s, equals to an N_{50} of about 3.5 to 4.5 [30].

Although Dutch regulations request to express the specific leakage for a pressure reference of 10 Pa difference, the results measured at 50 Pa difference will also be taken into account in our analysis. The use of a 10 Pa pressure reference refers to conditions of Dutch dwellings can actually experience in common weather circumstances. The airtightness needs to be assessed preferably independent from weather conditions and, therefore, is being measured at much higher pressure difference levels of 50 up to 100 Pa. Eq. 1 was used to convert the specific leakage rate to 10 Pa.

3.2. Selecting the variables

Our literature study showed a range of influencing variables. Because many studies suggested that there is a correlation between the year a building was constructed and airtightness, the variable 'year of construction' (YEAR) is included in this research.

Variables related to structural building characteristics are 'construction method' (CM) and 'construction typology' (CT) will also have our interest, given the attention these characteristics already received in former studies. The construction method corresponds to how the building has been constructed, either by on-site construction, by prefabrication or by a combination of both. Construction typology corresponds to the main material use in the construction, being: e.g. concrete, timber, masonry or steel.

Variables related to non-structural building characteristics that are included in this research are type of dwelling (DT), roof type (ROOF), design target (Q_{EPC}), and floor area (FLOOR). Different types of roof such as: pitched roof, flat roof, shed roof or combination of roofing are tested because different roof types have different construction details. Due to a lack of information in the reports, some variables mentioned in the literature study, such as the type of ventilation type and the sort of insulation, cannot be taken into account in our study.

The last variable to be included in our analysis is an indicator for sighted leakages in the building under investigation. Multiple reports at our disposal reflect on the air leakage by either thermal images or using smoke identifying the location of leakage paths. A last variable in form of a construct will be tested to show the relationship between leakages that occur in the building and building airtightness. We will use four classifications to reflect on the number and size of these leakages. Level 1 is for the smallest leakage and level 4 is for the biggest. To accumulate this different level of leakages, we compute the total score of leakages and name it under a new construct 'LK_{TOTAL}'. This construct Total Leakage is defined by the cumulative amount of all leakage observed. We express it by means of the following equation:

$$LK_{TOTAL} = 1 \cdot \#LK_{LEVEL\ 1} + 2 \cdot \#LK_{LEVEL\ 2} + 3 \cdot \#LK_{LEVEL\ 3} + 4 \cdot \#LK_{LEVEL\ 4} \quad (2)$$

3.3. Method of analysis

The information derived from the blower door test reports on the selected variables and specific leakage rate was stored in a Microsoft Excel spreadsheet to ease the categorization of the measurement results. For the purpose of analysis the spreadsheet was exported to the statistical software program IBM SPSS 20. The variables derived from the literature study and the construct LK_{TOTAL} are the independent variables, while the specific leakage rate at 10 Pa difference (w_{10}) and 50 Pa difference (w_{50}) act as dependent variables.

Variables YEAR, DT, CM, CT and ROOF are regarded as nominal data. To check the relations between these variables and dependent variables, an ANOVA test was run. Variables FLOOR, Q_{EPC} and LK_{TOTAL} are scale data. Therefore, linear regression analysis is carried out to study these relationships. For both sorts of data, correlation analysis is carried out for all dependent variables and independent variables. In the ANOVA test the significance of each variable will be assessed according to the P-value of the F-test, and applying a confidence interval of 95%. This means that a Pearson value (p-value) higher than 0.05 is considered to be insignificant. F-test helped to interpret the ratio of the between-groups-variance and the within-groups-variance. The F test can only show if there is significant difference between groups, but does not inform us about its position. Therefore, a post-hoc Scheffe test was run to identify if a significant difference exists. Furthermore, the interaction between variables will be studied using a two-way ANOVA test.

4. Results

In total our database comprises the measurements of 320 Dutch dwellings. 7.5% of the measurements were taken during construction, 70% around completion, 8.1% during occupancy and for 14.4% of the cases the moment of measurement was unknown. The average specific leakage rate at 10 Pa of all 320 dwellings is 0.55 $dm^3/s \cdot m^2$ (SD = 0.538). There appeared nine extreme cases with specific leakage rate higher than 2.0 $dm^3/s \cdot m^2$, as can be seen in Fig. 1. As indicated by the red line in Fig. 1, the compulsory w_{10} in energy performance regulations is for dwellings often set at 0.625 $dm^3/s \cdot m^2$. In our data collection 77.2% of the dwellings comply to this maximum.

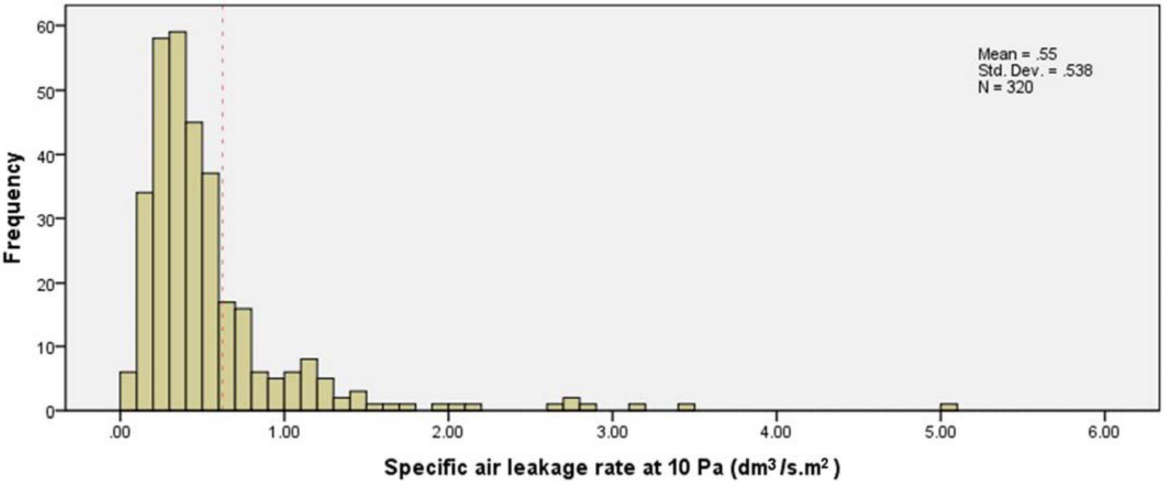

Figure 1 Distribution of the specific air leakage (w_{50min} = 0.06 $dm^3/s \cdot m^2$, w_{50max} = 5.04 $dm^3/s \cdot m^2$)

Some of the collected reports did not mention all the building characteristics needed for analysis, which caused us to create data groups ‘unknown’ when conducting the analysis for particular variables. 282 of the collected reports specified the dwelling type, 164 mentioned the construction method, 201 specified the construction typology, 288 mentioned the roof type and only 230 of the collected reports reported the leakages in the dwellings. Leakages found and assessed in the reports by images consist for 41% of leakages at window-wall interface, 22% in joints between floor and wall, 3% in joints between ceiling and wall, 7% were found in roof joints, 14% in plumbing installations, 5% in electrical sockets and 8% around the ventilation system. A few reports gave relatively little insights in the object under study. Only 310 of the collected reports mentioned the location of the building. No data was available on houses in the province of Drenthe; one of the twelve Dutch provinces. In our data collection dwellings in the province of Utrecht have on average the lowest specific leakage rate of 0.32 $dm^3/s \cdot m^2$ compared to other provinces, followed by Limburg 0.33 $dm^3/s \cdot m^2$ and Groningen 0.38 $dm^3/s \cdot m^2$. The highest of 0.68 $dm^3/s \cdot m^2$ is reported in Zeeland.

5. Analysis

5.1. Correlation analysis

The first analysis carried out is the correlation analysis between on the one hand the dependent variables w_{10} and w_{50}, and on the other the independent variables found in literature. The Pearson value suggests the type of correlation and how strong the correlation is. In this case the correlation is significant at 0.01. N shows how much valid data was used to analyse the correlation; missing data was not included in the analysis.

Table 2 Results of correlational analysis

	N	w_{10}	w_{50}
Total Leakage (LK_{TOTAL})	230	.437* (.000)	.426* (.000)
Design Target (Q_{EPC})	293	.064 (.272)	.073 (.212)
Floor Area (FLOOR)	320	-.097 (.083)	-.073 (.192)
Year of Construction (YEAR)	317	-.543* (.000)	-.531* (.000)
Dwelling Type (DT)	320	-.086 (.125)	-.060 (.288)
Construction Method (CM)	320	-.230* (.000)	-.204* (.000)
Construction Typology (CT)	320	-.160* (.004)	-.119* (.033)
Roof Type (ROOF)	320	-.088 (.117)	-.074 (.187)

*Significant at 0.05, w_{10} = specific leakage rate at 10 Pa difference, w_{50} = specific leakage rate at 50 Pa difference, N = number of valid cases

Table 2 shows that variables 'year of construction', 'construction method', 'construction typology' and 'total leakage' are significant and might be a good predictor to specific leakage rate at 10 Pa. Due to their P values, -0.543 and 0.437, the variables 'building year' and 'total leakage' seem to be the best predictors. Based on the specific leakage rate at 50 Pa, the variables year of construction, construction method and total leakage are also significant.

This empirical part of our study sought to see the correlation between numbers of leakage path by accumulating it using construct LK_{TOTAL}. A positive correlation was found between measured specific leakage rate at 10 Pa difference and total leakages in the building with $r = 0.437$, $p < 0.05$ (2-tailed) for 10 Pa difference, as plotted in Fig. 2a. Further statistical tests revealed the correlation for measured specific leakage rate at 50 Pa and total leakages ($r = 0.426$, $p < 0.05$, 2-tailed). However, only 19.1% of the variation in w_{10} and only 18.2% of the variation in W_{50} can be explained by the variable total leakages. This result points out that leakages as assessed in our reports by professionals contribute to the building airtightness in considerable amount.

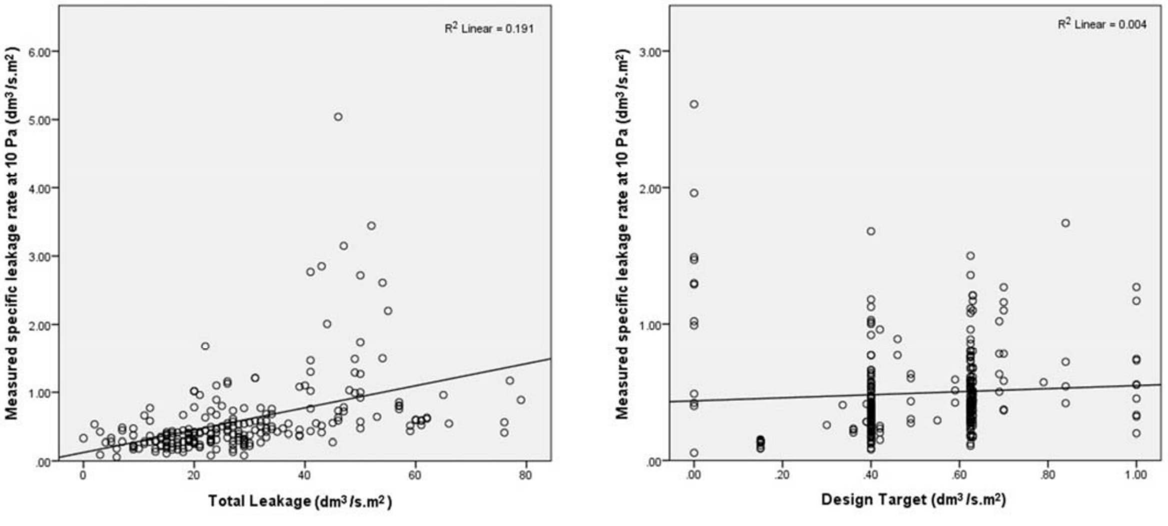

Fig. 2. (a) Scatter plot of the total leakage construct LK_{TOTAL}; (b) Scatter plot of the design target Q_{EPC} expressed in $dm^3/s \cdot m^2$

Dwellings often need to comply with a q_{v10} that is part of compulsory Energy Performance Indicators (EPI). This q_{v10} operates as a target value for building designs. In 91.6% of the cases the report mentions the targeted q_{v10}. A value of 0.15 $dm^3/s \cdot m^2$ at maximum was targeted in 8.5% of the cases, below 0.4 $dm^3/s \cdot m^2$ for 49.5% and below 0.625 $dm^3/s \cdot m^2$ for 91.1% of the cases. However, with $n = 293$, $r = 0.064$, and $p = 0.272$ no significant correlation was found between the variable design target and specific leakage rate at 10 Pa difference, nor was it found at 50 Pa difference ($n = 293$, $r = 0.073$, $p = 0.212$). The scatter plot for targeted airtightness and specific leakage rate at 10 Pa (Fig. 2b) shows that the assigned q_{v10} on EPC does not necessarily ensure the accomplishment of building airtightness.

Analysis was also carried out for the correlation between measured specific leakage rate and floor area. No significant correlation was found between floor area and the specific leakage rate at 10 Pa difference ($n = 320$, $r = -0.097$, $p = 0.083$) or at 50 Pa difference ($n = 320$, $r = -0.073$, $p = 0.192$).

5.2. Analysis of variance – one way ANOVA test

The correlation analysis only shows whether there is a correlation between variables, but not the effect of one variable on another. Therefore, ANOVA tests were conducted.

The first step enabling us to conduct the ANOVA test, was recoding the year of construction into specific time periods. Categories were chosen on basis of the era in which a certain Building Code applied, being the years 1992, 2003 and 2012. Fig. 3a shows that older buildings constructed before 1993 in general have higher specific leakage rates (on average 3.09 dm^3/s·m^2) compared to newer buildings (0.17 dm^3/s·m^2 and 0.52 dm^3/s·m^2). However, the measurement results were dominated by post-2012 buildings (92.2%). Consequently and including some extremes, the values are widespread.

To compare the means of building airtightness among different categories of year of construction, a one-way ANOVA F-test was used. Its F of 68.876 ($p < 0.01$) at 10 Pa difference and 61.864 ($p < 0.01$) at 50 Pa difference pointed out that the difference between groups is significant. The test of homogeneity, Levene Statistic 10.192 ($p < 0.05$), showed that the variance between the four groups is not statistically equal. It means one group differs significantly from the others. Therefore, a post-hoc Scheffe test was run to reveal where the differences lie between groups. Because the homogeneity test (Levene Statistic 7.468, $p < 0.05$) suggested the same results, the same procedure applies for the targeted specific leakage rate at 50 Pa.

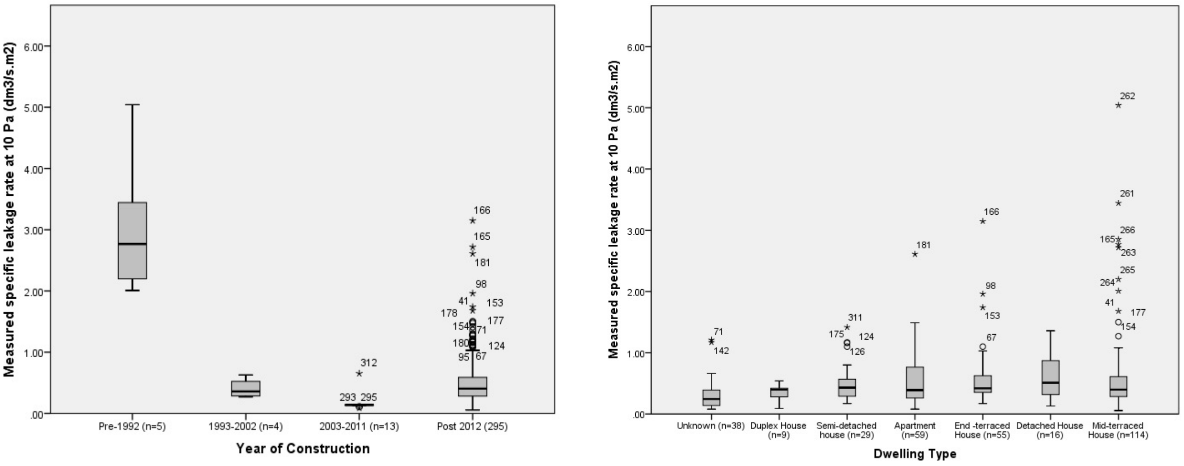

Fig. 3. (a) Specific leakage rate by year of construction YEAR; (b) Specific leakage rate by dwelling type DT

There is a positive linear relationship amongst the groups from pre-1992 until the building code of 2003. This might be caused by the spread in the group of post-2012 dwellings, and seems to confirm that this variable, 'year of construction', intentionally or unintentionally encompasses (multiple) other variables. On the other hand, statistics suggest that there is a significant difference in means specific leakage rate at 10 Pa difference ($p < 0.05$) between buildings from pre-1992 with each of the three other categories and between buildings from 2003-2011 and buildings from post 2012. The result on the mean specific leakage rate at 50 Pa differences shows slightly different results. A significant difference only exists between buildings from pre 1992 and the other three categories. Our analysis indicates that newly built dwellings are considerably more airtight than older buildings.

In our second step, resulting in Fig. 3b, the residential buildings studied were grouped into seven types of dwellings, namely: apartments, duplex houses, end-terraced houses, mid-terraced houses, semi-detached houses, and detached houses. The remaining buildings of which the sort of building was not known, were grouped as unknown. ANOVA tests were run to compare between-groups means divided by the within-groups one. The test of homogeneity (Levene's test) shows that variance between groups on specific leakage rate at 10 Pa difference (Levene's test 1.122 $p = 0.349$) equals those at 50 Pa different (Levene's test 0.914 $p = 0.485$). However, the results of the ANOVA test suggests otherwise. A F ratio of 2.064 ($p = 0.016$) implies that the differences between means of specific leakage rate at 10 Pa difference were statistically not significant. The same conclusion applies to the means of specific leakage rate at 50 Pa difference ($F = 2.222$ $p = 0.041$). Post-hoc test suggest that there is significant difference in means specific leakage rate at 10 Pa difference ($p < 0.05$) between apartment, end-terraced house and detached house; while at 50 Pa difference, only occur between apartment and end-terraced house. In conclusion, because statistics suggest that means between groups are not significant, therefore, the variable 'dwelling type' is a not suitable predictor for specific leakage rate, neither at 10, nor at 50 Pa difference,.

The third step involves the construction method, see Fig. 4a. The dwellings studied are constructed using three different methods: on-site construction, prefabrication or a combination of both. Other buildings with a build method unknown belong to the group ‘unknown’. An F test result of 8.578 ($p < 0.01$) suggests that there is significant difference in mean specific leakage rates at 10 Pa difference between groups. So do the results for a specific leakage rate at 50 Pa difference ($F = 6.790$ $p < 0.01$). The test of homogeneity (Levene Statistic 5.077, $p < 0.05$) suggests that the variance between the four selected groups is not statistically equal. It means there is at least one group that differs significantly than the others. Therefore, a post-hoc test was run to reveal where the differences lie between the groups. The same procedure applies for the target of specific leakage rate at 50 Pa (Levene Statistic 2.714, $p < 0.05$) where the homogeneity test suggests different conclusion. The results of our post hoc test suggest that there is a significant difference between the group ‘combination of both’ and group ‘unknown’ in means of specific leakage rate at 10 Pa difference ($p < 0.05$). The results on the mean specific leakage rate at 50 Pa differences point in the same direction. This means that there is no significance different of means between group except for buildings that was built with combination of both construction method and buildings that fall into group ‘unknown’.

The construction typology is categorized as a fourth step according to the material of the structure, which are: concrete, wood frame, masonry, steel construction and group ‘unknown’. F test of 4.890 ($p < 0.01$) suggests that there is significant difference in mean specific leakage rate at 10 Pa difference between groups. The other results ($F = 2.855$ $p < 0.01$) also suggest that there is a significant different in mean specific leakage rate at 50 Pa difference between groups, as is shown by Fig. 4b. The test of homogeneity (Levene Statistic 3.088, $p < 0.05$) suggests that the variance between the four groups is not equal. It means there is at least one group that differs significantly than the others. However, due to the lack of data on steel construction, a post-hoc test cannot be run.

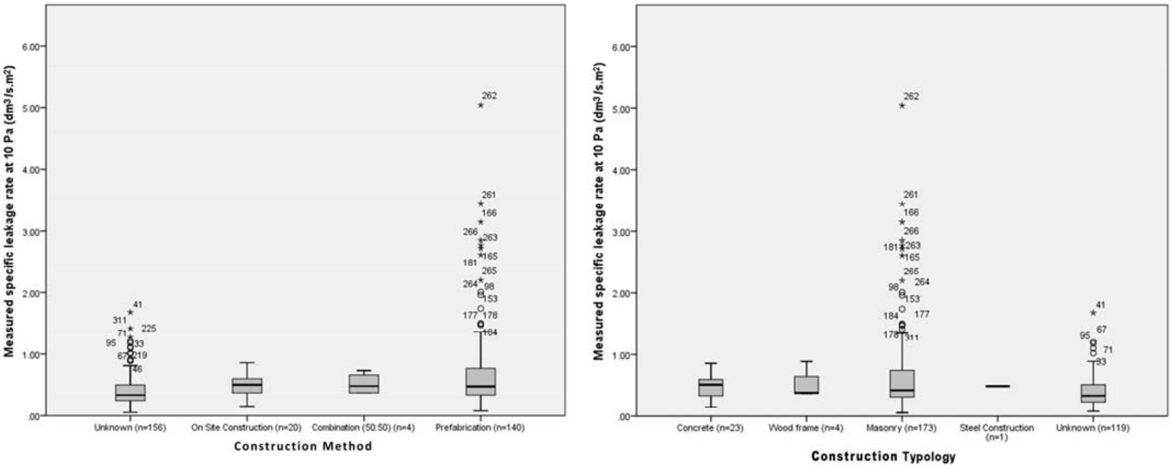

Fig. 4. (a) Specific leakage rate by construction method CM; (b) Specific leakage rate by construction typology CT

In our final one way ANOVA test, the dwellings were grouped according to their roof typology. We were able to distinguish between shed roof, flat roof, pitched roof, a combination of roof types and those of which the roof type is unknown (see Fig. 5). The test of homogeneity (Levene Statistic 2.551, $p = 0.802$) suggests that the variance between these five groups is equal. The same procedure applies for the target of specific leakage rate at 50 Pa (Levene Statistic 1.804, $p = 0.128$) and the homogeneity test suggests the same conclusion. ANOVA test results suggest ($F = 4.533$, $p < 0.01$), for target of specific leakage rate at 10 Pa differences, that the difference between groups is significant. Likewise, the results with specific leakage rate at 50 Pa difference with $F = 4.719$ and $p < 0.01$ are likewise. A post-hoc test was run to find where the differences lie between groups. In case of roof type variables, the results suggest that there is significant difference in means specific 10 Pa leakage rates ($p < 0.05$) between group ‘shed roof’ and ‘pitched roof’; and group ‘combination of roofs’ and ‘flat roof.’ Similar findings were found on the mean specific leakage rate at 50 Pa difference.

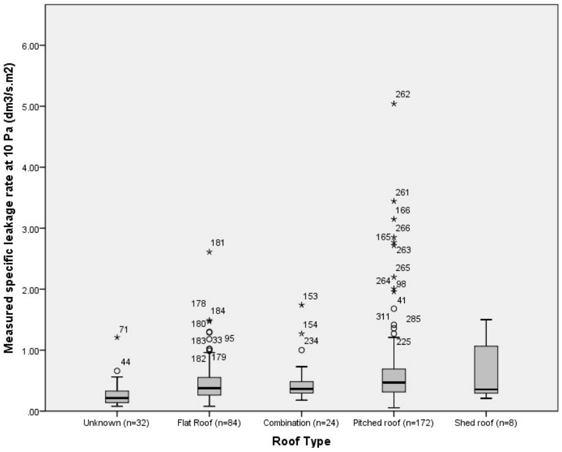

Fig. 5. Specific leakage rate by roof type ROOF

5.3. Analysis of variance – two way ANOVA test

The analysis above suggests that all variables, except floor area, design target and dwelling type are significant to predict specific leakage rate at 10 Pa difference. Even though every variable is significant, or equivalent as having main effect on building airtightness, the interaction between variables might have effect on building airtightness as well. Therefore, two-way ANOVA tests were run to analyse the interaction between variables. The difference between one-way and two-way ANOVA is that one-way ANOVA only studies main effect of variables to the target variables, while two-way ANOVA also studies whether interaction between variables giving effect on target variables. There are six variables included in the analysis, which, as shown in Table 3, resulted in seventeen pair of two-way ANOVA to run. Although previous analysis shows both measured specific leakage rate at 10 and 50 Pa difference, the main target of this research is still the Dutch context with 10 Pa difference.

However, not all variables showed interaction effect and cannot be accounted as good predictors. The results of two-way ANOVA test suggest that interaction effects occur between building year built x total leakages ($F = 6.655$, $p < 0.01$) with adjusted R-squared 0.703; total leakages x roof type ($F = 2.128$, $p < 0.01$) with adjusted R-squared 0.528; total leakages x construction method ($F = 3.135$, $p < 0.01$) with adjusted R-squared 0.609; total leakages x construction typology ($F = 3.676$, $p < 0.01$) with adjusted R-squared 0.607. These results make us believe that interaction between total leakage and other variables effect building airtightness. The results of our analysis are summarised by Table 3.

Table 3 Results of the exploratory analysis

Variables	Method of analysis	p-value*	F-test	Pearson's r	R squared
Total Leakage (LK_{TOTAL})	Linear regression	.000		.680	.457
Design Target (Q_{EPC})	Linear regression	.479		.071	-.002
Floor Area (FLOOR)	Linear regression	.000		.548	.295
Year of Construction (YEAR)	One-way ANOVA	.000	30.894		.398
Dwelling Type (DT)	One-way ANOVA	.016	2.649		.314
Construction Method (CM)	One-way ANOVA	.000	8.578		.348
Construction Typology (CT)	One-way ANOVA	.001	4.890		.325
Roof Type (ROOF)	One-way ANOVA	.001	4.553		.323
YEAR x LK_{TOTAL}	Two-way ANOVA	.000	6.655		.791
YEAR x DT	Two-way ANOVA	.768	0.264		.414
YEAR x ROOF	Two-way ANOVA	.433	0.617		.410
YEAR x CM	Two-way ANOVA	-	-		.421
YEAR x CT	Two-way ANOVA	-	-		.414
LK_{TOTAL} x DT	Two-way ANOVA	1.000	0.462		.687
LK_{TOTAL} x ROOF	Two-way ANOVA	.001	2.128		.753
LK_{TOTAL} x CM	Two-way ANOVA	.000	3.135		.771
LK_{TOTAL} x CT	Two-way ANOVA	.000	3.676		.770
DT x ROOF	Two-way ANOVA	.251	1.263		.091
DT x CM	Two-way ANOVA	.855	0.567		.115
DT x CT	Two-way ANOVA	.985	0.259		.081
ROOF x CM	Two-way ANOVA	.701	0.637		.109
ROOF x CT	Two-way ANOVA	.622	0.735		.098
CM x CT	Two-way ANOVA	.352	1.048		.085

*Significant at 0.05

5.4. Regression analysis

Aforementioned analysis shows that variable ‘year of construction’ (YEAR), ‘total leakages’ (LK_{TOTAL}), ‘roof type’ (ROOF), ‘construction method’ (CM) and ‘construction typology’ (CT) might predict building airtightness in terms of specific leakage rate at 10 Pa. Therefore, our initial overall model to relate specific leakage to the total leakage construct, year of construction, roof type, construction method and construction typology, looks as follows:

$$w_{10} = \alpha + \beta_{LKtotal} \cdot LK_{TOTAL} + \beta_{YEAR} \cdot YEAR + \beta_{ROOF} \cdot ROOF + \beta_{CM} \cdot CM + \beta_{CT} \cdot CT \qquad (3)$$

Considering Eq. 3 regression analysis (with confidence level 95% = 1.960) was run. Although some would prefer the ‘stepwise’ or ‘forward’ method [20] over the ‘enter’ method, all three methods were applied using SPSS 20 with similar results. The first two methods show the different regression results by accounting only the most significant variables, and comparing directly models with multiple significant variables, while the ‘enter’ method only shows one model with the variables selected. As is shown in Table 4, regression analysis indicated that roof type, construction method and construction typology are not significant. Therefore, after removing the not significant variables, regression was run again resulting in the following simplified equation:

$$w_{10} = \alpha + \beta_{LKtotal} \cdot LK_{TOTAL} + \beta_{YEAR} \cdot YEAR \qquad (4)$$

As can be seen in Table 4, Eq. 4 has slightly lower R-square than Eq. 3, meaning that 42.1% of the measured specific leakage rates in our data collection can be explained by this relation expressed in Eq. 4. However, Eq. 4 only accounted significant variables, while in case of Eq. 3 all have a significant influence according to our ANOVA tests, but not according to the multiple linear regression test.

Table 4 Coefficient and adjusted R-squared value for both models

Coefficient	Regression 1 (Eq. 3)	t	p-value	Regression 2 (Eq. 4)	t	p-value
α	2.412 ± 0.561	8.485	.000	2.362 ± 0.477	9.764	.000
β_{YEAR}	-0.555 ± 0.115	-9.530	.000	-0.553 ± 0.115	-9.534	.000
$\beta_{LK;TOTAL}$	0.013 ± 0.004	6.233	.000	0.013 ± 0.004	7.150	.000
β_{ROOF}	0.025 ± 0.025	.708	.480			
β_{CM}	-0.102 ± 0.102	-1.963	.051			
β_{CT}	0.051 ± 0.051	1.148	.252			
Adjusted R-square	0.425			0.421		
F	34.365		.000	83.036		.000

6. Discussion

The conducted ANOVA tests show that older buildings tend to be leakier than newer buildings. The findings from the regression analysis confirm that the year of construction actually have influence over airtightness. This is in line with observations of Chan, Joh & Sherman [14], Montoya et al. [20], and Sinott & Dryer [17]. However, this observation will have little impact in practice, because Building Codes often only affect designs of buildings that still need to be constructed. Factors directly related to materials and building practices prevalent in a certain era, such as construction method, material used and construction technology, are concealed in the ‘year of construction’.

Our analysis shows that the newly introduced construct ‘total leakage’ has a strong correlation with specific leakage rate. Even though ANOVA test showed relationships between specific leakage rate and several variables, Post-hoc Scheffe tests suggested that there is no significant difference by means of ‘construction method’, ‘construction typology’ or ‘roof type’. This signifies that Dutch dwellings seem to equal each other in airtightness regardless the material and construction typology used. Furthermore, no correlations were found between specific leakage rate and ‘floor area’ or ‘design target’ specified when assessing the EPC.

Even though ‘year of construction’ and ‘total leakage’ both had an effect on specific leakage rate, their influences is not simultaneous but interactive. This means that the effect of total leakage is dependent on the age of the dwelling and vice versa. Total leakage also has interaction with other significant factors which are: roof type, construction method and construction typology. However, as predictors they are statistically insignificant; the interaction effect has no consequences on specific leakage rate.

This research has multiple implications. Based on the significance building characteristics determined from the ANOVA test, regression results suggests that only the ‘year of construction’ and the ‘total leakage’ influence specific leakage rate at 10 Pa difference. Although the first has influence on specific leakage rate, this discovery, however, will have little effect on post-2012 buildings. At the end of the day, restrictions in building codes on building airtightness are only relevant for new buildings. This study confirms that ‘year of construction’ and ‘total leakages’ actually have influence on building airtightness as suggested in the literature. Apparently the influence of these factors is subject to their interaction with each other as confirmed by the two-way ANOVA test. In addition, ‘year of construction actually’ encompasses other factors such as the type of construction, building material, construction method, HVAC system and insulation type. This is because these factors cannot be dissociated from the prevalent practices of relative periods in time. On the other hand, leakage paths found in some parts of a building is still a relevant finding because it still could be considered during the construction of new houses. The results from multiple linear regression did not show confident adjusted R-square. Therefore, a reliable model could not be generated with the findings of this study.

This research, however, has also some limitations. Since this study analysed results from many other scientific studies, one of the shortcomings of it is the heterogeneity of the results from the included studies can be affected. And this is because there are inherent differences in the individual studies such as method of obtaining data, analysing them and interpreting them. This research uses the term specific leakage rate to refer to building airtightness while other studies use different terms to normalize building airtightness and measurement of such concepts could yield different outcomes. Also since this research uses regression to attempt to develop a model, such model method is only applicable if the new data is in range of a dataset from which the model was derived from. Another limitation to this study is the lack of data we experienced for some of the characteristics of the more than 300 cases. Completing these empty fields is important when improving the reliability of findings. For future research projects on the topic of airtightness, it seems wishful to meticulously maintain and add to (national) databases of blower door test reports. Also information on the measured buildings preferably is to be added.

7. Conclusion and recommendations

Our findings revealed that ‘total leakage’, ‘year of construction’, ‘roof type’, ‘construction method’ and ‘construction typology’ have a relationship with airtightness; and only ‘year of construction’ and ‘total leakage’ influence the building airtightness. This research also aimed to explore if roof type influences specific leakage rate, because previous studies overlooked it. A remarkable finding is that roof type is actually related with specific leakage rate although it has no effect on it. Together with variable total leakage, roof type has an interaction effect on specific leakage rate. This might support the idea that leakage path found in the roof joint contribute to total air leakage and, consequently, affect building airtightness.

Since the overall effect of the variables studied was still relatively modest, it makes us think that a reliable model cannot be developed out of those variables. Further research is necessary to identify cogent variables that could have effect on building airtightness. Our findings can be a springboard for that research. Particularly the given that the variable ‘year of construction’ encompasses multiple building characteristics, such as ‘building material’, ‘building technology’ and ‘building practise’, seem to call for further testing. Ventilation system and insulation type are also building characteristics that need additional attention, because a ventilation system requires certain holes to be made in the building envelope and the type of insulation relates to the quality of building envelope.

As this research particularly considered residential buildings, future studies could be carried out on commercial buildings. Furthermore, experimental research could be carried out to find out if interference on variables affects building airtightness. Different materials can be applied, when retrofitting old buildings. By measuring improvements in building airtightness, insights van be gained on what intervention is needed to ensure a proper airtightness and ultimately energy efficiency. One can not change the year of origin of a building, but in old and new dwellings leakages can be minimized by paying close attention to details and this is anchored more on the quality of workmanship. As empirical data showed leakage paths and damage levels align with the total leakage of a dwelling. This suggests that attention to details matters and as literature shows [16, 23, 24], workmanship is critical to achieve building airtightness. Statistics also showed the same results that leakages occur in the building give significant influence on specific leakage rate, which in this case happen at 10 Pa difference. Therefore, more attention should be paid to minimizing air leakage at the early phases of construction and this is dependent on the quality of workmanship. Also other studies have suggested that supervisor and management play important role in achieving high quality workmanship and this could have positive impact on attaining less leakages and subsequently more airtight building.

Acknowledgements

The authors would like to express their gratitude to the Dutch 3TU.Bouw Center of Excellence for the Built Environment and the Indonesia Endowment Fund for Education of the Ministry of Finance of the Republic of Indonesia for their financial support. Furthermore, our gratitude goes to those who helped us in acquiring test reports with the results of certified blower door tests.

References

[1] EU. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Off J Eur Union 2010:13–35.

[2] BRIS Bouwbesluit Online. Bouwbesluit 2012 n.d. http://www.bouwbesluitonline.nl/Inhoud/docs/wet/bb2012 (accessed February 25, 2015).

[3] Krstić H, Koški Ž, Otković II, Španić M. Application of neural networks in predicting airtightness of residential units. Energy Build. 2014;84:160–8.

[4] Sadineni SB, Madala S, Boehm RF. Passive building energy savings: A review of building envelope components. Renew. Sustain. Energy Rev 2011;15:3617–31.

[5] Logue JM, Sherman MH, Walker IS, Singer BC. Energy impacts of envelope tightening and mechanical ventilation for the U.S. residential sector. Energy Build 2013;65:281–91.

[6] Nabinger S, Persily A. Impacts of airtightening retrofits on ventilation rates and energy consumption in a manufactured home. Energy Build 2011;43:3059–67.

[7] Jokisalo J, Kurnitski J, Korpi M, Kalamees T, Vinha J. Building leakage, infiltration, and energy performance analyses for Finnish detached houses. Build. Environ 2009;44:377–87.

[8] Pan W. Relationships between air-tightness and its influencing factors of post-2006 new-build dwellings in the UK. Build. Environ 2010;45:2387–99.

[9] Alev Ü, Eskola L, Arumägi E, Jokisalo J, Donarelli A, Siren K, et al. Renovation alternatives to improve energy performance of historic rural houses in the Baltic Sea region. Energy Build 2014;77:58–66.

[10] Sherman MH, Chan R. Building Airtightness : Research and Practice. 2004.

[11] Santos HRR, Leal VMS. Energy vs. ventilation rate in buildings: A comprehensive scenario-based assessment in the European context. Energy Build 2012;54:111–21.

[12] Mickaël D, Bruno B, Valérie C, Murielle L, Cécile P, Jacques R, et al. Indoor air quality and comfort in seven newly built, energy-efficient houses in France. Build. Environ 2014; 72:173–87.

[13] Relander TO, Holøs S, Thue JV. Airtightness estimation - A state of the art review and an en route upper limit evaluation principle to increase the chances that wood-frame houses with a vapour- and wind-barrier comply with the airtightness requirements. Energy Build 2012;54:444–52.

[14] Chan WR, Joh J, Sherman MH. Analysis of air leakage measurements of US houses. Energy Build 2013;66:616–25.

[15] Chan WR, Nazaroff WW, Price PN, Sohn MD, Gadgil AJ. Analyzing a database of residential air leakage in the United States. Atmos Environ 2005;39:3445–55.

[16] CEN. EN Standard 13829: Thermal performances of building - determination of air permeability of buildings - fan pressurization method. Brussels: European Committee for Standardization; 2000.

[17] Sinnott D, Dyer M. Air-tightness field data for dwellings in Ireland. Build. Environ 2012;51:269–75.

[18] Kalamees T. Air tightness and air leakages of new lightweight single-family detached houses in Estonia. Build. Environ 2007;42:2369–77.

[19] Pinto M, Viegas J, de Freitas VP. Air permeability measurements of dwellings and building components in Portugal. Build. Environ 2011;46:2480–9.

[20] Montoya MI, Pastor E, Carrié FR, Guyot G, Planas E. Air leakage in Catalan dwellings: Developing an airtightness model and leakage airflow predictions. Build. Environ 2010;45:1458–69.

[21] Sfakianaki a., Pavlou K, Santamouris M, Livada I, Assimakopoulos MN, Mantas P, et al. Air tightness measurements of residential houses in Athens, Greece. Build. Environ 2008;43:398–405.

[22] Alfano DFR, Dell'Isola M, Ficco G, Tassini F. Experimental analysis of air tightness in Mediterranean buildings using the fan pressurization method. Build. Environ 2012;53:16–25.

[23] Bossche Nvd, Huyghe W, Moens J, Janssens A, Depaepe M. Airtightness of the window-wall interface in cavity brick walls. Energy Build 2012;45:32–42.

[24] Relander TO, Bauwens G, Roels S, Thue JV, Uvsløkk S. The influence of structural floors on the airtightness of wood-frame houses. Energy Build 2011;43:639–52.

[25] Relander TO, Heiskel B, Tyssedal JS. The influence of the joint between the basement wall and the wood-frame wall on the airtightness of wood-frame houses. Energy Build 2011;43:1304–14.

[26] Langmans J, Klein R, De Paepe M, Roels S. Potential of wind barriers to assure airtightness of wood-frame low energy constructions. Energy Build 2010;42:2376–85.

[27] Relander TO, Kvande T, Thue JV. The influence of lightweight aggregate concrete element chimneys on the airtightness of wood-frame houses. Energy Build 2010;42:684–94.

[28] Kuindersma P, Nieman HM. Luchtdicht bouwen, theorie-ontwerp-praktijk. Rotterdam: 2013.

[29] ISO. ISO Standard 9972: Thermal performance of buildings — Determination of air permeability of buildings — Fan pressurization method. vol. 2nd. Geneva: 2006.

[30] De Gids WF, Cornelissen HJM, Jong P d. Infiltratieverliezen U Bouw. Delft: 2010.