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The Theory of Ventilation Drying Applied To New Zealand Cavity Walls

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The Theory of Ventilation Drying Applied to New Zealand Cavity Walls

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ABSTRACT

Drained and ventilated cavity designs are standard practice in masonry veneer construction and open rainscreen stucco walls have been around for much of New Zealand's construction history. Both of these wall designs have a satisfactory record of managing moisture, but there is no calculation basis for linking the size of ventilation openings or cavity dimensions with the need for moisture control. This paper offers a preliminary analysis of the cavity ventilation processes and shows how ventilation rates depend on wind and buoyancy pressures in the New Zealand climate. Ventilation rates are estimated for drained and ventilated cavities having well defined vent sizes, but it turns out to be more difficult to do the same for open rainscreen walls. Here the ventilation process is likely to be dominated by natural infiltration through the wall. Differences between open rainscreen and drained and ventilated walls are presented in the context of theoretical drying rates in the New Zealand climate.

KEYWORDS: weathertightness, rainwater leaks, building moisture performance

1. WATER MANAGED WALLS IN NEW ZEALAND

All residential walls manage water leaks through the cladding to some extent. Even barrier walls such as rigid backed stucco and traditional EIFS walls incorporate a second line of defence in the form of a building wrap. Other wall types make a more deliberate attempt to manage water and the following generic categories can be described as follows:

1. **Drained and ventilated cavity** – Here the cladding is separated from the remainder of the wall by a cavity that is vented at the top and bottom and detailed to allow water to drain from the base of the wall.
2. **Open rainscreen walls** – This is similar to a drained and ventilated cavity wall, but without deliberate ventilation openings at the top of the cavity.
3. **Drainage plane** – Here the cladding is separated from the inner wall by a very narrow cavity designed only to drain water from the back of the cladding. The cavity can be formed in many ways, e.g. by a fibrous drainage mat or grooves in the back of the cladding.

Most walls probably fall somewhere between these classifications, e.g. open rainscreen walls may have infiltration openings at the top of the cavity and act more like a drained and ventilated system. Alternatively, the cavity in some drainage planes could be partially ventilated and work more like an open rainscreen.

Brick veneer is the most widely used drained and ventilated wall type in New Zealand. It has a relatively trouble-free track record of managing water leakage in New Zealand (Bassett, Clark and Camilleri, 2005). Figure 1 shows a cross-section of a brick veneer wall with cavity, drainage and ventilation provisions. Recommendations for cavity depth and ventilation opening sizes vary a little between Standards and the practical literature on design and construction, but the underlying principles of the drained and ventilated designs have changed little over many years.

The perpend openings required by New Zealand Standard NZS 3604:1999 amount to one 75 mm high opening by the width of the mortar joint at centres of about 800 mm (typically 900 - 1000 mm^2 of ventilation opening per m of wall). Similar ventilation openings at the top of the cavity, or a continuous 10 mm wide opening, complete the ventilation path.

Some stucco wall designs include a cavity and a ventilation and drainage vent at the base of the wall. Generally these wall cavities are not vented at the top and can be regarded as a classic open rainscreen. Figure 1 gives a cross-section of a stucco cavity wall showing provisions for ventilation and drainage at the base of the cavity. Most stucco walls are barrier systems, eg rigid backed and direct fixed to the framing. Because of this, it is difficult to resolve performance differences between cavity and rigid backed stucco from records of field investigations.

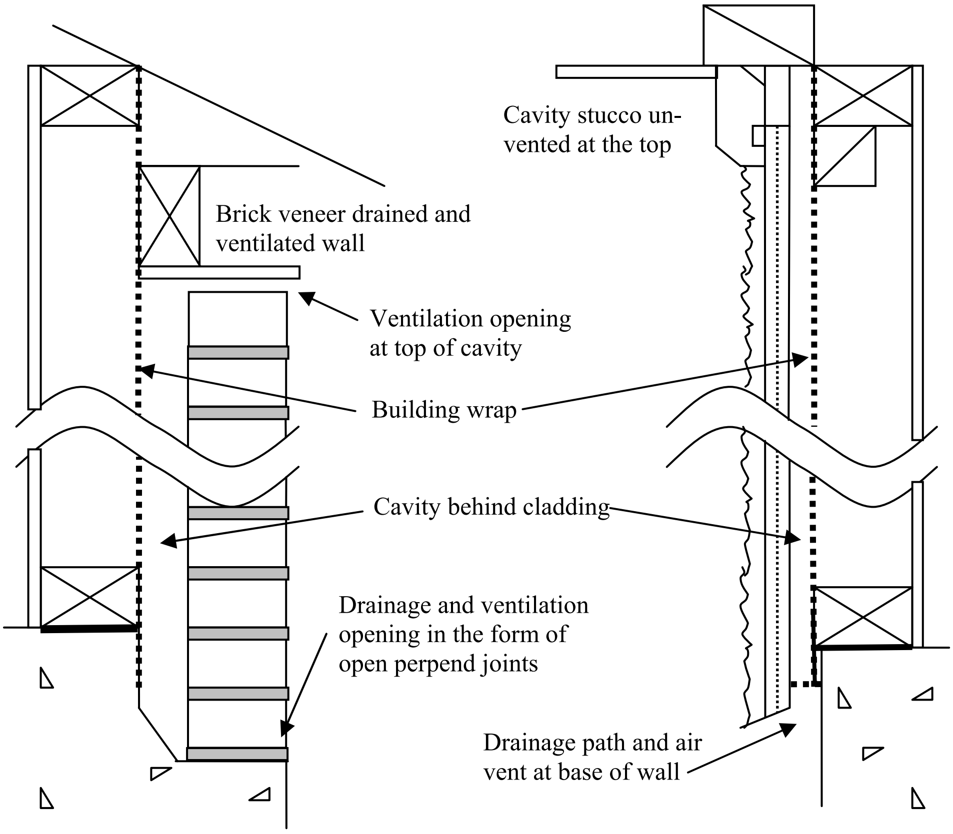

Figure 1: Two common water managed wall designs used in New Zealand.

2. THE SCIENCE OF VENTILATION IN CAVITY WALLS

2.1 Stack and wind pressure drivers of ventilation

Some early work on the thermal influence of air flows in the construction cavities was carried out in Europe. In more recent times, Burnett and Straube (1995) examined the fluid dynamics of cavity ventilation processes and estimated air exchange rates in the context of North American building and climate. The same methods are used here to estimate ventilation and drying rates in New Zealand wall cavities.

The main driving forces of ventilation in a drained and ventilated cavity are wind pressure and stack pressure. The buoyancy pressure differences between the top and bottom vents of a cavity can be expressed in terms of the absolute temperatures T_{cavity} and $T_{outside}$ and the height h in SI units as follows:

$$\Delta P_{stack} = (\rho_2 - \rho_1)gh = \left[\left(\frac{352}{T_{cavity}} - \frac{345}{T_{cavity}^{\ 2}} \right) - \left(\frac{352}{T_{outside}} - \frac{345}{T_{outside}^{\ 2}} \right) \right] gh$$

The squared terms can be ignored at room temperatures, so the stack pressure difference driving ventilation through a cavity can be simplified to:

$$\Delta P_{stack} = 3465\, h \left(\frac{1}{T_{cavity}} - \frac{1}{T_{outside}} \right)$$

Wind pressures on a building are complex and dynamic, but it is possible to estimate average ventilation rates in drained and ventilated cavities using average wind speed data. The wind pressure difference between the top and bottom vents of a wall cavity ΔP_{wind} can be expressed in terms of the wind speed at roof height v, the density of the air ρ and a wind pressure coefficient C_p as follows:

$$\Delta P_{wind} = \frac{\rho}{2} v^2 \left(C_p^{top\,vent} - C_p^{bottom\,vent} \right) \tag{1}$$

The total pressure between top and bottom vents can now be written as the sum of the stack and wind terms:

$$\Delta P_{total} = \Delta P_{stack} + \Delta P_{wind} \quad \text{or} \quad \Delta P_{total} = 3465\, h \left(\frac{1}{T_{cavity}} - \frac{1}{T_{outside}} \right) + \frac{\rho}{2} v^2 \left(C_p^{top\,vent} - C_p^{bottom\,vent} \right)$$

2.2 Air flow resistances in cavities and vents

The theory of laminar and turbulent flow in ducts is well established and has been applied to water managed cavities by Burnett and Straube (1995). An outline of the theory is provided here in the context of a brick veneer wall shown in Figure 2.

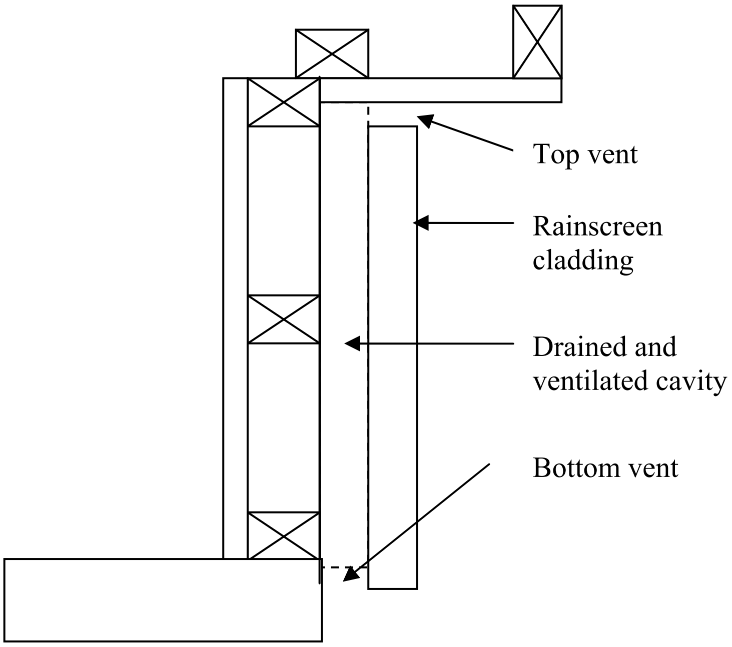

Figure 2: Drained and ventilated cavity with top and bottom vents.

The applied pressure across the system will be distributed across the vents and the cavity as follows:

$$\Delta P_{total} = \Delta P_{top\,vent} + \Delta P_{bottom\,vent} + \Delta P_{cavity}$$

Air flow rates through vents depend on the detailed geometry of the opening and on whether the flow is laminar or turbulent. Air flows through a range of vents were measured by Burnett and Straube who confirmed the validity of the following relationship between the air flow rate Q through an open vent (excluding capillary type vents) and the driving pressure difference ΔP:

$$Q = A\,C_d\left(\frac{2\,\Delta P}{\rho}\right)^{0.5}$$

A is the cross-sectional area of the vent, ρ is the density of air (taken as 1.2 kg/m^3) and C_d is a flow coefficient. The value of C_d for perpend openings in a brick veneer wall was found to be $C_d = 0.63$ and the exponent was confirmed as being close to 0.5. If the opening is very small and better described as a capillary path, an exponent closer to 1.0 would be expected. Slot type vents (such as a continuous slot at the base of a wall panel) are often better described in terms of the following formula involving a friction factor ξ:

$$\Delta P = \xi\,\frac{\rho}{2}\left(\frac{Q}{A}\right)^2 \qquad (2)$$

Typical values for ξ are $\xi = 0.5$ for entry into a slot type vent and $\xi = 0.88$ for air leaving the opening.

The air flow rate through the cavity itself will depend on whether the flow is laminar or turbulent. The transition between these flow regimes occurs at a Reynolds number between 2000 to 3000, which for cavity dimensions in the likely range (20 mm to 50 mm) occurs at velocities around 1 m/s. This translates to ventilation rates of 50 l/s.m and 20 l/s.m respectively, which is shown later to be outside the normal range. By assuming that air flow in the cavity is laminar and applying the Darcy-Weisbach equation, the following relationship can be derived between the applied pressure ΔP and the flow rate Q in a cavity:

$$\Delta P = \frac{Q\,h}{4611\,\gamma\,d^3\,b}$$

All values are in SI units and the cavity is h high, d deep and b wide and the blockage factor γ depends on the extent to which the cavity is obstructed. For clear cavities $\gamma = 1$, but where there are obstructions γ can be taken as the fractional reduction in the cross-section of the cavity. Mortar protrusions in a brick veneer cavity are considered by Burnett and Straube to have a value of $\gamma = 0.8$.

Assembling the expressions for ΔP across the vents and the cavity for a brick veneer wall ventilated through perpend openings gives the following relationship:

$$\Delta P_{total} = \frac{\rho}{2}\left(\frac{Q}{C_d\,A_{top\,vent}}\right)^2 + \frac{\rho}{2}\left(\frac{Q}{C_d\,A_{bottom\,vent}}\right)^2 + \frac{Q\,h}{4611\,\gamma\,d^3\,b}$$

The following alternative relationship is preferred where the vents take the form of long slots, e.g. between a cladding and a building wrap.

$$\Delta P_{total} = \xi \frac{\rho}{2}\left(\frac{Q}{A_{top\,vent}}\right)^2 + \xi \frac{\rho}{2}\left(\frac{Q}{A_{bottom\,vent}}\right)^2 + \frac{Q\,h}{4611\,\gamma\,d^3\,b} \tag{3}$$

3. VENTILATION RATES IN DRAINED AND VENTILATED WALL CAVITIES

The most common drained and ventilated cavity walls in New Zealand are brick veneer and battened walls based on a 20 mm cavity depth. The dimensions of vents, cavities and air flow characteristics vary in practice, but for the purposes of preliminary ventilation calculations, the values in Table 1 have been adopted.

Table 1: Typical cavity and vent dimensions.

Property	Brick veneer walls	Battened cavity walls
Depth of cavity	50 mm	20 mm
Top vent area	900 mm^2/ m	1000 mm^2/m
Bottom vent area	900 mm^2/m	1000 mm^2/m
Cavity breadth	Un-partitioned	Partitioned at about 600 mm
ξ (top)	0.5	0.5
ξ (bottom)	0.88	0.88
Height of cavity (h)	2.0 m	2.0 m
γ	0.8	1.0

3.1 Wind pressures

Pressure coefficients from Bowen (1976), as summarised by Liddament (1986), have been chosen to represent top and bottom vents at 10% and 80% of the building height. The building is assumed to be in an urban residential setting surrounded by other buildings and trees of similar height. Table 2 gives the pressure coefficients assumed for top and bottom vents.

Table 2: Pressure coefficients at vent locations on a low rise building in a suburban setting.

Wind pressure coefficients for top vents								
Wind direction	N	NE	E	SE	S	SW	W	NW
Building face N	0.16	0.15	-0.23	-0.03	-0.16	-0.26	-0.41	0.15
E	-0.41	-0.36	0.16	-0.36	-0.23	-0.03	-0.16	-0.03
S	-0.16	-0.26	-0.41	0.15	0.16	0.15	-0.23	-0.26
W	-0.23	-0.03	-0.16	-0.23	-0.41	-0.36	0.16	-0.36
Wind pressure coefficients for bottom vents								
Wind direction	N	NE	E	SE	S	SW	W	NW
N	0.2	0.15	-0.15	-0.16	-0.17	-0.16	-0.23	0.15
E	-0.23	-0.38	0.2	-0.38	-0.15	-0.42	-0.17	-0.42
S	-0.17	-0.16	-0.23	0.15	0.2	0.15	-0.15	-0.16
W	-0.15	-0.42	-0.17	-0.42	-0.23	-0.38	0.2	-0.38

In the case of the un-partitioned brick veneer cavity it is necessary to calculate a pressure coefficient to represent the pressure in the cavity C_p^{cavity}. The cavity wind pressure coefficient is defined in the usual way so that the wind pressure difference across a vent ΔP_{wind} can be expressed as follows:

$$\Delta P_{wind} = \frac{\rho v^2}{2}\left(C_p^{cavity} - C_p^{vent}\right)$$

Equating ΔP_{wind} to the pressure difference in equation 2 leads to the following expression for the wind driven air flow rate through a vent:

$$Q = \frac{Av}{\sqrt{\xi}}\sqrt{\left(C_p^{cavity} - C_p^{vent}\right)} \qquad (4)$$

For an un-partitioned brick veneer cavity, the value of C_p^{cavity} can be determined iteratively by requiring mass balance in the air flows into and out of the cavity. For an idealised building having equal ventilation areas on each of the north, south, east and west faces and an unrestrictive cavity, the value of C_p^{cavity} varies from -0.16 to -0.18 depending on wind direction. If all wind directions are equally likely, the average value of $\sqrt{\left(C_p^{cavity} - C_p^{vent}\right)}$ can be calculated and with the wind pressure coefficients in Table 2, the equivalent value of $\left(C_p^{cavity} - C_p^{vent}\right) = 0.13$. This is used later to estimate the average wind driven ventilation rate in an un-partitioned brick veneer wall cavity in Table 4.

Where the cavity is partitioned vertically by battens, then the cavity no longer acts as a conduit connecting all of the vents. In this case, the cavity ventilation process can be modelled as a series of unconnected vertical conduits, each connected to a top and bottom vent. If top and bottom vents are the same size, then C_p^{cavity} is simply the average of the $C_p^{top\ vent}$ and $C_p^{bottom\ vent}$. Averaged over all wind directions and wall orientations, the Cp difference for a partitioned cavity is as follows:

$$\left(C_p^{cavity} - C_p^{vent}\right) = 0.10$$

3.2 Average wind speeds in New Zealand

The wind pressures that drive water into buildings tend to be the peak values that occur several times a year. From a drying point of view, the average pressures are more important because the drying process can take place over several days after wetting. The average wind speed is also useful because the flow rates through the vents (which support most of the ΔP across a ventilated cavity) are simply proportional to v. This can be seen in equation 4. Binned wind speed data has been prepared for earlier studies of natural ventilation by Bassett (2001), and this data can be used to estimate average wind speeds at typical building heights above ground. Average wind speeds and pressure differences are given in Table 3 for ten city locations and the two cavity types under consideration. The data applies to a low rise residential building (roof height of 3 m above ground) in an urban setting with similar sized buildings within 6 m of each other.

Table 3: Average wind speeds 3 m above ground and average pressure difference across a vent for two wall cavity types in several New Zealand city locations.

NZ Location	Average wind speed m/s	ΔP across an un-partitioned brick veneer vent (Pa)	ΔP across a partitioned cavity vent (Pa)
Auckland	1.9	0.28	0.22
Hamilton	1.5	0.18	0.14
Rotorua	1.7	0.23	0.17
New Plymouth	2.3	0.41	0.32
Palmerston North	1.8	0.25	0.19
Wellington	3.8	1.13	0.87
Nelson	1.5	0.18	0.14
Christchurch	1.8	0.25	0.19
Dunedin	1.6	0.20	0.15
Invercargill	2.3	0.41	0.32
Average	**2.0**	**0.35**	**0.27**

3.3 Average cavity ventilation rates due to wind pressures

It is now possible to calculate average air flow rates through the two cavity types identified earlier, e.g. an un-partitioned brick veneer cavity with open perpend vents at the top and bottom, and a 20 mm deep vertically partitioned cavity with slot openings at the top and bottom. Figure 3 shows how the ventilation rate (expressed in l/s.m) varies with the applied pressure, and Table 4 provides a summary of average ventilation rates for the two cavity types in three wind zones representing high, medium and low wind areas in New Zealand. The range of air flows presented in Figure 3 is limited to the laminar range where the Reynolds number is less than 3000.

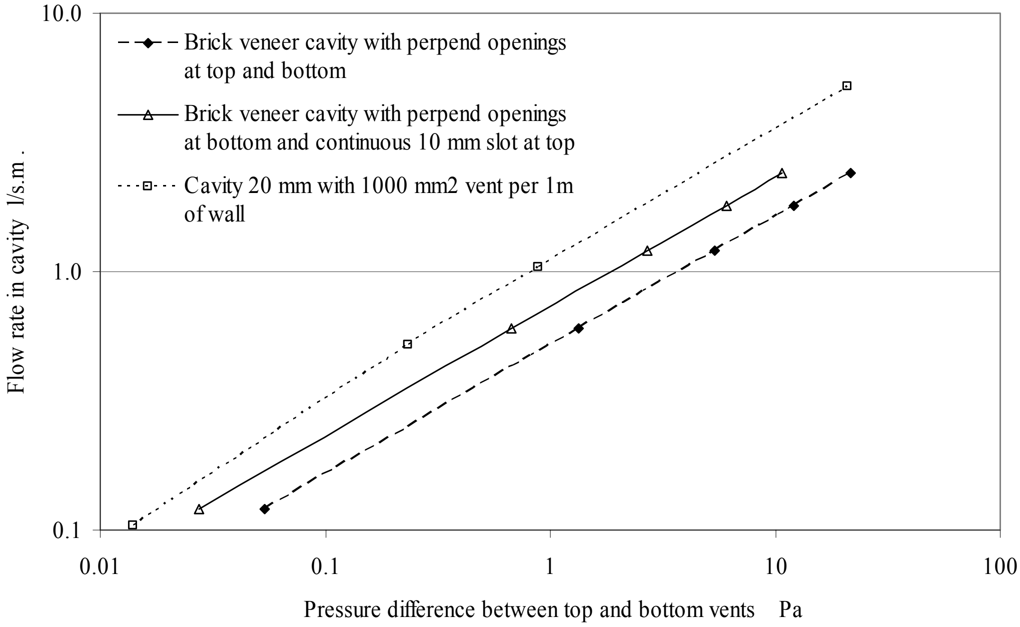

Figure 3: Laminar air flow rates in a range of cavity and vent combinations against the air pressure difference between top and bottom vents.

Table 4: Average wind driven ventilation rates in wall cavities in three New Zealand climates.

Variable	**High wind area represented by Wellington**	**Average wind area represented by Auckland**	**Low wind area represented by Nelson**
Average wind speed at 3 m height (m/s)	3.8 m/s	1.9 m/s	1.5 m/s
Kinetic pressure at average wind speed (Pa)	8.7 Pa	2.2 Pa	1.3 Pa
Average C_p driving air through each brick veneer vent	0.13	0.13	0.13
Average C_p driving air through each vent in a battened cavity	0.10	0.10	0.10
Average pressure driving the brick veneer cavity ventilation process	2.25 Pa	0.56 Pa	0.35 Pa
Average pressure driving the 20 mm partitioned cavity ventilation process	1.7 Pa	0.43 Pa	0.14 Pa
Average flow rate in brick veneer cavity with a continuous 10 mm top vent	1.1 l/s.m	0.6 l/s.m	0.4 l/s.m
Average flow rate in brick veneer cavity with perpend openings 1000 mm^2/m	0.8 l/s.m	0.4 l/s.m	0.3 l/s.m
Flow rate in 20 mm deep partitioned cavity and 1000 mm^2/m of opening at the top and bottom of the wall	1.5 l/s.m	0.7 l/s.m	0.4 l/s.m

Ventilation rates have recently been measured in drained and ventilated cavities by Bassett and McNeil (2005), and have compared favourably with the calculated ventilation rates presented here. It should be noted that if the methods are to be used for in a specific building, then it will be necessary to obtain specific wind pressure coefficients by direct measurement or using a wind-tunnel. The results in Table 4 must be regarded as an indication only of likely cavity ventilation rates.

4. VENTILATION DRYING IN OPEN RAINSCREEN WALL DESIGNS

Open rainscreen walls differ from drained and ventilated cavity walls in not being deliberately vented at the top of the cavity. The ventilation rate in the cavity of an open rainscreen will be a combination of infiltration and an air flow rate caused by fluctuating wind pressure and temperature.

4.1 Ventilation due to temperature and wind pressure fluctuations

The effect of fluctuating wind pressure has been discussed by Etheridge (1999) in the context of building ventilation and by Burnett and Straube (1995) for water managed cavities. The size of the effect can be estimated by differentiating the ideal gas law as follows:

$$P = \frac{nRT}{v}$$

where P and T are atmospheric pressure and temperature (absolute) and v is the volume of a parcel of air and R is the universal gas constant and n the quantity of gas in moles. Holding the air temperature constant and substituting for nR in terms of the cavity volume V and the constant temperature T gives:

$$\left(\frac{\partial v}{\partial P}\right)_T = -\frac{V}{P}$$ and the effective ventilation rate Q as follows:

$$\left(\frac{\partial v}{\partial P}\right)_T = \left(\frac{\partial v}{\partial t}\right)_T \left(\frac{\partial t}{\partial P}\right)_T = Q \Big/ \left(\frac{\partial P}{\partial t}\right)_T \quad \text{and} \quad Q = -\frac{V}{P}\left(\frac{\partial P}{\partial t}\right)_T$$

If the cavity volume remains constant under fluctuating pressure the ventilation rate can be expressed in terms of the rate of change of wind pressure as plotted in Figure 4. In this case, a cavity depth of 100 mm has been chosen to include the insulated areas as well as the water managed cavity because the air in both will respond to changing wind pressure. Typical rates of wind pressure change have been indicated by Burnett and Straube to be less that 100 Pa/s with average values closer to 10 Pa/s. Figure 4 indicates that “wind pumping” ventilation rates are expected to lie in the range of 0.01 to 0.1 l/s.m.

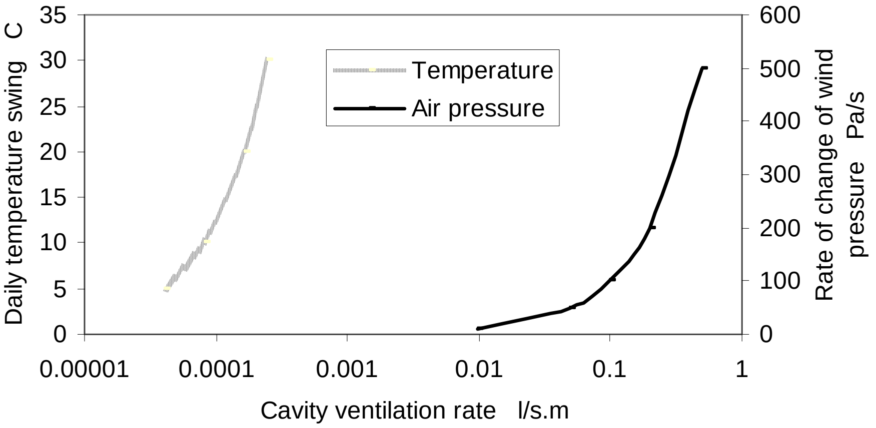

Figure 4: Cavity ventilation rates per m of wall length due to temperature and air pressure changes. The cavity is assumed to be 2 m high by 100 mm deep (includes insulated cavities).

Daily air temperature changes will also change the quantity of air in a wall cavity and a similar procedure has been used to estimate an effective cavity ventilation rate as a function of the daily temperature swing. This is shown in Figure 4 to be an insignificant driver of cavity ventilation.

4.2 Cavity ventilation due to infiltration

The ventilation rates calculated above for open rainscreen wall cavities are likely to be exceeded by natural infiltration. Most of the infiltration data in New Zealand has been measured as part of earlier building ventilation studies and does not directly resolve the infiltration flows that might ventilate an open rainscreen cavity. Nevertheless, it is a common practice (Bassett 2001) to assign 40% of bulk infiltration in New Zealand houses to openings around doors and windows. These flows bypass the cavities as well as a further 40% through ceilings and floors. The remaining 20% might be regarded as an upper limit of the infiltration that could ventilate the wall cavities. Table 5 recalculates this infiltration on a wall length basis for a 150 m^2 single story building with a wall perimeter length of 50 m. Because these are estimates, no adjustments have been made to reflect any particular climate or wind exposure.

Table 5: Estimated cavity infiltration rates assuming 20% of building infiltration passes through the wall cavities of a house with a 150 m^2 floor area and 50 m wall perimeter.

Building airtightness classification	Building infiltration rate	20% infiltration component ventilating wall cavities	Cavity ventilation rate on a wall length basis
Airtight	0.3 ac/h	22 m^3/h	0.1 l/s.m
Average	0.5 ac/h	36 m^3/h	0.2 l/s.m
Leaky	0.7 ac/h	50 m^3/h	0.3 l/s.m
Draughty	0.9 ac/h	65 m^3/h	0.4 l/s.m

In addition to infiltration through the wall, there will also be natural infiltration paths at the head of the cavity and through the cladding itself. In fact, the presence of these leakage paths may eliminate some of the difference between open rainscreen and drained and ventilated designs in practice. Infiltration leakage openings of this type have been used by Bassett and McNeil (2005) to explain ventilation rates measured with a tracer method. It will be possible to be more specific about ventilation rates in open rainscreen cavity walls when the infiltration paths present in New Zealand walls have been studied in more detail. In the meantime, the experimental data confirms that infiltration processes can dominate those due to temperature and wind pressure fluctuation.

5. DRYING FROM VENTILATED CAVITIES

Water can be removed from construction cavities by a variety of processes including liquid drainage, ventilation, capillary transport in materials and vapour diffusion through materials. Moisture removal due to ventilation can be estimated if certain assumptions are made. The loss of moisture from a free water surface (the back of the rainscreen wall) can be equated to the moisture loss by ventilation in the following mass balance equation:

$$A\,h(p_{saturated} - p_{cavity}) = -F\,V(m_{outside} - m_{cavity})$$

Where A = area of wet rainscreen wall per m of wall perimeter (m^2)
h = moisture film transfer coefficient ($kg/s.m^2.Pa$)
p = water vapour pressure (Pa)
F = ventilation rate per m of wall cavity (s^{-1})
V = volume of cavity per m of wall (m^3)
m = density of water in the air ($kg/\ m^3$)

Applying the ideal gas law to the water vapour component in the air:

$$p = \frac{n\,R\,T}{V}$$

and

$$m = \frac{p\,W\,V}{1000R\,T}$$

Where n = quantity of vapour (moles)
R = the universal gas constant 8.314 (J/mole K)
T = temperature absolute (K)
W= the molecular weight (18 g/mole for water vapour)

Substituting for m in the mass balance equation gives:

$$p_{cavity} = \frac{\dfrac{F\,V\,W}{1000R\,T} + A\,h\,p_{saturated}}{\dfrac{F\,V\,W}{1000R\,T} + A\,h}$$

And the mass flow can be calculated from the left hand side of the mass balance equation. The loss of moisture from a 2.4 m high brick cavity (depth of 40 mm) is presented in Figure 5 for a range of ventilation rates expressed in l/s per meter of wall perimeter length. For simplicity, a steady temperature of 15^o C is assumed to apply inside and outside the cavity with an outdoor RH of 80%.

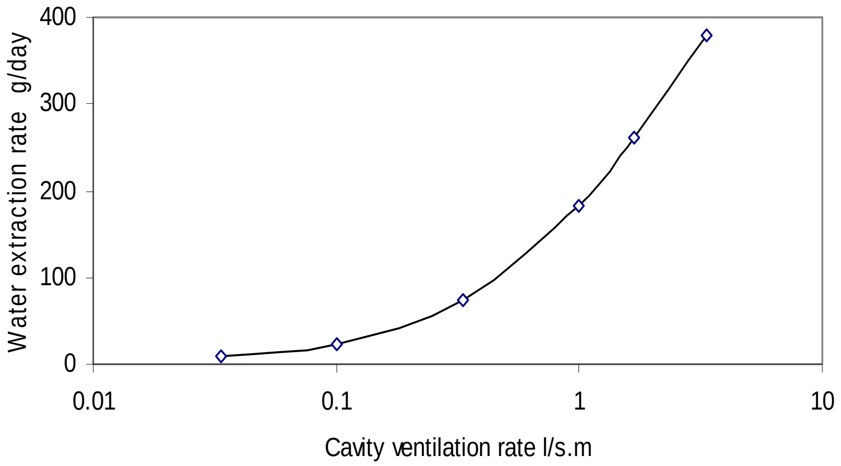

Figure 5: Calculated water extraction rates per m of wall from a brick veneer cavity.

It has been assumed that water will evaporate from the entire back of the rainscreen wall, but in practice a water leak may only wet a limited area of perhaps 10% or less. It turns out though that the rate limiting term in the mass balance equation is the moisture carrying capacity of the air ventilating the cavity. For a ventilation rate of 0.1 l/s.m, the air leaving the cavity has an RH of 99.9% and at 1 l/s.m it is 95%. It will be necessary to more carefully consider the accessibility of water to the air at higher ventilation rates, or where there are other rate limiting processes such as wicking through bulk materials.

6. CONCLUSIONS

The basic physics of ventilation in water managed cavities has been applied to open rainscreen and drained and ventilated wall designs in the context of New Zealand climate and building. Approximate ventilation rates and moisture extraction rates have been calculated with the following conclusions.

1. Average ventilation rates in drained and ventilated walls with 1000 mm^2 of vent area in the head and foot of the cavity are likely to fall in the range 0.3 to 1.5 l/s.m in low rise residential buildings in sheltered urban subdivisions. The moisture extraction capability of these ventilation rates has been estimated to fall in the range 20 to 200 g/day.m.
2. Ventilation rates in open rainscreen wall cavities due to temperature and wind pressure fluctuations are likely to be exceeded by infiltration driven air flows. Preliminary estimates based on whole building airtightness data give ventilation rates in the range 0.1 to 0.4 l/s.m which overlap the range of ventilation rates in drained and ventilated wall cavities.

7. ACKNOWLEDGEMENTS

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