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Brick Cavity Walls: A Performance Analysis Based on Measurements and Simulations

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ABSTRACT: After world war two, cavity walls became a widespread external wall type in the cool but humid climate of North Western Europe. Moisture tolerance of the unfilled construction was excellent. Instead, calculation and testing underlined that the unfilled cavity walls of that era performed poorly from a thermal insulation point of view. After the energy crisis of 1973, cavity filling was therefore introduced as the main upgrade. Hence, extensive testing revealed upgrading was less simple than expected. Air in- and exfiltration through the wall, wind washing behind the fill, thermal stack induced air looping around the fill and thermal bridging all cooperated in lowering expected thermal quality of the filled walls. Anyhow, at the same time testing underlined that moisture tolerance remained outstanding in the cool, humid climate of North Western Europe also without cavity ventilation. That resulted in a set of recommendations how to construct high performing filled cavity walls.

KEY WORDS: cavity walls, thermal insulation, insulation efficiency, cavity ventilation, moisture tolerance.

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Figures 1, 6–8, 11, 12 and 14 appear in color online: http://jen.sagepub.com

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PREAMBLE

THIS ARTICLE IS part of a series which started masonry walls, insulated at the inside, followed by EIFS-insulated masonry walls. In it, performance of insulated envelope parts is analyzed using the outcome of laboratory research, field experiences and modeling.

INTRODUCTION

Brick cavity or brick rain shield walls, as they are called in North America, are a widespread external wall type in North Western Europe. Until the first energy crisis of 1973, they were composed of a 9–12 cm thick brick veneer, an air space (the cavity) and a 9–19 cm thick inside leaf in concrete blocks, perforated large format bricks or calcium silicate blocks, finished with an inside plastering (Figure 1). Although much older (Von Esmarch, 1902), this construction type gained most of its popularity after the Second World War. The reason for that was its superior rain-tightness. A cavity wall combines three lines of defense: run-off along the exterior surface, absorption by the veneer wall and run-off at the cavity side, with the cavity acting as a capillary break. The construction type also guaranteed a better thermal quality than a massive wall. The inside leaf in

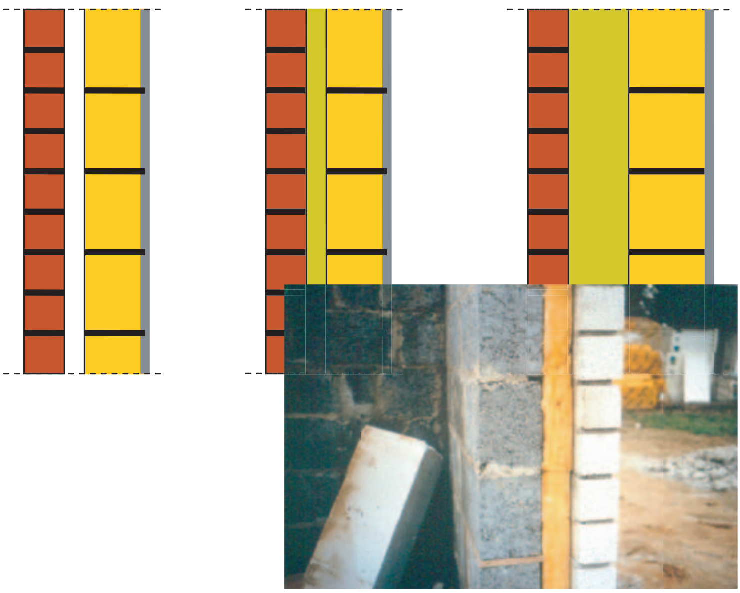

Figure 1. *Partially and fully filled cavity walls.*

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fact kept its thermal resistance independent of weather conditions while the air space added some 0.17 m K/W and the wetness of the brick veneer hardly affected the clear wall thermal transmittance of 1.4–1.9 W/(m^2 K) (Hisschemöller, 1960). That value was judged acceptable, especially because the wall's mass provided a good transient response.

With the energy crisis of 1973 and the necessity to increase energy efficiency, cavity filling gradually became normal practice. Between the seventies and early nineties, clear wall thermal transmittances equal or just below 0.6 W/(m^2 K) were seen as state of the art (Stichting Bouwresearch, 1976; Vos, 1980; Van Es and Kreijger, 1986; Hens and Mohamed, 1995; Anon, 1992). In the nineties, with the concepts of low energy and passive buildings emerging in the wake of the Kyoto agreement, a whole wall thermal transmittance around 0.2 W/(m^2 K) became a new reference in the cool climate of Belgium.

AN OVERVIEW OF BRICK CAVITY WALL RESEARCH

In the Netherlands B. Vos was the first to analyze cavity walls as a system with cavity ventilation as one of the issues (Vos, 1963). His conclusion was that ventilation added no benefit in terms of a better moisture tolerance. Cavity trays with weep holes above grade and above all openings to drain the cavity side run-off back to the outside were the solution. Later-on, he published a paper on rain penetration through brick veneers (Vos and Tammes, 1976) and tested the thermal performance of several insulating fills (TNO, 1980).

During the same period in the UK, rain penetration tests were conducted by BRE on walls of existing dwellings, having a brick veneer which hardly absorbed water, and a cavity which was <65 mm wide (Newman et al., 1982a,b). The results were alarming. Every wall with empty cavity showed leakage, while all cavity fills, except one, aggravated the problem. Hence, a detailed inspection of the unfilled walls revealed that careless bricklaying had turned some 55% of the ties into mortar bridges between the brick veneer and the inside leaf. However, even when most were cleaned before filling, still, water penetrated. There of course was a difference between the fills, with rock fiber and polystyrene beads behaving the best.

In 1984, the Fraunhofer Institut für Bauphysik in Germany published a very complete research report on filled cavity walls (Künzel, 1983; Künzel and Mayer, 1984). In a couple of follow up papers, Künzel argued that, as cavity ventilation had no real purpose, a complete fill is equally moisture tolerant as a partial fill. The fact that complete fills failed more frequently when subjected to a standardized wind driven rain test was blamed as being a consequence of the nonrealistic character of such test. (Künzel, 1990, 1991).

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The Laboratory of Building Physics of the K.U. Leuven, Belgium, started cavity wall research in the late seventies. Thermal bridging was the first topic to be looked at. In fact, in the early years after 1973, a cavity fill was an addition to a construction that was brick-laid as a noninsulated wall with the cavity closed around windows, with lintels, sills and floors contacting the brick veneer and without any perimeter insulation (Standaert, 1985). During the second half of the eighties, the attention shifted to air looping around the cavity fill. Lecompte proved that bad workmanship in terms of an air layer left between the fill and the inside leaf had devastating effects on the actual *U*-factor of a partially filled wall. An increase up to 250%, compared to the intended value of 0.35 W/(m^2 K), was measured (Lecompte, 1989). That result changed construction practice. In the years after, cavity ventilation was reassessed as designers and builders went on to believe in its supposed benefits (Hens and Mohamed, 1995). Research in the second half of the nineties went to field testing on cavity walls with an intended *U*-factor of 0.2 W/(m^2 K) (Hens et al., 2001). After 2000, cavity walls with glued concrete block veneer and open head joints between the blocks captured full attention (Hens et al., 2005)

PERFORMANCE ANALYSIS

The Array of Envelope Performances

The term performance applies to all quantifiable physical qualities, a building, a building component or a layer may have. Typical for true performances are predictability at the design stage and controllability during and after construction. Table 1 contains an excerpt of the array of envelope performances listed in the final report of IEA Annex 32 on Integral Building Envelope Performance Assessment (Hendriks and Hens, 2000). The further analysis uses that excerpt as a guide.

Air-Tightness

Air-tightness figures as an umbrella performance, which impacts thermal transmittance, dynamic thermal response, moisture tolerance, sound insulation, draft discomfort and energy consumption. As Figure 2 shows, several flow patterns are distinguishable, of which the most detrimental ones are: air infiltration and exfiltration, air looping and wind washing.

The air in- and out-flow rate g_a in kg/(m^2 s) is given by (ASHRAE, 2005):

$$g_a = C\Delta P_a^n \quad (\text{kg/(m}^2\text{s)}) \tag{1}$$

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Table 1. The annex 32 performances for heat and mass, acoustics and service life.

Topic	Performances
Heat and mass	Air tightness – Air permeance – Ventilation and wind washing – Buoyancy flow around the fill Thermal insulation – Clear and whole wall U-value Transient thermal response –Temperature damping –Dynamic thermal resistance –Admittance Moisture tolerance – Rain penetration – Interstitial condensation Thermal bridging – Temperature ratio
Acoustics	Airborne noise reduction
Service life	Physical attack (stress and strain due to moisture and temperature gradients, frost attack, salt attack) Chemical attack Biological attack

with C the air permeance coefficient in $\mathrm{kg/(m^2\,s\,Pa^n)}$, n the air permeance exponent and ΔP_a the difference in air pressure over the wall at the spot under consideration. That difference combines wind over- or under-pressure with stack effects and fan over- or under-pressure. The formula is typically rewritten as $g_\mathrm{a} = K_\mathrm{a}\Delta P_\mathrm{a}$ with K_a $(= C\Delta P_\mathrm{a}^{n-1})$ the air permeance.

Veneer walls are not airtight. In fact, the air permeance coefficient (C) may vary between $3.5 \times 10^{-5}\,\mathrm{kg/(m^2\,s\,Pa^n)}$ for well pointed masonry and no open head joints above cavity trays to $6 \times 10^{-3}\,\mathrm{kg/(m^2\,s\,Pa^n)}$ for un-pointed masonry and open head joints above cavity trays. The air permeance exponent n changes from 0.8 in case a veneer is correctly pointed and has no open head joints to 0.5 when two or more head joints per meter run are open. If an air pressure difference of 50 Pa is maintained across the veneer, the numbers given result in air in- or outflows between 2.4 and 127 $\mathrm{m^3}$ per square meter of wall and per hour (Hens, 2006).

Analogous air permeance coefficients and exponent values are measured for inside leafs without plaster finish. Acceptable air-tightness of a cavity wall, therefore, is only achievable if the inside leaf gets a plaster finish. In such case, the air permeance coefficient may be as low as $10^{-5}\,\mathrm{kg/(m^2\,s\,Pa^n)}$, which gives air in- or out-flows at 50 Pa air pressure difference below 1.5 $\mathrm{m^3}$

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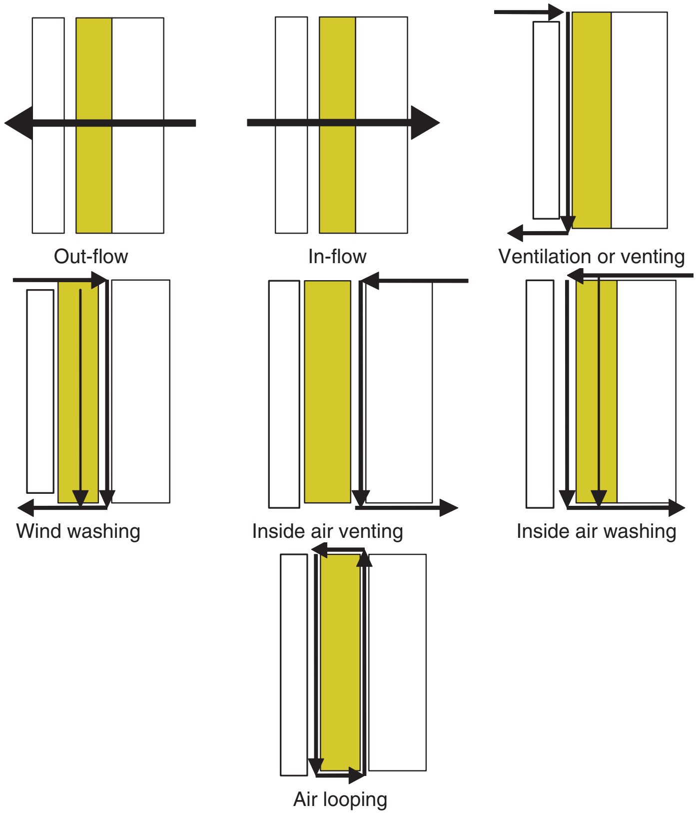

Figure 2. *The different air flow modes in cavity walls.*

per square meter of wall and per hour. Good air-tightness is a prerequisite for excellent hygrothermal and acoustical performance (Hens, 2006).

If exact information is lacking, then the permeance coefficients (C) and exponents n of Table 2 are a safe choice.

Wind washing behind the cavity fill and air looping around the fill become obvious when that fill is not firmly pressed against the inside leaf, so leaving an air layer there, and if unfilled space is left at the top and bottom of the cavity (Figure 3).

Clear Wall and Whole Wall Thermal Transmittance (U_o, U)

CLEAR WALL

Let us first assume perfect air-tightness. Without cavity fill, the clear wall thermal transmittance (U_o) of a masonry cavity wall touches

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Table 2. Default values for the air permeance of cavity walls.

Wall	C kg/(m^2 s Pa^n)	$n-1$ –
Brick veneer, pointed with two open head joints per meter	2×10^{-3}	0.55
Inside leaf, pointed but not plastered, bricks	4×10^{-5}	0.8
Inside leaf, pointed but not plastered, air permeable blocks	4×10^{-4}	0.75
Inside leaf, plastered	10^{-5}	0.8

Figure 3. *Practice example of bad workmanship, leading to air layers at both sides of the fill and a huge air gap at the bottom of the cavity.*

1.4–1.9 W/(m^2 K), which is much higher than actually preferable. With a 4 cm thick PUR partial fill or a 6 cm thick mineral fiber full cavity fill, a 14 cm thick lightweight brick inside leaf and the typical 30 cm wall thickness as used in Belgium, the lowest clear wall thermal transmittance achievable

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is 0.34 W/(m^2 K), i.e., too high to deserve the qualification low energy. That demands a value 0.2 W/(m^2 K) or less. Realizing such low value demands a thicker wall with as a result a loss in net or an increase in gross floor area and therefore an extra increase in costs. Minimum thickness needed in fact is 39 cm, of which 15 cm goes to the cavity, fully filled with mineral fiber or partially filled with 10–12 cm thick PUR-boards.

An air-permeable masonry cavity wall shows a different response. In fact, infiltration and exfiltration turns the wall into a heat exchanger between the conduction mode and the air-linked enthalpy flow. The result is a steady state conduction flow, which varies along the flow path and a clear wall thermal transmittance which depends on the location in the wall, where the conduction flow is considered. Its value increases from the inside to the outside for air exfiltration and decreases from the inside to the outside for air infiltration. The difference with the constant conduction-based clear wall thermal transmittance, an airtight wall has, augments with increasing airflow rate. If we restrict the clear wall thermal transmittance caption to the inside and outside surface, then the values become:

$$\begin{array}{ll} \text{At the inside surface} & \text{At the outside surface} \\ U_{\text{inside}} = \left|\dfrac{c_a g_a}{1-\exp(c_a g_a R_T)}\right| & U_{\text{outside}} = \left|\dfrac{c_a g_a \exp(c_a g_a R_T)}{1-\exp(c_a g_a R_T)}\right| \end{array} \tag{2}$$

with g_a the density of airflow rate in kg/(m^2 s), negative for infiltration and positive for exfiltration, c_a the specific heat capacity of air in J/(kg K) and R_T the thermal resistance environment to environment of the airtight cavity wall in m K/W. Equations (2) follow from the solution of the steady state one-dimensional conservation of energy equation in a medium where mass transport along the axis considered takes place:

$$\frac{d^2\theta}{dx^2} - \frac{c_a g_a}{\lambda}\frac{d\theta}{dx} = 0. \tag{3}$$

In that equation, g_a is the air flux along the x-axis, c_a is the specific heat capacity of air and λ is the thermal conductivity of the material. Figure 4 gives the increase and decrease of the conduction-related clear wall thermal transmittance if measured on the inside surface for a wall with a nonrendered concrete block inside leaf. Despite 15 cm of cavity fill, the apparent clear wall value touches 2.72 W/(m^2 K) at the inside when the outside air pressure is higher then 16 Pa. Of course, in- and exfiltration always develop simultaneously, the one at the windward and the other at the leeward side or the one below and the other higher up in case of stack flow, resulting in heat recovery and less energy needed in comparison to a system

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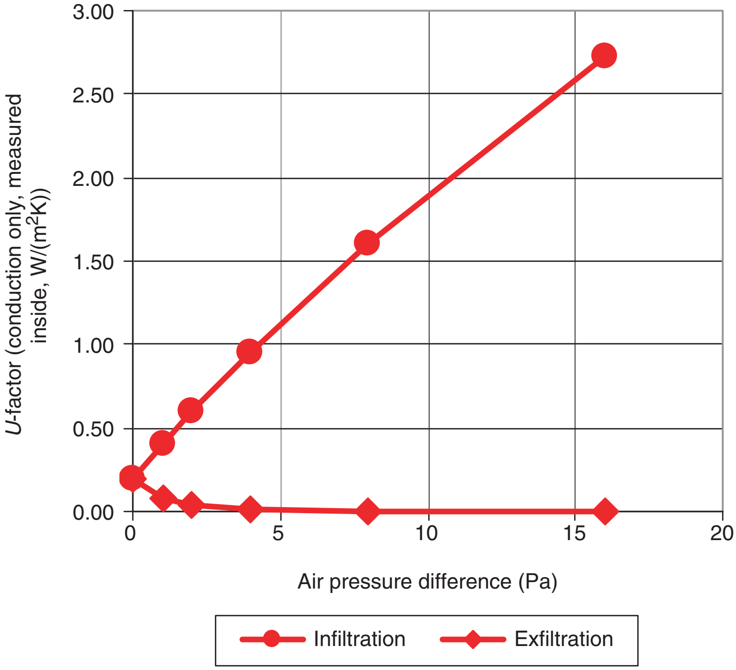

Figure 4. *Apparent clear wall thermal transmittance by heat conduction only as measured at the inside of an air permeable filled cavity wall.*

where the same airflow enters through ventilation grids (Buchanan and Sherman, 2000).

The above results hold in case the cavity fill is perfectly constructed. To overcome imperfections some designers still consider cavity ventilation as a necessity. For that purpose, two head joints per meter run are kept open in the veneer wall at the bottom and the top of each floor, while the cavity gets a partial fill. If, in such case, an air layer is left behind the fill and if the top and bottom of the cavity remain unfilled, then wind entering the cavity through the upper open head joints will wash the air layer behind. In highly insulated cavity walls, the effects on the clear wall thermal transmittance are quite accurately predictable, using a model which assumes exterior conditions in the cavity at the veneer side and a washing flow behind the fill given by:

$$G_{a2} = G_a \frac{d_2^3}{d_1^3 + d_2^3} \tag{4}$$

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where G_a is the total air flow entering through the open head joints, d_1 is the average thickness of the cavity between veneer and cavity fill and d_2 is the average thickness of the air layer behind the fill. The effective clear wall thermal transmittance then is close to:

$$U_{eff} = U_o\left[1 + \frac{R_{12}}{R_{i2}H} f(B_2)\right] \tag{5}$$

with $B_2 = (R_{2i} + R_{12})/(R_{2i}R_{12}c_aG_{a2})$ and $f(B_2) = [1 - \exp(-B_2H)]/B_2$. That equation assumes a constant washing flow in the air layer behind, while conduction from the inside and conduction across the insulation layer are considered one-dimensional and perpendicular to the air layer. These assumptions give as energy balance for an elementary height dh:

$$\frac{\theta_i - \theta_{c2}}{R_{2i}} + \frac{\theta_1 - \theta_2}{R_{12}} = c_a G_{a2}\frac{d\theta_2}{dh} \tag{6}$$

i.e., a differential equation of first order, which is easily solved. That solution allows calculating Equation (5). In both equations, R_{2i} is the thermal resistance between the middle of the air layer behind the insulation and inside, R_{12} the thermal resistance of the insulation included half of the thermal resistances of the two air layers, H the distance between the open head joints below and above and G_{a2} the washing flow. Figure 5 gives results for a highly insulated cavity wall and a wind pressure difference between the open head joints above and below, ranging from 1–16 Pa. The increase in apparent clear wall thermal transmittance is highly non linear and quite disastrous. While an air layer of 15 mm behind the fill adds some 20% to the clear wall value, that addition becomes 100% if that layer becomes 20 mm wide!

Thermal looping gives an analogous increase in clear wall thermal transmittance (Lecompte, 1989). In such case, temperatures in the cavity behind the veneer and in the air layer behind the fill are approximated by

$$\frac{d^2\theta_1}{dz^2} + B\frac{d\theta_1}{dz} + C\theta_1 = D_1 \qquad \frac{d^2\theta_2}{dz^2} + B\frac{d\theta_2}{dz} + C\theta_2 = D_2 \tag{7}$$

with:

$$B = \frac{P_{e1} + 2P_{12} + P_{2i}}{1000G_a} \qquad C = \frac{P_{e1}P_{12} + P_{2i}P_{12} + P_{e1}P_{2i}}{1000^2G_a^2}$$
$$D_1 = \frac{P_{e1}(P_{12} + P_{2i})\theta_e + P_{12}P_{2i}\theta_i}{1000^2G_a^2} \qquad D_2 = \frac{P_{2i}(P_{12} + P_{e1})\theta_i + P_{12}P_{e1}\theta_e}{1000^2G_a^2} \tag{8}$$

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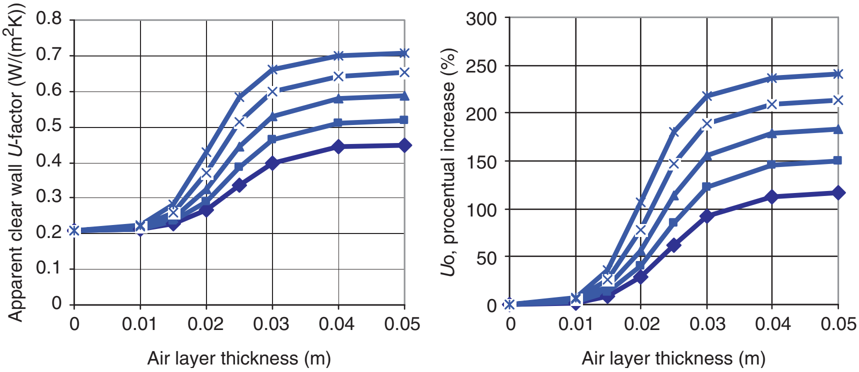

Figure 5. *Apparent clear wall thermal transmittance of a filled cavity wall suffering from wind washing in the air layer behind the fill with wind pressure difference as parameter and the thickness of that air layer as ordinate (from highest to lowest curve: 16 Pa, 8 Pa, 4 Pa, 2 Pa, 1 Pa).*

with P_{e1} thermal permeance between the outside and the middle of the air layer between the veneer wall and the cavity fill, P_{12} thermal permeance across the cavity fill from the middle of air layer before and the air layer behind the fill, P_{2i} thermal permeance between the middle of the air layer behind the fill and inside and G_a the looping air flow, whose value follows from the equilibrium between the stack force and the flow resistance over the loop around the fill. The effective thermal transmittance in such case is close to:

$$U_{\text{eff}} = U_{\text{o}}\left[1 + \frac{1}{r_1}\left(\frac{a-1}{a+1}\right)\frac{R_{12}}{R_{i2}H}\right] \tag{9}$$

where r_1 is the root $(-B - \sqrt{B^2 - 4C})/2$ of the Equation (7), while the coefficient a is equal to $\exp(r_1 H)$. Table 3 lists some experimental results, while Figure 6 proves the existence of looping through an infrared picture of an outside leaf.

In reality, thermal looping and wind washing act in combination, making things even worse, as is put in evidence by the test building results of Tables 4 and 5. In both tables, bad workmanship refers to open joints left between the insulation boards in combination with an air layer behind the fill, while good workmanship refers to care in mounting, leaving no open joints and no air layer behind. The data underline that a badly mounted mineral fiber full fill is less sensitive to looping than a badly mounted foam board full and partial fill. Comparison of the values before and after

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Table 3. Partially filled cavity wall, hot box test results showing the effect of air looping on the measured effective U-value (Lecompte, 1989).

Cavity wall

2 m height, 10 cm wide cavity, 50 mm XPS fill, movable veneer wall

		Open joints		Bounday conditions		*U*-value W/(ṁ K)	
Cavity fill/veneer (mm)	**Air layer fill/inside leaf (mm)**	**Up (mm)**	**Under (mm)**	θ_e (°C)	θ_i (°C)	**Intended**	**Effective**
45	**5**	0	0	1.0	19.7	**0.35**	**0.35**
		2	2	1.0	20.1	**0.35**	**0.39**
		5	5	0.9	19.1	**0.35**	**0.41**
		18	18	0.9	19.9	**0.35**	**0.42**
40	**10**	0	0	1.5	21.3	**0.34**	**0.34**
		2	3	0.8	20.0	**0.34**	**0.49**
		7	3	0.8	19.1	**0.34**	**0.51**
		11	8	1.6	22.4	**0.34**	**0.73**
		22	17	1.6	23.0	**0.34**	**0.75**
25	**25**	0	0	1.2	23.0	**0.35**	**0.36**
		2	3	1.0	20.8	**0.35**	**0.41**
		5	5	1.0	18.7	**0.35**	**0.73**
		18	18	1.1	18.1	**0.35**	**0.84**

air-tightening shows that no exfiltration worsens the results. The reason for that is simple. The heat flux by conduction was measured at the inside surface. With exfiltration, the temperature line in the wall turns from linear to concave exponential, resulting in less conduction there.

Clearly, air looping and wind washing should be avoided by all means. That demands an airtight inside leaf with pointed cavity side, a fill consisting of boards with soft backside that are pressed perfectly against the inside leaf and the use of screwed ties. An alternative is gluing the insulation boards against the inside leaf, the way EIFS-boards are fixed.

WHOLE WALL

The step from the clear to the whole wall thermal transmittance mobilizes thermal bridging. The whole wall thermal transmittance (U_{ww}) is calculated as:

$$U_{ww} = U_{cw} + \frac{\sum_{i=1}^{m} \psi_i L_i + \sum_{j=1}^{n} \chi_j}{A} \qquad (10)$$

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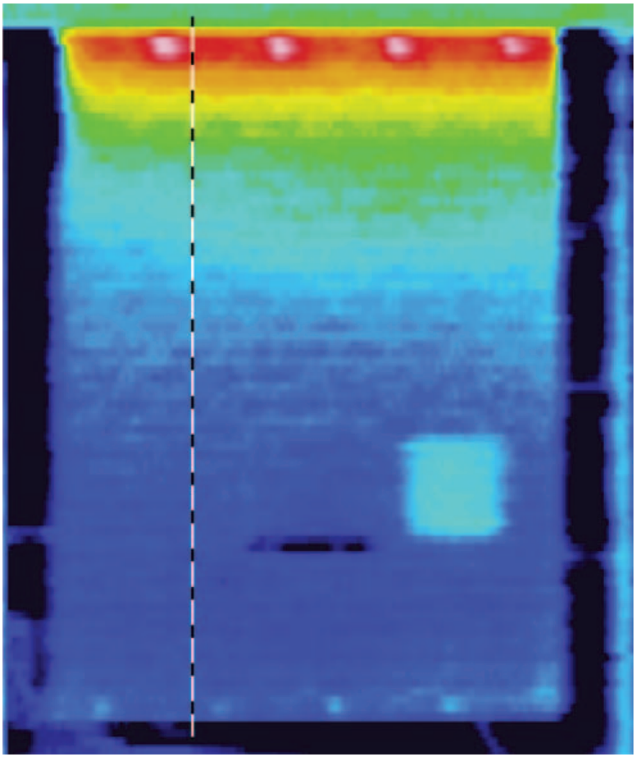

Figure 6. *Infrared picture of a brick veneer with a filled cavity behind suffering from air looping around the insulation.*

Table 4. Vliet test building, effective clear wall U-values, combined effect of thermal looping, wind washing and exfiltration.

Cavity wall: veneer filled cavity inside leaf, no render Workmanship?	**Fill**			**Measured *U*-value W/(m^2 K)**			
				First winter		**Second winter**	
	Partial	**Full**	**Intended *U*-value W/(m^2 K)**	**SW**	**NE**	**SW**	**NE**
Poor		MF	**0.22**	**0.37**	**0.32**	**0.39**	**0.33**
Good		MF	**0.22**	**0.22**	**0.21**	**0.21**	**0.21**
Poor	XPS		**0.21**	**0.86**	**0.86**	**0.86**	**0.86**
Good	XPS		**0.21**	**0.23**	**0.21**	**0.23**	**0.21**
Poor		XPS	**0.21**		**0.51**	**0.60**	**0.79**
Good		XPS	**0.20**	**0.21**		**0.22**	**0.22**

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Table 5. Vliet test building, effective clear wall U-values after air-tightening (a-t) the inside leaf. Combined effect of thermal looping and wind washing.

Cavity wall: veneer filled cavity inside leaf, no render Workmanship?	Fill		Intended U-value W/(m^2 K)	Measured U-value W/(m^2 K)			
				Second winter Before a-t		Second winter After a-t	
	Partial	Full		SW	NE	SW	NE
Poor		MF	0.22	**0.39**	**0.33**	**0.44**	**0.35**
Good		MF	0.22	**0.21**	**0.21**	**0.22**	**0.22**
Poor	XPS		0.21	**0.86**	**0.86**	**0.94**	**1.03**
Good	XPS		0.21	**0.23**	**0.21**	**0.27**	**0.21**
Poor		XPS	0.21	**0.60**	**0.79**	**0.68**	**0.94**
Good		XPS	0.20	**0.22**	**0.22**	**0.22**	**0.22**

with U_{cw} the clear wall thermal transmittance of the cavity wall, ψ_i the linear thermal transmittance of all linear thermal bridges in the surface A, L_i their length and χ_j the point thermal transmittance of all local thermal bridges within the surface A_i. Critical spots in cavity wall design and construction are the node with the floor on grade and the foundation wall, lintels above windows, the window reveals, the sills below the windows, the roof edges, balconies and others (Figure 7). If these details are solved as the figure shows on the right side for the window perimeter, then the whole wall thermal transmittance may stay acceptably close to the clear wall result. Of course, when clear wall values below 0.2 W/(m^2 K) are required, then, still, even with thermally correct details, the increase may pass 30%. Also see (Anon, 1996a,b).

Transient Response

The transient thermal response of an opaque envelope part is reflected in its temperature damping for a repetitive daily harmonic change in outside temperature, its dynamic thermal resistance for a repetitive daily harmonic change in outside temperature and a constant inside temperature and its admittance for a repetitive daily harmonic change in inside temperature at constant outside temperature. From a damping and admittance point of view, even a noninsulated, airtight brick cavity wall outperforms a well insulated timber framed wall. Filling the cavity greatly enhances damping and pushes the dynamic thermal resistance to much higher values.

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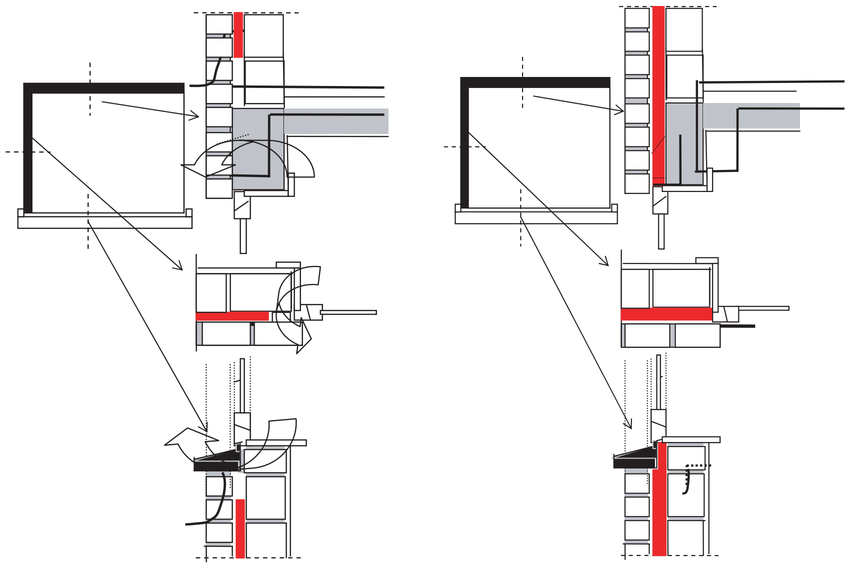

Figure 7. *Detailing the window perimeter, the bad and the good.*

The admittance, however, hardly changes, as the 24 h values in Table 6 underline.

All that changes when the wall is air permeable and outside air infiltrates. Figure 8 shows how temperature damping and the dynamic thermal resistance of an air permeable cavity wall with 15 cm mineral fiber cavity fill both deteriorate while the admittance increases a little.

However, one should not overestimate the importance of a high temperature damping, a high dynamic thermal resistance and a high admittance. In cool climates, the transients do not impact energy consumption for heating, while avoiding summer overheating demands above all less solar gains and well designed night ventilation. The first is achieved by limiting the glass surface at the sun-sides or installing controllable outside solar shading devices there, while for night ventilation to be effective, accessible thermal mass, expressed in terms of enough inside surfaces with high admittance, is needed.

Moisture Tolerance

CAVITY VENTILATION

Unfilled Cavity Walls

Unfilled cavity walls were renowned for their moisture tolerance. The heaviest moisture load – wind-driven rain – was barred by drainage

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Table 6. Harmonic properties of a filled cavity wall for an oscillation period of 24 h.

	Temperature damping		Harmonic thermal resistance		Admittance	
Wall	**–**	**Time lag (h)**	**(m^2 K/W)**	**Time lag (h)**	**(W/(m^2 K)**	**Time lag (h)**
Partial fill, inside leaf masonry 14 cm thick, plastered						
3 cm XPS, $U_o = 0.56$ W/($\dot{m}$ K)	23.9	11.3	6.5	9.7	3.7	1.6
12 cm XPS, $U_o = 0.24$ W/($\dot{m}$ K)	66.1	12.3	17.8	10.7	3.7	1.6
Complete fill, inside leaf masonry 14 cm thick, plastered						
5 cm MF, $U_o = 0.51$ W/($\dot{m}$ K)	30.4	11.6	8.1	10.0	3.8	1.5
15 cm MF, $U_o = 0.21$ W/($\dot{m}$ K)	85.2	12.6	22.6	11.1	3.8	1.5

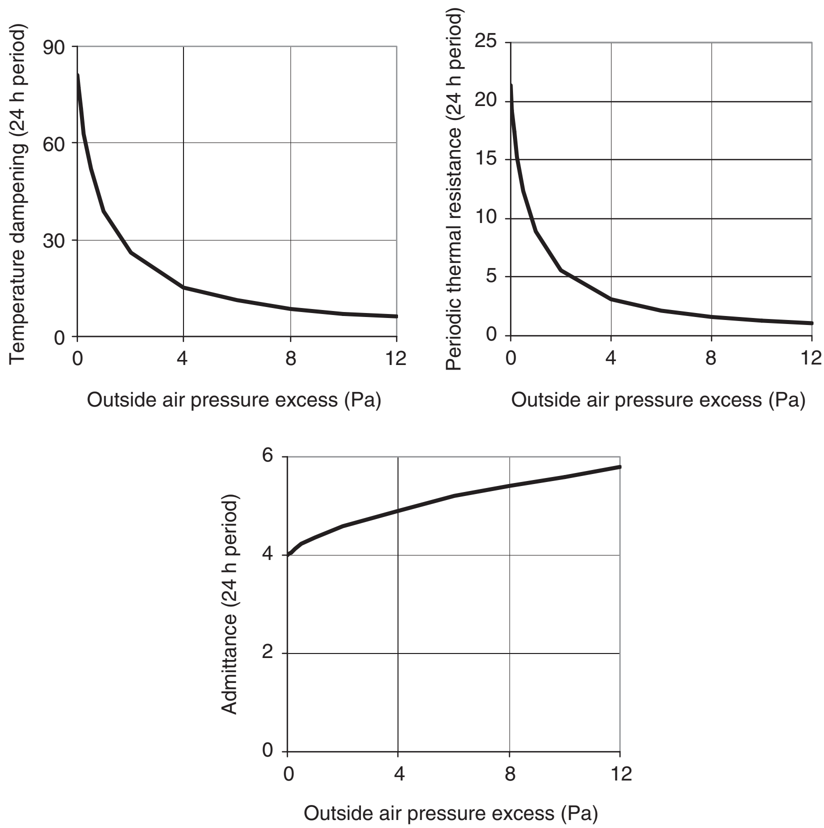

Figure 8. *Temperature damping, dynamic thermal resistance and thermal admittance of a $U = 0.2$ W/(m^2 K) filled, air permeable cavity wall in infiltration mode.*

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at the outside surface, buffering by the brick veneer and run-off at the veneer's backside, the main mechanism for leakage to the cavity side being gravity flow through micro-cracks between brick and mortar in the head joints. Only a small percentage of that cavity side run-off reached the bottom of the cavity where a tray directed it back to the outside. The rest was sucked by the bricks and joints. Built-in moisture dried easily to the in- and the out-side, while interstitial condensation caused no harm at all. Even if some vapor humidified the veneer from inside, the amounts were minimal compared to the rain sucked.

The high thermal transmittance in fact figured as the only weakness of such unfilled wall. Especially behind furniture, a monthly mean inside surface relative humidity beyond 80% was not unlikely, resulting in fouling and mould growth.

Despite that trustable moisture tolerance and despite the research results commented above, many went on promoting cavity ventilation as a necessity to maintain moisture tolerance. Drying was thought to be strongly enhanced that way, so making the veneer less prone to frost damage, while ventilation was also said to compensate for negligent workmanship and to assure 'breathing'. None of these arguments is based on physical evidence. Firstly, as calculation, summarized in Figure 9, show, brick veneers are too air permeable to have a nonvented cavity. For 0°C outside and 20°C inside in still weather the figure pictures the air passing the veneer and shows the flow along a 6 cm wide unfilled cavity with an airtight inside leaf. Secondly, ventilation has a positive and a negative effect on drying. It in fact lowers vapor pressure in the cavity, enhancing drying this way, but decreases the average winter temperature in the veneer, retarding drying that way. The result is such marginal increase in drying rate that the word 'strongly' must be quoted as completely exaggerated. Finally, negligent workmanship of course is a completely wrong argument as this may create the impression that ventilated cavity walls do not demand care in brick-laying. Ventilation is a measure without any true advantage. The only thing needed are the trays at the bottom of the cavity and above lintels and two open head joints per meter run above it in the veneer wall.

Filled Cavity Walls

The query about ventilation got more intense after cavity filling started. At that time, erroneous interpretation of the dew-point method, believing that the whole zone with a dew-point above the local temperature experienced interstitial condensation, convinced many practitioners a full fill turned wet by the phenomenon while a partial fill facing a ventilated cavity remained dry. So, full fills were quoted as unacceptable. First mistake of course was the misinterpretation of the dew-point method.

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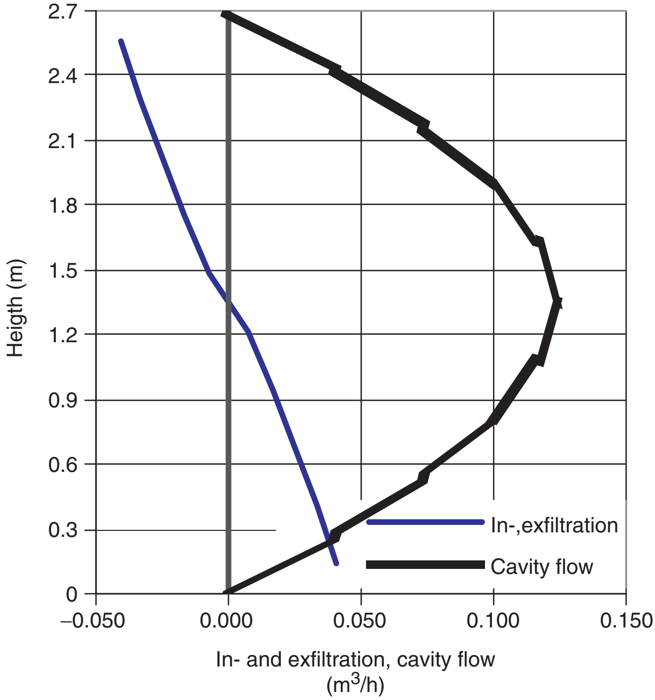

Figure 9. *In- and exfiltration through the brick veneer and venting flow in the cavity.*

As partial water vapor pressure at a given temperature can never pass saturation pressure at that temperature, a dew-point line can never cross a temperature line. The only thing possible is the vapor pressure line becoming a tangent to the saturation pressure course. With that in mind, one may prove that in winter interstitial condensation in a filled cavity wall, if any, is always deposited against the cavity side of the veneer wall, where the condensate is sucked by the bricks or runs off, just as rain that penetrates the head joints does.

Anyhow, because of the rumor around it, cavity ventilation was nevertheless picked up again and studied through laboratory and field measurements on walls with a partial filled and compared with fully filled walls, see Figures 10 and 11 (Hens et al., 1955). Especially the laboratory results, summarized in Figure 10, tend to support the claims cavity ventilation accelerates drying and thus, is a necessity. An in depth analysis of the results, however, showed that wetting by the simulated rain events was so intense, that even the outer surface of the full fill

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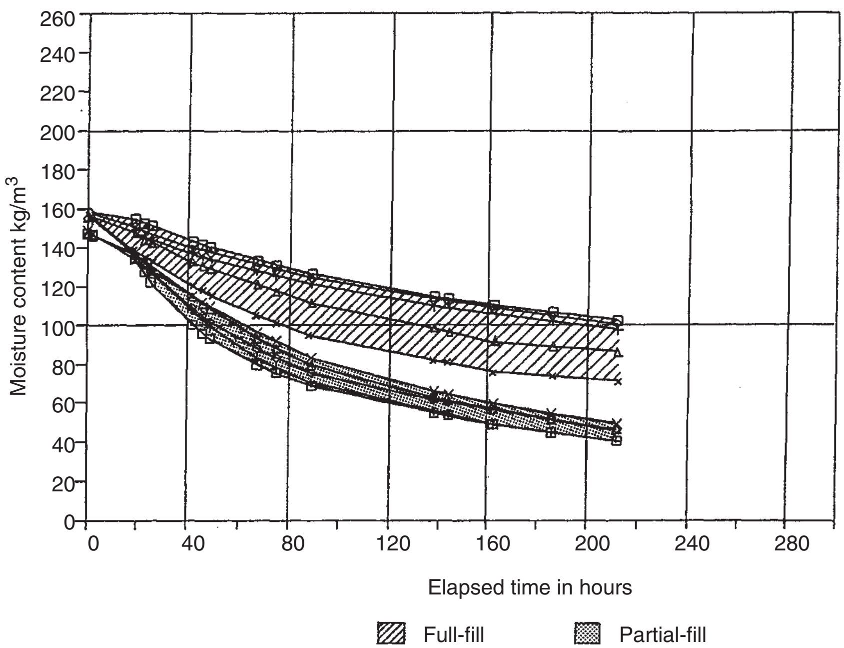

Figure 10. *Steady state drying of the brick veneer of a vented, partially filled and a fully filled cavity wall.*

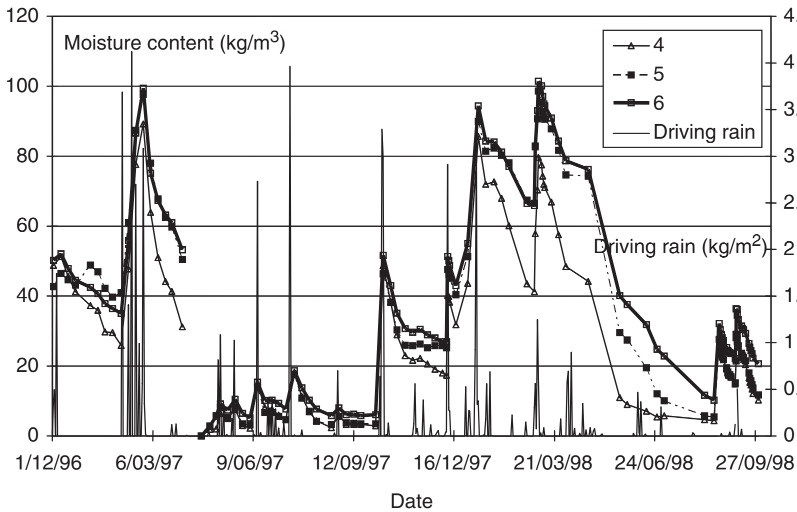

Figure 11. *Test building measurements on south–west facing cavity walls, one (wall 4) with partially filled ventilated cavity, the other two (walls 5 and 6) with fully filled cavity. Moisture content in the brick veneer: Wall 4: XPS, partial fill, capillary brick, Wall 5: XPS, full fill, capillary brick, Wall 6: XPS, full fill, capillary brick.*

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picked up water. As soon as steady state drying started, that surface moisture condensed at the back side of the veneer, transposing pure drying into a combination of backside wetting and front side drying. The field measurements, instead, showed that drying acceleration in the cool climate of Belgium was so limited that the measure can not save frost sensitive bricks from damage, while well-fired bricks do not demand ventilation to remain frost damage free. In fact, the differences in peak moisture contents between the fully filled and partially filled walls with cavity ventilation, seen in Figure 11, did not reflect the effect of ventilation but the difference in wind driven rain load on the walls. At the same time, comparing the slopes of the drying curves after each rain event proves that for the three walls drying to the outside dominates over cavity side drying. In fact, the slopes typically balance between hardly to somewhat steeper for the ventilated wall.

Some still forward ventilation as a measure to avoid summer condensation in the fill. However, in all nonventilated walls tested over the years, no problems arose because of that.

To conclude, in cool climates ventilation clearly is not the key parameter when judging the moisture tolerance of insulated cavity walls.

WIND-DRIVEN RAIN

Rain barring does not differ between a filled and an unfilled cavity wall: drainage at the outside surface, buffering by the veneer, run-off at the veneer's backside with collection on a cavity tray below and outflow through two open head joint per meter run. Surely, with a concrete block veneer, backside run-off may become quite important (Figure 12). As a full fill can contact the veneer, the insulation material used should be water-repellent or impervious for water while the joints between the boards and the cavity ties must be detailed in a way they prevent run-off from jumping to the inside leaf.

It is interesting to know what happens with the buffered water in the veneer wall. According to the measured data of Figure 11 a veneer hardly dries in winter, while in springtime, summer and autumn, drying alternates with wetting. On sunny summer days, a then wet veneer facing south–west may reach 50–55°C on its outside surface, giving partial water vapoar saturation pressures up to 12,000–15,000 Pa (Figure 13). The result is intense evaporation. Part of that vapor diffuses to the inside, a process inducing summer condensation in the fill if vapor permeable, and limited humidification of the inside leaf's cavity side. Monitoring yet showed that the phenomenon is too transient to give problematic wetting of a brick inside leaf. The vapor permeable fill, instead, may accumulate some moisture. Once the weather turns colder, the whole deposit diffuses back to the veneer, where it condenses and creates a situation comparable to rain

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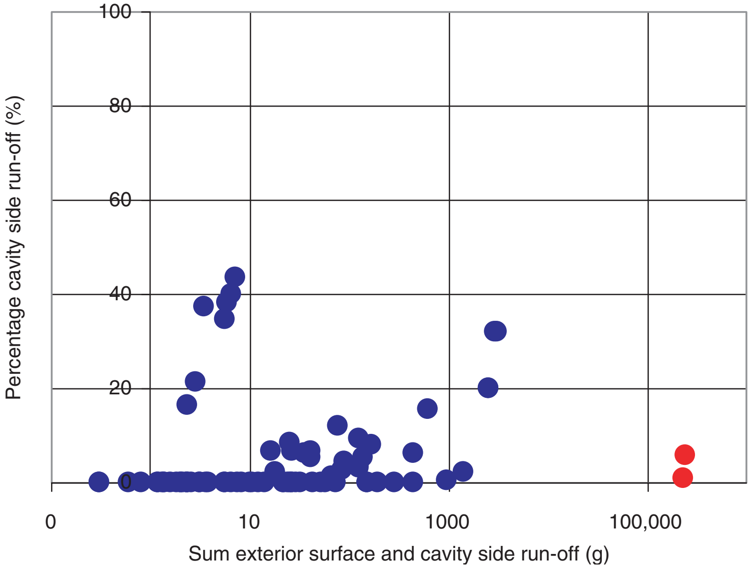

Figure 12. *Test building measurements on south–west facing cavity walls with concrete block veneer. Cavity side run-off, compared to outside surface drainage, as measured during a period of two years. The blue dots give the field measuring results, the red dots represent the results measured during a wind driven rain test in the laboratory.*

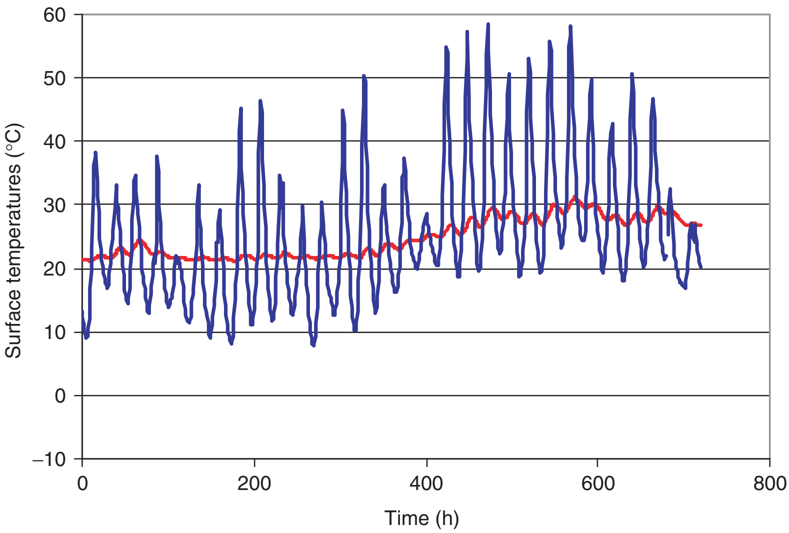

Figure 13. *Test building measurements on south–west facing cavity walls with concrete block veneer. Outside surface temperature of the veneer wall (blue line) and inside surface temperature of the inside leaf (red line).*

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reaching the veneer's backside: adsorption first, followed by run-off when the flows pass the absorption rate. Such re-evaporation/condensation loop anyhow increases the heat loss during autumn as long as summer condensate in the insulation is present.

BUILT-IN MOISTURE

Built-in moisture is a temporary situation. Yet, if wetness is left in the inside leaf when the cold season begins, that moisture will partly diffuse to the veneer wall, resulting in some condensation in the fill when vapor permeable, and some deposit at the veneer's backside. Once there, the absorption and run-off phenomenon, as seen with wind-driven rain, is repeated. In summer, built-in moisture still present in the veneer will mix-up with the buffered rainwater and attribute to temporary summer condensation.

INTERSTITIAL CONDENSATION

In winter, for an inside partial water vapor pressure high enough, the vapor produced inside condenses at the backside of the veneer wall. The amounts deposited are largely influenced by the air permeability of the wall, as was underlined by a hot box/cold box experiment on two brick cavity walls, one airtight and the other air permeable, see Figure 14. Without air pressure differences, both walls react the same way on a difference in vapor pressure between hot- and cold-box: a very slow increase in moisture pick-up by the veneer wall. As soon as an air overpressure is created in the hot box, the air-permeable wall sees its veneer picking up much more moisture than the airtight wall does. The difference in wetting rate also augments with increasing overpressure. That behavior follows the theory, which states that for an air permeable, filled cavity wall the amount of condensate deposited at the backside of the veneer increases approximately in proportion to the air outflow rate (Hens, 2007):

$$g_c = 6.2110^{-6} g_a \left\{ \frac{p_i - p_{sat,c} \exp[6.2110^{-6} g_a (Z_T - Z_c)]}{1 - \exp[6.2110^{-6} g_a (Z_T - Z_c)]} - \frac{p_{sat,c} - p_e \exp[6.2110^{-6} g_a Z_c]}{1 - \exp(6.2110^{-6} g_a Z_c)} \right\}. \quad (11)$$

In that formula, p_i is the inside partial water vapour pressure, p_e the outside partial water vapor pressure, $p_{sat,c}$ the partial water vapor saturation pressure at the backside of the veneer, Z_T total diffusion resistance of the cavity wall ($Z = 0$ outside), Z_c diffusion resistance of the veneer wall and g_a the air flow rate. Proportionality reigns until the outflow becomes so high

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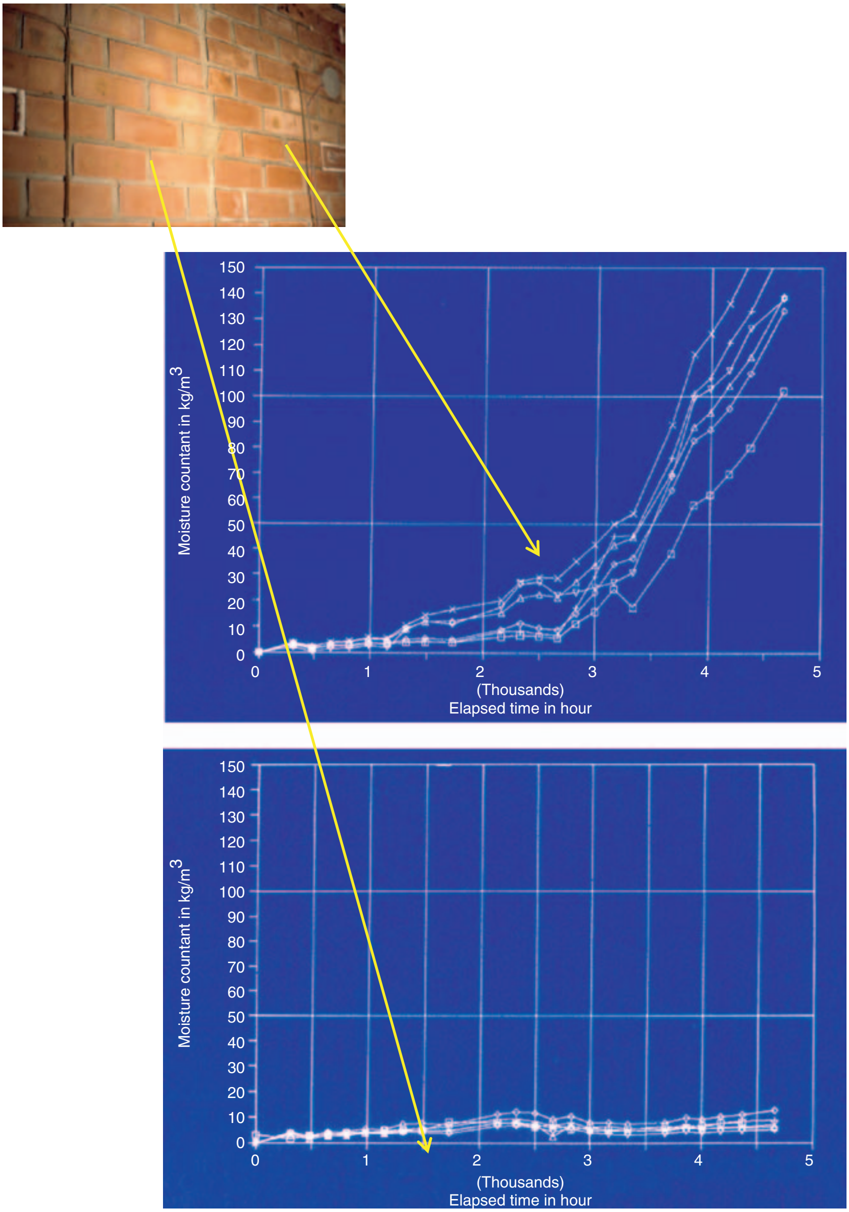

Figure 14. *Hot box test on an air permeable and airtight partially filled cavity wall, moisture built up in the brick veneer as a result of interstitial condensation, caused first by diffusion, followed by exfiltration related advection.*

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that the temperature at the veneer's backside nears the dew-point of the inside air:

$$\theta_c = \theta_e + (\theta_i - \theta_e)\frac{1-\exp(c_a g_a R_c)}{1-\exp(c_a g_a R_T)} \rightarrow \theta_{d,i}, \quad p_{sat,c} = F(\theta_c). \qquad (12)$$

Here, $\boldsymbol{\theta}_e$ is outside temperature, $\boldsymbol{\theta}_i$ inside temperature, $\boldsymbol{\theta}_{d,i}$ inside dew-point, c_a specific heat capacity of air, R_c thermal resistance of the veneer wall included the outside surface resistance and R_T thermal resistance of the cavity wall included the inside and outside surface resistances. From there on, the deposit progressively falls back zero (Figure 15):

Abundant condensation would not harm a cavity wall when bricks and mortar are frost resisting and have a low salt content. Perhaps, in springtime, some efflorescence may develop on the bricks and the joints.

MOISTURE TOLERANCE?

The evaluation underlines that, as stated by Vos, Künzel, and others (Vos, 1963; Vos, 1976; Künzel and Mayer, 1984), filled cavity walls show a moisture tolerance, nearly as good as their unfilled predecessors, on

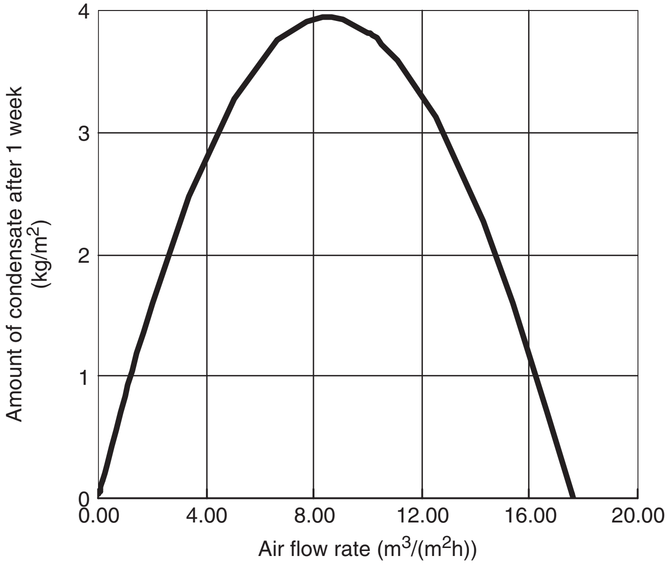

Figure 15. *Calculated amount of exfiltration related interstitial condensation after a cold week as a function of the inside/outside air pressure difference (outside temperature of −2.5°C, hardly any sun, relative humidity 98%, inside temperature 20°C, inside vapour pressure excess some 650 Pa).*

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condition that neither design flaws nor workmanship imperfections intervene as trouble-makers. And of course, the bricks used for the veneer should be well fired, capillary-active, frost-resisting and of low salt content.

Filled walls with painted veneer and a veneer build of glazed bricks are perceived as being more prone to moisture damage. The reason mentioned is that painting and glazing augments the surface diffusion resistance, leading to a condensation deposit in winter in the veneer, directly behind the paint or finish. Table 7 underpins that increase by comparing the measured diffusion resistances of such finishes with the average outside surface film resistance for diffusion. The differences are striking with multipliers, ranging from 116 to 2900. Modeling, however, shows that most vapor still condenses at the veneer's backside, with only a small amount wetting the bricks behind the finish.

The true reason for more frequent frost and salt damage is rain being absorbed by the veneer and prevented from drying to the outside. Rain hitting a painted or glazed veneer runs of. Paints yet easily show small imperfections at the interfaces between bricks and mortar joints, while the joints in a glazed brick veneer may suck-up the run-off from the bricks without any restriction. The high diffusion resistances of the finishes, however, retard drying of the bricks to a level that the equilibrium between wetting and drying turns into wetting prevailing. That way, the bricks may end up showing wetness above capillary, worse, above the critical value for frost. In two damage cases with painted veneer walls, the bricks had a capillary moisture content of 84 and 130 kg/m^3, respectively, while the moisture content on site passed 176 and 232 kg/m^3 (Anon, 1978, 1982). Frost/thaw cycling will then result in frost damage. As moisture tends to move to the cold side, the slow evaporation through the paint may also promote salt deposit behind, with osmotic action and degradation of the paint as a consequence.

Table 7. Measured diffusion resistance of different veneer finishes at 86% relative humidity.

Finish	**Surface diffusion resistance $\times 10^6$ (m/s)**
None	65
Acrylic paint	2268
Structured, fiber-reinforced paint	5940
Glazed bricks	18,846
Water repellent treatment	756

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Thermal Bridging

Heat loss effects were commented together with the thermal transmittance. Table 8 summarizes the temperature ratios and whole wall thermal transmittances measured during a sequence of hot box–cold box experimental set-ups, comparing a $2.4 \times 2\,m^2$ large filled cavity wall with window edge details having a correct thermal break with a $2.4 \times 2\,m^2$ large filled cavity wall with window edge details without thermal break (Hens et al., 1999). The differences are large. With thermal break, temperature ratios all lay far above 0.7, the critical value for mould to develop, while without, the sill and lintel are very close to that threshold. At the same time, no thermal break around the window added 53% to the clear wall thermal transmittance, compared to an identical wall with thermal break.

Airborne Noise Reduction

Brick cavity walls demonstrate excellent sound insulation. Guaranteeing 52 dB attenuation at 500 Hz is not a problem on condition that the inside surface is plastered or the cavity side of the inside leaf is pargeted with a cement mortar. Otherwise, lack of air-tightness may degrade the potentially good performance. Also postfilling with stiff insulation foam that contacts both cavity sides causes a decrease in sound insulation. Measurements showed losses up to 10 dB, compared to the unfilled wall.

Service Life

The main durability problems that may trouble the service life of a cavity wall are: (1) frost damage, (2) rain penetration, and (3) mold development.

Table 8. Thermal bridging, measured temperature ratio's and whole wall U-factors.

Cavity wall	Clear wall *U*-factor ($W/(m^2K)$)	Temperature ratio 5 cm from the window frame			Whole wall *U*-factor
		Sill	Lintel	Edge	$W/(m^2\,K)$
6 cm full fill, no thermal break between inside leaf and brick veneer around window	0.51	0.67	0.71	0.78	0.78
10 cm full fill, thermal break between inside leaf and brick veneer around window	0.32	0.82	0.90	0.88	0.32

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Their likeliness is above all coupled to the design flaws and workmanship imperfections listed in Table 9. Hens analyzed the risk the aforementioned problems may happen, risk being seen as the product of the probability the flaws and imperfections happen, multiplied with the relative distress they cause on a scale from zero to one (Hens et al., 1999). In this case, mould and rain penetration were given the highest relative distress, i.e. close to 1. As Table 10 shows, the most common flaws and imperfections encountered in practice all heighten mould risk. Rain penetration figures second, although the flaws and imperfections which affect that problem are less probable. Frost damage is rather rare and, when it happens, it is a sole consequence of the usage of frost sensitive bricks.

CONCLUSIONS

A detailed performance analysis reveals brick cavity walls have the potential to act as a high quality envelope solution. Air-tightness should not be a problem, on condition that the wall is plastered at the inside. Thermal transmittance may be lowered to a level that the solution deserves the classification low energy. Anyhow four conditions should be

Table 9. Brick cavity walls, typical design flaws and workmanship imperfections.

Design flaws	
D1.	Closers around windows and doors, lintels insulated at the inside
D2.	Concrete floors touching the brick veneer
D3.	No plastering inside, concrete blocks used for the inner leaf
D4.	Bottom flashing from the inner leaf down to the outer leaf not indicated on the drawings. A number of designers only mention that feature in the specifications
D5.	Cavity wall two stories high, without intermediate flashing at half height
D6.	No soffit at the top of the wall
Workmanship imperfections	
W1.	Flashing from the inner leaf down to the veneer not installed or installed faulty
W2.	Flashing filled with mortar debris
W3.	Partial fill not pressed against the inner leaf, fill starting above the lower flashing, gap left at the top of the wall
W4.	Complete fill, ties sloping from the brick veneer down to the inner leaf
W5.	Complete fill, mortar debris in the joints between the boards
W6.	Complete fill, joints between boards open, lower board contacting the brick veneer
W7.	Complete fill, flashing above windows draining in the fill
W8.	Partial or complete fill, no thermal insulation below the flashing at the lintels
W9.	Header joints in the inner leaf hardly filled with mortar

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Table 10. Brick cavity walls, risk assessment (reference: all newly built dwellings with a cavity wall).

	Risk	
	Mold	**Rain**
D1	0.019	
D2	0.0095	
D3		See D5, D6
D4		See W7
D5		See D6:
D6		0.00625
W1		0.003125
W2		0.00125
W3	0.17–0.61	
W4		
W5		see D5, D6
W6		
W7		0.005625
W8	0.024	
W9		
Sum	0.2225–0.6625	0.01625

fulfilled for that: a thick enough cavity fill, the fill very well pressed against the inside leaf and dense enough as to avoid wind washing behind and thermal stack induced air looping around, the inside leaf airtight, all details designed with a low linear thermal transmittance in mind. The nonsteady state response is excellent, in fact, so good that the requirements left to avoid overheating concern the total area of glazed surfaces, their orientation, the usage or not of solar shading and the possibilities of night ventilation.

Also without cavity ventilation, moisture tolerance is outstanding. In fact, the hygric effects of ventilation in a cool climate are too marginal compared to the probability it enhances wind washing and air looping with very negative consequences for thermal performance. Establishing good sound insulation is no problem, while service life is only endangered by design flaws and workmanship imperfections.

To guarantee that very good overall performance, a series of practices, when designing and brick-laying filled cavity walls, should be respected:

1. The wall must be airtight. The best way to achieve is by plastering the inside leaf at the inside
2. Trays that send run-off at the cavity side of the veneer back to the outside must be inserted above every cavity closure, be it above grade, above

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lintels or where fills start. Trays above lintels must have stand-up sides which prevent run-off from dripping on the fill
3. The fill must be well pressed against the inside leaf. Best solution in partial filling is to use stiff filling boards with soft backside. Fully filling is best done with medium soft boards
4. The screwed cavity ties should slope towards the brick veneer
5. Thermal bridges must be avoided by all means. That is best done by applying thermal cross sections which do not disrupt insulation continuity
6. The correct built-up sequence is first the inside leaf, included all trays, then fixing the fill and finally brick-laying or gluing the brick or block veneer. Such sequence demands the use of outside scaffolding.

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