Ventilated Wall Claddings: Review, Field Performance, and Hygrothermal Modeling

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ABSTRACT

The use of ventilated air spaces behind claddings has been shown to influence the performance of some wall assemblies. Recently completed field and laboratory research has shown that cladding ventilation has the potential to increase drying and reduce wetting from absorptive claddings and sun-driven moisture.

The use of one-dimensional hygrothermal simulation software has been well established for a wide range of wall and roof assemblies. However, the use of such software has previously had a limited ability to accurately model the physics of enclosures with ventilated claddings. The most recent version of WUFI 4.1 (a widely used hygrothermal simulation package) adds the ability to model enclosure systems that incorporate embedded sources and sinks of moisture and heat. This capability can be used to model source effects, such as air and rain leakage within a wall assembly, or sinks, such as drainage and ventilation.

This paper investigates the use of the WUFI "source and sink" approach in a one-dimensional model to simulate ventilation and rain leakage behind claddings. The simulation predictions are compared to the field performance of several different wall assemblies. Lessons learned on the use of this new model will be discussed. The impact of such effects as rainwater leaks and cladding ventilation rates are also investigated.

INTRODUCTION

The balance between wetting, drying, and safe storage is critical to the long-term performance of building enclosures. Where wetting cannot be controlled to acceptable levels, safe storage and drying become critical. Many common building materials have little safe storage capacity—that is, they cannot be exposed to high levels of moisture for long periods of time.

The sheathing is one building component often made of moisture-sensitive materials placed directly behind the cladding and separated by only a thin membrane and air gap. For some periods of time, the sheathing can be expected to be exposed to rainwater wetting from the exterior or condensation wetting (air leakage or vapor diffusion) from the interior. Protecting the sheathing from moisture is seen as important and has been the goal of many product manufacturers, builders, and practitioners over several decades. However, experience has shown that accidental leaks can still occur; therefore, the role of drying is very important to the moisture balance.

Moisture can be transported by airflow (convection), diffusion, or gravity into and through an enclosure wall assembly. Drainage will remove much of the bulk moisture by gravity when a drainage path is provided; however, moisture can still remain adhered or absorbed to materials within the wall assembly. The amount of moisture that can be safely absorbed or stored depends on the material properties. Drying can occur by vapor diffusion, evaporation, desorption, or by air convection (i.e., ventilation). Vapor diffusion is shown to be a relatively slow process, particularly when low permeance materials are used within the wall assembly. Evaporation or desorption can only occur when moisture is able to get to the surface of the material (often only at the cladding or interior surface) and be removed by the flow of air. Allowing evaporation or desorption to occur at layers within the wall assembly, particularly at the

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sheathing, and removing the excess moisture by ventilation to the exterior provides an effective means to remove additional moisture directly from sensitive materials and improve the drying potential of some wall assemblies.

It is becoming more common in North America to construct walls with claddings separated from the framed wall by an air cavity. This is used as a rain-control strategy to eliminate capillary flow between the cladding and sheathing, provide drainage of incidental moisture, and provide some venting or ventilation to remove evaporated/desorbed moisture. Practitioners and builders have sometimes found this gap to be beneficial, particularly in rainy climates such as coastal British Columbia where so-called "rainscreen" wall assemblies are now required by code for most new buildings. The separation of the cladding from the wall assembly has sparked much debate among the building science community. The functions and benefits of providing this cavity are not seen as necessary by all parties involved, and the actual characteristics of the cavity and vent/drains have not been scientifically determined to perform as required. The minimum size of the air gap is also debated; however, recent work has shown that walls with even very small continuous gaps (<1 mm) can drain well (Smegal 2006). Although the drainage and a capillary break are obvious improvements, the need for and role of ventilation in improving drying is still debated. Recent ASHRAE-sponsored research, however, has been able to predict ventilation rates and show the benefits of ventilation on ventilation drying and reduction of inward solar-driven vapor (Burnett et al. 2004).

The ability to model the impacts of ventilation within wall assemblies using hygrothermal models has so far been limited to a few research-grade two-dimensional models. Recently the Fraunhofer Institute for Building Physics and Oak Ridge National Laboratory (IBP/ORNL) enhanced their one-dimensional hygrothermal software, WUFI 4.1, which is used by many practitioners worldwide. The new enhancement can account for the two-dimensional effects of ventilation within wall assemblies by modeling heat and moisture sources or sinks at any layer within the wall. In addition, the 1% driving-rain load mentioned in the proposed new *ASHRAE Standard 160, Design Criteria for Moisture Control in Buildings* (ASHRAE n.d.), can be easily simulated.

This paper discusses how source and sinks can be used in a hygrothermal model to simulate rain leaks and ventilation drying. The model results are compared to measured field data for common wall assemblies with ventilated claddings, and guidance is provided for calculating cladding ventilation rates and performing accurate simulations.

The role of ventilation in wall performance, the fluid flow mechanics, and previous research are reviewed first to provide the foundation for the research presented here.

Background

It is well accepted that moisture is one of the primary causes of premature building enclosure deterioration. Excess moisture content combined with above-freezing temperatures

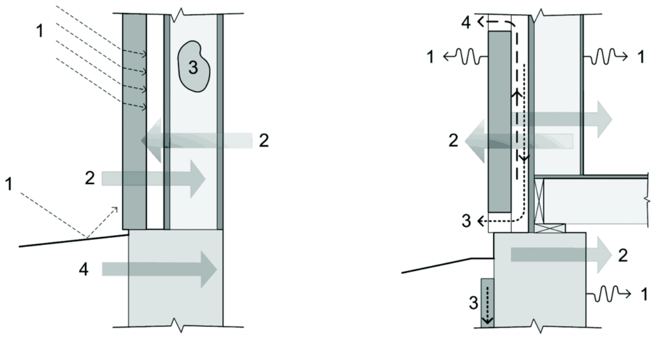

Figure 1 *Wetting (left) and drying (right) mechanisms for walls.*

for long enough will cause rot, mold growth, corrosion, and discoloration of many building materials. The four major moisture sources and transport mechanisms that can damage a building enclosure are (Figure 1, left side):

1. Precipitation, largely driving rain or splash-back at grade
2. Water vapor in the air transported by diffusion and/or air movement through the wall (both to interior and exterior)
3. Built-in and stored moisture, particularly for concrete or wood products
4. Liquid and bound ground water, driven by capillarity and gravity

At some time during the life of a building, wetting should be expected at least in some locations. In the case of a bulk water leak, drainage, if provided, will remove the majority of the moisture from the wall cavity. However, a significant amount of water will remain absorbed by materials and adhered to surfaces. This remaining moisture can be removed (dried) from the wall by the following mechanism (Figure 1, right side):

1. Evaporation (liquid water transported by capillarity to the inside or outside surfaces)
2. Evaporation and vapor transport by diffusion, air leakage, or both either outward or inward
3. Drainage of unabsorbed liquid water, driven by gravity
4. Ventilation by convection through intentional (or unintentional) vented air cavities behind the cladding

A balance between wetting, drying, and storage is required to ensure the long-term durability of the building enclosure. Some commonly used building materials are more sensitive to moisture (e.g., paper-faced gypsum and untreated wood-based sheathings) and require a higher drying potential than the more durable materials they replace (e.g., concrete, masonry, or solid sawn timber). Several widespread building enclosure failures in the past decade, including those in Vancouver, BC; Wilmington, NC; Minneapolis, MN; and other locations in North America, have further raised the awareness and impact of moisture and its impact on building materials (Crandell and Kenney 1996; Morrison Hershfield 1996; Brown et al. 1997, 2003; Barrett 1998; RDH 2001).

Recent building enclosure failures have shown that the drying potential of some wall assemblies in certain climates may be insufficient when exposed to accidental wetting or leaks. As a response to these failures, drained walls have been widely recommended to deal with rainwater penetration. However, cladding ventilation may be needed or useful to increase drying for some wall assemblies in some climates. Ventilated claddings can also control wetting due to inward-driven vapor from rain wetted absorbent claddings. The use of large ventilated and drained cavities has already been mandated by some building codes (NBCC 2005).

Some definitions are useful. A *ventilated* wall is one that has vent openings at the top and bottom of an air cavity to promote air circulation. A *vented* wall has only vent openings at the bottom of the wall, usually provided for drainage (Straube and Burnett 1995). Some exchange of air between the exterior and cavity will occur in a vented wall; however, the volume will be small and the area over which it acts is limited compared to a ventilated wall.

In both ventilated and vented walls, the cladding is separated from the rest of the wall assembly by a gap or cavity. A water resistive barrier (WRB), which acts as a drainage plane and secondary capillary break, is usually provided to the interior of the cladding and ventilated cavity. The cladding and gap, while significantly limiting the amount of rain penetration, are not relied upon to stop all water. The WRB is also not expected to be completely water tight and may allow some small amount of liquid water penetration. The gap must be drained to the exterior using flashings at penetrations and at the base of the wall.

A *rainscreen* wall, as discussed in this paper, is composed of a cladding (stucco, vinyl, cement board, wood) over a ventilated and drained cavity, with flashed details at windows, penetrations, and other transitions.

Not all drained walls are ventilated, and simply providing a drainage cavity does not ensure ventilation will occur. Vent locations and details are important and should be understood by designers.

The principle of using drained claddings with a vented or ventilated cavity behind is not new and has been used for several centuries. For example, brick veneer has typically been installed away from the sheathing since the late 19th century (although the cavity was often blocked with mortar droppings or filled with insulation). The benefits of providing this vented or ventilated cavity has been debated and the topic of much research in the past few decades.

PREVIOUS RESEARCH

The previous field research, ventilation mechanics, and driving forces are discussed.

Field Research

As early as the late 1970s and early 1980s the role of ventilation behind wood claddings was being investigated in Atlantic Canada as problems with warping and paint deterioration of wood sidings became apparent in some climates (Marshall 1983). Wood siding manufacturers performed in-house tests and found that placing wood siding over a strapped air cavity reduced the occurrence of such moisture problems (Morrison Hershfield 1992).

Throughout the 1980s, a growing number of moisture-related failures were discovered in the Canadian housing stock. Field exposure test huts were constructed in different Canadian climates to study the drying of wood-frame walls, particularly when constructed initially with saturated lumber as was common practice for parts of the country (McCuaig 1988; Forest and Walker 1990; Burnett and Reynolds 1991). These studies showed that drying built-in moisture was practical and possible and also provided some evidence that cladding ventilation could improve drying. However, the studies were not conclusive, as test variables were insufficiently controlled to isolate the role of ventilation and its specific impact on drying.

In Europe, the Franhofer-Institut für Bauphysik (IBP) conducted field monitoring of ventilation flow and drying effectiveness for different panel claddings in several different projects. Popp et al. (1980) found that the drying rate of an initially wetted aerated concrete block work wall was significantly faster when the cladding was ventilated or even vented compared to an impermeable cladding, which was adhered directly to the concrete.

Similar results of ventilation drying effectiveness were also shown by Mayer and Künzel (1983), who measured ventilation behind large cladding panels on a three-story building in service. The two forces affecting ventilation were found to be wind-induced pressure differences and solar-induced thermal buoyancy. Hourly air velocities were measured between 0.05 and 0.15 m/s when the wind-speed was between 1 and 3 m/s. Wind direction influenced the ventilation air velocity more than wind speed. From the testing, they concluded that a clear cavity depth of 20 mm was generally sufficient for panel-type claddings, and although a large vent area is not absolutely necessary for acceptable wall performance, it is a practical means of removing trapped moisture. Finally it was recommended that, should moisture-sensitive materials be used in the backup wall, the upper and lower vent openings should be as large as possible to afford increased ventilation rates.

In the United States, the impacts of cladding ventilation on wood-frame walls was also investigated by TenWolde and Carll (1992) and TenWolde et al. (1995). These studies found that in walls with little or no air leakage (from the interior), cavity ventilation promoted drying. When air leakage was allowed, it dominated the results.

In full-scale Canadian field studies, Straube and Burnett (1995) and Straube (1998) investigated the role of air spaces in ventilation drying and pressure moderation behind brick veneer and vinyl siding. The study outlined methods to calculate ventilation flow and found that cladding ventilation could be useful as a means to control inward vapor drives behind brick veneers.

Two Canadian laboratory studies investigated the role of ventilation drying of walls in Vancouver, BC, in the late 1990s. The studies were directly a result of the "leaky-condo crisis," where a large number of moisture failures were observed in the recently constructed residential housing stock in coastal British Columbia (Morrison Hershfield 1996; Barrett 1998). Both Morrison Hershfield (1999) and Forintek (2001) undertook laboratory studies to determine the impact venting or ventilation had on the performance of wood-frame wall assemblies.

In the Morrison Hershfield (1999) study, full-scale insulated wall assemblies with stucco cladding were constructed and initially wetted on the interior side of the sheathing. The walls were exposed to approximately 10°C exterior conditions with no air movement or solar radiation. The major conclusions of the study were that drying was slow for all wall types and that the ventilated rainscreen wall design did not enhance drying of water that penetrates into the stud cavity. Even though the parameters were untested, the authors concluded that solar radiation and wind would have no significant effect on drying, nor would other types of cladding. Applying the physics of thermal and moisture buoyancy described in the next section, calculated natural ventilation rates and driving temperature differences are very low for these walls, and in hindsight it is clear why ventilation drying would not have been effective in these test conditions.

The Forintek (2001) envelope drying rate analysis (EDRA) study was larger and studied more parameters in simulated environments. Two phases were completed, one without simulated exterior wind and solar effects and one with. Solar radiation was simulated up to a 120 W/m^2 peak, equivalent to diffuse radiation on a north-facing wall in Vancouver. Wind pressure differences of 1 to 5 Pa between top and bottom vents were also simulated. The walls were initially soaked to pre-wet the sheathing and studs and, hence, had a relatively uniform distribution of moisture. The sample walls included both stucco and vinyl siding, vented and ventilated designs, spun-bonded polyolefin and building paper sheathing membranes, and oriented strand-board and plywood sheathing. Some of the conclusions from the study included the following:

- Walls with cavities (vented and ventilated) dried faster than comparable panels without cavities (face-sealed). There was a substantial range in the drying rates: as much as three times higher drying rate for comparable walls with a ventilated cavity than for those without.
- Ventilation (top and bottom vents) resulted in marginally faster drying than vented (bottom vents) walls. The width of cavity was also important, and those walls with cavities of 19 mm dried faster than 10 mm.
- Walls with plywood dried faster than comparable walls with OSB sheathing. OSB has a lower vapor permeance than plywood and may have restricted the drying through the sheathing to the exterior.
- Solar radiation increased drying rates of the ventilated walls but had little effect on the face-sealed walls (all walls were restricted from drying to the interior by a low permeance interior vapor barrier).

Recently, ASHRAE sponsored a large research and development project, ASHRAE Research Project 1091, "Development of Design Strategies for Rainscreen and Sheathing Membrane Performance in Wood Frame Walls" (Burnett et al. 2004; Karagiozis 2004; Shi et al. 2004; Straube et al. 2004), to study the mechanics of ventilation in wall systems and assess the potential for ventilation drying of common, above-grade residential wall assemblies. Three institutions were involved in this project, namely, the Pennsylvania Housing Research/Resource Center at Penn State (PHRC/PSU), the Building Engineering Group at the University of Waterloo (BEG/UW), and the Building Technology Center at Oak Ridge National Laboratory (BTC/ORNL). The project produced a total of 12 reports and numerous conference and journal papers and is summarized by Burnett et al. (2004).

A review of the literature and theory was performed, hygrothermal properties of several materials were determined, a study of ventilation flows was performed for brick veneer and vinyl siding, the impact of ventilation drying was determined, computational fluid dynamics (CFD) simulations were performed, and the moisture-expert hygrothermal model was validated using the field data, which allowed further parametric simulations to be performed. The following conclusions were made from the study:

- Ventilation rates are dependent on the cladding and venting configuration (size and type of openings) and strongly influenced by weather events (wind and solar radiation). Brick veneer walls had lower ventilation rates than vinyl siding walls.
- Solar-driven vapor diffusion can act to redistribute vapor from within the wall to the interior, where it can condense and in some cases cause damage. Cladding ventilation reduces the magnitude of this flow, as this vapor is directly removed to the exterior.
- Installing vents at both the top and bottom of a brick wall cavity was shown to benefit drying. Ventilation was more effective than venting (bottom vents only).
    - For a 1.22 m wide by 2.4 m high brick wall with a 20 mm deep cavity with two open head joints (no bug screen) at top and bottom, ventilation rates were predicted and confirmed to be between 0 and 90 ach or 0 and 0.50 l/s/m^2 of cladding.
    - Plastic bug screens typically installed in the vent openings are restrictive to flow and will significantly reduce this ventilation rate by an order of magnitude.

- The vinyl siding profile tested allowed significant ventilation-induced drying with or without furring strips, as it was inherently very leaky. Considerable flow occurs across the cladding upward, downward, and laterally.
    - For a 1.22 m wide by 2.4 m high wall, contact-applied vinyl siding can be expected to be in the range of 0.6 to 2.7 lps/m^2 for pressures of 1 to 10 Pa.
- The effective ventilation rate behind the cladding was dependent on both the wall system and exterior climate. High winds and high temperature gradients produced higher flow rates.
- Fast-drying wall designs can be repeatedly wetted over several years and remain in almost perfect condition without damage.
- Higher ventilation rates behind the cladding increased the drying rate of an initially wetted wall, as shown in Figure 2.

Also part of ASHRAE RP-1091, the Moisture-Expert hygrothermal model was validated with measured laboratory and field results of ventilated walls. Good agreement between the modeled and measured data was demonstrated (Karagiozis 2004). Using the model, parametric simulations were performed to make recommendations to other wall assemblies and in different climates.

Recently, Bassett and McNeil (2006) measured ventilation flows behind several cladding types in a field exposed lab in New Zealand using CO_2 as a tracer gas. Claddings included fiber cement board, EIFS, and brick veneer. The researches found excellent agreement between calculated and measured results using equations provided by Straube and Burnett (1995), which are essentially the same as those presented in the next section by Straube et al. (2004). Calculated versus measured ventilation rates are shown in Figure 3 with good agreement for four different ventilation configurations tested. The drained and ventilated walls have top and bottom vents, open rainscreen walls have only bottom vents, and drainage plane walls only have bottom vents, but airflow is restricted by the use of a nylon drainage mat in the cavity.

McNeil and Bassett (2007) also showed good correlation between faster sheathing drying rates with higher ventilation rates (as a function of venting strategy).

Recent studies of drainage spaces behind claddings further show the impact of cladding ventilation on wall performance. At the University of Waterloo, Smegal (2006) showed that while the majority of water that enters the cavity behind the cladding will be drained, some moisture will also remain after drainage stops, stored on surfaces by surface tension, and/or absorbed into porous materials. Even vinyl siding will store a considerable amount of moisture in the drainage tracks and by capillary suction between laps. After drainage is complete (within a few seconds), the most effective way to remove this additional moisture from the wall assembly is by ventilation.

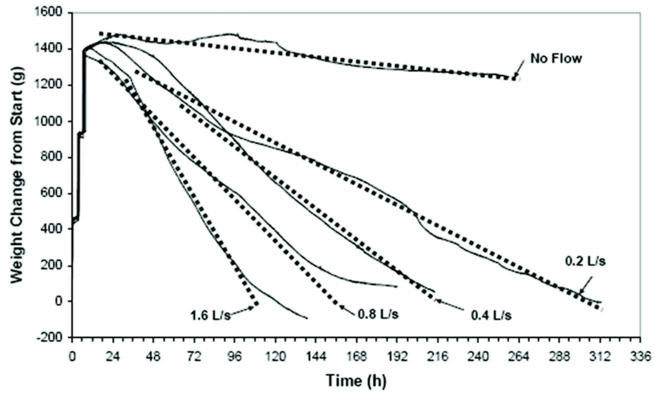

Figure 2 *Drying comparison for a 50 mm cavity with different ventilation rates (Schumacher et al. 2003).*

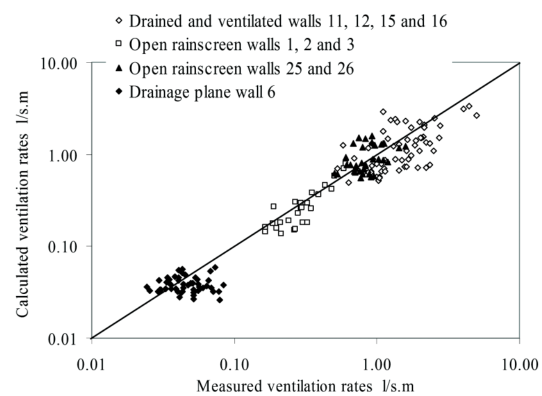

Figure 3 *Ventilation rates behind claddings (Bassett and McNeil 2006).*

In summary, while some of the past research shows conflicting results, the consensus in recent years is that cladding ventilation can improve the drying potential of wood-frame walls when exposed to initial or periodic wetting events. Measured ventilation flow rates show good agreement with the presented theory and can be predicted using CFD models. Therefore, the ventilation theory could potentially be applied to a hygrothermal model to predict field performance.

Ventilation Mechanics

Ventilation drying occurs when convective forces cause moist air to be moved out of an air space and replaced with drier air. Drying of an air space involves the evaporation or desorption of moisture from materials adjacent to the air space, followed by convective transport of moisture to the exterior environment. Ventilation within a wall system therefore has potential as a means of drying for some wall systems.

Ventilation flow through a wall cavity is analogous to fluid flow through a pipe network with calculable pressure drops from cavity friction and vent openings. Fluid flow equations are well developed from civil and mechanical engineering applications and are presented in the current *2005 ASHRAE Handbook—Fundamentals* (ASHRAE 2005).

Methods to numerically calculate airflow rates through ventilation spaces behind cladding and determine the forces driving ventilation are presented by Straube and Burnett (1995), Straube (1998) and most recently by Straube et al. (2004) using empirical and well established fluid flow mechanics. Pressure differences between the top and bottom vents will drive ventilation flow through the cavity, and at equilibrium the pressure drop across the cavity and vent openings will equal the pressure difference as a result of the driving forces. Driving forces include thermal and moisture buoyancy and wind pressures.

The following equations developed in ASHRAE Research Project 1091 (Straube et al. 2004) are summarized here for a panel cladding with a continuous vent opening and a brick veneer wall with discrete vent openings (at head joints).

The pressure balance through the ventilated cavity can be simplified as follows:

$$\Delta P_{total} = \Delta P_{entrance} + \Delta P_{cavity} + \Delta P_{exit} \tag{1}$$

For a panel cladding, such as stucco or cement board with continuous slot vents, the pressures can be determined from the following:

$$\Delta P_{total} = C_{entrance} \cdot 0.5\rho \cdot V^2 + \frac{32 \cdot k_f \cdot V \cdot \mu \cdot L}{\gamma_c \cdot D_h^2} + C_{exit} \cdot 0.5\rho \cdot V^2 \tag{2}$$

where

C = flow coefficient for the entrance/elbow/exit, from published literature

ρ = density of air, kg/m^3

V = velocity through the vent or cavity, m/s

k_f = correction factor for a rectangular conduit

μ = dynamic viscosity of air ($18.1 \cdot 10^{-6}$ N·s/m^2 [ASHRAE 2005])

L = cavity length, m

γ_c = cavity blockage factor to account for mortar protrusions, etc.

D_h = hydraulic diameter of the cavity, m

For brick veneers, the vents can be treated as standard sharp edge orifices (Straube and Burnett 1995), and the equation is simplified as follows:

$$\Delta P_{total} = \left(\frac{Q_{vent1}}{0.6 \cdot h_{v1} \cdot w_{v1} \cdot \gamma_{v1}}\right)^2 + \frac{32 \cdot k_f \cdot V \cdot \mu \cdot L}{\gamma_c \cdot D_h^2} + \left(\frac{Q_{vent2}}{0.6 \cdot h_{v2} \cdot w_{v2} \cdot \gamma_{v2}}\right)^2 \tag{3}$$

where

Q_v = airflow through each vent, m^3/s

h_v = vent height, m

w_v = vent width, m

γ_v = vent blockage factor to account for bug screens, obstructions, etc.

Guidance to selecting appropriate cavity or vent blockage factors can be found in Straube et al. (2004). These factors are related geometrically to correct for the actual versus intended size of the opening (i.e., a cavity blockage factor of 0.5 relates to a 50% restriction in size).

The equations presented here assume laminar flow, which typically occurs in the field. Where turbulent flows occur, the equations can be modified accordingly. CFD modeling refinements by Piñon et al. (2004) and Stovall and Karagiozis (2004) confirm the development of fully laminar airflows within the cavity and refine some loss coefficients in brick vents to reflect nonlaminar flow.

Four typical North American wood-frame wall assemblies with ventilated claddings are compared below using the flow theory presented above. Details were selected to be representative of common practice and to show the relative differences in ventilation flows between cladding types as a result of the selected vent configurations. The four walls are described in Table 1, and using the presented equations, the air velocity and ventilation flow versus pressure is presented in Figures 4 and 5.

As shown, the wall systems with large open vents (panel claddings) will experience large ventilation rates at relatively low driving pressures. Therefore, under normal conditions they will be well ventilated, whereas wall systems with small restricted vents require much higher driving pressures to attain large ventilation rates.

Vinyl siding, while commonly used, was not compared above, as ventilation flow cannot be accurately calculated. Laboratory testing has shown that vinyl siding profiles are very leaky and have numerous flow paths through and around the cladding (VanStraaten 2004). However, for modeling purposes it can be assumed the ventilation rate is very high when vinyl cladding is used, and one could calculate flows for a panel cladding (Equation 2) with wide open, unobstructed vents as a reasonable estimate to account for the leakage through multiple paths.

Once the flow versus pressure relationship is determined for a specific wall and vent arrangement, the driving pressures can be applied to determine the ventilation rate.

Driving Forces

Ventilation flow is driven by a combination of thermal buoyancy, moisture buoyancy, and wind pressures. When a difference of pressure between the air cavity and exterior exists, ventilation flow will occur. Thermal buoyancy and moisture buoyancy are relatively predictable and often steady, and can be high when the materials lining the ventilation cavity are wet. Combined thermal and moisture buoyancy can

Table 1. Ventilation Cavity and Vent Details for Four Cladding Types

	Cement Stucco on Backer Board on Strapping	Horizontal Wood Siding (or Cement Board) on Strapping	Brick Veneer with Top and Bottom Vents	Metal Panel with Slot Vents
Cavity Notes	19 × 38 mm wood strapping at 400 mm (16 in.) on center	19 × 38 mm wood strapping at 400 mm (16 in.) on center	25 mm (1 in.) open cavity, brick ties as required	12 mm open cavity, steel z-girts at 914 mm (3 ft) on center
Cavity width	362 mm (14.5 in.)	362 mm (14.5 in.)	Continuous, per 1000 mm (3.28 ft) width	914 mm (3 ft)
Cavity depth	19 mm (0.75 in.)	19 mm (0.75 in.)	25 mm (1 in.)	12 mm (0.5 in.)
Cavity weight	2743 mm (9 ft)	2743 mm (9 ft)	2743 mm (9 ft)	2743 mm (9 ft)
Cavity blockage factor, γ (0.01 to 1)	0.9 (assume slight bowing of stucco backer board when stucco is installed)	1.0 (cladding is rigid enough to span between strapping)	0.8 (mortar protrusions in well constructed brick veneer)	1.0 (smooth metal panel)
Vent Notes	Continuous through-wall flashing at floor height top and bottom	Continuous through-wall flashing at floor height top and bottom	Spaced every two bricks top and bottom	Drilled or punched slot vents top and bottom
Vent dimensions	12 mm bottom, 12 mm top, both continuous	19 mm bottom, 19 mm top, both continuous	10 mm × 65 mm spaced at 400 mm	6 mm × 25 mm spaced at 456 mm (1.5 ft)
Vent blockage factor (0.01 to 1)	0.5, mesh bug screen, estimate	0.5, mesh bug screen, estimate	0.1, plastic bug screen insert (Straube 1998)	1.0, open slots, no restrictions

be calculated from the following simple equation (Straube et al. 2004):

$$\Delta P_{buoyancy} = [\rho_{exterior} - \rho_{interior}] \cdot g \cdot L \quad (4)$$

where ρ is the density of moist air at specific temperature and RH (ASHRAE 2005).

Wind pressures are highly variable and can be very large for short periods of time. For wind to drive ventilation pressures, a pressure differential must occur between connected vent openings and this pressure difference must vary with wind speed and direction (Straube 1998; Straube et al. 2004).

The wind pressures on the wall are typically presented as a fraction of the stagnation pressure ($P_{stagnation}$) and correlated to a specific wall on a building using a ventilation pressure coefficient (C_{pv}) where the ventilation pressure ($P_{ventilation}$) is determined by the following:

$$P_{stagnation} = \frac{1}{2}\rho \cdot V_{wind}^2 \quad (5)$$

$$P_{ventilation} = C_{pv} \cdot P_{stagnation} \quad (6)$$

Simple stagnation pressure coefficient (C_p) factors have been developed for square building shapes and could be used for static cases where the C_p factor at the top and bottom vent is determined and the difference between the two is the ventilation factor (C_{pv}). Unfortunately the basic factors rarely represent buildings in the field (due to shape and other influ-

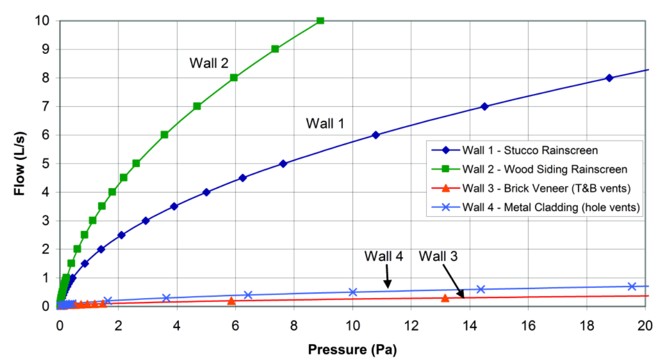

Figure 4 *Velocity airflow versus pressure for walls 1–4.*

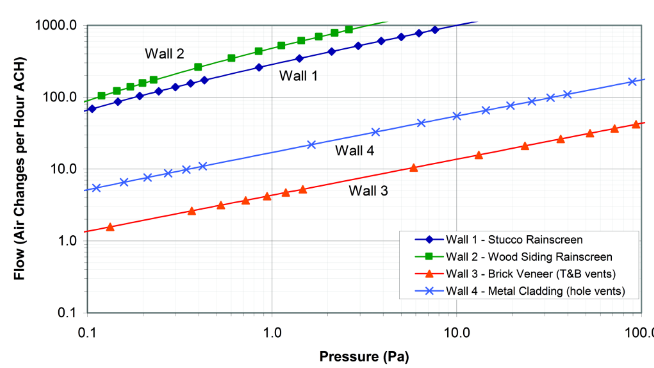

Figure 5 *Airflow (ach) versus pressure for walls 1–4.*

ences) and vary with wind direction. More accurately, these C_p factors can be determined for a specific building with use of CFD modeling, wind tunnel studies, or field monitoring.

MEASURED PERFORMANCE OF WALLS WITH VENTILATED CLADDINGS

Field data were collected from monitored buildings in Vancouver, BC, and Waterloo, ON, with a range of different wall assemblies and cladding. The data are used in this paper to demonstrate the impact of cladding ventilation and to validate the hygrothermal model.

The data from Vancouver are taken from several residential buildings with ventilated rainscreen claddings that were monitored for a period of five years from 2001 to 2006. A total of five buildings were monitored as part of the project; however, only data from the three wood-frame buildings are presented in this paper (referred to as Buildings 1, 2, and 4 for consistency with other reports). The research project was undertaken by RDH Building Engineering (RDH), Canada Mortgage and Housing Corporation (CMHC), the Homeowner Protection Office (HPO), and British Columbia Housing Management Commission (BCHMC). Data collection methodology, building details, and results are presented in more detail in RDH (2005) and Finch (2007).

The data from Waterloo are taken from a research project at the University of Waterloo's field exposure and test facility (BEGHut). Data from a set of wood-frame walls with ventilated brick veneer monitored in a recent study are presented in this paper. The data collection methodology for the walls presented in this paper is discussed by Finch et al. (2007a) and is consistent with Straube (1998), and VanStraaten (2004).

For both studies, sensor and instrumentation methodology can be found in Straube et al. (2002). A summary of the monitored walls is provided in Table 2, including an overview photograph of the building, a typical wall assembly, and ventilation cavity details.

Predicted Cavity Ventilation

Hourly wind ventilation pressures were calculated for the BEGHut brick veneer walls from Equations 4, 5, and 6 in addition to previously developed wind directional ventilation pressure coefficients from Straube (1998) (i.e., same building, wall type, and vent arrangement as previously studied). Total driving pressures were compared before and after the addition of the wind pressures and, while significant as a percentage, had only a small impact on the overall ventilation rates. Wind pressures increased the average annual ventilation rate from 1.6 to 2.1 ach on the north to 2.2 to 2.3 ach on the south, the baseline being thermal and moisture buoyancy pressures only. The wind pressures evened out the differences between the shaded north and solar-exposed south elevation.

Table 2. Summary of Monitored Field Buildings

Vancouver—Building 1 Four-story, vinyl-clad rainscreen walls, new construction	**Vancouver—Building 2** Four-story, stucco-clad rainscreen walls, rehabilitation project	**Vancouver—Building 3** Four-story, cement-board rainscreen (floors 2–4) and brick veneer (floor 1), new construction	**Waterloo—BEGHut** One-story, brick veneer, field-exposed test facility
			
• vinyl siding • 19 mm ventilated cavity (19 mm treated wood strapping at 400 mm) • 2 layers 30 min building paper • 13 mm plywood • 140 mm fiberglass batt • 6 mil polyethylene • 12 mm gypsum drywall • latex paint and primer	• 19 mm stucco cladding • 19 mm ventilated cavity (19 mm treated wood strapping at 400 mm) • layer SBPO housewrap • 13 mm plywood • 140 mm fiberglass batt • 4 mil polyethylene • 12 mm gypsum drywall • latex paint and primer	• 6 mm cement board • 19 mm ventilated cavity (19 mm treated wood strapping at 400 mm) • 2 layers 30 min building paper • 13 mm plywood • 89 mm fiberglass batt • 6 mil polyethylene • 12 mm gypsum drywall • latex paint and primer	• 89 mm clay brick • 38 mm ventilated cavity (openings at 400 mm top and bottom) • 1 layer SBPO housewrap • 12 mm OSB sheathing • 140 mm open or closed cell sprayfoam • 12 mm gypsum drywall • latex paint and primer
Continuous vent openings at 2nd and 4th floors (cavity flashing). Approximately 12 mm opening between vinyl starter track and metal flashing.	Continuous vent openings at every floor level (cavity flashing). Approximately 12 mm opening top and bottom vent with bug screen.	Continuous vent openings at every floor level (cavity flashing). Approximately 12 mm opening top and bottom vent with bug screen.	Brick vent slot openings at every other brick top and bottom (400 mm on center). 10 mm × 65 mm opening with plastic bug screen insert.

For the three Vancouver buildings presented, wind direction and ventilation pressure coefficients cannot easily be determined, as the buildings are a different shape and height and have a different vent configuration than the BEGHut. Therefore, cladding ventilation as a result of wind pressure was excluded from the analysis of these walls. However, it will be shown later that the additional effect of wind-driven ventilation may only have a minor impact on the results, as high ventilation rates are already observed from thermal and moisture buoyancy alone. Although wind significantly improves ventilation behind the claddings of these buildings, it will be shown that buoyancy pressures alone can generate high ventilation flows. Once high ventilation flows are reached, the additional impact of wind-induced ventilation has little impact on the performance of these wall assemblies.

Applying the pressure-ventilation relationships, an annual histogram of calculated ventilation rates for an east-facing rainscreen stucco wall in Vancouver, BC, (Building 2) is compared to both a north and south facing brick wall for Waterloo, Ontario, (BEGHut) in Figure 6. Note that wind pressure-induced ventilation is excluded from the Vancouver building.

The BEGHut calculated ventilation rates are consistent with previously reported values (Straube 1998), accounting for the flow reduction from the plastic bug screen brick vent inserts. The calculated ventilation rate for Building 2 (stucco rainscreen) is similar to that measured by Bassett and McNeil (2006) in Figure 3. Bassett and McNeil measured average ventilation rates of 0.5 to 5 L/s/m for similar type walls, which equates to 40 to 400 ach, similar to the distribution of rates shown above.

While the annual average ventilation rate has been shown, it tells little about the hourly or daily ventilation rates. Figure 7 shows the hourly calculated ventilation rate for two days during March 2002 for Building 2 in Vancouver, which compares to the cavity and exterior air temperature and the impact of solar radiation on the east wall surface.

The impact of solar radiation and cavity temperature driving buoyancy pressure differences is shown. March 1 was a cloudy day and had low solar radiation and a reduced ventilation rate. March 2 was a clear day and solar radiation increased the cavity temperature 20°C above the ambient exterior air temperature. The temperature differential between the cavity and exterior air acted strongly to drive the large ventilation rates during the day when the sun was out. Hence, the role of solar radiation is important and cannot be excluded from the analysis of cladding ventilation rates.

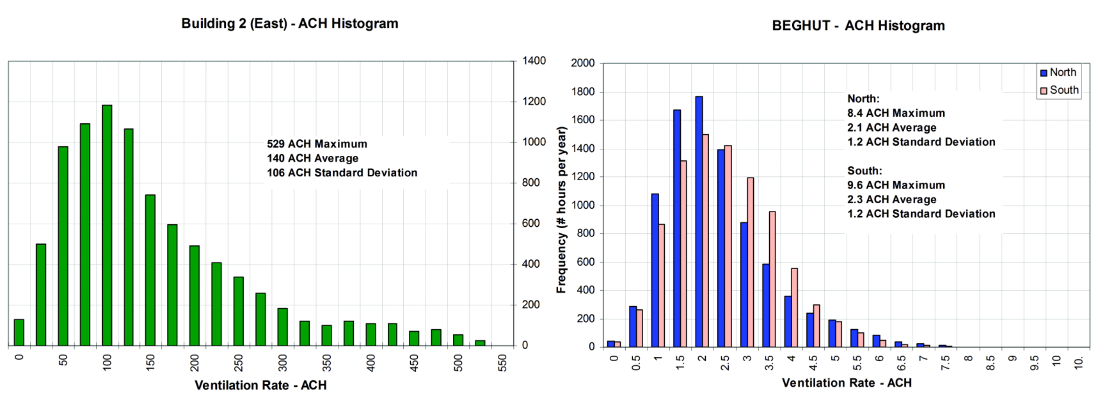

Figure 6 *Building 2 in Vancouver and BEGHut in Waterloo—Annual ventilation ach histograms.*

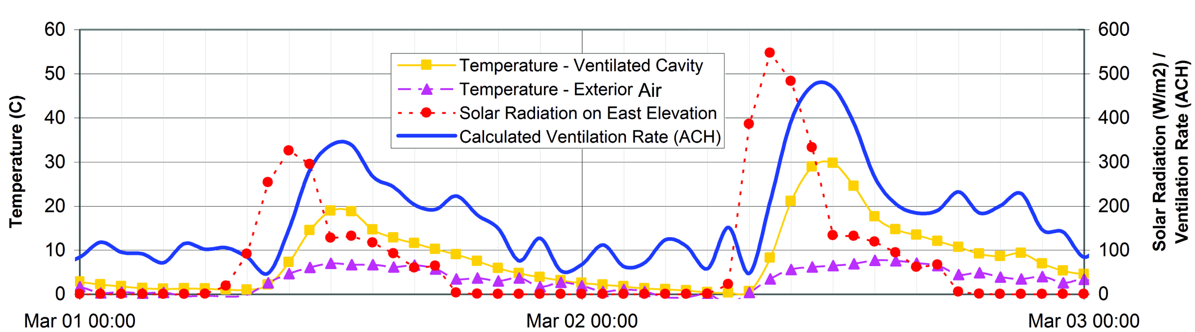

Figure 7 *Building 2 calculated ach versus measured temperatures and solar radiation.*

HYGROTHERMAL MODELING OF VENTILATED CLADDING

Commercially available one-dimensional hygrothermal software, such as WUFI 4.0 1D, are often used by practitioners to perform design analyses or forensic simulations of wall and roof assemblies. To assist in making design decisions, several cases can be modeled together with different variables (including materials or boundary conditions) to develop an understanding of the performance range of a particular system. The limitation of such current hygrothermal software includes the inability to model air leakage or account for ventilation or rain leaks. The latter ability is important if one is to meet the proposed new ASHRAE Standard 160 (ASHRAE n.d.) requirement for 1% of the driving-rain load to be modeled as leaking past the cladding.

Currently modeling of walls with cladding ventilation tends to yield inaccurate results unless modifications are made to the cladding materials or assembly to approximate the effects of ventilation (this is discussed in detail in the next section).

To account for ventilation, IBP has introduced a new version of WUFI 4.1 that can model heat and moisture sources and sinks within wall assemblies at locations other than the exterior or interior boundary layers. In addition to ventilation, rain leaks, air leaks, or heat sources can be added to layers within the assembly and modeled. Different types of moisture and/or thermal sources or sinks can be modeled as follows (Kehrer 2006):

1. Source from file (constant or at user defined interval)
2. Source as fraction of boundary conditions (i.e., 1% driving-rain load for the proposed ASHRAE Standard 160 [ASHRAE n.d.])
3. Source derived from air change rate in a ventilated gap (constant or user defined interval)

In the third option, WUFI 4.1 allows the user to ventilate airspaces by assigning either a fixed or hourly ventilation rate (in the form of ach). The moisture added to or extracted from the cavity is modeled as a well-mixed process as follows:

$$Q_m = \frac{\text{ach}}{3600} \cdot d_{cavity} \cdot (X_{out} - X_{cavity}) \tag{7}$$

where

Q_m = the moisture source/sink strength, kg/m^{2}s
X_{out} = water content of the outdoor air, kg/m^3
X_{cavity} = water content of the cavity air, kg/m^3

The thermal source is calculated as follows:

$$Q_t = \rho_{out} \cdot \frac{\text{ach}}{3600} \cdot d_{cavity} \cdot C_{p,\,Air} \cdot (T_{out} - T_{cavity}) \tag{8}$$

where Q_t is the thermal source term (W/m^2) and $C_{p,\,Air}$ is the specific heat capacity of dry air at constant pressure, moisture excluded.

When the simulation is complete, the user can check for errors and the balances to ensure the accuracy of the calculations.

The accuracy of previous versions of WUFI have been verified against many full-scale field studies of enclosure performance (roofs, walls, foundations, parking garage decks, etc.) over a number of years (Karagiozis et al. 2001; Künzel 1998a, 1998b; Straube and Schumacher 2003). The source and sink model builds on the existing platform.

The use of a two-dimensional hygrothermal model may be more accurate at modeling the effects of ventilation or leaks. However two-dimensional models may not be required in all situations or practical for some users. Modeling the impacts of leaks or ventilation in a two-dimensional model is currently time consuming. Therefore the ability to estimate some two-dimensional effects (heat and moisture sources, i.e., rain and air leaks or ventilation) in existing one-dimensional models which are fast, well benchmarked, and widely used is desirable for practitioners.

A single wall assembly is used throughout this paper for comparing field and modeled results. This wall is representative of Building 2 (see Table 2 for details). The monitored wall is exposed, faces east, and is on the fourth floor. A rain deposition factor (RDF) of 0.5 was used, which was calibrated using collected driving-rain data for the east wall of this building (Finch 2007). The vent configuration and blockage factors are consistent with Wall 1 as presented earlier (19 × 364 × 2743 mm cavity, 12 mm vent openings, 0.5 blockage factor for fine mesh bug screens). Moisture content data are typically presented for the plywood sheathing as it is a measure of the performance of a wall; however, the temperature, relative humidity, and dewpoint (or absolute moisture) readings throughout the wall were compared to measured data when making conclusions regarding the accuracy of the modeling.

Previous Modeling Techniques

A number of modeling techniques have been used by practitioners in the past to model wall assemblies with ventilated claddings. These techniques have included the following:

1. **Ignoring Ventilation Effects.** The traditional approach has been to ignore the impact of ventilation by inserting a still-air cavity behind the cladding and in some cases (where ventilation is very low, in dry climates, or with high permeance cladding) this may produce reasonable results. However, for most climates and wall assemblies, this method will yield inaccurate results, highlighting the importance of ventilation and the cladding properties.
2. **Effective Cladding Permeance.** The user modifies the vapor permeance of the cladding material by an order of magnitude depending on the estimated ventilation rates. Effective permeance can be calculated using methods as shown by TenWolde and Carll (1992) and Straube and Burnett (1995, 2005), which typically results in an order of magnitude increase to the cladding vapor permeability. The

cladding is left in the model as a screen to account for solar radiation heating and moisture storage from wetting events. The effective vapor permeance, which is determined by the user, has a significant impact on the results and, hence, can be subjective based on the user's experience.

3. **Removal of Cladding.** The user removes the cladding from the model and at the same time rain and solar radiation loads are typically turned off in the model to prevent the sheathing from being directly wetted or solar heated. The impacts of solar radiation and rain have a significant result on the moisture distribution, wetting, and drying and therefore this method tends to underestimate the moisture loading.
4. **Using Cavity Conditions as Exterior Boundary Conditions.** Involves using measured cavity conditions (*T*/RH) as the exterior boundary conditions in a KLI file with the cladding and air cavity removed. This method has been shown to be accurate at capturing the wall performance to the interior of the cladding (Finch et al. 2007a, 2007b). However, it can only be used if collected cavity data are available. It is not useful to the general user who uses a model to design and therefore it is not discussed further in this paper.

The sheathing moisture content of a stucco-clad rainscreen wall (Building 2) modeled using the different techniques discussed above are reported in Figures 8 and 9. The wall assembly listed in Table 2 with materials properties in the WUFI database was used. A "face-sealed" case (one in which the stucco is in direct contact with the water resistant barrier) was also modeled for comparison. Face-sealed assemblies have a poor record of performance in Vancouver due to sheathing rot and decay (Morrison Hershfield 1996).

Experience and moisture probe testing of wood-frame buildings in Vancouver's coastal climate has shown a seasonal moisture trend from low in the summer (5%–15% moisture content) to high in the winter (15%–25% moisture content). The moisture content of the sheathing is at its highest during the wet winter months, starting during the first significant rainfalls in fall (October–November) until the warmer and drier weather in spring (March–April). Similar trends have been observed in ventilated rainscreen walls of the Vancouver monitoring study for the past five years (Finch 2007). Not including the effect of ventilation in the model results in a significant (as much as 15% higher moisture content) overprediction of the moisture content and a shift in the peak moisture levels until the summer months.

Therefore, when the modeled results show skewed curves with peak moisture contents occurring in late spring and early summer, the user should be aware that the results may not be accurate. This occurs in the model as rain, which coupled with higher exterior temperatures and solar radiation acts to drive moisture into the wall (reverse vapor drive) and elevate sheathing moisture levels. Allowing this moisture to dissipate (less

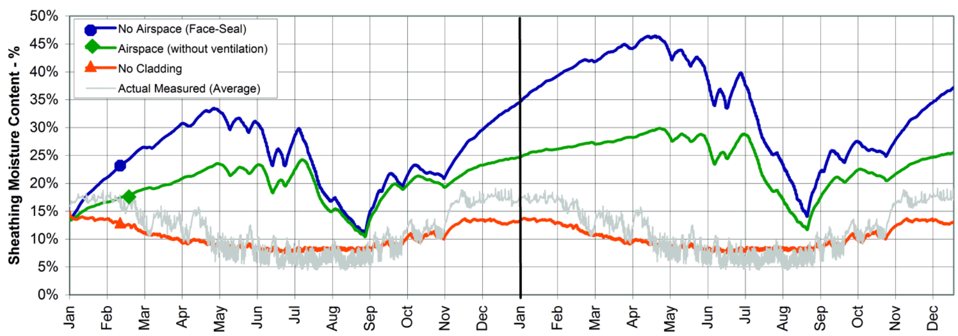

Figure 8 *Hygrothermal modeling techniques—comparison of modeling techniques (1 and 3).*

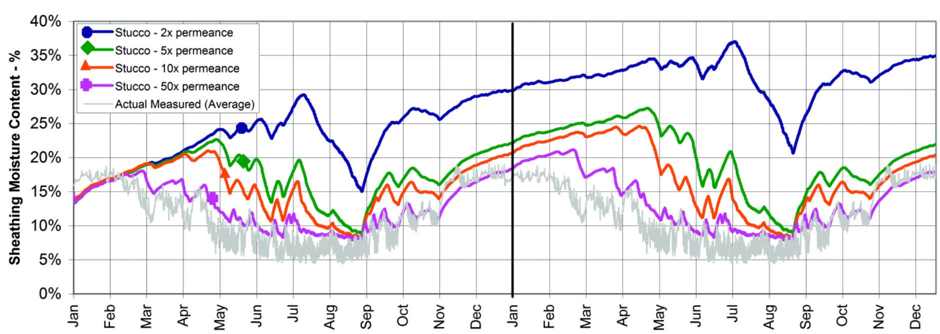

Figure 9 *Hygrothermal modeling techniques—comparison of effective cladding permeance.*

permeable cladding or ventilation) shifts the peak to the wet winter months.

Source and Sink Approach to Modeling Ventilated Claddings

The impact of the ventilation rate was investigated with the model for the stucco rainscreen clad wall used in the previous example. Fixed ventilation rates of 1, 10, 50, 100, 140, and 200 ach were considered as well as an hourly varying ventilation calculated from the buoyancy pressures alone (Equation 4). From the results shown in Figure 10, it is again clear that the cladding ventilation rate can have an important effect on the modeled performance of rainscreen walls in Vancouver's climate. Lower ventilation rates will result in higher sheathing moisture contents for prolonged periods of time during the warm spring and summer months, which could allow mold growth and decay.

The use of the calculated ventilation rate for buoyancy only results in a close fit to the data. Higher ventilation flow rates likely occur in the field because of the flow induced by wind. Using a fixed or annual average (140 ach in the case of Building 2) ventilation rate can predict field performance with reasonable accuracy and captures the trends of the sheathing moisture content. For these simulations, the annual average rate is sufficient for most modeling purposes. Obviously, using the actual hourly ventilation rate is more accurate; however, it may not be worth the extra effort.

For the results shown above, the buoyancy pressures were calculated using the measured cavity temperature and RH. Without these field measurements, one can estimate the hourly ventilation rate iteratively by trial and error using the following method:

1. Calculate the flow versus pressure relationship for the wall assembly and venting arrangement you wish to model.
2. Choose an annual ventilation rate and run the model.
3. Export predicted hourly cavity temperature and RH.
4. Calculate thermal/buoyancy and wind pressures to predict a new hourly ventilation rate.
5. Run model with new calculated hourly ventilation rate.
6. Compare cavity *T*/RH with previous.
7. Repeat until *T*/RH from previous case is close enough to previous case.

In our experience, convergence occurs within one or two iterations.

Future software versions could automate this iterative and time-consuming process. Users could input the wall cavity and vent dimensions and details, and the software could apply the relationships and automatically determine the cladding ventilation based on wind and thermal/moisture buoyancy pressures.

Validation with Measured Field Data

The source and sink approach was applied to the stucco-clad wall of Building 2 and the vinyl cladding of Building 1. It was necessary to add a small amount of moisture storage (about 0.7 kg/m^2 at saturation) to account for the liquid water that can be stored in the tracks of the vinyl cladding. If this amount of storage is not added, the moisture content is under-predicted in the model and varied from 6% to 12% instead of 8% to 17% moisture content.

Measured field data from rainscreen clad walls in Vancouver, BC, show good correlation with the WUFI model using either hourly or annual average cladding ventilation rates (Figure 11). Sheathing moisture contents for Buildings 1 and 2 are shown. The modeled results are plotted against eight measured locations in each building (four monitored areas at the center of the wall and at details) to show the range observed in the field results. A relatively large scatter exists in the measured data; however, the trends are consistent and captured accurately by WUFI. Other parameters, including temperature and relative humidity through the wall, were compared and shown in more detail by Finch (2007). Results from Building 4 (cement board cladding) are not shown here but demonstrate similar results; however, good agreement with the model required a different sorption isotherm for plywood than in the WUFI database.

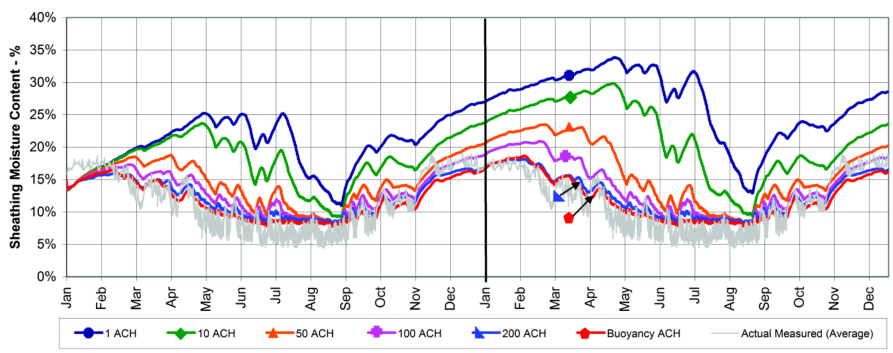

Figure 10 *Effect of cladding ventilation on moisture content of sheathing.*

Material properties have a significant impact on the modeling results. Results shown here are for first run-type simulations where materials from the WUFI database were used (with the exception of vinyl siding and cement board, which were modified to provide additional moisture storage to more accurately reflect measured results). Further research and measurements of cladding properties should be performed to update the material database.

The measured data from the brick veneer walls in the BEGHut were also compared to the WUFI model using hourly ventilation rates. The ventilation rates within the brick veneer are lower (<10 ach) and, hence, the wall assembly is more sensitive to moisture loading from the absorptive cladding. The measured and modeled results closely correlate when the rain loading is carefully controlled using RDFs previously determined for the BEGHut. Again, the model is sensitive to the material properties of the brick veneer and, depending on which database material is used, slightly different results will occur. The ventilation rate was also found to have a strong influence on the moisture content of the sheathing. Increasing the cladding ventilation rate reduced the sheathing moisture content, particularly when exposed to higher driving rain. However, in practice it may be difficult to effectively increase the ventilation rate in brick veneer walls with traditional venting arrangements.

Impact of Leaks

The impact of rainwater leaks on the performance of rainscreen wall systems in Vancouver, BC, was also modeled. The stucco-clad rainscreen Building 2 model was used with a leak depositing moisture at one of two locations within the wall assembly. The total calculated driving rain on the east elevation was 373 kg/m^2 when an RDF of 0.25 was used. A leak as a percentage of the driving rain was modeled for three cases: 0.1% (0.37 kg/m^2), 0.5% (1.87kg/m^2), and 1.0% (3.73 kg/m^2). The moisture source was placed into the model at either the exterior or interior surface of the plywood sheathing. It was found that adding the leak to the exterior surface of the sheathing membrane has only a negligible impact on the sheathing moisture content, as the additional moisture was removed by the high ventilation rate (annual average 140 ach) for this particular wall assembly. However, when the leak occurred past the WRB at either plywood surface, it was absorbed and increased the sheathing moisture content. The results for six cases are presented in Figure 12. The leak at the exterior side of the sheathing is shown in the left plot, and the leak at the interior insulation/sheathing interface is shown in the right plot. Vapor diffusion drying was prevented to the interior by the use of a polyethylene vapor barrier and, as no annual storage was observed, all added moisture from the leak was removed from the wall assembly by ventilation to the exterior.

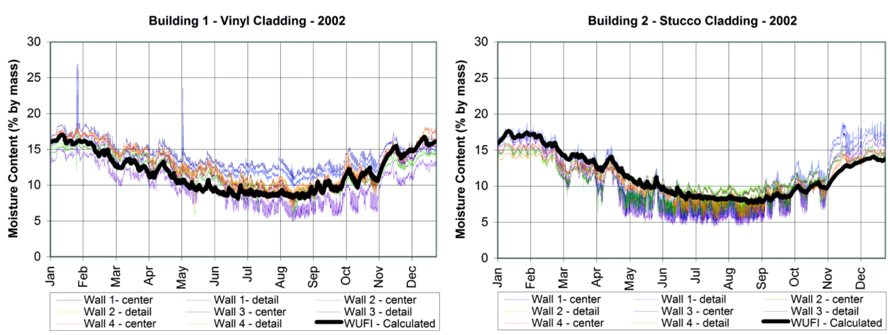

Figure 11 *Buildings 1 and 2 2002 measured versus calculated sheathing moisture content.*

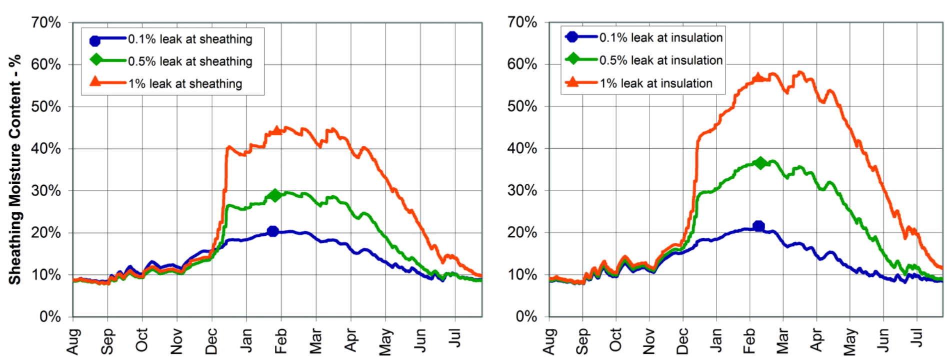

Figure 12 *Effect of rainwater leaks in a stucco-clad rainscreen wall in Vancouver, BC.*

All cases dry out by the summer in this climate but reach dangerous levels for other months if more than 0.1% leakage occurs. The location of the leak can be seen to have an impact on the results, but higher sheathing moisture contents are reached when the leak occurs at the interior face of the sheathing. As expected, this indicates that the vapor permeance and moisture transport properties of the sheathing can somewhat limit or reduce the drying potential.

In reality, most leaks tend to be localized—not uniformly distributed as assumed by the model—and, hence, some redistribution of moisture will occur within the wall assembly. To model the effect of a small leak and the impact it has on the surrounding materials, two-dimensional or three-dimensional models may be required to properly account for redistribution to unwetted materials. The one-dimensional model can show the effect of large widespread leaks but may not be able to accurately model small isolated leaks. Further research is required in this field before guidelines can be developed to accurately model different types of leaks.

CONCLUSIONS AND RECOMMENDATIONS

While some previous research of ventilation drying shows conflicting results, the consensus in recent years is that cladding ventilation may increase the drying potential of a wall and reduce wetting from absorptive claddings and sun-driven moisture. Higher ventilation rates are shown to result in faster drying rates of wood sheathings. Measured ventilation rates in the field and laboratory show good agreement with the predicted rates calculated from fluid flow mechanics theory. The probable range of ventilation rates depends on the cladding type, cavity dimensions, and venting arrangement, and is determined by thermal and moisture buoyancy and wind pressures.

It was shown that current one-dimensional hygrothermal software has a limited ability to model the wetting and drying of walls with ventilated claddings. Minor modeling adjustments were found to be limited in their accuracy for some ventilated cladding scenarios. The new version of one-dimensional WUFI 4.1, which can model heat and moisture sources and sinks within wall assemblies, can overcome many of the limitations of using one-dimensional models. This hygrothermal model was validated with measured field data from three buildings constructed with ventilated claddings in Vancouver, BC, and one in Waterloo, Ontario.

Results from the new model highlight the importance of cladding ventilation for several wood-frame wall assemblies. When hourly or annual average cladding ventilation rates are calculated using the theory outlined and ventilation is modeled as a source/sink, the correlation between the field measured and modeled results is excellent. Further modeling shows that higher ventilation rates can improve the performance of certain wall assemblies (reduce sheathing or overall moisture levels and reduce solar-driven moisture).

The larger the cavity, the greater the ventilation flow for similar driving pressures. The vent openings are a critical detail and should be made as large and unobstructed as possible without allowing rain penetration or bird/animal/insect ingress. Brick vent bug-screen inserts are especially problematic and by removing the inserts the ventilation rate can be increased by a factor of ten for similar driving pressures. Alternately, larger or additional vent openings (between every brick) may be an option to improve ventilation rates and, thus, drying potential.

The impact of a rainwater leak that penetrates the wall assembly can also be modeled, and it was shown that continual leaks (as a fraction of the driving rain load) can lead to elevated moisture contents even in ventilated rainscreen wall assemblies. Selection of an appropriate leak size is up to the user and will vary depending on climate and exposure. Further research should be performed to determine the validity of modeling small leaks with a one-dimensional hygrothermal program, and the impacts of three-dimensional redistribution of moisture.

The hygrothermal model could also be updated to calculate flow versus pressure relationships for user-defined wall assemblies and vent configurations. The hourly ventilation flow rates could then be determined by the software based on thermal and moisture buoyancy and wind pressures.

REFERENCES

ASHRAE. 2005. *2005 ASHRAE Handbook—Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. n.d. *BSR/ASHRAE Standard 160P, Design Criteria for Moisture Control in Buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Forthcoming.

Barrett, D. 1998. The renewal of trust in residential construction—Part 1. Commission of Inquiry into the Quality of Condominium Construction in British Columbia, Canada.

Bassett, M.R., and S. McNeil. 2006. Measured ventilation rates in water managed wall cavities. *Proceedings from the 3rd International Building Physics Conference, Montreal, Quebec, Canada*, pp. 403–10.

Burnett, E., and A. Reynolds. 1991. Final report—Ontario wall drying study. University of Waterloo, Building Engineering Group Report for Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Burnett, E., J. Straube, and A. Karagiozis. 2004. Synthesis report and guidelines, ASHRAE 1091 Report #12 prepared by the Pennsylvania Housing Research/Resource Center, Pennsylvania State University, for ASHRAE.

Brown, W., P. Adams, T. Tonyan, and J. Ullett. 1997. Water management in exterior wall claddings. *Journal of Thermal Insulation and Building Envelopes* 21:23–43.

Brown, W., K. Chouinard, M. Lawton, A. Patenaude, and J. Vlooswyk. 2003. Field experience with moisture management—Putting principals into practice. *Building Science Insight Proceedings of the Seminar Series, 15 Canadian locations*, *October 2003 to January 2004*.

Crandell, J., and T. Kenney. 1996. *Investigation of Moisture Damage in Single-Family Detached Houses Sided with Exterior Insulation Finish Systems in Wilmington, NC.* NAHB Research Center, Inc., Upper Marlboro, MD.

Finch, G. 2007. The performance of rainscreen walls in coastal British Columbia. Masters thesis, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, Canada.

Finch, G., J. Straube, and B. Hubbs. 2007a. Hygrothermal performance and drying potential of wood frame rainscreen walls in Vancouver's coastal climate. *Proceedings from 11th Canadian Conference on Building Science and Technology*, *Banff, Alberta*.

Finch, G., J. Straube, and M. Richmond. 2007b. Field performance of spray polyurethane foam: The role of vapour diffusion control. *Proceedings from 11th Canadian Conference on Building Science and Technology*, *Banff, Alberta.*

Forest, T., and I. Walker. 1990. Drying of walls—Prairie region. CMCH Report by Department of Mechanical Engineering, University of Alberta, Edmonton, Canada.

Forintek. 2001. Envelope drying rates experiment. Contract 99-2221, Forintek Canada Corporation for Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Karagiozis, A. 2004. Benchmarking of the moisture-expert model for ventilation drying. ASHRAE 1091 Report #10 prepared by Oak Ridge National Laboratory report for ASHRAE, Inc., Atlanta.

Karagiozis, A.N., H.M. Künzel, and A. Holm. 2001. WUFI-ORNL/IBP—A North American hygrothermal model. *Proceedings of the Performance of Exterior Envelopes of Whole Buildings VIII*, *Clearwater Beach, Florida.*

Kehrer, M. 2006. Personal communication regarding WUFI 4.1 BETA program using sources and sinks, July 13.

Künzel, H.M. 1998a. Effect of interior and exterior insulation on the hygrothermal behaviour of exposed walls. *Materials and Structures* 31:99–103.

Künzel, H.M. 1998b. More moisture load tolerance of construction assemblies through the application of a smart vapor retarder. *Proceedings of the Performance of Exterior Envelopes of Whole Buildings VIII*, *Clearwater Beach, Florida*, pp. 1129–32.

Marshall. 1983. Moisture induced problems in NHA housing—Parts 1, 2 and 3. Marshall, Macklin, Monaghan Ltd. Report for Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Mayer, E., and H. Künzel. 1983. Untersuchungen über die notwendige hinterlüftung an auenwandbekeidung aus groformatigen bauteilen. Research Report B Ho 1-83, Fraunhofer Institut für Bauphysik, Holzkirchen, Germany.

McCuaig, L. 1988. Final report on the drying of walls—Atlantic Canada 1987. Canada Mortgage and Housing Corporation, Ottawa, Ontario.

McNeil, S., and M. Bassett. 2007. Moisture recovery rates for walls in temperate climates. *Proceedings from 11th Canadian Conference on Building Science and Technology*, *Banff, Alberta*.

Morrison Hershfield. 1992. Moisture in Canadian wood-frame house construction: Problems, research and practice from 1975 to 1991. Morrison Hershfield Ltd. Report for Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Morrison Hershfield. 1996. Survey of building envelope failures in the coastal climate of British Columbia. Morrison Hershfield Ltd. Report for Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Morrison Hershfield. 1999. Stucco-clad wall drying experiment. Morrison Hershfield Ltd. Report for Canada Mortgage and Housing Corporation, Ottawa, Ontario.

NBCC. 2005. *National Building Code of Canada*, 12th edition. Ottawa, Ontario: National Research Council of Canada.

Piñon, J.P., E.F.P. Burnett, D. Davidovic, and J. Srebric. 2004. The airflow characteristics of ventilated cavities in screen type enclosure wall systems. *Proceedings of the Performance of Exterior Envelopes of Whole Buildings IX*, *Clearwater Beach, Florida*.

Popp, W., E. Mayer, and H. Künzel. 1980. Untersuchungen über die belüftung des luftraumes hinter vorgesetzten fassadenbekleidung aus kleinformatigen elementen. Research Report B Ho 22-80, Fraunhofer Institut für Bauphysik, Holzkirchen, Germany.

RDH. 2001. Study of high-rise envelope performance in the coastal climate of British Columbia. RDH Building Engineering Report for Canada Mortgage and Housing Corporation, Ottawa, Ontario.

RDH. 2005. Performance monitoring of rainscreen wall assemblies in Vancouver, British Columbia. RDH Building Engineering Report for Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Schumacher, C., X. Shi, D. Davidovic, E. Burnett, and J. Straube. 2003. Ventilation drying in wall systems. *Proceedings of the 2nd International Conference on Building Physics*, *Leuven, Belgium*.

Shi, X., C. Schumacher, and E. Burnett. 2004. Ventilation drying under simulated climate conditions. ASHRAE 1091 Report #7 prepared by the Pennsylvania Housing Research/Resource Center, Pennsylvania State University, for ASHRAE.

Smegal, J. 2006. Drainage and drying of small gaps in wall systems. Masters thesis, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, Canada.

Stovall, T.K., and A. Karagiozis. 2004. Airflow in the ventilation space behind a rainscreen wall. *Proceedings of the Performance of Exterior Envelopes of Whole Buildings IX*, *Clearwater Beach, Florida.*

Straube, J.F. 1998. Moisture control and enclosure wall systems. PhD dissertation, University of Waterloo, Waterloo, Ontario, Canada.

Straube, J., and E. Burnett. 1995. Vents, ventilation, and pressure moderation. University of Waterloo Building Engineering Group Report for Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Straube, J., and E. Burnett. 2005. *Building Science for Building Enclosures*. Westford, MA: Building Science Press.

Straube, J.F., and C.J. Schumacher. 2003. Hygrothermal enclosure models: A comparison with field data. *Proceedings of the 2nd International Conference on Building Physics, Leuven, Belgium,* pp. 319–26.

Straube, J., D. Onysko, and C. Schumacher. 2002. Methodology and design of field experiments for monitoring the hygrothermal performance of wood frame enclosures. *Journal of Thermal Insulation and Building Envelopes* 26(2):123–51.

Straube, J.F., E. Burnett, R. VanStraaten, and C. Schumacher. 2004. Review of literature and theory. ASHRAE RP-1091 Report #1 prepared by University of Waterloo, Building Engineering Group, for ASHRAE.

TenWolde, A., and C. Carll. 1992. Effect of cavity ventilation on moisture in walls and roofs. *Proceedings of the Thermal Performance of the Exterior Envelopes of Buildings V, Clearwater Beach, Florida*, pp. 555–62.

TenWolde, A., C. Carll, and V. Malinauskas. 1995. Airflows and moisture conditions in walls of manufactured homes. *Airflow Performance of Building Envelopes, Components and Systems*, eds. Mark P. Modera and Andrew K. Persily. Philadelphia: ASTM, pp. 137–55.

VanStraaten, R. 2004. Measurement of ventilation and drying of vinyl siding and brick clad wall assemblies. Masters thesis, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, Canada.