AIRTIGHTNESS OF THE WINDOW-WALL INTERFACE IN MASONRY BRICK WALLS

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ABSTRACT

In recent decades there has been an increased focus on enhanced thermal resistance of building components and as a consequence, the relative importance of airtightness on the overall energy losses of buildings has increased significantly. The construction industry requires practical information on the airtightness of individual construction elements and building envelope interfaces. A literature review on the airtightness of window-wall interfaces has shown that no experimental data are available for masonry construction. This paper offers an investigative study on the airtightness of window-wall interfaces of masonry walls, for 13 different installation methods. The results show that the selected solutions cover a wide range of airtightness levels, from 0m³/h.m up to 31m³/h.m at 50 Pa. The experiments have permitted determining that a very good performance can be obtained by using polyurethane foam and caulking, airtight membranes, polyurethane foam and plywood framing, and plaster and caulking. On the contrary, mineral fibre insulation, a partial fill with polyurethane foam and plaster without caulking should be avoided when good airtightness is required. Furthermore, a comprehensive methodology for error calculation is offered, based on error propagation of partially correlated parameters, including the effect of measurement errors, extraneous air leakage and conversion to standard boundary conditions.

KEYWORDS

airtightness, window-wall interface, brick cavity wall,

INTRODUCTION

Throughout the last few decades an increasing number of countries are enforcing energy codes and existing codes are getting stricter in respect to energy usage in homes. In addition, there has been a general increase in the price of energy (U.S. E.I.A, 2008). Airtightness is one of the defining factors in energy use in buildings. In a moderate climate such as that found in Belgium, infiltration of cold air accounts for up to 20% of overall primary energy use for code-compliant buildings (VEA, 2009). Obviously, in colder climates the more pronounced effects of infiltrating cold air in buildings will result in code requirements for improved energy efficiency and thus promote better construction practice concerning airtightness (Sherman and Chan, 2004). In general, the existing housing stock in colder climates is more airtight as compared to homes located in moderate climates (McWilliams and Sherman, 2005). One might expect that more airtight buildings are constructed over time due to stricter building codes, but an analysis by Bossaer et al. (1998) on 51 homes built before and after the implementation of the first energy building code in Belgium showed no difference in respect to airtightness. However, the energy code in Belgium only provides recommendations on airtightness in relation to HVAC-systems, contrary to that required in other countries, e.g. Norway, Sweden and the US (Limb, 2001). The average airtightness (n_{50} , the measured air volume flow at 50Pa pressure difference divided by the interior volume of the building) of detached residential buildings in Belgium in 1995 was 11.7 air changes h^{-1} (Bosaer et al., 1998; results were recalculated to meet ISO 13829:2001 requirements). A more recent study by Laverge et al. (2010) on newly built residential dwellings shows that the air leakage has decreased significantly in 15 years, and is now about 6.0 air changes h^{-1} at 50Pa pressure difference. This decrease is mainly caused by an increased awareness concerning airtightness by architects, contractors and building owners. The required level of airtightness of buildings in Belgium will most likely become stricter in the future. In 2006 the airtightness of only 1,5% of all newly built dwellings was measured, whereas in 2009 already over 7% were tested using a pressurization test (VEA, 2011). There is an urgent need for standard details at openings in buildings that would minimize air leakage at these vulnerable locations (Hens, 2011); this has become apparent from the increased number of airtightness tests that are now being carried out. It is evident that the building stock in Belgium has poor airtightness performance and from this it can be surmised that there is likewise a lack of knowledge at the designer's side in respect to achieving adequate airtightness in homes. For wood-frame construction interesting research was published by Relander et al. on different components and interfaces (Relander et al., 2010, 2011). The window-wall interface is one of the key air infiltration pathways in wood-frame construction (Relander et al., 2008). Consequently, there is a high probability that this will likewise be the situation for masonry cavity walls.

Energy concerns are not the only reason to focus on airtightness. A lack of airtightness can cause cold draughts, lower acoustical performance of the building envelope, interfere with the balance of a HVAC-system, promote interstitial condensation through exfiltrating air and surface condensation through infiltrating air. Research by Lacasse et al. (2003) even suggests that deficiencies in airtightness have an effect on the watertightness of the window-wall interface: over the course of watertigthness tests those window-wall assemblies that were less airtight achieved reduced levels of pressure equalisation that resulted in higher rates of water infiltration into the assembly.

Based on the rising demand from the building industry for standard details for airtight construction in masonry cavity walls, and the fact that window-wall interfaces can account for significant air losses, and as well, the lack of information found in literature on this topic, a research project was initiated to provide practical information on this topic. This paper reports the results of an experimental study on 13 different installation methods for windows in masonry cavity walls. Section 3 provides details on the relevant standards, the test method and experimental setup, and a thorough error analysis based on error propagation of partially correlated parameters. In section 4 the different installation methods are described using detailed sectional drawings and description, whereas the results are reported in section 5. Next to that, section 5 also comprises an analysis of window-wall interface air leakage as compared to overall building airtightness.

LITERATURE REVIEW

The typical construction method and materials of different components of the building envelope vary geographically, according to climate, natural resources and building practice employed in a particular geographical location. This paper only focuses on the window-wall interface in brick cavity masonry walls. These walls are typically representative of current building practice and consist of an inside leaf in extruded large format perforated bricks, a cavity partially or fully filled with insulation and an outer masonry veneer wall. The airtightness of the wall is secured by a layer of plaster, typically sprayed to the interior side of the interior brick wall and scoured manually. Such type of walls are characteristic of North-Western European building practice (e.g. Belgium, The Netherlands, Northern France, Great Britain). This section of the paper is comprised of an analysis of experimental data on the airtightness of window-wall interfaces as found in literature, and includes some general guidelines or estimation techniques for assessing air leakage in homes which are often used or cited. The air flow rate through an opening for an applied pressure difference is commonly expressed by the empirical power law equation (1):

$$\dot{V} = C.\Delta P^n \qquad (1)$$

With $\dot{V}$: air flow rate (m³/h), ΔP: pressure difference (Pa), and C: flow coefficient (m³/h.Pa^n) and n: flow exponent (-). A summary of results derived from different sources can be found in Van Den Bossche et al. (2012). Most literature dealing with airtightness of window-wall interfaces originates from countries having a cold climate, and practically all reported measurements were completed on wood-frame constructions. Even though most joints have a similar width, there is a large variety in air flow rates for similar products. For example, the installation of mineral wool limits the air flow to around 1.5m³/h.m at 50Pa when placed correctly and well compressed, and ca. 5m³/h.m when installed incorrectly. Backer rods can be very airtight, and the air leakage should be below 1m³/h.m at 50Pa, whereas open cell products and self-expanding products generally perform poorly. Tapes and membranes are more airtight, between 0 and 0.31 m³/h.m at 50Pa, but also susceptible to improper installation. Polyurethane foam and sealants are practically perfectly airtight when installed correctly. The effect of a window sill on the overall performance of the window-wall interface was not evident in any of these publications, and neither was it included in this research project.

For this reason a new test series was setup, specifically devoted to masonry cavity wall construction, as described in section 4 of this paper. Before discussing the results, the issue of measuring uncertainty in air leakage measurements is first addressed.

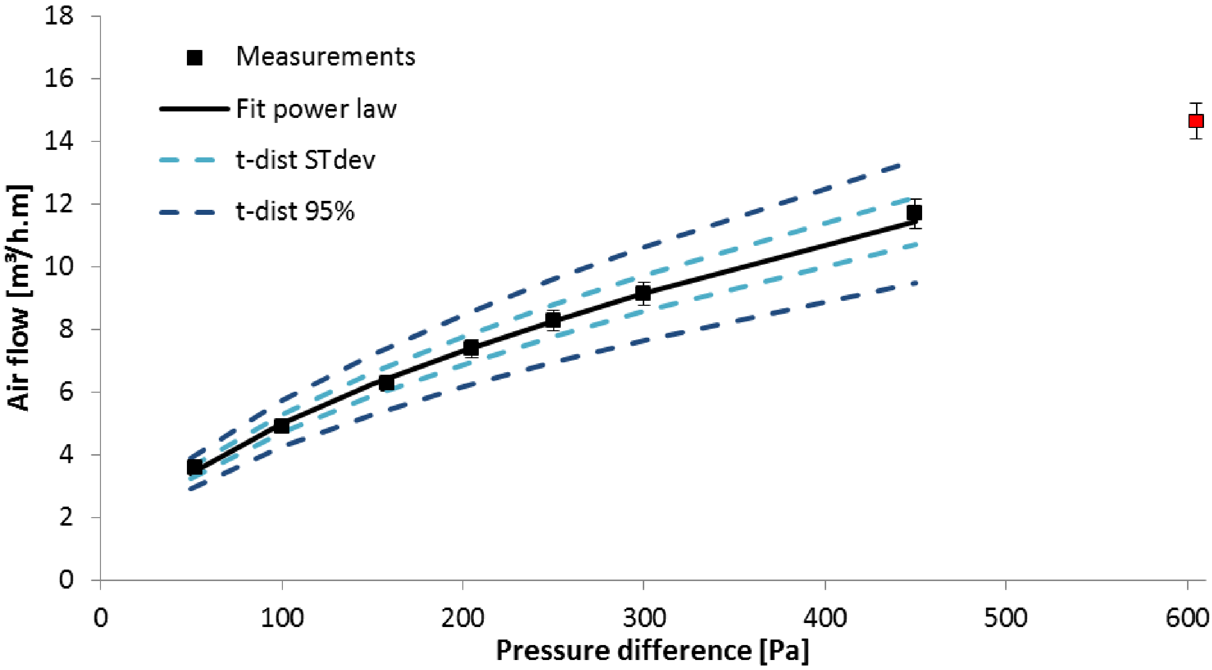
TEST METHOD

Procedure

The test samples were measured using a standard calibrated test rig which is used on a daily basis to test the airtightness of window frames according to NBN EN 1026:2000. In absence of any specific guidelines for window-wall interfaces, the test protocol was based on the one for window frames given in NBN EN 1026: it seems reasonable to apply pressure differences corresponding to the typical product specification of windows to the window-wall interface. After three pulses at 110% of the maximum test pressure, the sequence is as follows: 50-100-150-200-250-300-450-600 Pa. The same procedure is then repeated but with negative pressures.

The window itself was non-operable, and the glazing stop was sealed on both sides (glass side and frame side) to ensure that no air was infiltrating through the window and influenced the measurements. Furthermore, smoke pencils were used to trace and visualize leakage paths in the sample. The extraneous air leakage was measured before, in between and after the tests. The experimental data reported in this paper were calculated by subtracting the first extraneous air losses from the measured air flows. If there was a slight difference in extraneous air leakage before and after the sample measurement, the lowest value of extraneous air loss was chosen to provide a conservative result. The test sequence described above was also used for quantifying the extraneous air losses, but with an airtight plate installed over the window opening (Figure 2). The plate covered 5cm of plaster around the window reveal, and was sealed to the plaster by means of a compressed closed cell neoprene backer rod and caulking. The test rig was designed to be as airtight as possible, to reduce the overall error on the results. The leakage of the test rig was adjusted by consecutive testing, but even after optimization the degree of air loss remained in a range of 0.5 – 0.6m³/h.m at 50Pa for the different measurements of extraneous leakage. As 6 out of 13 measured installation methods have an air loss ranging between 0 and 0.2m³/h.m at 50Pa, the effect of the extraneous air loss is significant. This caused quite large uncertainty intervals for results of the most airtight installation methods. The temperature, relative humidity and barometric pressure was recorded during each test, in order to convert the results to standard boundary conditions.

The error analysis was based on the calibration error of the test rig, error due to conversion to reference conditions, the chauvenet criterion, and error propagation in the power law. More details on the error analysis methodology can be found in (Van Den Bossche et al., 2012).



Air flow measurement with power law and t-distribution uncertainty interval of installation SPF-all (the red mark was rejected according to the Chauvenet-criterion).

Test specimens

In order to measure the airtightness of the window-wall interface in cavity brick walls, two test walls were built to represent different situations. The first wall was considered as common practice and was comprised of an aluminum window frame in a brick cavity wall having 8cm of polystyrene insulation and 3cm of air cavity. Note that the majority of newly built walls in Belgium incorporate an air cavity to ensure adequate drainage and easy of execution. For this specimen, two different interior finishes for the window reveal were applied: a wooden window trim (test setup A); or a layer of gypsum plaster on the reveal (test setup B). Test setups A and B were thus applied on the same wall, but have a different interior finish.

Currently in Belgium (and perhaps elsewhere in Northern Europe where homes constructed of brick masonry walls are current practice) there is a tendency to place more insulation in brick cavity walls to comply with energy standards with the expectation of reducing energy losses and thereby lowering heating costs. Extremely low energy buildings can have cavities (width of insulation plus empty cavity) up to 24cm wide in order to obtain, e.g., passive house certification. As the window frame is typically recessed about 10cm from the outer masonry plane, the installation technique should take into account the eccentric structural load of the window with regards to the inner bearing masonry wall. This eccentric load can be dealt with by mounting strong brackets at the sill, or for small to moderately sized windows by installing a plywood framework all around the window frame. Even if the window is too big and extra brackets are required at the sill, the plywood frame still offers additional benefits, such as ease of installation, rigid backing for the interior finish, and additional rigidity for the window installation. The latter technique was thus applied, also because it is currently the most common approach used in buildings certified for extremely low energy usage . The second wall was thought representative of well insulated buildings, and consisted of a wooden window frame in a brick cavity wall having 20cm of polystyrene insulation and a 2cm air cavity (setup C). For setup C it was anticipated that the performance would be independent to the type of interior finish. For both walls, the windows are 1.23m wide and 1.48m high (according to the product standard NBN EN 14351-1:2006, and representative of typical dimensions for windows in Belgium), and both walls were 1.92m by 2.02m (2m adjusted to brick module).

Figure 2a. calibration setup for measuring extraneous air leakage of the setup. Figure 2b. Installation of aluminum window frame and wood reveal.

In test setups A and B the window was installed using typical mounting brackets, whereas in setup C, given that the use of wide cavity brackets were not an option, there was a plywood framework to which to secure the window unit and that was fixed to the interior brick wall. It was anticipated that the interior finish of setup C (paint on plywood, window trim or gypsum plaster) would not affect the airtightness performance because the continuity of the airtight layer was guaranteed by the airtight plywood framework. In both test setups the horizontal projected gap between frame and wall was 2.5cm; this is a typical size and allows adequate tolerance for installation. Note that the perimeter was not exactly the same for both setups because in setup C the plywood framework at the perimeter of the window required a slightly bigger opening in the wall to obtain the same degree of tolerance. In both cases the window was recessed 10cm from the outer plane of the wall. Contrary to common practice, the joint between the exterior brick wall and the window frame was not caulked during testing. It was assumed that brickwork typically does not contribute to the airtightness due to open drains and vents in the façade. Note that the installation methods were only designed for airtightness testing; other parameters such as watertightness and thermal performance were not considered here. Consequently, no statements are made in respect to other parameters and the drawings only report the installation as it was tested. All of the different materials used to fabricate the test specimens were randomly selected and installed by professional craftsmen. Caulking and sprayed in place polyurethane foam (SP-PUR) were always left for at least one day to cure prior to testing, and plaster was permitted to cure for at least two days. Figure 2 shows the measurement of extraneous air leakage of test setup C.

In these tests, no differentiation was made between the head, jambs or sill, similar to that reported in all of the papers cited in Table 1. Furthermore, it should be noted that the results represent the air leakage along the linear interface, as well as any local deficiencies situated at the corners. For test setup A the perimeter was 5.32m and this obviously included the four (4) corners. It is likely that the corners are less airtight than the linear joints due to additional interfaces coming together and issues related to ensuring airtight installation at these locations. As the results are expressed per meter of joint length, this implies that the results presented in this paper might underestimate the air leakage for windows having a lower area to perimeter ratio given that in such instances the air leakage at the corners is more important.

INSTALLATION METHODS

The selection of the different installation methods was discussed with building practitioners, window installers and manufacturers in collaboration with the Belgian Construction Certification Association (BCCA), specifically the group working on window-wall interfaces. An overview of the installations is described in Table 2, and drawings are provided in Figure 3. In setup A, the window is installed with 10 mounting brackets (3 on each jamb, 2 on head and sill), and the interior finish consists of a wooden window trim. In test setup A seven different installation methods for the aluminium window frame were measured, with varying installation methods for a plywood window trim primarily using mineral fibre, SP-PUR and caulking. The SP-PUR used in the different installation methods is a one-component low-expansion foam with a high elastic recovery, and was applied with a foam applicator gun system. In test setup B the windows were installed in the same wall as setup A, also with 10 mounting brackets, but the interior finish consisted of gypsum plaster, a technique which is currently highly used in contemporary architectural practice. When the plaster is applied on the reveal just on to the window profile, the drying of the plaster induces a shrinkage crack at the interface (installation RP) this approach allows high air flow rates through the cracks. Such cracks are afterwards typically enlarged due to thermal movement of the window and deformation by mechanical loads (wind forces or operating forces). This can be resolved by installing a vinyl end profile for the plaster, and then placing a backer rod and caulking between the end profile and the window frame (RP stop). This technique only uses standard techniques from the building industry, and is airtight enough to be applied in passive homes. Another solution is the use of airtight membranes, equipped with a woven layer that allows plaster to adhere on the membrane. The membrane itself consisted of a polyester foil, with a pressure sensitive adhesive on one end that was adhered to the window frame, and a butyl layer on the other end that was attached to the interior brickwork.

No.	Setup	Abbreviation	Description
1	A	Empty+C	Cavity between the brick wall and window casing and trim is empty.
2	A	MF loose +C	Cavity is packed with medium density mineral fibre
3	A	MF dense +C	Cavity is packed with high density mineral fibre
4	A	SP-PUR-e +C	Cavity is partially filled with SP-PUR (exterior side)
5	A	SP-PUR-I +C	Cavity is partially filled with SP-PUR (interior side)
6	A	SP-PUR-all	Cavity is entirely filled with SP-PUR, no caulking between the window frame and the window casement
7	A	SP-PUR-all + C	Similar to No. 6 (SP-PUR-all), but with caulking between window and window trim
8	B	RP	An XPS substrate was mounted to masonry brick wall; a layer of plaster was placed onto window frame. A minor crack was induced between window frame and plaster due to drying shrinkage of plaster.
9	B	RP stop	Similar to No. 8 (RP), but instead a plaster stop profile was installed, and in between a backer rod and caulking ensured the airtightness
10	B	PR foil-e	An airtight membrane was adhered to side of window frame on one side, and on the other side to interior masonry brick wall. A thick layer of plaster connects plaster on wall to window frame.
11	B	PR foil-i	Similar to No. 10 (PR foil-e), but in this case the foil was adhered to the interior side of the window frame after the window was installed and fixed with brackets.
12	C	WF SP-PUR	Cavity between wooden frame and insulation and interior brick wall was filled

		-all	with spray-in-place foam. Plaster was applied over SP-PUR, but shrinkage induced crack was apparent between plaster and frame.
13	C	WF SP-PUR -all +C	Similar to No. 12 (WF SP-PUR-all), but there was no crack between plaster and wood framing, e.g. by means of caulking.

Table 2: Window installation methods in test setup A, B and C.

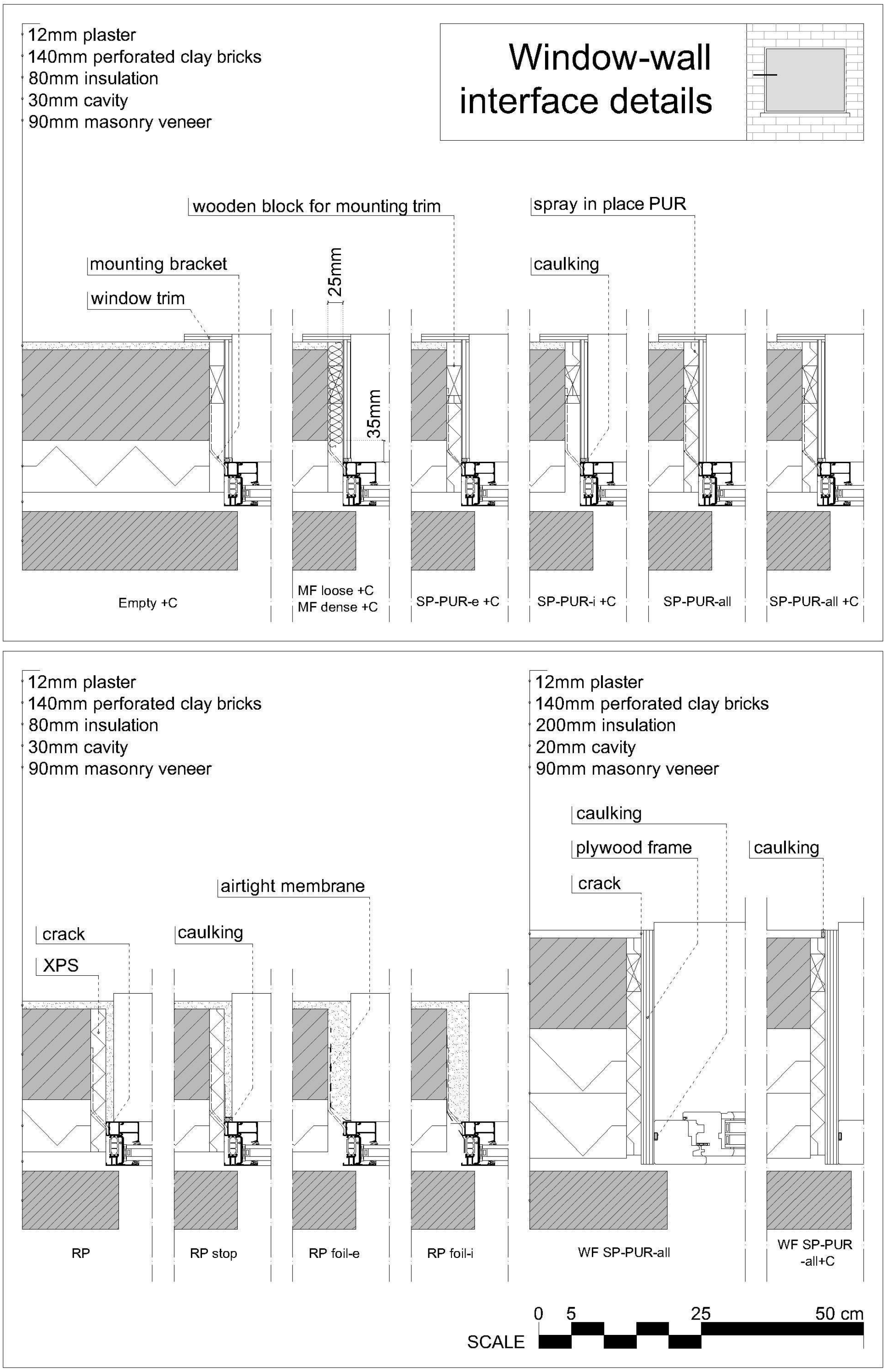


Figure 3. Window-wall interface details. Empty: no insulation in interface. C: caulking on interface with window. MF: mineral fibre insulation in interface. SP-PUR: spray-in-place polyurethane foam. e: insulation on exterior side of interface. i: insulation on interior side interface. all: interface completely filled with insulation.

RP: reveal covered with plaster. Stop: end profile for plaster is installed with caulking. Foil-i: foil adhered on interior side of window frame. Foil-e: foil adhered on side of window frame, on top of mounting brackets. WF: plywood frame is attached to window frame.

The third series of tests were done on a different wall that represented a situation for well insulated buildings (i.e. buildings having e.g. 200mm of insulation). Here the windows were installed using a plywood frame attached to the window profile: caulking was used at the corners between horizontal and vertical to ensure the airtightness. In the first test the cavity between interior brickwork and plywood was filled with SP-PUR, and plaster was applied over the SP-PUR just on to the plywood frame (WF SP-PUR-all). Due to the drying of the plaster there was also a shrinkage crack. In the second installation, the plaster was connected airtight to the wood framing by means of caulking.

RESULTS

The air leakage results through the different window-wall interface installation methods are summarized in Table 3. The leakage (V_{50}) was measured under both positive (pressure acting on the exterior side of the wall) and negative pressure, and for both values the standard deviation σ_v is reported based on the error propagation derived for the leakage coefficients as used in the power law. Table 3 also reports two air flow rates just below zero, which is obviously not possible. However, these were the results of the regression analysis, and one can easily see that a large part of the confidence interval lies above zero.

	POSITIVE		**NEGATIVE**		**AVERAGE**	
m³/h.m@50Pa	**V_{50}**	**σ_v**	**V_{50}**	**σ_v**	**V_{50}**	**σ_v**
Empty +C	**32,82**	2,04	**28,75**	2,06	**30,78**	2,06
MF loose +C	**11,29**	0,41	**11,99**	0,28	**11,64**	0,35
MF dense +C	**3,19**	0,26	**2,60**	0,21	**2,90**	0,24
SP-PUR-e +C	**1,23**	0,47	**0,90**	0,18	**1,06**	0,32
SP-PUR-i +C	**1,67**	0,19	**1,86**	0,16	**1,77**	0,18
SP-PUR-all	**1,79**	0,36	**0,94**	0,29	**1,36**	0,32
SP-PUR-all + C	**0,00**	0,28	**-0,01**	0,17	**0,00**	0,22
RP	**2,63**	0,18	**3,16**	0,29	**2,90**	0,24
RP stop	**0,08**	0,04	**0,07**	0,04	**0,08**	0,04
PR foil-e	**0,12**	0,14	**0,14**	0,13	**0,13**	0,14
PR foil-i	**0,24**	0,12	**0,13**	0,14	**0,19**	0,13
WF SP-PUR-all	**-0,03**	0,13	**0,24**	0,08	**0,10**	0,10
WF SP-PUR-all +C	**0,01**	0,09	**0,06**	0,08	**0,03**	0,08

Table 3. Air leakage of the 13 installation methods at 50 Pa.

Out of 13 tests, the air leakage of 7 samples show a higher leakage rate at positive pressure difference compared to a negative pressure difference, but only for 2 cases the error bars do not overlap. Similarly, only for two cases the flow at a negative pressure is significantly larger than the air flow at positive pressure. Conversely, based on the single-point measurements at 50Pa with smaller errors, 9 installation methods show a significantly higher air leakage for positive pressure differences, and 3 are significantly lower than the air flow at negative pressure difference. For most installations there is no obvious explanation for the difference in flow rate due to the direction of the pressure difference, except for the installations with airtight membranes where positive pressures induce ballooning of the membrane and thus higher flow rates. Note that only airtightness is reported in this paper; other aspects e.g. thermal performance may be equally important, but are not discussed here.

Test setup A

The tests showed that loose mineral fiber cannot adequately tighten the interface and consequently this resulted in significant air losses (11,64m³/h.m). Even densely packed mineral fiber still allowed quite significant air losses (2,90m³/h.m) as compared to the other installations. The use of SP-PUR performs reasonably well, even if the cavity between the interior brickwork and window trim is only partially filled. On the other hand, SP-PUR performs extremely well (0,00m³/h.m) if that cavity is completely filled and the joint between the window trim and window frame is tightened by means of a backer rod and caulking. If only the exterior side is filled (SP-PUR-e +C) air infiltrated through the joints of the brickwork. If there is SP-PUR on the interior side of the cavity, air might infiltrate through the interface of trim and frame, or through the joints of the different parts of the window trim (such as SP-PUR-i +C). SP-PUR-all was completely filled with spray in place foam, but contrary to the other installation methods, there was no caulking between trim and window which resulted in high local air flows located at the mounting brackets because the foam was unable to fill all the gaps and slits around the brackets. The results on this setup correlate quite well with the results found in literature (see Table 1) on airtightness of window-wall interfaces in wood-frame construction, although the results in this study are typically higher compared to that found in literature. This is probably because the interface in masonry construction is more irregular compared to wood frame construction. Contrary to wood, the masonry itself is not airtight which introduces a higher susceptibility to flaws and less redundancy at the interface.

Test setup B

The setup with the membrane adhered to the side of the window (PR foil-e) proved to be more airtight than the installation where the foil was installed from the interior side after the window was mounted (PR foil-i). The main locations for infiltration in both cases were the corners: for the first case the foil was folded with an overlength (at the corner the foil did not follow the perimeter; an additional 10cm was folded in order to cope with the difference in perimeter dimensions of window frame and window opening), in the second case the foil was not continuous at the corners, but locally cut for an overlap and fixed with caulking. The results on installations that rely on membranes for airtightness show good agreement with the results found in literature. One paper [22] reports high infiltration rates, but this was for poor installation quality which was not the case here.

Test setup C

Due to the drying of the plaster there was a shrinkage crack between plaster and plywood, but this only had a minor effect on the air losses. The difference in air flow between the installations with and without caulking was very small: the airtightness of the spray in place foam was also tested separately and was proved to be airtight. Both these installations could be recommended for use in passive homes. In practice, the plywood is typically covered with a gypsum board or other finishing. However, the tests done in the lab indicated the performance of the interface, regardless of the interior finish. Test results taken from the literature relating to window-wall installations using SP-PUR show similar levels of performance.

Practical implications

The interpretation of the absolute values can easily be understood by means of an example. Based on an extensive survey (Bossaer et al. 2008), one can assume that the average Flemish detached residential building has 105.0m of window-wall interface (including door to wall interface, excluding door sill, excluding garage doors), and an internal volume of 516.1m³. Figure 4 shows the share of the air loss through the different installation methods of the window-wall interface compared to the overall building air losses for a range of building airtightness levels. The legend is ranked according to the air loss, from leaky to tight (MF dense +C coincides with RP). The effect of choosing a different installation method can be found by following the black dotted lines: changing to a more airtight installation method will decrease the overall airtightness along the path of the dotted lines, depending on the original level of building airtightness. Consider a building with airtightness of $n_{50,A}$, air loss of the window-wall interface of $\dot{V}_{WWI,A}$, total length of the window-wall interfaces, L, and interior volume of the building V_b. The effect of a different window-wall interface ($\dot{V}_{WWI,B}$) can be calculated as follows:

$$n_{50,B} = n_{50,A} - \frac{V_{WWI,A} \cdot L}{V_b} + \frac{V_{WWI,B} \cdot L}{V_b} \qquad (12)$$

The sensitivity of the building airtightness to the window-wall interface installation method is thus quantified by the ratio L/V_b.

There are no absolute guidelines on how airtight a window-wall interface should be, or what proportion in air leakage a or a set of windows should have as compared to the overall air leakage of a building. Next to that, there is very little information on the actual airtightness of other components or interfaces in buildings with masonry cavity walls, or how significant their share is in respect to the overall air losses of the building. However, taking into account the numerous locations in a building where infiltration may occur, it seems advisable to set boundaries for the window-wall interface. For example, the air loss could be limited to 10% of the overall building leakage, which is a conservative value based on the comparative analysis of different sources of air leakage in residential buildings (Van Den Bossche, 2005). For a chosen building airtightness, it would be advisable that only the installation methods below the 10% line be used to avoid excessive air loss through the window-wall interface. Figure 4 indicates that this assumption is also feasible in practice, because for different levels of airtightness performance, a range of installation methods could comply with these requirements. The average building airtightness n_{50} of newly built detached residential buildings in Flanders is 6 air changes h^{-1}, which, if one considers the suggested 10% limit, results in a maximum air loss through the window-wall interface of 3,3m³/h.m at 50Pa. An airtightness of $3h^{-1}$ can be regarded as reasonably airtight and passive houses are very airtight ($0{,}6h^{-1}$). The air loss through the window-wall interface should be below respectively 1,6 m³/h.m at 50Pa and 0,33m³/h.m at 50Pa. Although these values are project-specific, they offer a reference to assess the performance of the measured installation methods. Note that this analysis was only done for an average detached residential building assuming a 10%-limit for air losses through the window-wall interface, and it is advisable to do this analysis for a project based on the actual interior volume of the building, the total length of the window-wall interfaces, and the required level of building airtightness.

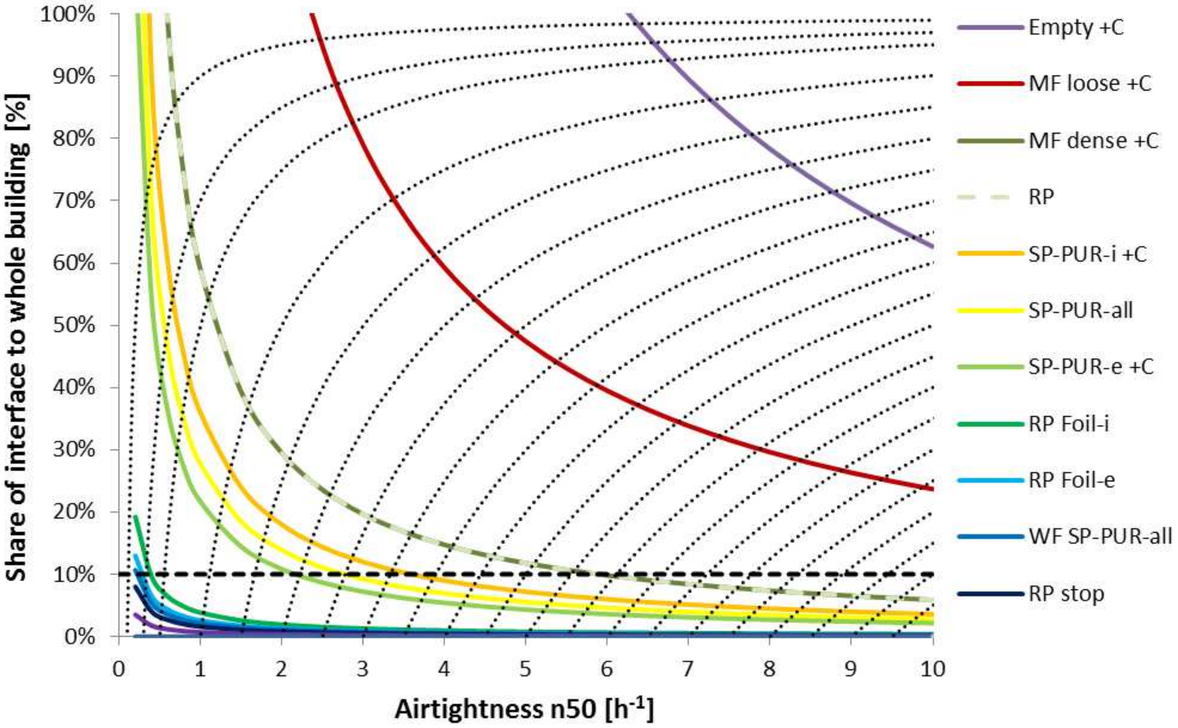


Figure 4. Proportion of air leakage through window-wall interface in relation to overall building airtightness

Based on the assumptions above, the installation methods designed as Empty +C and MF loose +C should in all instances be avoided. Whereas those methods designated as MF dense +C, RP, SP-PUR-i +C, SP-PUR-all and SP-PUR-e +C can be used for building airtightness requirements ranging between 2 and 6 h^{-1}, depending on the specific installation method. The other solutions (RP foil-e, RP foil-I, WF SP-PUR-all, RP stop, WF SP-PUR-all+C, SP-PUR-all+C) are recommended to achieve n_{50}-values below $1h^{-1}$ as might be used to achieve very low air leakage rates as for example passive homes.

CONCLUSIONS

For buildings in Belgium with a regular, code-compliant, thermal performance, recommendations were derived to limit the air losses through the window-wall interface: it seems advisable that these should be below 3,3m³/h.m at 50Pa. For passive houses, for which the energy loss requirements are significantly more stringent, the admissible air leakage decreases to 0,33m³/h.m. This is based on a detached residential building of average construction, for which an arbitrary limit of 10% of the total building air leakage was assumed; the overall effect will vary according to the internal volume of the building and the total length of the window-wall interface. For a specific project the effect of the window-wall interface on the overall building airtightness can easily be estimated using the results of this study.

The experimental results show reasonable correlation with the results found in literature for window-wall interfaces in wood-frame homes. No insulation or the use of loose fiber insulation to obtain adequate airtightness seems to be insufficient: the air loss was above 3,3m³/h.m (at 50Pa), whereas densely packed mineral fiber was only just below that limit. Only partially filling the cavity between the casing and the brick wall with SP-PUR is already a significant improvement, but the interior brick wall is not very airtight, and still allows some air to enter through cracks. When the entire cavity is filled with SP-PUR there is, in principle, a continuous airtight layer from wall to window frame. The performance of the installation method proved to be sensitive to errors during installation: the space behind the mounting brackets can be difficult to reach and should be completed with great care to ensure airtightness. However, such deficiencies are mitigated by installing caulking at the interface between the window casing and the window frame; in this instance, the air leakage is reduced to below 0,33m³/h.m. The results in respect to airtightness of the installation method using gypsum plaster on the reveal provided considerably higher air leakage rates than expected (2,90 m³/h.m); this is due to shrinkage cracks between the plaster and window frame. This situation was resolved either by using an end profile for the plaster with backer rod and caulking; or by applying an airtight membrane on the interface. Due to sensitivity to leakage at the window corners, the installation with a membrane adhered on the side of the window frame before installation proved to be more airtight than the case where the membrane was installed on the interior side. The solutions with end profile and membranes are sufficiently tight that these may be used when constructing very airtight buildings such as passive homes. The installation method for well insulated buildings using a plywood frame around the window was also very airtight (below 0,33m³/h.m), and this method incorporates considerable redundancy.

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