Drainage, Ventilation Drying, and Enclosure Performance

John F. Straube, Ph.D. **Eric F. P. Burnett, Ph.D.**

ABSTRACT

This paper explores the influence and role of both drainage and ventilation drying on the ability of enclosure assemblies to control moisture. Drainage is often the most direct method of removing water from within a wall (i.e., from exfiltration condensation or rain penetration), but it is often not sufficient to provide moisture control. Design approaches that rely solely on drainage to remove moisture from behind the outer layers or cladding ignore the significant quantities of moisture that can be stored in the outer layers of most enclosure walls.

Most cladding systems have relatively low vapor permeability and therefore tend to restrict diffusive drying. Moisture trapped in or behind the cladding can be transported into the enclosure by solar-driven diffusion, especially in air-conditioned buildings. Rather than control vapor diffusion, a 6 mille vapor retarder close to the interior may, in many instances, exacerbate wetting and greatly retard drying.

The role of ventilation within walls, especially for North American conditions, has not been well researched and there does not appear to be any consensus with respect to the effect of ventilation on drying. We have found that airflow behind the cladding (ventilation) can be an important means of removing moisture stored within and behind vapor impermeable cladding. Calculations, lab experiments, field monitoring, and anecdotal evidence all show that ventilation can not only improve the drying capacity of wall assemblies, it is sometimes necessary for proper performance.

Several years of temperature, humidity, and moisture data collected from full-scale wall assemblies installed in a natural exposure and test facility are used to demonstrate these points.

INTRODUCTION

Moisture is one of the most important factors affecting the durability and performance of building enclosures, especially in cold climates. The design of moisture-tolerant enclosures should involve the simultaneous consideration and balancing of the potentials for wetting, storage, and drying. Design guidelines may stress the avoidance of wetting, but the increase of safe moisture storage capacity or drying potential can also improve the moisture tolerance of an assembly.

Drainage is usually regarded as the most important drying mechanism, and internal drainage has recently received much attention with regard to walls clad with exterior insulation and finish system (EIFS), wood siding, stucco, etc. Screened and drained wall systems are widely recommended for all but the driest climates. Drainage, however, does not necessarily remove sufficient moisture to ensure proper enclosure performance—other drying mechanisms must be provided. One drying mechanism that has not received the attention it is due is ventilation.

This paper presents a brief overview of how moisture is stored in hygroscopic materials and typical screened and drained enclosure wall systems. Available moisture-removal mechanisms will be discussed. Ventilation drying is examined in some depth with the aid of theoretical calculations, laboratory tests, and field measurements. Several important implications for enclosure design and performance are presented and briefly discussed.

MOISTURE CONTROL

A logical approach to the development of a moisture-control strategy for enclosure assemblies would assess the moisture storage and transport characteristics of the system as

John F. Straube is a research engineer with the Building Engineering Group, University of Waterloo, Waterloo, Ontario, Canada. **Eric F. P. Burnett** is a professor in the Departments of Civil and Environmental Engineering and Architectural Engineering at Pennsylvania State University, University Park, Pa.

well as the wetting and drying potentials. Moisture transport, wetting, storage, and drying are briefly discussed below.

Moisture Transport

Drainage is a liquid flow mechanism driven by gravity. Capillary transport, driven by gradients in suction stress, is another possible mechanism for transporting liquid moisture, although capillarity transport can only redistribute moisture, not remove it, from the enclosure. Vapor diffusion, driven by gradients in the vapor content of the air, and convection, driven by air pressure differences, are the primary mechanisms transporting vapor.

Wetting

Wetting, theoretically speaking the increase in moisture content of a system, occurs by several mechanisms. Vapor adsorbs to the internal surface area of porous materials, liquid is absorbed by capillary attraction into cracks and pores, and liquid water and frost can adhere to surfaces.

It needs to be emphasized that wetting is a dynamic process and that the drying of one material may occur by the wetting of another.

Moisture Storage

Enclosure systems constructed of hygroscopic porous materials (e.g., wood, stucco, brick) can store significant quantities of water. The capillary forces in such porous building materials will continue to absorb water until the material's moisture content reaches its capillary saturation moisture content. Conversely, drainage cannot begin until the capillary saturation moisture content is reached or the rate of water deposition exceeds the rate of absorption.

With regard to the latter point, it can be shown that many wetting mechanisms deposit water at rates slow enough for most of the water to be absorbed. For example, condensation tends to deposit moisture slowly. As a result, the material on which condensation occurs (e.g., brick veneer, gypsum, or waferboard sheathing) often has sufficient time to absorb the deposited moisture. Driving rain deposition often occurs slowly enough for brick veneers and many stucco finishes to absorb much of the water (Straube 1998). Therefore, it is reasonable to assume that in many building enclosure wetting situations, a material must reach capillary saturation before a sufficient volume of water will bead on the surface and thus allow drainage to occur.

The threshold moisture content level that corresponds to most moisture-related damage mechanisms is often equivalent to that material's moisture content when that material is in equilibrium with an environment of approximately 80% relative humidity (RH) (Ashton 1970; Baker 1969; Sereda 1975). At this relative humidity, both fungal growth and corrosion can be sustained, provided temperature conditions are favorable. This is a first-order estimate, since wood may require higher RH levels for decay fungi to act, and steel may corrode at lower RH levels. Nevertheless, it is reasonable to use the moisture content of a material at 80% RH as a conservative threshold level for performance problems.

Figure 1 is a plot of the moisture content (in mass percent) vs. relative humidity for several common building materials (Künzel 1997). The difference between the capillary saturation moisture content and the "safe" moisture content level at 80% RH is tabulated.

Provided that a smooth and unobstructed path exists, gravity drainage can remove the greatest volume of water in the shortest time and, hence, can be one of the most important mechanisms for moisture removal from within a building enclosure. However, even in perfectly constructed envelopes, a significant volume of moisture cannot be drained. Regardless of its source, moisture that enters an enclosure assembly can be stored in a variety of ways (Figure 2):

1. as water trapped at mortar dams in brick veneer walls or poorly drained portions of other types of walls;

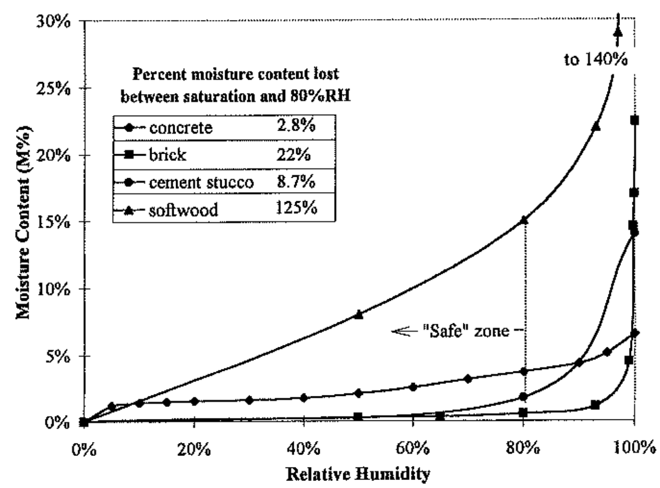


Figure 1 *Sorption isotherms of some cladding materials.*

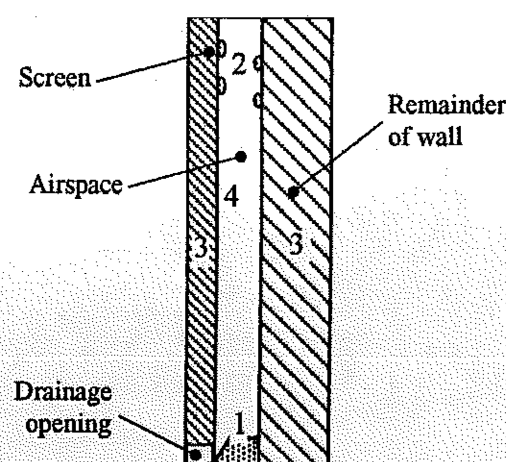


Figure 2 *Moisture storage in screened and drained wall systems.*

2. as droplets (or frost) adhered by surface tension to the backside of the cladding or front side of the inner wall layers;
3. adsorbed or absorbed (i.e., retained by capillarity) in hygroscopic building materials (especially brick, wood, fibrous insulation, paper, etc.); and
4. as vapor in the air.

All of the moisture stored by the mechanisms listed above cannot be removed by drainage (below the capillary saturation moisture content, water will not leave a material by gravity forces). Therefore, it can be concluded that drainage, while necessary, is not sufficient to ensure a safe moisture content—a significant amount of moisture must be removed by other mechanisms in order to reduce the moisture content to below the "safe" 80% RH level.

We also have reason to believe that drainage may not necessarily be the largest contributor to moisture removal. For example, field monitoring of more than 20 well-built low-rise screened and drained wall panels over a two-year period found only a few instances in which water was measured draining from behind brick veneer, vinyl, or other drained cladding systems (Straube and Burnett 1997). In the few instances in which a measurable amount of drainage did occur, the amount of water collected was less than 50 mL/m^2. The greater the driving rain exposure and the lower the absorbance of the cladding, the more often and the greater the volume of drainage.

Drying

Moisture is usually removed from within drained-screened walls by several transport mechanisms acting in series, often with phase changes. For example, water trapped in the stud space of a wall may be directly removed by drainage, but it is much more likely that this liquid will be absorbed by the wood (capillary transport), evaporated (phase change), and then leave the assembly in vapor form by diffusion or convection.

Moisture that is stored within porous or hygroscopic materials, such as wood siding and brick veneers, or inner wall layers, such as expanded polystyrene (which can easily store several times its own weight), waferboard, and gypsum sheathing, can only be removed in vapor form. Water stored in most cladding materials can be capillary transported to or near the exterior surface; here it can leave by diffusion to the outdoor air. Alternatively, drying can proceed toward the interior of the assembly, where the vapor can then be adsorbed by other hygroscopic materials or can pass through the assembly to the interior air. Materials within the assembly and not in capillary contact with the cladding can dry only by vapor diffusion through the cladding or toward the interior.

In summary, moisture can be removed from an enclosure wall (i.e., dry) in a variety of ways (Figure 3):

1. gravity drainage of liquid moisture;
2. capillary transport to, and evaporation from, the outer surface of the screen;

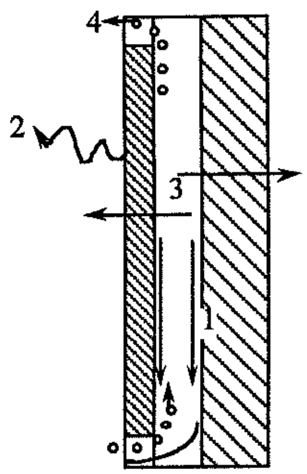


Figure 3 *Moisture removal in drained-screened walls with ventilated air spaces.*

3. diffusion and/or convection of water vapor outward through the screen and inward into the wall or building interior; and
4. convective flow of exterior air through the air space, (e.g., ventilation).

Drained wall systems without vents, face-sealed and perfect barrier walls, and solid walls will, of course, have fewer possible drying mechanisms.

A layer of 6 mille (0.15 mm) thick polyethylene is often placed just outside the interior finish, either because building codes require it or because it is deemed good practice. The water-vapor permeance of 0.15 mm polyethylene sheet is about 3.4 ng/Pa·s·m^2 (ASHRAE 1997). This permeance is so low, and its location so close to the interior, that little diffusive drying into the building can be expected. Therefore, drying of walls with an interior polyethylene vapor barrier can only proceed outward, i.e., to the exterior, or to the interior via air leakage (convection). Significant amounts of moisture redistribution from outer layers to inner or vice versa may, of course, still occur.

Outward diffusive drying of the inner layers of a wall will be greatly retarded in walls that have a cladding with high vapor resistance. For example, the water-vapor permeance of 90 mm thick brickwork is 45 ng/Pa·s·m^2 (ASHRAE 1997); in Canada this qualifies it as a Type 2 vapor barrier. Other types of finishes such as cement-based stucco, plywood siding, natural stone veneers, and some synthetic exterior finish systems may also have high vapor resistances.

Therefore, to increase the drying capacity, and thereby the moisture tolerance, of an enclosure system, it follows that

- the vapor permeance of inner layers should be high enough to allow inward drying while still controlling outward-acting wintertime diffusion condensation, and
- the vapor permeance of the cladding should be increased or some other means found to allow vapor to leave via the exterior of the enclosure.

The first conclusion suggests that "more is not necessarily better" when choosing a vapor diffusion retarder for some wall systems in some climates. Although this first conclusion clearly has important implications, the focus of this particular paper is the second conclusion, specifically the contention that ventilation may be beneficial to enclosure performance by providing a means of allowing water vapor to exit via the exterior of the enclosure.

VENTILATION DRYING

This section of the paper develops the physics of ventilation drying and demonstrates a means of assessing the influence of ventilation flow on wall drying. Most of the physics are developed more fully in Straube and Burnett (1995) or Straube (1998).

In theory, ventilating the space behind the cladding with outdoor air offers two major benefits:

- the flow of relatively dry outside air allows convective drying of all surfaces lining the air space (e.g., the inside face of the cladding and the outside face of the inner wall layers), and
- water vapor diffusing through the inner wall layers can bypass the vapor diffusion resistance of the cladding and be carried directly outside.

Thus, ventilation could increase the drying potential of walls, especially in assemblies that either store significant amounts of water in their outer layers or have a cladding with high vapor resistance.

The heat capacity of air is so limited that little heat can be carried out of the air space by ventilation (unless there are very large and fast airflows). In most enclosure walls, ventilation will not affect the insulation value of the air space for the majority of the time as long as the insulation (e.g., insulating sheathing, batt) is protected from wind washing. Very small airflows can, however, transport significant quantities of moisture if they act for long enough. Because the air space in many walls is usually warmer and contains more moisture than the outdoor air, even small ventilation flows over many days have the potential to remove useful amounts of moisture.

Forces Driving Ventilation Flow

A combination of wind pressure differences, thermal buoyancy, and moisture buoyancy drives ventilation flow. The provision of vent openings at both the top and bottom of the air space will generally promote the most ventilation flow because these vent locations take maximum advantage of both buoyancy forces and spatial wind pressure variations.

Wind pressure is probably the most important force driving ventilation flow. For most locations, the wind exceeds 1 m/s 80% to 90% of the time, but the average wind velocity is generally quite low (3 m/s to 4 m/s at 10 m above grade). Although low-rise houses are often protected from wind effects (both by neighboring buildings and their location close to the ground), mid- and high-rise buildings are usually fully exposed to the wind. Measurements on low-rise buildings (Straube and Burnett 1995) show that average wind pressures driving ventilation can be expected to be in the order of 1 pascal (Pa). The average pressure will fall in a wide range between 0.1 Pa and 10 Pa, depending on the geometry and size of the building, the location and distance between vents, and wind speed and wind direction.

Increasing temperature and/or water-vapor content will decrease the density of air; these changes in density generate buoyancy effects that can drive ventilation airflow. Measurements of solar heating and outward heat flow in winter cause the air space of typical brick veneer walls to be an average of at least 3°C to 5°C above ambient over the entire year (Straube and Burnett 1997). Daily variations of 10°C to 30°C above ambient can be expected if the enclosure is exposed to the sun. Thermal buoyancy pressures can be found from (Straube and Burnett 1995):

$$\Delta P = 3465 \cdot \Delta h \cdot (1/T_{amb} - 1/T) \tag{1}$$

where

ΔP = pressure difference driving ventilation flow (Pa),
Δh = difference in height between vents (m),
T_{amb} = exterior ambient temperature (K),
T = temperature in the air space (K).

Average pressures of the order of 1 Pa can be expected due to the combined effects of moisture and temperature buoyancy. Moisture buoyancy is a small (i.e., $\Delta P < 1$ Pa) but sometimes important contributor to ventilation pressures.

Ventilation Flow

The amount of ventilation airflow can be found using standard fluid mechanics given the driving pressures and the physical characteristics of the enclosure. There are two major flow-resisting mechanisms: friction with the sides of the airflow path (the air space) and the restriction of airflow through the vents.

The roughness of the air space sides is not very important to flow in most practical situations, but the partial blockage of the air space by mortar fins, strapping, furring, bulging insulation, displaced building paper, etc., can be very important. Wide air spaces are suggested as a practical means to overcome these potential blockages. In wall systems with discrete vents (e.g., masonry veneers), the vents themselves impose most of the resistance to airflow. Increasing the vent area results in a directly proportional increase in the airflow through the air space of such systems. European open-jointed panel cladding systems generally permit an order of magnitude more airflow than typical masonry veneer wall systems because of the large vent areas (more than 1% of wall area) and clear cavities used in the former. Airflow through clear cavities of 12 mm (i.e., a commonly specified dimension) behind drained-screened stucco and EIFS systems is expected to lie somewhere between brick veneers and open-jointed cladding.

A review of the literature, simple calculations, and some field measurements of ventilation pressures (Straube and Burnett 1995) confirm that the flow generated by typical driving pressures (0.5 Pa to 2 Pa) can be expected to be in the order of 0.2 m^3/h to 2 m^3/h per m^2 of cladding. (These values naturally depend on the vent area and the depth and degree of blockage of the air space.) Field measurements of well-vented wall systems (i.e., vent areas of more than 1% of wall area) show that such systems typically experience flow velocities of 0.05 m/s to 0.2 m/s (Jung 1985; Popp et al. 1980; Künzel and Mayer 1983). Schwarz (1973) and Uvsløkk (1988) both found higher average velocities behind well-vented cladding panels with continuous slotted vents.

Although large vent areas are recommended to increase ventilation flow, it is presumed here that the cladding is not part of the air barrier system. Most modern walls with drainage openings fit this description, and larger vent areas will not compromise the airtightness of the wall system.

European codes are generally more specific regarding the size and location of vents and require much higher vent areas than North American codes. Most of the relevant wall cavity ventilation research has been conducted in Europe. Despite the extensive use of ventilated cladding systems in Europe, the benefits, drawbacks, and mechanics of ventilation flow have not been clearly defined. Moreover, very little work has been focused on masonry veneer wall systems.

Predicting Ventilation Drying

Given a knowledge of the quantity and quality (i.e., temperature and moisture content) of the ventilating air, the maximum drying capacity can be estimated. However, several simplifying assumptions must be made:

1. the air in the space is well mixed, i.e., the moisture content is constant over the whole air space;
2. the rate of drying is controlled by the rate of ventilation flow, not the rate of evaporation from the material along the sides of the air space; and
3. the drying process does not modify temperature conditions.

Field monitoring of various wall systems has shown that the first assumption is quite accurate under most conditions. Because the vapor permeance of air is so high, it is difficult for large gradients of air moisture content to form in clear air spaces. This assumption is no longer valid under high flow conditions near the inlet vent because the rate of diffusive redistribution within the space is less than the convective vapor flux under these conditions.

The second assumption is also valid as long as the ventilation flow rate is low and the sides of the air space are wet (i.e., the rate of evaporation is greater than the ventilation drying rate). As the moisture content of the material surfaces falls significantly below capillary saturation, this assumption becomes progressively less accurate. However, materials that have a high moisture diffusivity and vapor permeance fit this assumption well. It follows that calculations based on this assumption are peak drying rates or drying rates when the air space sides are saturated; it is precisely these conditions that one is trying to alleviate by means of ventilation drying.

The validity of the third assumption depends on the drying rate. At low ventilation rates, the specific heat capacity of air is too low to change the temperature conditions of the air-space air or sides. At low drying rates, the amount of latent heat required to evaporate moisture is very small and has little effect on temperatures. Very high drying rates, such as would occur during a sunny period immediately after a rain event, might depress the temperature. This assumption limits the accuracy of calculations to ventilation drying during extreme events, i.e., the third assumption is valid most of the time.

In summary, the three assumptions listed above are valid for low ventilation flows (i.e., those typically experienced) and air spaces that have wet materials (i.e., those walls that require drying).

Example Calculation

Consider a well-built brick veneer wall system with a 50 mm air space and open head joint vents spaced at 600 mm on center, both at the top and the bottom of the air space. Assume that a layer of 12.7 mm OSB (oriented strand board) sheathing (density 700 kg/m^3) has been saturated by exfiltration condensation over the course of a winter.

If exterior conditions are 7°C and 85% RH (vapor pressure: 851 Pa), the outdoor contains about 6.6 g per m^3. If the sun shines on the wall, the air space temperature can rise to at least 20°C above the outdoor temperature for six to eight hours. The humidity in the air space will also be nearly 100% RH (as it must be if the materials lining the sides of the air space are saturated); air at 27°C can store 25.8 g per m^3. The difference of about 20 g per m^3 is the amount that can be removed by ventilation. As discussed earlier, ventilation flows of 0.2 to 2 $m^3/m^2{\cdot}h$ might be expected in such a wall (Straube and Burnett 1995). This flow rate is so small that it generates flow velocities of only 2.6 mm/s to 26 mm/s in a 2.4 m high air space. Over an eight-hour period at a flow rate of 1 $m^3/m^2{\cdot}h$, the moisture content of the materials lining the air space could drop by as much as 160 g; this could reduce the moisture content of the OSB by almost 2%. The temperature would also drop a few degrees because of the heat of evaporation.

Diffusive drying of the sheathing can be calculated in a similar manner. If the sheathing is at 27°C and 100% RH (3567 Pa), drying by diffusion would be:

$$(3567-851)\text{Pa} \times 46\ \text{ng/Pa}{\cdot}\text{s}{\cdot}\text{m}^2 \times 3600\ \text{s/hr} \times 8\ \text{hrs} = 3.6\ \text{g/m}^2.$$

In this simple example, ventilation drying would remove more than 40 times the amount of stored moisture as diffusive drying.

Equivalent Vapor Permeance

The simple example calculation shown above is still somewhat unwieldy and does not permit the easy comparison of the effects of ventilation. Although the tabulated values for cladding materials such as metal and vinyl indicate these materials are perfect vapor barriers, cladding systems made of these materials are clearly not vapor impermeable. For these types of cladding materials (vinyl siding, metal panels), the satisfactory performance of wall assemblies can only be explained by the ventilation, albeit exceedingly small, of the air space, often through small unintentional openings. It would also be useful to have a permeance value for ventilated brickwork that can be used in one-dimensional calculations (such as those outlined in *ASHRAE Fundamentals* [ASHRAE 1997] or in computer models such as MOIST, MATCH, and WUFI).

Using the assumptions listed earlier, it is possible to determine the combined or effective vapor permeance for an enclosure layer, which includes the effects of both diffusion and airflow. The mass of water in air can be found from a form of the ideal gas law:

$$w_v = \frac{P_v \cdot V}{R_v \cdot T} \tag{2}$$

where

w_v = mass of water (kg),

P_v = vapor pressure of water (Pa),

V = volume of air (m^3),

R_v = gas constant for water vapor (461.5 J/kg·K), and

T = temperature (K).

For a difference in vapor pressure, assuming well-mixed air in the air space and a small temperature difference between the airstreams, the mass of water transported by an air volume exchange is

$$\Delta w_v = \frac{\Delta P_v \cdot \Delta V}{R_v \cdot T}. \tag{3}$$

If the temperature difference is not small and accuracy is important, Equation 2 would need to be evaluated at each temperature.

The property that defines the amount of diffusive water-vapor transport across a material layer is called the water-vapor permeance. For a unit change in vapor pressure and volumetric flow rate, Equation 3 yields a system property that can be considered to be the equivalent vapor permeance of the cladding due to ventilation airflow. Using a parallel flow model, the combined effect of diffusion and ventilation can be modeled as a combined equivalent permeance.

For a ventilation flow rate of 0.00028 $m^3/m^2 \cdot s$ (1 $m^3/m^2 \cdot h$), a vapor pressure difference of 1 Pa, and a mean temperature of 15°C, the mass of water transferred will be

$$\Delta w_w = \frac{1 \cdot 0.00028}{461.5 \cdot (273 + 15)} \cdot 10^{12} \text{ ng/kg}$$

$$= 2100 \text{ ng/Pa} \cdot \text{s} \cdot \text{m}^2.$$

This value of permeance is over 40 times that of a 90 mm brick masonry veneer—this is the same conclusion reached in the previous example. Such calculations indicate that, at the very least, small rates of ventilation can play a very important role in bypassing the vapor resistance of the cladding. Even with a ventilation rate of only 0.1 $m^3/m^2 \cdot h$, the transfer of vapor out of the cavity by mass transport is likely to be four to five times greater than that by diffusion alone.

The air velocity in a cavity 2.5 m high and 50 mm deep necessary to generate 1 $m^3/m^2 \cdot h$ of airflow is 0.014 m/s. Compare this velocity to the measured velocities (of 0.05 m/s to 0.5 m/s) referenced earlier. A velocity of 0.014 m/s is so small that it is exceptionally difficult to measure and the pressures necessary to generate this small flow rate are generally considered so small as to be insignificant (i.e., $\Delta P << 1$ Pa). Ventilation drying may have been dismissed in much of the literature because of the difficulty of measuring such small velocities (e.g., less than about 0.2 m/s) and pressures. However, the preceding examples confirm that very small ventilation rates can have a significant influence on the actual vapor permeance of the cladding system and, thus, on the drying performance of the wall assembly.

The concept of equivalent vapor permeance allows for a quantitative assessment of the importance of ventilation airflow to drying. Equivalent conductances, or surface films, are widely used to model convective and radiative heat transfer as conductive heat flow. The equivalent vapor permeance allows convective vapor flow to be modeled as diffusive flow. The important role of the sun and the wind is also explicitly incorporated in the assumptions that need to be made for these calculations.

Note that the existing research into attic and crawl space ventilation is not directly related to enclosure wall ventilation. Attics have much greater air volumes, less rain penetration and absorption, and higher measured rates of ventilation and tend to be affected by night-sky cooling. Crawl space ventilation flows are smaller than attic flows, but the air space temperature is not increased by solar radiation. In fact, the hygrothermal state of crawl spaces is often greatly influenced by the ground conditions. Ventilation wetting is often possible in crawl spaces.

FIELD MONITORING

The authors have been conducting full-scale field testing of enclosure wall systems since 1988. The primary objective in most of the several projects completed has been the study of hygrothermal performance of wall systems common to colder climates. In particular, means of minimizing rain penetration, methods of ensuring drainage and predicting driving rain, the mechanics of ventilation drying, and the drying of built-in moisture have been studied.

To support the theoretical studies of ventilation drying, measurements of ventilation pressures, wall temperatures, and air vapor content were taken in full-scale walls exposed to the natural environment in several projects (Straube and Burnett 1995, 1997).

Well over 50 wall panels involving 25 different types of wall systems have been monitored. To illustrate the role of ventilation drying, two different brick veneer wall systems will be examined. Figure 4 presents a simplified horizontal cross section of each.

Test panels for walls A and B were built following current practice for masonry-clad, framed wall systems in Canada. The brick veneer on these panels was built with great care to ensure that the 30 mm wide air space (slightly larger than the nominal 25 mm typically provided) was kept clear of mortar dams, bridges, and droppings. Panel A employed mineral fiberboard insulation (48 kg/m^3 density) on exterior gypsum sheathing. Panel B incorporated insulating Type III extruded polystyrene sheathing and sheathing paper.

Common to all panels was an 85 mm clay brick veneer with open head joints at 600 mm on center, top and bottom, 38 mm × 89 mm wood or steel framing (single top and bottom plates with studs at 400 mm on center) filled with low-density batt insulation, a 0.15 mm (6 mille) polyethylene vapor retarder ($M = 3.4$ ng/Pa·s·m^2), and painted gypsum board interior finish. The combination of interior drywall and polyethylene was confirmed to be airtight by testing.

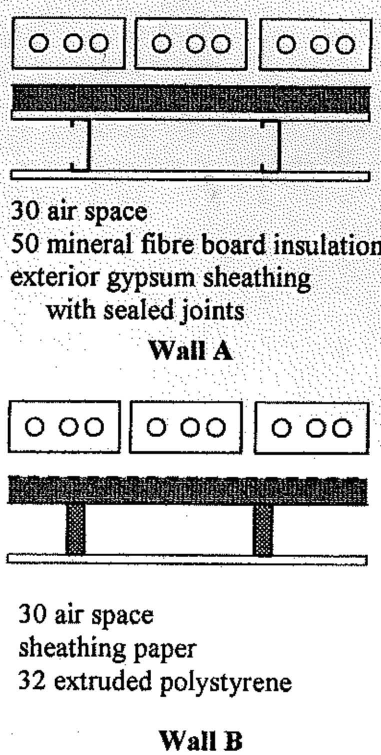


Figure 4 *Simplified wall cross sections: painted interior drywall and 6 mille poly were common to both systems.*

The gypsum sheathing in Wall A was vapor permeable ($M > 2000$ ng/Pa·s·m^2). Wall B employed an asphalt-impregnated perforated sheathing paper ($M = 300$ to 700 ng/Pa·s·m^2 depending on RH) and extruded polystyrene insulating sheathing ($M = 40$ ng/Pa·s·m^2).

One panel of wall type A was built and installed facing east. Four panels of wall type B were built, and one panel was installed facing north, south, east, and west. The 1.2 m wide and 2.4 m high full-scale panels were installed in the natural exposure and test facility located in southwestern Ontario, Canada.

Each panel was instrumented with 12 to 15 temperature sensors, 3 to 6 pairs of Delmhorst pins near the center of the studs and plates (for measuring wood moisture content), and 4 to 6 relative humidity transducers. A special base detail allowed cavity drainage to be intercepted and measured. The panels were installed in July or August and exposed to the environment for more than 24 months. The sensors were read every five minutes, and average values were stored. The interior conditions were maintained at 50±5% relative humidity and 21±1°C.

Panel A was monitored for one year with its vents open and for one summer with its vents sealed airtight. Drainage from the weep holes was always intercepted, collected, and measured. The four Wall B panels were continuously monitored over the same period.

Results

Figure 5 is a plot of the framing moisture content of each of the panels over a 12-month period. The line labeled "vented" is for 1996 and that labeled "unvented" is for 1997. The plot of wall panel B is for 1997 (1996 was essentially the same). During the summer of 1996, the moisture content of the vented Wall A climbed to almost 15%. This is not a dangerous level, but it clearly shows that summertime wetting could occur in Wall A. Wall B exhibited no such wetting because of

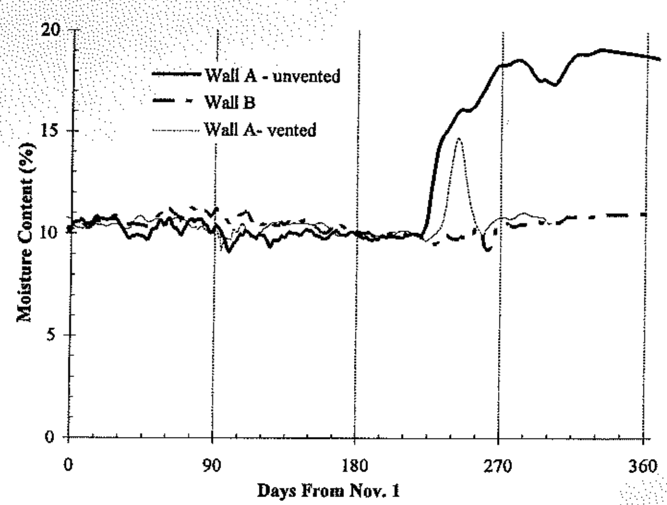


Figure 5 *Framing moisture content vs. time.*

the relatively vapor-resistant exterior sheathing. It is clear that sealing the vent openings on June 1, 1997 (Day 211), had a significant impact on the moisture content of Wall A.

The temperature and relative humidity measurements were used to calculate the moisture content of the air in the air space. Over the summer period, the average moisture content of the exterior air in 1996 was 9.6 g/m^3. Over the summer period in 1997, the average exterior air content was 9.1 g/m^3. The average moisture content of the air in the air space of the well-vented Wall A was 10.9 g/m^3, about 1.3 g/m^3 higher than the exterior. During the following summer when Wall A was unvented, the moisture content in the air space was 13.1 g/m^3, 4 g/m^3, or 44% above that of the exterior. The well-vented east-facing Wall B exhibited air space moisture content of 1.0 g/m^3 (11%) above the exterior during the same period. These average values suggest that venting the air space had a significant effect on the moisture content of the air in the air space.

The moisture content of the air was also examined on an hourly basis. Figure 6 compares the moisture content of the air in the stud space, air space, and exterior during a typical week in July for Wall A when it was vented and when it was unvented. The moisture content in the air space is clearly much more closely coupled to the exterior in the vented case than the unvented case. Water vapor that is driven off hygroscopic materials, especially the brickwork, by solar heating enters the air-space air but is unable to leave by ventilation in the unvented wall.

In the unvented case, the influence of the high air moisture content is reflected in the stud space of the wall because of the vapor-permeable sheathing. The high moisture content level of the air space occasionally resulted in condensation on the polyethylene. This condensation and the prolonged high relative humidity resulted in the observed higher moisture content.

The importance of the temperature difference between the outside air and the air-space air was discussed earlier. Figure 7 presents a plot of the relative distribution of hourly average exterior air temperature and cladding temperature for a three-month summer period (a total of about 2800 data points). Because of solar heating, the brickwork temperature is higher on average (by almost 7°C) and more variable than the exterior. The temperature difference between the cladding and the ambient air significantly increases the potential for drying from both faces of the cladding.

It is the temperature difference between the air space and the exterior air that is of particular interest for ventilation drying. Figure 8 compares the distribution of this temperature difference for the air space in Wall A when the wall was vented and unvented. Two important points are illustrated by these data. First, the average temperature in the air space is considerably higher than the exterior air temperature (by about 5°C). Secondly, the difference between the air space temperature of the vented and unvented wall configuration is practically negligible. Hence, the assumption that ventilation airflow will not cool the cladding is valid for a well-vented brick veneer. Because the vapor-carrying capacity of air is nonlinearly

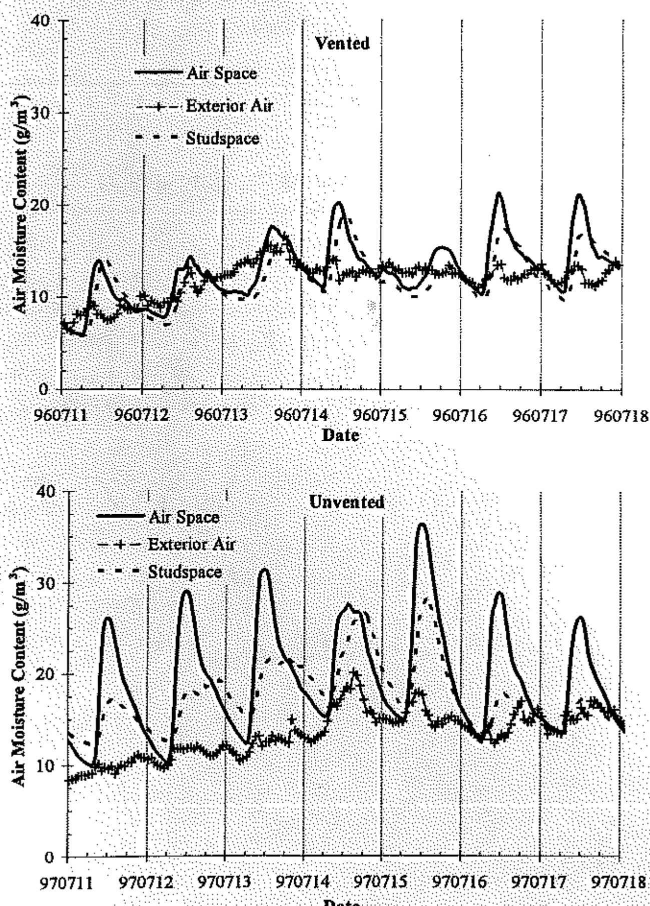
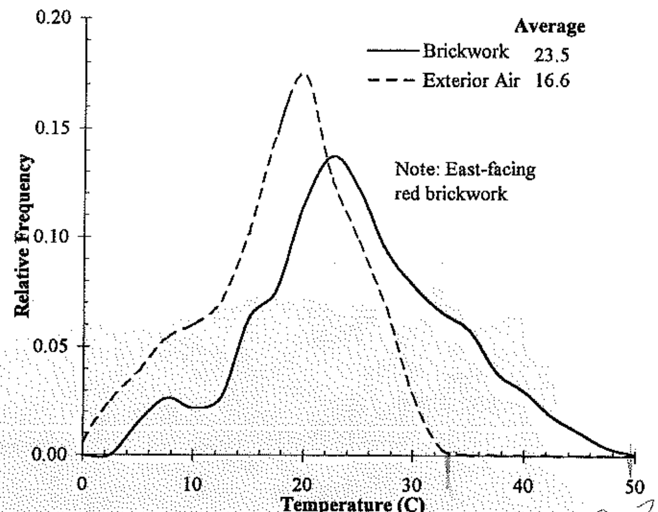


Figure 6 Hourly moisture content of Wall A—vented (top) vs. unvented (bottom).



323

Figure 7 Distribution of hourly average brick veneer and exterior air temperature over summer period.

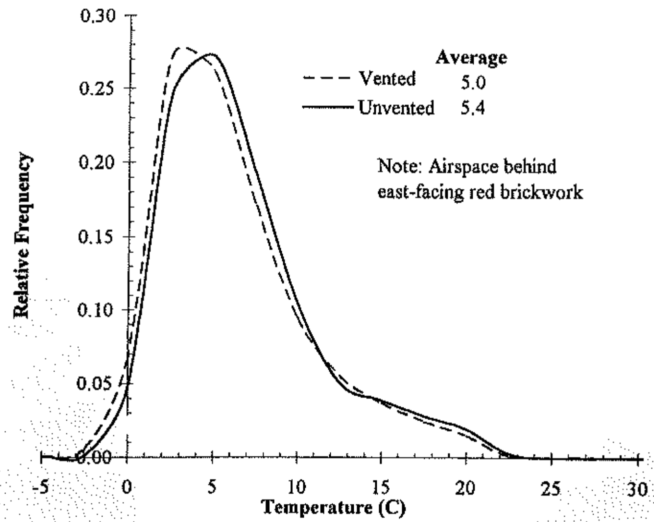


Figure 8 *Distribution of the difference between air space and exterior air temperature of vented and unvented walls.*

related to temperature, the 10% of the time that the air space is more than 12°C above the exterior has a disproportionate effect on the drying potential.

INWARD VAPOR DIFFUSION

The wetting exhibited by Wall A is an example of warm weather, solar-driven condensation caused by the evaporation and inward vapor transport of moisture stored in the enclosure. Although widely recognized in the research community (Wilson 1965; Sandin 1991; Hens and Fatin 1995), the control of inward vapor transport through enclosures in cold and temperate climates is rarely considered by most design professionals. Ventilation appears to be one method of controlling this type of wetting; another is the use of more vapor-resistant layers (the approach of Wall B). Both of these methods are used (perhaps unwittingly) in many walls and are the reason that inward diffusion is not often seen as a serious problem. However, if ventilation is restricted and the wall has very little vapor resistance between the cladding and an inner vapor-retarding layer (e.g., poly), problems can arise.

The authors are of the opinion that some moisture problems ascribed to water penetration may, in fact, be due to inward vapor drive condensation (e.g., "water penetration" of vapor-permeable housewraps may be exacerbated by inward drives). Some professionals are advocating the use of heavier, less permeable building papers (e.g., 30-pound felt) or multiple layers of the same. These building papers often have sufficient vapor resistance to limit or avoid warm weather condensation but may reduce outward drying of moisture from other wetting mechanisms. Ventilation can also be used to control inward vapor drives by allowing the vapor to escape to the exterior by convection.

CONCLUSIONS

It should be evident that drainage is a necessary water-removal mechanism in screened walls. However, because a significant quantity of moisture can be stored in hygroscopic materials, drainage may not be sufficient to remove all potentially damaging moisture from rain penetration and exfiltration condensation. Diffusive drying and ventilation drying are, therefore, important mechanisms for removing moisture that is inevitably stored in a drained-screened wall assembly.

Ventilation drying can theoretically bypass the vapor resistance of the cladding and thereby improve enclosure drying. The role of the sun and wind must be accounted for in any realistic assessment of ventilation drying. Although ventilation flow rates are very small and difficult to measure, field measurements confirm the promise of ventilation drying. Much more fieldwork needs to be conducted employing carefully designed experiments.

The interaction of ventilation and inward vapor drives was also demonstrated. Since diffusive drying to the inside can be important, the current practice of installing very low-permeance vapor diffusion retarders needs to be questioned. For many climates and many types of wall systems, wintertime wetting by diffusion is an insignificant wetting mechanism.

ACKNOWLEDGMENTS

This research is part of the In-Service Performance of Enclosure Walls Project. The support, technical input, and funding of the seven corporate partners (Brampton Brick, Canada Brick, Celfortec, Durisol Materials, Owens-Corning Canada, Roxul Insulations, and Sto Corporation) have been invaluable and is gratefully acknowledged. The Ontario government provided funding through the University Research Initiative Fund. The Vents and Ventilation Drying Project was supported by the Canada Mortgage and Housing Corporation. The assistance and technical review of CMHC's project manager, Pierre-Michel Busque, was most helpful.

REFERENCES

ASHRAE. 1997. *1997 ASHRAE Handbook—Fundamentals*. Atlanta: American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc.

Ashton, H.E. 1970. CBD 124, *Biological attack on organic materials*. Ottawa: National Research Council Canada.

Baker, M.C. 1969. CBD 111, *Decay of wood*. Ottawa: National Research Council Canada.

Hens, H., and A. Fatin. 1995. Heat-air-moisture design of masonry cavity walls: Theoretical and experimental results and practice. *ASHRAE Transactions* 101(1): 607-626.

Jung, E. 1985. Dauerstandverhalten von Verblendziegelmauerwerk unter Witterunsbeansphruchung und Auswirkungen von Kerndämm-Maßnahmen. *Baustoffindustrie*, No. 6, Nov., pp. 185-188.

Künzel, H.M. 1997. Material databank of WUFI version 2.0, Hygrothermal modeling software. Collected by Fraunhofer Institut for Building Physics, Holzkirchen, Germany.

Künzel, H., and E. Mayer. 1983. *Untersuchung über die notwendige Hinterlüftung an Außenwandbekeidung aus großformatigen Bauteilen.* Schriftenreihe 3/1983: Bundesminister für Raumordnung, Bauwesen, und Städtebau, Bonn. Germany.

Popp, W., E. Mayer, and H. Künzel. 1980. *Untersuchungen über die Belüftung des Luftraumes hinter vorgesetzten Fassadenbekleidung aus kleinformatigen Elementen.* Forschungsbericht B Ho 22/80: Fraunhofer Institut für Bauphysik, Holzkirchen, Germany.

Sereda, P.J. 1975. CBD 170, *Atmospheric corrosion of metals.* Ottawa: National Research Council Canada.

Straube, J.F., and E.F.P. Burnett. 1997. *In-service performance of enclosure walls. Volume 1: Summary final report.* Building Engineering Research Report, University of Waterloo.

Straube, J.F., and E.F.P. Burnett. 1995. *Vents, ventilation drying, and pressure moderation.* Building Engineering Research Report for Canada Mortgage and Housing Corporation, Ottawa.

Straube, J.F. 1998. Moisture control in enclosure walls. Ph.D. thesis, University of Waterloo, Waterloo, Ontario, Canada.

Uvsløkk, S. 1988. The importance of wind barriers for insulated wood frame constructions. *Proc. of Symposium and Day of Building Physics, Lund University, August 24-27, 1987*, pp. 262-267. Swedish Council for Building Research.

Sandin, K. 1991. *Skalmurskonstruktionens fukt- och temperaturbetingelser.* Rapport R43:1991 Byggforskningsrådet, Stockholm, Sweden.

Schwarz, B. 1973. Witterungsbeansphruchung von Hochhausfassaden. *HLH* Bd. 24, No. 12, pp. 376-384.

Wilson, A.G. 1965. Condensation in insulated masonry walls in the summer. *Proc. RILEM/CIB Symposium, Helsinki*, pp. 2-7.