Airtightness of the window-wall interface in masonry brick walls

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ABSTRACT: There is a general consensus that buildings should be well insulated in order to reduce energy losses through transmission and increasingly, attention is paid to ventilation systems as a means of controlling energy losses by integrating heat exchangers and demand controlled control algorithms. However, contrary to the use of additional insulation and the implantation of ventilation systems, the requirement for airtightness is all too often disregarded in the construction industry today. Not only because the principle of airtightness may be more difficult to put into practice, but also because the effect is generally not taken into account in energy calculations unless a blower-door measurement has been completed. It is to be noted that blower-door measurements to determine airtightness is not standard practice in most countries with a moderate climate like Belgium. In order to stimulate the implementation of airtight construction practice more research is needed on airtight solutions in particular for masonry construction as this is the predominant method of building construction in Northern Europe (excluding the Scandinavian countries). This paper focuses on the performance of different solutions for ensuring the airtightness of the window-wall interface. The continuation of the airtight plane from the plaster to the window frame by an air seal can consist of, e.g., membranes, sprayed foam, gaskets and sealant joints. The performance of these different solutions are evaluated by lab experiments on a full scale mock-up of a masonry brick wall with a typical window of 1.23m wide and 1.48m high. The airtightness is measured on a standard test rig for window frames according to the procedure given in ISO 6589 and EN 12114. Based on the results of the experiments it was possible to formulate practical guidelines in regards to airtightness installation of windows for the building industry. Depending on the objectives concerning energy-savings of a specific project it would be possible to select a limited number of window-wall interface designs that can achieve the required level of overall airtightness for the building. Different types of interfaces may be desirable for standard practice, low-energy buildings and zero-energy houses. The results derived from this experimental work will help architects and contractors evaluate the quality of interfaces during and after completion on site.

1 INTRODUCTION

Throughout the last few decades an increasing number of countries are enforcing energy codes and existing codes are getting stricter. In addition, there has been a general increase in the price of energy (U.S. Energy Information Administration, 2008). An analysis of residential energy use between 1973 and 1999 and the relation between energy prices, building codes, income levels and final energy use per capita can be found in Unander et al. (2004). As well, the growth of an environmental awareness has placed energy efficiency on the political agenda. However, the trade-off between rising consumption and improving energy efficiency is superseded by the expanding economies of developing countries (Tol et al., 2009). Tol predicts that in the U.S. there will be no decrease in carbon dioxide emissions in the next few decades. Hence, it can be assumed that building codes and energy regulations will only get stricter.

Airtightness is an important factor in determing energy use in buildings. In a moderate climate like Belgium infiltration of cold air accounts for up to 20% of overall energy loss for code-complient buildings (VEA, 2009a). 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 (Mc Williams and Sherman, 2005). In general, the existing housing stock in colder climates is more airtight as compared to homes located in moderate climates (Sherman and Chan, 2004). One might expect that more airtight buildings are constructed over time due to rising energy prices and stricter building codes, but an analysis by Bossaer et al. (1998) on 51 houses built between 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 of Belgian detached residential buildings is 11.7 h^{-1} air changes at 50Pa pressure difference (Bossaer et al., 1998; results were recalculated to meet ISO 13829 requirements). These values are well above all recommendations in national standards (Limb, 2001) and typical measurements in the U.S., Canada and Sweden (ASHRAE, 1991). There is a clear need for more information on the airtightness of recently constructed buildings in Belgium.

Energy concerns are not the only reason to focus on airtightness. A lack of airthightness 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: less airtight constructions achieve lower pressure equalisation and during measurements high water infiltration rates were monitored.

2 LITERATURE REVIEW

Contrary to the overall insulation level of a building, the airtightness is not an area-averaged value. Any deficiency can have a major effect, so attention should be paid to every aspect of the building envelope. Research and guidelines are required on the airtightness of floors, walls, roofs, windows, doors, interfaces, penetrations etcetera. The typical construction method and materials of those 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 cavity brick masonry walls. These walls consist of an inner masonry wall of extruded clay brick, a cavity partially filled with insulation and an outer brick wall. The airtightness of the wall is secured by a layer of gypsum plaster, manually applied to the interior side of the interior brick wall. This type of wall is typical of north-western European building practice (e.g. Belgium, The Netherlands, Northern France, Great Britain). This section of the paper comprises an analysis of experimental data on the airtightness of window-wall interfaces found in literature, including some general guidelines or estimation techniques 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):

$$Q = C.\Delta P^{n} \tag{1}$$

With Q: air flow rate (m^3/h), C: flow coefficient ($m^3/h.Pa^n$), ΔP: pressure difference (Pa) and n: flow exponent (-). All results are converted into these quantities (discharge coefficient C_d for converting e.g. Equivalent Leakage Areas is assumed to be 1, flow exponent in general is 0.66). Results are summarized in Table 1 and classified into low, mean and high air leakages, but these classes can have a slightly different meaning, as explained below.

AIVC (Orme and Leksmono, 2002) reports median values (mean), 25%-fractiles (low) and 75%-fractiles (high) for window-wall interfaces (results based on laboratory and field tests, construction type undefined).

ASHRAE - US (1993) offers a ‘best estimate’(mean), minimum (low) and maximum (high) values for low-rise residential building applications (wood-frame and brick cavity walls). Although the results are expressed as air leakage per square meter, this is considered as a typographical error and should be reported as per meter joint; in this way the results have the right order of magnitude.

The *SENVIVV-study - Belgium* (Bossaer et al., 1998) reported an estimation technique for residential buildings. There is only one value for window-wall interfaces of brick cavity walls, regardless of execution method.

SBR – The Netherlands (van den Engel and Op’t veld, 2001) reports a mean and low reference value for the airtightness. The two classes may apply according to the type of ventilation system in the building.

Relander et al. - Norway (2008) did an extensive study on the airtightness of sealant methods in wood-frame houses. Five sealing techniques for a 15mm joint were tested (low), and for some methods the effect of faulty workmanship was characterized (high).

Proskiw – Canada (1994) reports leakage characteristics for eight different sealing methods for wood-frame constructions (13mm gap at side and top, 32mm gap at bottom). Every method was installed and tested five times by two different persons to obtain representative values. The minimum (low), mean and maximum (high) values are reported here.

Höglund and Jansson – Sweden (1984) tested the airtightness of five methods for sealing window-wall interfaces in wood-frame houses (joint width not reported).

Louis and Nelson – US (1995) reported measurements for a wood-frame construction and several brick cavity walls, but as the results are reported per window (window dimensions are not documented), these are not included in the summarizing table.

CMHC – Canada (1991) reported on the airtightness of 12.7mm wide joints in wood constructions before and after simultaneous exposure to extended pressure and temperature differentials. A selection of the initial results is reported here.

[m³/h.m] at 50Pa	low	mean	high
AIVC			
caulked joints	0.016	0.119	0.571
uncaulked joints	2.523	2.904	3.189
ASHRAE			
masonry, uncaulked	0.373	0.425	0.674
masonry, caulked	0.072	0.085	0.137
wood, uncaulked	0.098	0.111	0.177
wood, caulked	0.020	0.020	0.033
SENVIVV			
undefined	-	1.000	-
SBR			
undefined	1.040	2.080	-
Relander et al.			
Mineral wool	1.490	-	4.030
Self expanding sealing strips	3.930	-	10.870
Backer rod	0.970	-	1.240
Tape	0.000	-	-
Airtight membranes	0.310	-	6.960
Proskiw			
No treatment	4.867	4.965	5.176
Conventional fibreglass	1.592	1.830	1.997
high density fibreglass	0.530	1.239	1.628
backer rod	0.089	0.253	0.420
casing tape	0.003	0.013	0.021
poly-return	0.042	0.096	0.237
poly-wrap	0.002	0.015	0.027
PU foam	0.000	0.031	0.155
Höglund and Jansson			
mineral wool	-	5.000	-
plastic coated mineral wool	-	0.900	-
airtight membranes	-	0.100	-
caulking	-	0.100	-
foam	-	0.100	-
CMHC			
Mineral wool	1.305	4.004	10.797
Closed cell backer rod	0.033	0.058	-
Open cell backer rod	-	18.288	-

Table 1. Airtightness measurements of window-wall interfaces in literature

Most literature dealing with airtightness of window-wall interfaces originates from countries with 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 is 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.

3 EXPERIMENTAL SETUP

3.1 *Standards*

The airtightness of building components and building elements can be measured according to standard NBN EN 12114 (CEN, 2000) or NBN ISO 6589 (ISO, 1992). The testing procedure in both standards is very similar, although the CEN standard includes more specific restrictions and guidelines on the accuracy of the measurements.

The CEN standard suggest at least 7 measured points, with a maximum pressure difference in accordance to the appropriate product specification. In absence of such a specification, one of the following pressures should be assumed as maximum pressure: 50-100-200-500-1000 Pa. The ISO standard does not give any maximum values, but the test sequence should be: 50-100-150-200-300-400-500-600-(600 + X.250) Pa. Both standards specify three rapid pulses of 10% higher than the maximum pressure difference. Furthermore, both standards only require testing with positive pressures (external pressure on a building higher than internal pressure).

3.2 *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 (CEN, 2000). The specifications and accuracy lie well within the limits required by the standards mentioned above. 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. After the 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. Although slightly divergent from the generic airtightness test standards, it provides information for both positive- and negative pressure conditions. Next to that, the lab has been certified for airtightness testing on window frames for over 35 years, and by using an existing test protocol it is likely to achieve a higher degree of reproducibility.

The extraneous air leakage was measured before and after the first series of tests: the air leakage augmented with 0.68m³/h at 50Pa. The experimental data reported in this paper are calculated by subtracting the first extraneous air losses from the measured air flows. The change in extraneous leakage results in an additional 0.13m³/h.m at 50Pa for the lower error bar (Setup A). The extraneous air leakage of the other setup did not change. Hence a overestimation of the air losses is considered as a conservative approach.

3.3 *Measurement error*

The maximum error on the flow coefficient can be calculated using the 5% error limits on the air flow meter and 5% error on the pressure difference meter (maximum errors according to EN 12114). Assuming these are not correlated, and assuming a maximum flow exponent of 1, the maximum error becomes 7.1%. On one hand, by using the actual errors based on calibration measurements, the error changes over the spectrum based on the ranges of the 5 orifice openings used in the measurements, and is limited to about 3%. Whereas on the other hand, the measurement of the specific setup might be relatively accurate, the overall error in quantifying the installation method in general might be very large. Proskiw (1994) measured variation coefficients ranging from 0.03 to 0.85 (except for PU foam, where it was 2.24).

Furthermore, there are several other errors that need to be reported: the extraneous air leakage was measured by studiously taping an airtight polyethylene membrane on the corners of the test specimen. Hence, the interface of the tape with the test setup might be an additional error on the measurement, as well as the 2,058m² of plaster on the wall which was considered perfectly airtight.

3.4 *Test specimens*

In order to measure the airtightness of the window-wall interface in cavity brick walls, two test specimens were built to represent different situations. Test setup A was considered as common practice and comprised an aluminum window frame in a cavity brick wall with 8cm of polystyrene insulation and 3cm of cavity. Test setup B was thought representative of well insulated buildings, and consisted of a wooden window frame in a cavity brick wall with 20cm of polystyrene insulation and a 2cm cavity. Both windows are 1.23m wide and 1.48m high (according to the product standard NBN EN 14351-1, and representative for typical dimensions), and both walls are 1.92m by 2.02m (2m adjusted to brick modulation). The window frames were adjusted and sealed with tape to be perfectly airtight.

In test setup A the window was installed using typical mounting brackets, whereas in setup B – due to the fact that wide cavity brackets are not an option – there was a plywood framework to hold the window unit that could be fixed to the interior brick wall. In the test setups the horizontal projected gap between frame and wall is 2.5cm, which is typical and allows adequate tolerance. Note that the perimeter is not exactly the same for both setups because in setup B the plywood framework around the window requires a slightly bigger opening in the wall to have the same tolerance. In both cases the window is recessed 10cm from the outer wall plane. 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. All of the different materials used to fabricate the test specimens were randomly selected and installed by professional craftsmen. Caulking and SPF were always left for at least a day to cure, and plaster dried over two days.

In this first series of tests, no differentiation was made between the head, jambs or sill. Future test series will include sill configurations as well. Furthermore, it should be noted that the results represents the air leakage along the linear interface, as well as any local deficiencies situated at the corners. For test setup A the perimeter is 5.32m and this obviously includes 4 corners. It is more likely that the corners are less airtight than the linear joints due to additional interfaces and feasibility problems. As the results are expressed per meter of joint length, this implies that these result might underestimate the air leakage for windows with a lower area to perimeter ratio.

4 INSTALLATION METHODS

4.1 *Standard practice*

In test setup A the airtightness of seven different installation methods were measured using positive and negative pressures. The selection of the different installation methods was discussed with building practitioners, window installers and manufacturers in collaboration with the Belgian construction certification association group working on window-wall interfaces. Note that the plaster on the wall is applied just onto the corner where, according to common practice, an end profile is situated. Testing is still ongoing and will include different installation methods with membranes as well. Most common finishing systems are either window casings with trims, or full plaster systems. Figure 1 depicts the different methods in standard practice.

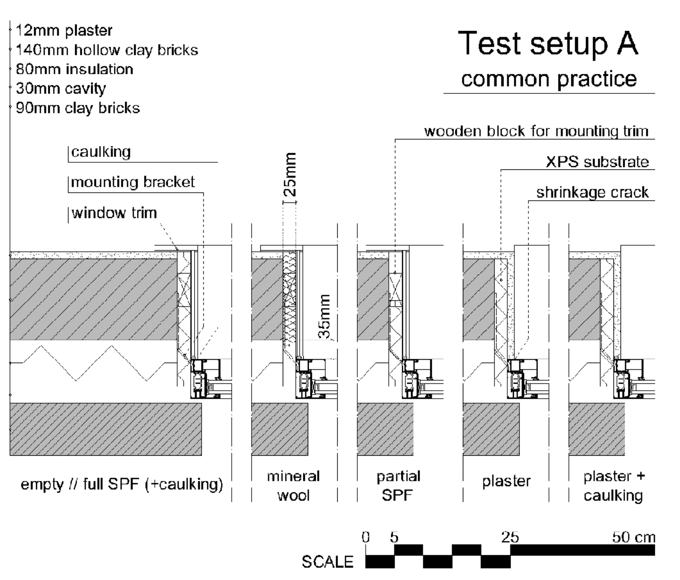

Fig 1. Installation methods – standard practice

Empty – the cavity between the brick wall and window casing and trim is empty. Although this is only seen in older buildings, it marks a reference point as worst case scenario.

Mineral wool – the cavity is packed with medium density mineral wool,.

Partial SPF – the cavity is partially filled with SPF. This might be more cost-effective as it is faster to install than the full SPF.

Full SPF – the cavity is entirely filled with SPF, but there is no caulking between the window frame and the window casement.

Full SPF + caulking – see full SPF; backer rod and caulking installed

Plaster – an XPS substrate is mounted to the masonry brick wall to cover the 25mm tolerance gap; a continuous layer of plaster is placed on to the window frame. A minor crack is induced between the window frame and the plaster due to drying shrinkage of the plaster.

Plaster + caulking – see Plaster; backer rod and caulking installed between the plaster and the window frame.

4.2 *Well insulated buildings*

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 cavity brick walls to comply with energy standards and in the expectation of 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 by installing a plywood framework all around the window frame. The latter technique was applied, because that is the most common approach used in buildings certified for extremely low energy usage (fig 2).

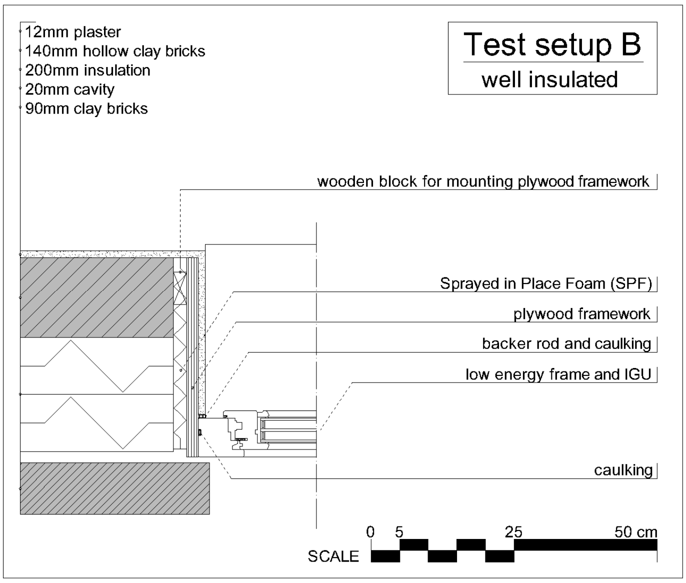

Fig. 2 Installation methods – well insulated

Full SPF – the cavity between the plywood frame and the insulation and interior brick wall is filled with sprayed in place foam. Between the window frame and the plywood frame there is caulking to ensure airtightness.

5 RESULTS

5.1 *Experiments*

Table 2 shows the results for the 7 airtightness measurements on test setup A, common practice, and 1 result for test setup B, well insulated. The average (positive and negative pressure) air flow rate at 50Pa per meter joint per hour is reported, including positive and negative absolute errors based on the calculation according to section 3.3 of this paper.

An empty casing results in very high air losses, which is only partly blocked with the installation of mineral wool. The effect of mineral wool insulation is in line with the measurements on window-wall interfaces in wood frame houses. The air leakage was slightly higher, probably because of geometrical boundary conditions which differ significantly due to the construction method.

In case of *partial SPF* the most important source of air leakage is the gap between the SPF and the plaster on the interior wall. Air can easily penetrate the brick wall with mortar joints, and flow along the uncaulked interface of the casing and the plaster to the inside. When the cavity between the casing and wall was completely filled with spray in place foam (*full SPF*), minor air flows were observed at the interface of the casing and the window frame. Indeed, those small leakage paths were located at the specific points where the mounting brackets of the window frame were fixed to the wall. Although the SPF installation was carefully done by an instructor of that particular product, it turned out that the mounting brackets might impede proper installation due to feasibility. When caulking was installed at the interface of casing and window frame (*full SPF + caulking*) the air loss was well below 0.05m³/h.m.

The use of plaster is considered to have a more modern look compared to the use of wooden casings from an architectural point of view. Furthermore, it should be quite straightforward to render airtight solutions for the installation method: airtight plaster is applied up to the window frame, and caulking can be used to make sure the joint in between is sealed. The caulking is not always applied in common practice, because the plaster is believed to adhere to the window frame to a sufficient degree as to avoid air leakage. However, due to the expected movement of the frame (e.g. thermal expansion, vibrations when opening and closing the window) the strain would likely be high enough to rupture the fragile bond at this interface. The results of the experiments on *Plaster* and *Plaster + caulking* are virtually identical, about 1m³/h.m at 50Pa. The effect of the caulking might be short circuited by the plaster that still adheres to the frame, but in any case the recorded air leakage is higher than expected.

The *full SPF* installation method for the well insulated test setup (with a plywood frame around the window) proved to be very airtight. The results are very similar to the *full SPF + caulking* on the setup according to common practice. This methodology basically integrates a triple barrier system: the SPF, the plywood frame around the window which is glued to the frame, and the continuous layer of plaster.

[m³/h.m] at 50Pa	average	error -	error +
Test setup A			
Empty	32.20	1.11	0.98
Mineral wool	6.54	0.34	0.21
Partial SPF	0.97	0.17	0.04
Full SPF	0.35	0.16	0.03
Full SPF + caulking	0.03	0.15	0.02
Plaster	0.99	0.18	0.05
Plaster + caulking	1.00	0.18	0.05
Test setup B			
Full SPF	0.098	0.02	0.02

Table 2. Experimental results

5.2 *Effect on overall building airtightness*

A study on 30 detached residential buildings in Belgium showed that the average area of windows and doors per house is 42.40m², and the average perimeter of windows and doors is 130.8m (Van Den Bossche, 2005). The average net interior volume of the buildings is 508m³, and the average measured airtightness 11.7h^{-1} at 50Pa (Bossaer et al., 1998; results were recalculated to meet ISO 13829 requirements). There are a few general recommendations on airtightness in Belgium: buildings with a balanced HVAC-system and HVAC-heat recovery system should have an airtightness below 3 h^{-1} and 1 h^{-1} respectively. For passive houses the limit is set to 0.6 h^{-1}. The Flemisch Agency for Energy also advises about 3 h^{-1} for low energy buildings (VEA, 2009b). Table 3 shows the relative contribution of the air leakage Q_{50} (air leakage at 50Pa) of the window-wall interface to the overall air leakage based on the averaged values mentioned above, for different levels of airtightness.

n_{50} \ Q_{50}	**5.0 m³/h.m**	**1.0 m³/h.m**	**0.3 m³/h.m**
11.7 h^{-1}	11.0%	2.2%	0.7%
3 h^{-1}	42.9%	8.6%	2.6%
1 h^{-1}	128.7%	25.7%	7.7%
0.6 h^{-1}	214.6%	42.9%	12.9%

Table 3. Relative contribution of air leakage through the window-wall interface to the overall building air leakage

The choice for a specific installation method depends on the required level of airtightness, and a whole range of practical considerations. Table 3 gives an indication of applicable installation methods for a specific project. Rather than suggesting a arbitrary maximum percentage to restrict the options, the choice should be made in consideration of e.g. financial cost, feasibility of proper installation on site and life cycle assessment. in comparison to other options to tighten the building envelope. An analysis by Van Den Bossche (2005) of 9 estimation techniques for the airtightness of existing residential buildings revealed that walls, roofs and floors represent about 40% of the overall air leakage; building envelope interfaces 15%; windows and doors 30%; and penetrations and local perforations 15%. Note that these percentages are only a vague indication, and change quickly when e.g. better windows are installed or cathedral roofs have proper air barriers.

6 DISCUSSION AND CONCLUSIONS

Airtightness is a key factor in the overall thermal performance of buildings. As energy codes become stricter, the relative importance of airtightness in achieving the requirements set out in the codes rises, so even for homes located in moderate climates it becomes a crucial parameter. A literature review shows that the airtightness of window-wall interfaces has previously been studied, but primarily in wood frame house construction. It was also evident from the results in this review that major differences in airtightness performance can arise due to poor installation, wrong product selection or local deficiencies. Comprehensive air leakage data on window-wall interfaces in cavity brick walls was not found. Solutions for ensuring adequate airtightness of brick cavity walls may face additional problems compared to wood frame construction. First of all, the general methodology to make walls airtight differs distinctly from methods to seal interfaces. Unlike the common air barriers and tapes used in wood frame housing, cavity brick walls rely on plaster for airtightness. Solutions require techniques which might not be common practice at this time. Secondly, typical tolerances in masonry brick walls are bigger than those in wood frame housing. Thirdly, the airtight layer on the wall and at the interface is typically hard to reach after installation, so repairs after inspection during e.g. a pressurization test is more difficult to complete.

The experimental results show reasonable correlation with the results found in literature for window-wall interfaces in wood-frame houses. The use of mineral wool to obtain adequate airtightness seems to be insufficient (> 5m³/h.m at 50Pa).

Filling the cavity between the casing and the brick wall only partially with SPF is already a strong improvement (1m³/h.m at 50Pa), but the interior brick wall is not very airtight, and still allows some air to enter via cracks.

When the entire cavity is filled with SPF 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 mounting brackets can be difficult to reach and should be completed with great care. By installing caulking at the interface between the window casing and the window frame this deficiency is repaired, and the air leakage drops from 0.35 to 0.03 m³/h.m at 50Pa.

The results of the installation method using plaster provided considerably higher air leakage rates than expected. At 50Pa the air leakage was 1m³/h.m, while a value below 0.5 or even 0.1m³/h.m was hoped for. No apparent leaks of deficiencies in the sample were observed. Further testing will be done to verify the results.

The installation method for well insulated buildings using a plywood frame around the window was very airtight (0.03m³/h.m at 50Pa), and incorporates considerable redundancy.

Future experiments will focus on installation methods with membranes, and the effect of installation flaws will be tested by providing typical deficiencies. Next to that, an assessment of different installation methods of sills is foreseen.

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