Modeled and Measured Drainage, Storage, and Drying behind Cladding Systems

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ABSTRACT

Drainage is widely accepted as one of the most effective measures for reducing moisture damage due to rain penetration. As a result, a significant proportion of residential and commercial cladding systems employ drainage as a rain control mechanism. Although drainage is effective, some water is always retained in the drainage space, either as droplets on the surface or absorbed and adsorbed to materials lining the drainage space. Previous ASHRAE-sponsored research has shown that ventilation behind the cladding can remove significant amounts of this retained moisture.

One-dimensional hygrothermal simulation is increasingly accepted as a practical and reliable tool for enclosure wall design and analysis. However, one-dimensional hygrothermal simulation cannot directly model the physics of drainage, storage and ventilation behind claddings. This paper investigates the use of enhancements to one dimensional models that might be used to simulate the hygrothermal performance of drained and ventilated wall systems.

The paper will document the experimental methodology, details, and results and discuss how this information can be applied to modeling drained wall systems. Practical applications and research questions arising from the work are presented.

INTRODUCTION

Drained wall systems are widely recommended as the best strategy for controlling rain penetration (Ritchie 1961, CMHC 1999, Lstiburek 2006). However, gaps behind cladding also can be used to encourage ventilation drying and to allow for construction tolerances of the cladding relative to its substructure. Although drainage is an effective means of rain control, the width of the gap required to allow drainage, and the rate of drainage required is still a matter of practical debate and research. It is also clear that drainage will not remove all the water that penetrates the cladding – some water is always retained on the drainage surfaces. Both these issues are the subject of the research reported in this paper.

BACKGROUND

Moisture in buildings is one of the leading causes of building enclosure failure. For moisture damage to occur four conditions must be met: moisture availability, a driving force, a path, and a material that is moisture susceptible at the temperature conditions. Moisture damage will only occur when these four conditions are met, and the safe storage capacity of a material is exceeded. Some materials (such as concrete) can store much larger amounts of moisture for longer periods of time than other materials (such as paper-facings) before their safe storage capacity is exceeded and a problem results.

It has been recognized for many years that using a drained approach to controlling rain penetration will often provide better control than other strategies such as perfect barrier and mass walls (Ritchie 1961, Lacasse et al 2003). A functional drained wall system is comprised of five critical components (see Figure 1):

1. a rainscreen (a cladding that acts as a screen to rain, sun, impact, fire and more),

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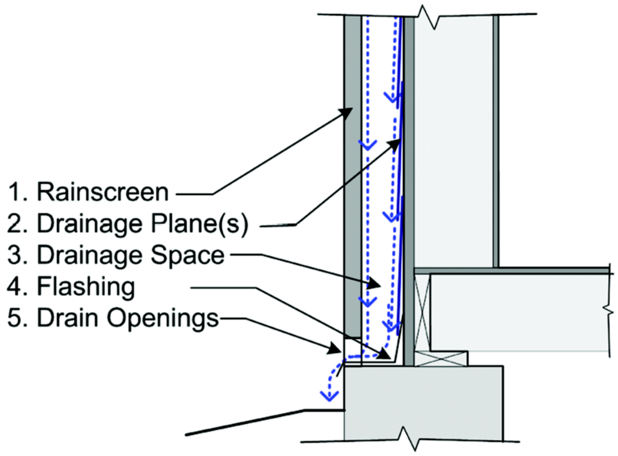

Figure 1 *Components of a functional drained wall system.*

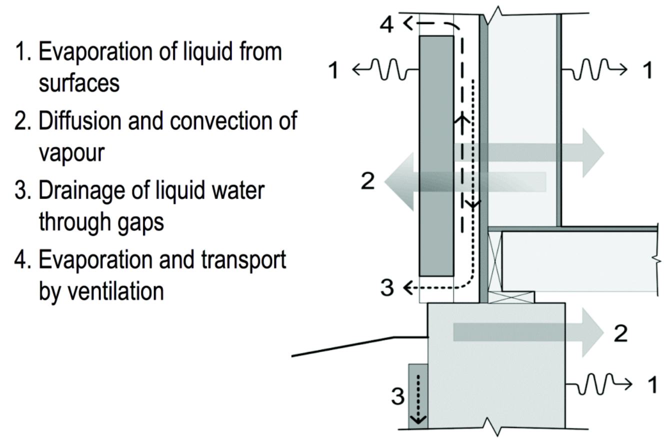

Figure 2 *Wall system dyring mechanisms (Straube and Burnett 2005).*

2. a drainage plane (a capillary break that resists the inward movement of liquid water),
3. a drainage gap or cavity.
4. a flashing system to direct vertically drained water horizontally out, and
5. weep or drain holes to allow water to pass back out through the cladding.

The role of the gap is to relieve the potential buildup of hydrostatic pressure due to gravity drainage of liquid water. If the gap is large enough, airflow through the gap can also allow ventilation and drying.

If liquid water penetrates the cladding some water will be stored even in a wall system with excellent drainage: water can be trapped in undrained depressions/obstructions in the wall system, on surfaces by surface tension, and/or absorbed into most building materials by capillarity. The only one of these storage mechanisms that is time-dependent is capillarity: water is wicked into an absorbent material at a decreasing rate as time progresses. Water vapour can also become adsorbed into building materials, or may be present in the air cavities in the enclosure. All of these mechanisms act to ensure that all water that penetrates the cladding is not drained. Hence to avoid moisture problems, some drying should be provided. (Straube & Burnett 1998).

Depending on the type of storage, several mechanisms are available for drying (Figure 2). Undrained moisture can be removed from the drainage gap by ventilation or diffusion. Moisture stored in the wall materials may also be able to move to exterior surfaces by capillarity and then be removed by evaporation.

Enclosure assemblies with a gap sufficiently large to allow gravity drainage are termed drained systems, and such assemblies with gaps sufficiently large to allow ventilation drying are termed “drained and ventilated systems. Although a drainage gap has been accepted as an effective means of handling liquid water penetration through the screen, and ventilation drying shown to be a potentially effective drying mechanism (Straube et al 2004), very little research has been undertaken to define the minimum or optimal gap size required for either drainage or ventilation drying.

Previous Research

Several recent research projects have investigated drainage and ventilation drying. Some are reviewed below.

An experimental study of drainage in small gaps behind cladding was previously conducted together with Oak Ridge National Labs and Building Science Corporation (Straube et al 2000). This study was limited to vinyl siding and stucco on various sheathing membranes. The experiments determined the drainage capability by applying water to the face of the cladding as a spray or poured into the top edge of the wall behind the cladding.

It was found that water that passed through joints and penetrations in the vinyl siding drained and was caught in the horizontal edges and directed laterally to the j-trim where it drained vertically. It was concluded that significant areas of the drainage plane were not wetted with either water application method. This conclusion was subsequently visually confirmed when 12 ft wide × 6 ft high samples of horizontal vinyl lap siding were tested when installed over a transparent plexiglass drainage plane.

The stucco wall assemblies were tested by pouring two litres of water behind the cladding. It was found that single layers of sheathing membrane bonded to the stucco and hence did not allow good drainage (as there was no gap). By adding an extra layer of sheathing membrane as a bond break, water drained well even though the gap was very small (under 1 mm) and discontinuous). Even corrugated polymeric housewrap performed poorly when installed directly behind stucco because of the bond formed, but the corrugated housewrap in

Table 1. Comparison of Rain Data Analysis to Leakage Test Standards

	Application Rate $l/m^2 \cdot min$	Pressure Difference, Pa
ASTM E514 Test Standard	2.3	500
ASTM E331 Test Standard	3.4	137
Calc. Avg. Canadian Driving Rain	0.012	10 (at 10 m)
Calc. 1% Canadian Driving Rain	0.170	84 (at 10 m)

combination with a felt paper bond break provided the fastest drainage of all walls tested.

We also previously investigated ventilation drying in wood frame walls together with Penn State University and Oak Ridge National Labs (Schumacher et al 2003). An experimental wall was wetted and then dried while resting on a load cell to constantly measure the changes in mass of the wall. A counterbalance was used to offset the dead load on the load cell and thereby greatly increasing the precision of the readings. This research demonstrated that larger gaps allowed for faster ventilation drying.

Research led by Onysko (2006) at Forintek investigated drainage and moisture retention behind EIF systems installed over trowel applied membranes. Their experimental approach injected small amounts of rain onto the drainage plane over several hours. They found that all injected water was not drained even when very hydrophobic drainage planes were used.

To better understand the required drainage capacity of a drainage gap, a driving rain and wind analysis was conducted using extensive Canadian weather data (Straube & Schumacher 2006). It was found that the driving rain deposition rate for an average driving rain event for all monitored Canadian cities was 0.7 mm/hr (0.012 l/m^2-min). For the extreme rain event, the 1% rain event (that is the rate us exceeded 1% of the hours during rain) was chosen. The limiting values for the 1% driving rain event ranged from 3.0 mm/hr (0.05 l/m^2-min) to 10.4 mm/hr (0.17 l/m^2-min) depending on the city studied

The calculated driving rain rates and wind pressures were compared to two water penetration test standards: ASTM E514 *Standard Test Method for Water Penetration and Leakage Through Masonry*, ASTM E331 *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference*. It can be seen that the testing standards imposed loads that are many times, often orders of magnitude, higher than even the most extreme rain event recorded in Canadian data. Although the peak driving rain rates are likely higher in hurricane regions, they are unlikely to be more than ten times those of the rainy regions of Canada.

Research Scope and Objectives

A research program was developed with two main objectives. The first objective was to determine the gap width that would allow for drainage. The other main objective was to develop a repeatable and defendable test method to characterize the drainage, storage and drying of drained wall systems.

The scope of the research was limited to lighweight claddings with relatively small gaps and spun-bonded polyolefin (SBPO), building paper, and trowel-applied sheathing membranes.

METHODOLOGY

From the previously-cited research at PSU and Forintek, it was clear that the temperature and RH conditions surrounding the test apparatus needed to be tightly controlled to avoid variations due to adsorption and to ensure repeatable drying rates. Hence, tests were conducted in the Building Engineering Group laboratory which is operated at target conditions of 20C and 50%.

A test apparatus capable of accepting walls weighing several hundred kg and resolving mass changes to several grams was constructed. The load cell was installed in tension to remove all lateral forces (Figure 3). Before each test, calibration weights were added to confirm the linear response of the system, and to calibrate its output. The amount of water drained from the system could also be measured gravimetrically using this apparatus.

Drainage Test Protocol

Based on ASTM E2273, we originally chose 8 liters of water as the volume to be poured behind the cladding in two doses. However, during the first tests it was noted that the amount stored in the wall reached almost the same maximum value even if a dose much smaller than 4 liters was used. In subsequent testing we chose to impose two doses of 1.5 liters for a 4 ft wide (1.2 m) × 7 ft (2.1 m) tall wall system, and two doses of 1.0 liter for smaller 3 × 6 ft (0.9 × 1.8m) specimens. In all cases drainage stopped within one to two minutes after water was no longer added to the drainage gap. Note that the maximum stored is defined here as the short-term storage quantity. Many materials can absorb much more moisture if the wetting is continued for much longer than the 1 minute test. However, the test protocol is not intended to measure the capillary uptake rates and sorption storage capacity of materials, but the short-term pseudo-instantaneous storage of draining water by surface tension.

Figure 5 shows a typical drainage and storage curve. The blue line is the mass of the test wall, the pink line is the mass of the drained water into the storage bucket, and the green line

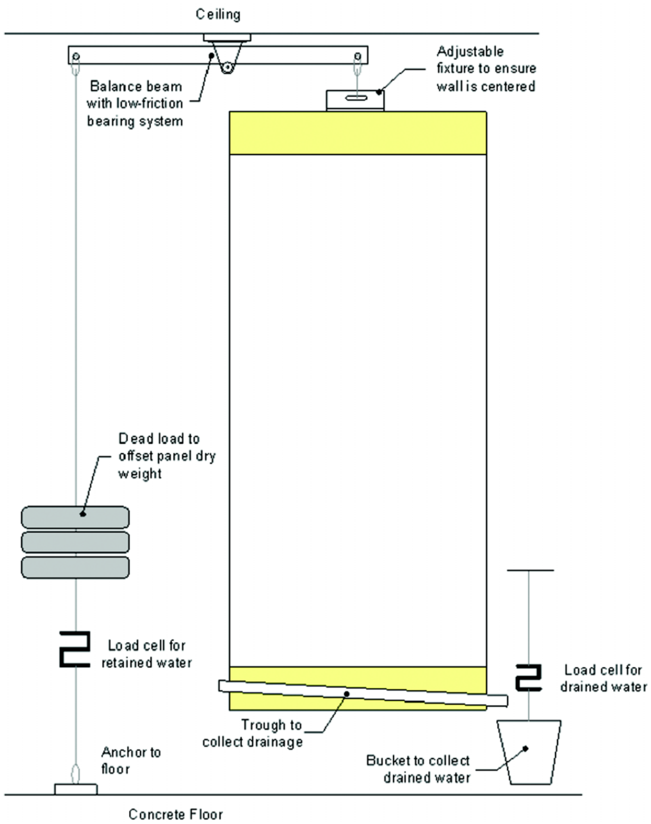

Figure 3 *Wall balance testing apparatus.*

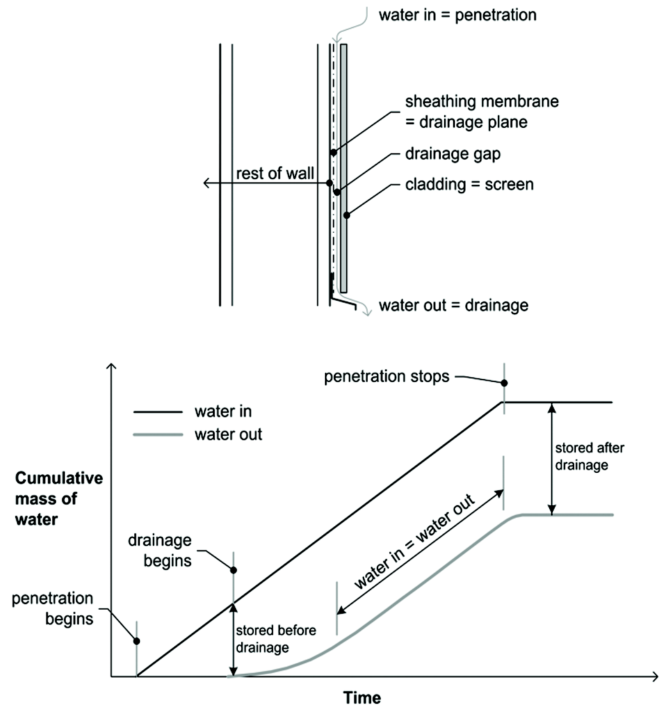

Figure 4 *Schematic form of test procedure and results.*

is the addition of the two, or the total water added to the system. The values used to characterize wall system performance were A, the initial or primary storage, and B, the final or secondary storage.

The final drainage test protocol chosen is:

1. Perform a calibration check of the load cells (a known weight is applied to the test wall and the reading from the balance is confirmed)
2. Pour a 1 or 1.5 litre dose into the drainage cavity over one minute [1]
3. Wait fifteen minutes to allow drainage to finish
4. Pour the second dose into the drainage cavity over one minute [1]
5. Wait fifteen minutes for drainage to finish
6. Begin drying test (if any)

The entire drainage test requires less than about one hour to complete. Most the results took the form shown generically in Figure 4. Figure 5 plots the data from an actual test.

Several drainage tests were conducted on fiber cement sheet applied over housewrap directly on framing (i.e. no sheathing) to demonstrate repeatability. These walls were tested in our labs as well as independently on a similar balance apparatus in a laboratory in Fontana, California. Six drainage tests were conducted on 4 × 8 ft (1.2 × 2.4 m) wall panels, three in each location, and there were two drainage tests conducted on a 4 × 4 ft (1.2 × 1.2 m) test wall, one in each location. With the exception of one the first tests conducted before the load cell was properly calibrated, the results, shown in Figure 6, demonstrate that the test protocol is very repeatable. It should also be noted that the drainage gap in these tests was in the order of one mm thickness as the flat sheet cladding was directly applied over the framing. Another comparison was conducted with vinyl cladding. This showed that even with a discontinuous drainage gap the results were repeatable (Figure 7).

Experimental Determination of Equivalent Gap Thickness

The width of large and uniform drainage gaps can be ascertained by direct measurement. However, for irregular gaps and/or small gaps, direct measurement is not practical. Hence, we devised a test method to use the flow of air as a means of measuring an equivalent gap width. For ventilation flow, this is a direct measure of the resistance of the gap to airflow, whereas for drainage flow it is merely a surrogate measure with some physical significance. This method was initially developed by Van Straaten and Straube (2004).

The pressure drop along a length of duct can be predicted by the Darcy-Weisbach equation:

[1] 1.0 L was used on wall specimens measuring 3 × 6 ft.

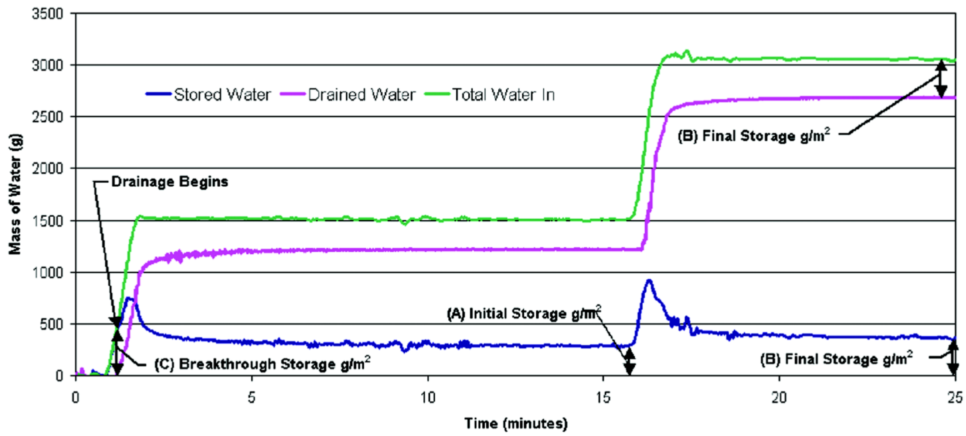

Figure 5 *Typical gravimetric drainage testing results.*

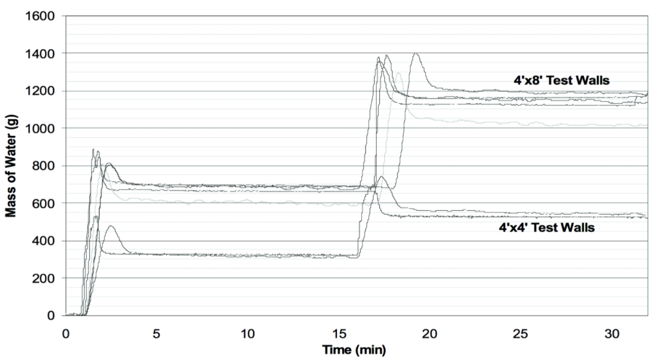

Figure 6 *Repeatability of test results conducted in two different laboratories.*

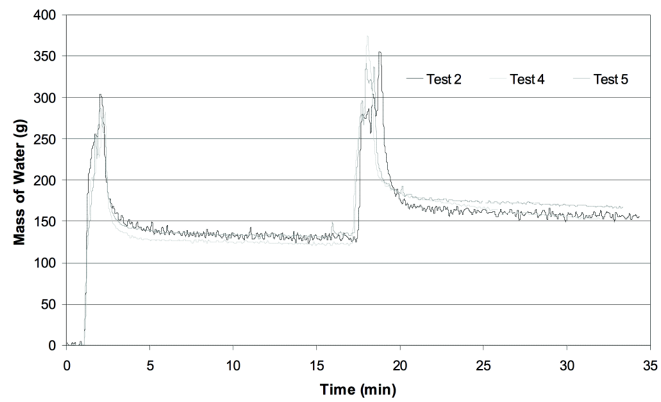

Figure 7 *Drainage test repeatability of vinyl siding.*

$$\Delta P_{conduit} = f \cdot \left(\frac{L}{D_h}\right) \cdot (0.5\rho \cdot V^2) \tag{1}$$

Where f is the friction factor, L is the length, D_h is the hydraulic diameter, V is the velocity, and ρ is the density of air in consistent units.

For a wide cavity with fully developed laminar flow the friction factor correction (k_f) is 1.5 and the friction factor (f) can be solved:

$$f = k_f \cdot f_{circular} = 1.5 \cdot \frac{64}{\mathrm{Re}} = \frac{96}{\mathrm{Re}} \tag{2}$$

The Reynolds number (Re) for standard conditions (with $\rho = 1.2$ kg/m^3 and $\mu = 18 \times 10^{-6}$ N s/m^2) is determined using:

$$\mathrm{Re} = 66400 \cdot D_h \cdot V \tag{3}$$

The average velocity (V) is the volumetric flowrate over the cross-section of the flow path:

$$V = \frac{Q}{A} = \frac{Q}{w \cdot d} \tag{4}$$

Combining equations results in the following pressure drop relationship:

$$\Delta P = \frac{L \cdot Q}{1153 \cdot w \cdot d \cdot D_h^2} \tag{5}$$

The test was conducted using a calibrated air flow device that controls the volume of air being passed through the wall section while measuring the pressure difference imposed. Negative pressures were applied to the wall sections because negative pressure tends to pull all the seals tighter to the wall section rather than opening them up. Based on our results the use of negative pressures tends to result in slightly lower system leakages than when positive pressure is applied, but these differences are very small, and hence expected to be insignificant, for a full-scale wall in service exposed to the small in-service pressures.

The first air test was conducted while leaving the opposite end of the wall section open thereby allowing the maximum amount of air to flow through the gap. A digital manometer was connected to the large pipe manifold at the top edge of the gap to measure the pressure difference across the wall section and a rotameter measured the flow.

The wall was also air tested with the bottom sealed to take into account all airflow paths other that the intended one. This approach accounts for other small leaks (in the wall or the apparatus) that may not be perfectly sealed. This quantity is termed system leakage. The results from both tests are plotted and a power law equation is derived to best fit each set of data points. The equation for the sealed wall can then subtracted from the equation for the open wall, and the resulting line.

A validation/calibration test was performed to ensure the test results were within the accuracy predicted for the experimental setup. The test length consisted of a 15 mm thick, 400 mm wide, 1.2 m long rectangular air cavity with stiff walls. The results (Figure 8) showed agreement within 5% of theoretcial calculations.

The pressure drop versus flow was measured for most of the drainage test specimens to define the equivalent gap width. A selection of results is shown below in (Figure 9). Interestingly, the wall with the 9 mm equivalent cavity width was a stucco wall applied over 19 mm vertical wood strapping at 400 mm centers. The asphalt board supporting the stucco had deformed during application and blocked the cavity significantly.

Drainage Testing of Idealized Walls

An initial test was conducted on an idealized wall. This wall comprised a small gap between two sheets of stiff acrylic sheet. The gap was maintained by a series of washers, almost exactly 1mm thick. This test was conducted twice. It was found that the gap stored 23 and 25 g/m^2. The amount of water stored in the drainage gap was therefore significantly less than the amount of water stored on a single sheet of acylic. It is hypothesized that this is because the 1mm gap did not allow large beads of water to form on the surface. This test provides the surprising result that it may be possible for a very small drainage gap to store less water than a large drainage space. The same might be true of a space filled with a drainage mat or fabric, but this requires more testing and research.

To determine the absolute minimum amount of moisture stored after drainage stops, several drainage tests of smooth non-absorptive materials were conducted. One test consisted of applying a fine spray of water onto a sheet of polyethylene while it was hung vertically. Three spray tests using the polyethylene sheet returned an average storage amount of 35 g/m^2. The same testing was conducted on a vertical acrylic sheet and the storage amount found to be approximately 65 g/m^2. Although, both materials appear smooth and are hydrophobic, we hypothesize that the greater hydrophobicity of the polyethylene sheet resulted in less storage.

These baseline tests showed that it is unreasonable to expect a wall to store less than about 30 g/m^2, and a wall with a wide (over 3 mm) gap can easily be expected to store over 60 g/m^2 even with very smooth and hydrophobic surfaces. This means that penetrating water less than this quantity will not drain, and that this stored water must be removed by other means (diffusion, wicking to the surface, or ventilation).

Test Program

Two categories of claddings were chosen for a larger test program. The first category includes those with a continuous drainage gap over the entire height of the wall, such as drained EIFS, stucco, or sheet cladding products. Hence, water that enters the top can only exit at the bottom. The second category includes those constructed with siding having a discontinuous drainage gap. Such gaps are designed to drain over the entire surface area of the wall so drainage will not only occur at the bottom such as vinyl siding or lapboard siding.

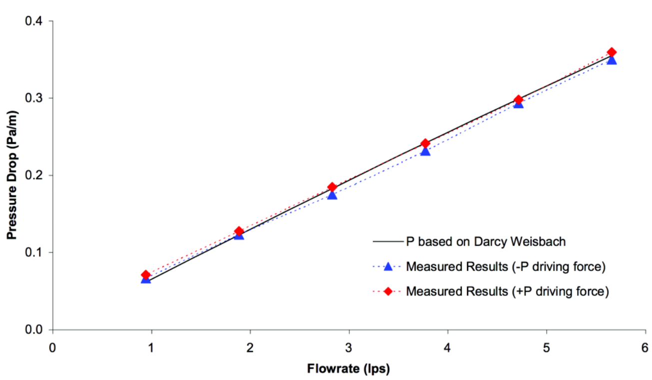

Figure 8 *Theoretical vs. actual pressure drops for rectangular cavity.*

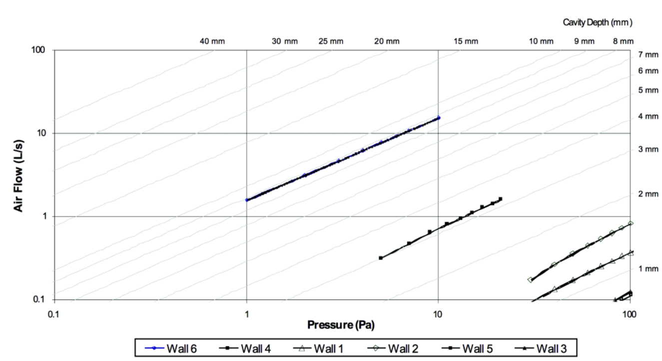

Figure 9 *Flow versus pressure and equivalent cavity width for six different walls.*

The three main variables examined during testing include the drainage gap width, the drainage plane material, and the cladding material. The drainage plane material and cladding generally form the surfaces of the drainage gap. The drainage gap materials are shown in Tables 2 and 3 and the drainage gap width is shown as the equivalent gap determined from the airflow testing. In some cases, the wall sizes for the drainage testing were 3 × 7 ft frames (instead of 4 × 8 ft) with a 3 × 6 ft test area as these were easier to handle in the lab. Storage amounts were always reported in g/m^2 to provide normalized values.

One of the main objectives of testing was to determine the minimum gap width required for drainage. Several of the walls had very small gaps. To measure these gaps, an air pressure versus flow test was used, and the results converted to an equivalent clear air space dimension. All of the gap widths reported in this paper are based on this equivalent measure. Some of the systems, such as two layers of building paper, returned values of less than 1 mm.

RESULTS

Well over 50 tests were conducted on more than 10 different cladding systems with different gap widths and drainage plane (WRB) materials using the standard drainage test method and apparatus developed. The results and analysis are

Table 2. Sheet Product Drainage Testing Results

System	Test	Drainage Plane	Cladding	Gap (mm)	Gap	(g/m2) initial	(g/m2) secondary
EIFS-1	Test 5	Glass Faced Gypsum	EPS with ext. finish	>1	formed by adhesive	90	74
	Test 6	Glass Faced Gypsum	EPS with ext. finish	>1	formed by adhesive	86	80
EIFS-2	Test 1	trowel applied	EPS with ext. finish	1.5	formed by adhesive	136	163
EIFS-3	Test 1	trowel applied	EPS with ext. finish	<1	1/4" by 1" grooves	186	199
	Test 2	trowel applied	EPS with ext. finish	<1	1/4" by 1" grooves	194	209
EIFS-4	Test 2	trowel applied	EPS with ext. finish	3	formed by adhesive	103	121
	Test 3	trowel applied	EPS with ext. finish	3	formed by adhesive	112	138
EIFS-5	Test 1	trowel applied	EPS with ext. finish	2	formed by adhesive	48	75
	Test 2	trowel applied	EPS with ext. finish	2	formed by adhesive	45	69
	Test 3	trowel applied	EPS with ext. finish	2	formed by adhesive	50	80
	Test 4	trowel applied	EPS with ext. finish	2	formed by adhesive	43	68
EIFS-6	Test 3	SBPO	EPS with cement coating		horiz and vert grooves	96	132
	Test 4	SBPO	EPS with cement coating		horiz and vert grooves	90	118
	Test 5	SBPO	EPS with cement coating		horiz and vert grooves	102	144
Stucco-1	Test 2	2 layers #15 felt	3/4" Cement Stucco	<1	2 layers #15 felt	211	302
	Test 3	2 layers #15 felt	3/4" Cement Stucco	<1	2 layers #15 felt	263	375
Stucco-2	Test 1	2 layers #15 felt	3/4" Cement Stucco	9	19 mm strapping	189	245
	Test 2	2 layers #15 felt	3/4" Cement Stucco	9	19 mm strapping	242	372
AGM-1	Test 1	Air Gap Membrane	Vinyl siding	3	formed by	141	173
AGM-1	Test 2	Air Gap Membrane	Vinyl siding	3	air gap membrane	142	167
Felt-1	Test 1	#15 paper	Vinyl siding		formed by siding	153	182
Felt-1	Test 2	#15 Paper	Vinyl siding		formed by siding	161	203
Towel-1	Test 1	Air Gap Membrane	fiber cement (paper towels)	3		574	1005
Towel-2	Test 1	#15 Paper	fiber cement (paper towels)	<1		583	984
Poly-1		polyethylene sheet	none		°	35	
Plexi-1	Test 1	acrylic sheet	plexiglas sheet	approx 1 mm		24	25
Plexi-1	Test 2	acrylic sheet	plexiglas sheet	approx 1 mm		21	23
Plexi-2	Test 1	acrylic sheet	none		°	65	
FCSheet-1	Test 1	SBPO	Fiber cement Sheet		formed by	223	378
FCSheet-1	Test 2	SBPO	Fiber cement Sheet		gaps and wrinkles	232	393
FCSheet-1	Test 3	SBPO	Fiber cement Sheet		between sheet and	245	411
FCSheet-2	Test 1	SBPO	Fiber cement Sheet		flat SPBO	201	344
FCSheet-2	Test 2	SBPO	Fiber cement Sheet		"	228	382
FCSheet-2	Test 3	SBPO	Fiber cement Sheet		"	229	400
FCSheet-3	Test 1	SBPO	Fiber cement Sheet		"	218	353
FCSheet-4	Test 1	SBPO	Fiber cement Sheet		"	204	364
FCSheet-5	Test 1	SBPO	Fiber cement Sheet		"	199	335

Table 3. Lap Siding Drainage Testing Results

System	Test	Drainage Plane	Cladding	(g/m2) initial	(g/m2) secondary
Vinyl Siding					
Vinyl-1	Test4	SBPO	Vinyl Siding	124	155
Vinyl-1	Test2	SBPO	Vinyl Siding	130	156
Vinyl-1	Test5	SBPO	Vinyl Siding	135	168
Vinyl-2	Test11	#15 Felt Paper	Vinyl Siding	146	172
Vinyl-2	Test9	#15 Felt Paper	Vinyl Siding	155	182
Vinyl-2	Test7	#15 Felt Paper	Vinyl Siding	152	189
Fibercement Siding					
FCSiding-1	Test10	SBPO	back-primed fibercement	93	129
FCSiding-1	Test8	SBPO	back-primed fibercement	96	126
FCSiding-1	Test6	SBPO	back-primed fibercement	92	135
FCSiding-2	Test16	#15 Felt Paper	back-primed fibercement	99	139
FCSiding-2	Test14	#15 Felt Paper	back-primed fibercement	90	141
Cedar Siding					
Cedar-1	Test13	SBPO	Untreated cedar siding	203	330
Cedar-2	Test12	SBPO	Untreated cedar siding	192	333
OSB Siding					
LP-1	Test17	SBPO	OSB manufactured siding	87	122
LP-2	Test15	SBPO	OSB manufactured siding	84	111

divided into walls with full-height continuous gaps and discontinuous gaps behind lap siding.

The results of the testing are summarized below in Tables 2 and 3. A more complete analysis of drainage results can be found in Smegal (2006).

Test Results: Continuous Gaps

The most general, and important, result of the testing is that fast drainage occurred in all of the walls with a continuous gap even if the gap is very small (approx 1 mm). Even the wall with direct applied stucco over two layers of building paper with a barely measurable gap (<1 mm), drained all of the test water. This conclusion is limited to the maximum rate of water entry imposed by the test method, that is, no more than 1.1 to 1.2 liters per meter width per minute. This rate of water entry will not be exceeded by almost any drained cladding unless a roof is drained directly behind the cladding. Note that none of the walls attempted to seal the drainage gap. In practice, the underside edge of cladding may be blocked with sealant, and this will eliminate or reduce drainage.

Another important observation from the tests conducted is that no correlation was found between the amount of moisture stored after drainage and the size of the gap. Absorbent materials lining the gap obviously increased the amount of moisture storage slightly. This is especially notable by inspecting the difference between the storage of the primary and secondary storage. As mentioned previously, the test method was designed to avoid testing capillary and sorption absorption/adsorption. In service, the materials would take up moisture as the very slow rate of penetrating water drained downward. Hence, the storage quantities in these tests are the minimum values to be expected.

Test Results: Lap Siding

An investigation into the drainage ability of lap siding products was conducted to see how various common products differ with respect to drainage, storage and drying. The lap siding products tested included vinyl siding, fiber cement siding, a manufactured and prefinished wood product, and unpainted cedar siding, installed on either SBPO or #15 felt.

The siding analysis provided some challenges since the drainage gap is discontinuous and of variable size. During the first drainage test, it appeared as if the majority of the water was draining over the front of the cladding. Dye was then added to the water to identify the drainage paths taken. Using this method it was shown that almost all of the water was removed from the drainage gap after only two rows of lap siding. This means that if the front of the siding is not sealed between the planks, then the cladding is inherently well drained. Installing siding products on strapping will not noticeably increase the drainage ability of the siding. However, strapping will allow ventilation drying and separate the contact line of the siding from the drainage plane. This latter feature may be quite important for the durability of the siding, the drainage plane, and the drainage path at details such as windows.

The siding storage results are shown in Tables 2 and 3. It can be seen that the cedar siding stored the largest amount of water. This is not surprising since the cedar siding was untreated on all sides. Future work will test back-primed and sealed cedar siding. The second highest storage value was achieved by vinyl siding. Vinyl, as a material, is non absorptive but the shape of the vinyl extrusion provides many channels where water can collect. Fiber cement siding and manufactured wood (both factory finished with non-absorptive coatings on all six sides) stored the least amount of water. Since the majority of water drained along the exterior of the siding, less water was absorbed and stored by these products.

In assemblies with non-absorptive surfaces on all sides (i.e., the EIFS) the water flow paths during drainage sometimes varided between tests. This could change the stored quantity somewhat. Hence, there are tests in which the initial storage was actually greater than secondary storage.

IMPLICATIONS AND FUTURE RESEARCH

The drainage rates measured were compared with the *extreme* 1% hourly rain deposition rates predicted in the driving rain study described earlier. It was found that even small gaps (1 mm) drained more water than would ever be expected in drainage gaps (i.e., drainage rates exceeded 1 liter/minute per meter width).

A 10 mm gap behind drained claddings (as required in some regions of Canada by the new National Building Code of Canada) is not required to ensure drainage. However, a 10 mm gap may be sufficient to provide useful ventilation drying behind some claddings in some climates if desired. In practice, drainage gaps much larger than 1 mm are often specified to accommodate construction tolerances. However, some products (such as drainage mats, factory grooved or dimpled insulations) are designed to ensure that a minimum drainage gap is provided, and hence, based on the test results presented, should not require a 10 mm gap if the purpose of the gap is drainage.

Although small gaps allow drainage at a sufficient rate, and do not store more water than larger gaps, small gaps essentially ensure that draining water contacts both the back of the siding and the front of the drainage plane. Larger gaps (ad hoc testing suggests gaps of 4–6 mm) might allow some of the drained water to remain attached to the back of the cladding only, thereby exposing the drainage plane to fewer hours of wetness. The reduction in wetting due to the use of such larger gaps has not been quantified, and in practice it is not clear what proportion of penetrating water is deposited on the drainage plane and what is deposited on the back of the siding.

COMPUTER MODELING STORED DRAINWATER

Given the knowledge that moisture is retained on drainage gap surfaces, it would be desirable to include this effect in hygrothermal computer models. Ideally, one would like to investigate the role of rain leakage storage and drainage.

The following method is proposed for use with the WUFI 4.1 computer model with source & sink enhancements. This one-dimensional model has been widely used and its accuracy has been verified against numerous full-scale field studies of enclosure performance (roofs, walls, foundations, parking garage decks, etc.) over a number of years (Kuenzel 1995, Kuenzel & Krus 1997, Kuenzel 1998, Hens et al 1996). It is one of the few models that can properly account for rain absorption (Straube 2003). Given the appropriate material data, WUFI calculates heat and moisture flow every hour under the influence of sun, rain, temperature and humidity. The newest version of the model allows the analyst to inject water between layers in the model to simulate rain leaks, or with some extra effort, to model air leakage condensation.

The moisture storage function (or the sorption isotherm plus capillary storage) is one critical piece of information that is needed for a hygrothermal simulation. The moisture storage function for a typical hygroscopic material is shown in Figure 10. The moisture storage function for an air gap is essentially flat, as it can store only a very small amount of moisture (the storage capacity of a cubic meter of air varies from a few grams to a few tens of grams whereas most hygroscopic materials store a few to many tens of kg/m^3).

The airspace properties provided in the database with WUFI have equivalent thermal properties to account for radiation and convection effects in addition the conductivity of air. Just as importantly, the air layer is defined to have a porosity of 1m3/m3: in essence this means as much as 1000 kg/m^3 can be stored at 100%RH in the model. This implied, and unrealistic, "storage capacity" provides for a significant amount of damping of moisture condensation and absorption by the materials lining the side of the air layer, and these assumed properties, although unrealistic, are often necessary to allow for converging results.

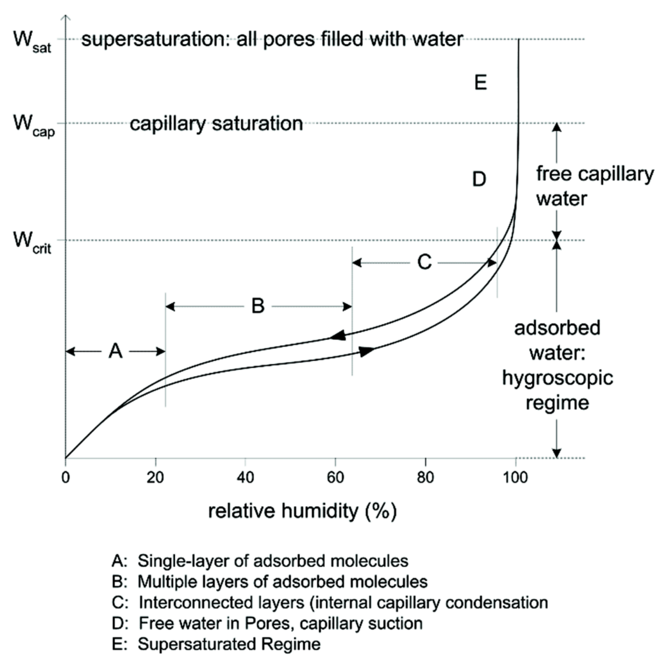

Figure 10 *Typical moisture storage function (Straube and Burnett 2005).*

Given the knowledge of realistic storage quantities of small gaps developed by the testing described, the air layer in WUFI can be replaced with a more realistic storage layer on one or either side of the air gap. Such a material should be defined to have a porosity sufficient to store the quantity of moisture that testing shows is realistic: for example, if 200 g/m^2 is found from testing, then a porosity of 0.2 m^3/m^3 would be appropriate for a 1 mm thick layer. The moisture storage function would ideally be zero until 100%RH, at which it would jump to the peak storage capacity. This approach places severe challenges on the numerical solution algorithms, and hence a sharp increase in moisture storage from zero to peak over an RH range of 95 to 100% is desirable. The heat capacity of the fictitious layer should be set very low, and the thermal conductivity, vapor permeability, and liquid transport set very high to ensure that the fictitious storage layer does not impact heat or moisture flow. Finally, any air layer in the system must have its porosity reduced to limit the moisture storage levels that are more realistic, i.e., in the order of 10 g/m^3.

EXAMPLE CALCULATION

To demonstrate the influence of storage its use in computer modeling, an example drained EIFS wall was simulated. The wall is situated on a low-rise building in Boston facing east (high driving rain exposure). The ASHRAE 160P coefficients for driving rain were set to FE = 0.5 and FD = 0.5. The wall comprised, from outside to inside, 3 mm synthetic lamina, 50 mm EPS, a 1 mm storage layer or air gap, crinkled housewrap, 11.6 mm of OSB, 140 mm of fiberglass batt insulation, and an interior surface of Kraft paper and gypsum board. All material properties except for the storage layer were default values and the simulations began with the materials at equilibrium with 80% RH. The outdoor weather of a cold year in Boston, and interior conditions of sinsusoidally varying temperature and RH (from 20 to 22 ºC and 40 to 60% RH) where imposed.

The storage level and the cumulative rain leak injected for the six cases are shown in Figure 11. It can be seen that for a storage medium with 50 g/m^2 peak storage capacity, the 0.5% rain penetration rate barely results in saturation of the layer for the latter part of the rain event whereas the 1.0% rain event completely saturates the layer. For a storage capacity of 200 g/m^2 the layer never reaches saturation and hence does not drain. Hence, for the smaller rain penetration rate, the higher storage layer behaves in almost exactly the same way as the lower storage quantity. For the high rain penetration rate (1.0%) the difference in behavior between the low and high storage capacity is significant.

The moisture content of the OSB (Figure 12) is shown for the 6 cases: rain penetration of 0.5% and 1% rain deposition, and walls with an air layer, a storage layer with 50 g/m^2, and a storage layer with 200 g/m^2. It is clear that the rain penetration rates have the greatest impact. However, the storage layer used also has a noticeable effect. The interaction of the penetration rates and storage explains the results. For the 0.5% rain penetration rate, all of the storage approaches result in the same OSB moisture content. For the higher penetration rate, the low storage rate (50 g/m^2) results in lower moisture content, as less of the penetrating water was retained in the layer after intense rain events.

CONCLUSIONS/RECOMMENDATIONS

The current testing standards for leakage of walls and windows use water application rates orders of magnitude higher than actual recorded rain events. By using such high and unrealistic water application rates some assemblies may be deemed unacceptable whereas when exposed to rain loadings in the field these assemblies may perform sufficiently well.

Although drainage is a powerful mechanism for removing penetrant rain water, some water is always retained on surfaces. A test apparatus and protocol were developed to precisely measure the amount of water retained after drainage. The repeatability of the developed protocol and test apparatus was demonstrated by multiple tests at two different labs.

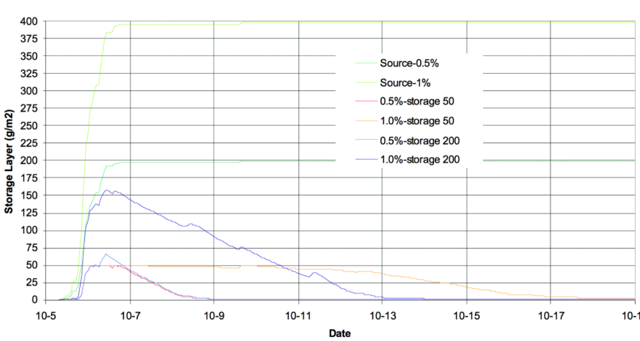

Figure 11

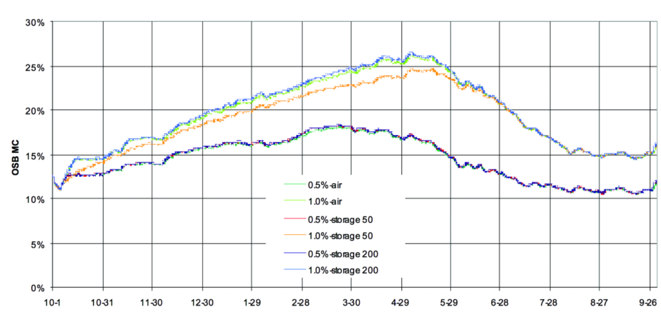

Figure 12

Testing found that even a small gap (approx 1 mm) will drain water at a rate considerably greater than rainwater is expected to penetrate behind claddings even in extreme conditions. For example, the measured drainage rate of a gap of about 1.0 mm wide was found to be in excess of 1.1 litre/minute-meter width, more than the extreme driving rain intensity for the worst climate in Canada.

Walls with lap siding tended to drain water out onto the face of the plank immediately below the plank at which the water was injected.

During testing of non absorptive materials, a suspended polyethylene sheet consistently stored 35 g/m^2 and a single acrylic sheet of acrylic stored 65 g/m^2. The drainage tests in the acrylic wall resulted in storage amounts of approximately 24 g/m^2 showing that in some special cases, a very small gap will actually store less water than a large drainage gap. To build on the knowledge gained in this research more investigation is needed to analyze the role of surface contact angles and moisture stored on non absorptive surfaces.

A method of computer modeling the quantity of storage measured in the lab tests was developed. An example EIFS wall was simulated with different rain penetration rates and different storage capacities. The storage capacity was shown to impact the performance.

ACKNOWLEDGMENTS

This research was partially funded by generous grants from the Dupont Young Professor Award program and by James Hardie Building Products. This support is gratefully acknowledged.

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