Understanding and Controlling Air Flow in Building Enclosures

John Straube, Professor of Building Science, University of Waterloo, Waterloo, Canada
jfstraube@uwaterloo.ca

1. Introduction

It has long been recognised that the control of air flow is a crucial and intrinsic part of heat and moisture control in modern building enclosures [Wilson 1963, Garden 1965]. That this statement is true for all climates has been a more recently developed awareness [Lstiburek 1994]. A large fraction of a modern, well-insulated building's space conditioning energy load is due to uncontrolled air leakage. Wintertime condensation of water vapour in exfiltrating air (or summertime condensation of infiltrating air) within assemblies is one of the two major sources of moisture in the above-grade enclosure (driving rain being the other). Air flow through the enclosure can also carry, exhaust gases, odours, and sounds through enclosures as well as mould spores and off gassing generated within the enclosure. Uncontrolled air leakage through the enclosure is therefore often a major cause of performance (e.g. comfort, health, energy, durability, etc.) problems.

Water vapour diffusion, while amenable to simple analysis, is often (but definitely not always) an insignificant source of moisture in modern building envelopes. Wintertime exfiltration condensation is, however, acknowledged as a common building performance problem in cold climates. Warm weather infiltration condensation is often a problem in warm and humid climates (e.g. the south-eastern States) and in some cases in cool climates, especially when air conditioning or cooling (e.g. arenas) is used.

Therefore, there are three primary classes of reasons why the control of air flow is important to building performance:

1. Moisture control – water vapour in the air can be deposited within the envelope by condensation and cause serious health, durability, and performance problems
2. Energy savings –air leaking out of a building must be replaced with outdoor air which requires energy to condition it. Approximately 30% to 50% of space conditioning energy consumption in many well-insulated buildings is due to air leakage through the building enclosure. Convective circulation and wind washing both reduce the effectiveness of thermal insulation and thus increase energy transfer across the envelope.
3. Comfort and health – cold drafts and the excessively dry wintertime air that results from excessive air leakage directly affect human comfort, wind-cooled portions of the interior of the enclosure promote condensation which supports biological growth which in turn affects indoor air quality, airborne sound transmission control requires good airflow control, and odours and gases from outside and adjoining buildings often annoy or cause health problems.

There are other circumstances that require the control of air flow; for example, to control smoke and fire spread through air spaces and building voids and shafts, but these are situations that deal with extreme events, not typical service. This document will emphasise airflow control and the avoidance of related moisture problems.

2. Fundamentals

For air flow to occur, there must be both:

- a pressure difference between two points, and
- a continuous flow path or opening connecting the points.

Although the prerequisites are obvious and simple to state, in practical design applications it is not always clear what the pressure differences are or how to assess the existence and nature of flow paths.

In general, the approach taken to control air flow is to attempt to seal all openings at one plane in the building enclosure. This primary plane of airtightness is called the *air barrier system*. The word system is used since airflow control is not provided by a material, but by an assemblage of materials which includes every joint, seam, and penetration.

The following sections will present forces driving flow, , air barrier systems, a discussion of flow within building enclosures, and air leakage tolerant enclosure designs.

3. Driving Forces

There are three primary mechanisms which generate the pressure differences required for air flow within and through buildings:

1. wind,
2. stack effect or bouyancy, and
3. mechanical air handling equipment and appliances.

Since, it is widely acknowledged that a perfectly airtight air barrier system is unlikely to be achieved in practise, it is also desirable to control the air pressure differences driving the flow. This typically means reducing the pressure imbalance created by HVAC systems, reducing stack effect pressures by compartmentalizing buildings vertically, and reducing wind pressures by compartmentalising building plans.

A short review of the three types of forces driving airflow is presented below.

3.1 Wind

Wind forces act on all buildings, typically creating a positive pressure on the windward face and negative (suction) pressures on the walls. Bernoulli's equation can be used to calculate the pressure imposed on a building as function of wind speed. The *stagnation pressure* is defined as the pressure exerted by a flow decelerated to zero speed, and is given by:

$$P_{stag} = \frac{1}{2} \cdot \rho \cdot V^2 \cong 0.65 \cdot V^2 \qquad [1]$$

where ρ is the air density [kg/m^3], approximately 1.3 kg/m^2 at 0 C and
V the wind velocity [m/s]

The pressure calculated from Equation 1 is not directly what is imposed on a building, and so a pressure coefficient is introduced to modify the stagnation pressure as:

$$P = C_p \cdot P_{stag} \qquad [2]$$

This pressure coefficient can be found for simple buildings in numerous references and ranges from a typical value of C_p = 07 to 0.8 on the windward side to Cp = -0.3 to -0.5 on the leeward. Local pressure coefficients around parapets, under glancing wind directions, and other turbulent flow conditions are often much larger, e.g., C_p = +3 to -5. Interior pressure coefficients range from -0.3 to -1.0, and the arithmetic sum is the net pressure acting across the enclosure. A concise summary of typical pressure coefficients can be found in Chpt 14 of the ASHRAE Handbook of Fundamentals [ASHRAE 1997]

Low-slope roofs tend to have mostly negative (uplift) pressures, especially on the leading edge (Figure 1). Roofs with slopes above about 25 degrees experience positive pressures on the windward face, and suctions on the leeward.

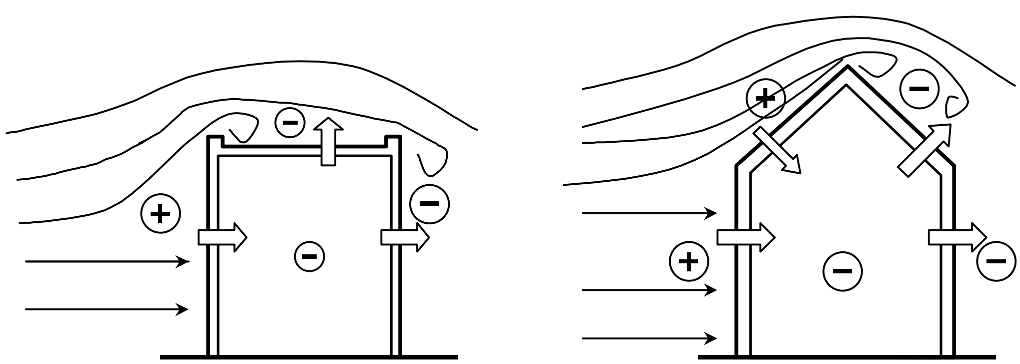

Figure 1: Wind Pressure Effects on Representative Buildings

3.2 Stack Effect

Stack effect pressures are generated by differences in air density with temperature, i.e. hot air rises and cold air sinks. The air within a building during the wintertime acts like a bubble of hot air in a sea of cold air. In the summertime the situation is reversed, although air temperature differences are usually less.

The density of dry air, ρ_a, varies with temperature. The greater the height of a column of air, the greater the potential difference in pressure if that column is at a different temperature. The pressure difference generated by a column of air h meters high with temperature difference between indoor and outdoor air at standard temperature and pressure is approximately:

$$\Delta P = 3465 \cdot \Delta h \cdot \left(\frac{1}{T_o} - \frac{1}{T_i}\right) \text{ [Pa]} \qquad [3]$$

where T_o and T_i are the outdoor and indoor temperatures respectively, (in **Kelvin** = Celsius + 273).

For example, if the air in a one meter high cylinder, open at the bottom and containing room temperature air (20 °C) is taken into the outdoors at a temperature of -10 °C, an outward pressure of 1.34 Pa would act at the top (Figure 2). The pressure at the bottom must be zero since it is connected to the outdoors. The horizontal plane at which the pressure equals the outdoor pressure (i.e. the difference is zero) is called the Neutral Pressure Plane (NPP).

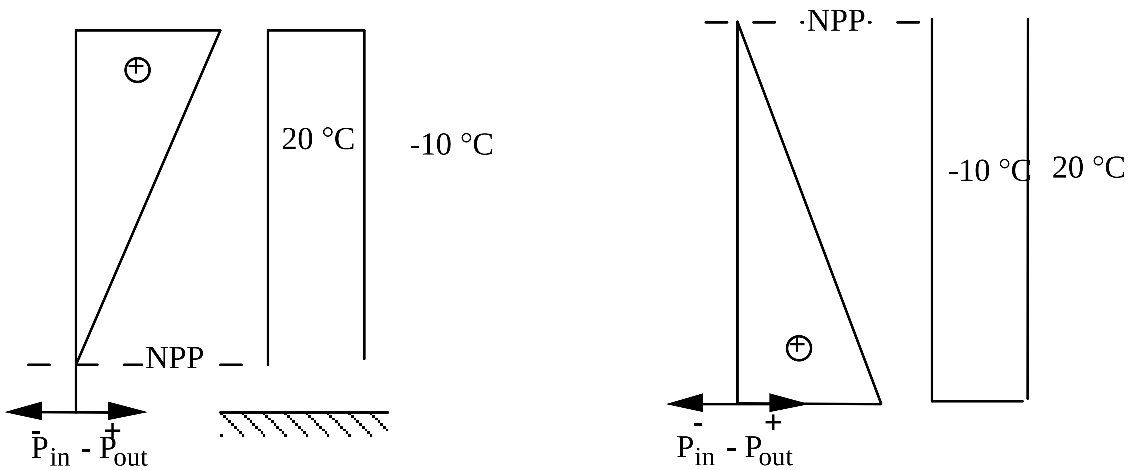

Figure 2: Pressure in Open-Ended Cylinder Due to Buoyancy

If the cylinder remained outdoors, the air it contained would slowly cool down to the exterior temperature and no pressure difference would exist. If the cylinder were then inverted and brought back indoors, the pressure at the closed end of the cylinder would again be 1.34 Pa acting outward as the cold air fell downward relative to the indoor air.

In the above examples, no flow occured because no flow path was provided. If an open-ended cylinder containing room temperature air where used, any temperature difference between the cylinder and the surrounding air would cause flow, and the warm air would be immediatley removed and replaced with cool outdoor air. However, if a heating coil were added to the cylinder to maintain the air temperature at 20 °C, airflow in the bottom would be heated. This is analagous to a heated building. Friction would slow air flow and result in a constant pressure drop along the height of the cylinder. Note that the NPP would now be located at mid-height and that air flow is involved (Figure 3). Obviously, the less air flowing through this cylinder the less heat energy required to maintain the interior of the cylinder at 20 °C.

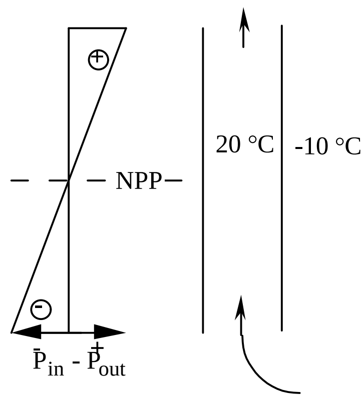

Figure 3: Flow Through A Heated Cylinder or a Building

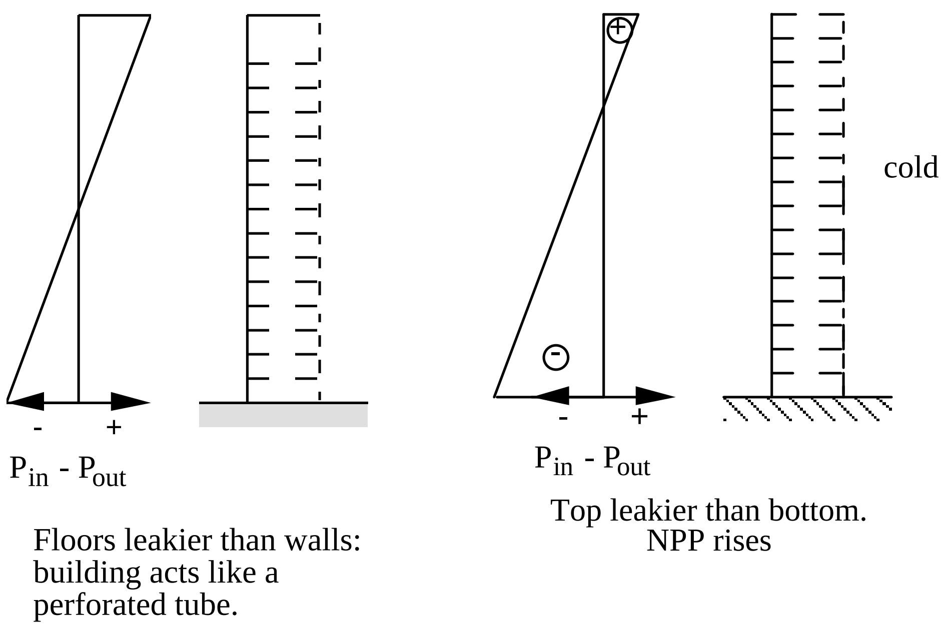

Figure 4: Stack Effect in Real Buildings

In warm climates and during warm weather, stack effect reverses and air is often drawn in at the top and pushed out at the bottom. Infiltration of warm moist air in warm weather can cause as many problems as exfiltration of warm moist air in the winter.

3.3 Mechanical Equipment

Fans and blowers cause the movement of air within buildings and through enclosures. By doing so, they can generate large pressures. If more air is exhausted from a building than is supplied, a net negative pressure is generated and vice versa.

If air is forced through the ducts that leave the building enclosure or pass outside the primary air barrier system (e.g., the very bad practise of placing ductwork in vented attics or crawlspaces) any leaks in the ductwork (and all ducts have some leakage, most ductwork is very leaky) will result in a net exhaust of air, and hence a net negative inward pressures on the building enclosure. The reverse can happen if leaky ducts outside the air barrier are under a net suction pressure.

Bathroom exhaust fans, clothes dryers, built-in vacuum cleaners, dust collection systems, and range hoods all exhaust air from a building. This creates a negative pressure inside the building. If the enclosure is airtight or the exhaust flow rate high, large negative pressures can be generated. These negative pressures have the potential to cause several problems:

- by driving inward air leakage through the enclosure, outdoor air may transport moisture into the enclosure during hot humid outdoor weather conditions
- the negative pressures can cause backdrafting of combustion appliances.
- The efficiency of most air handling devices will decrease with increasing back pressures.

bathroom fan	20 - 50 lps	40 - 100 cfm
range hood	25 - 125 lps	50 - 250 cfm
downdraft range system	to 700 lps	to 1500 cfm
clothes dryer	40 - 55 lps	80 -110 cfm
built-in vacuum cleaner	25 - 100 lps	50 - 200 cfm

Table 1: Representative Airflows Imposed by Residential Mechanical Equipment

Commercial HVAC systems both supply and extract air from buildings. This means both positive and negative pressure can be developed, depending on the balance of supply to exhaust flows. Dust collection systems, commercial range hoods and other industrial air handlers can move thousands of liters per second, seriously disturbing the pressure-flow relationship within a building and should be handled on an individual basis.

4. Controlling Air Flow Through Enclosures

Controlling the flow of air across the enclosure, e.g., from the interior to the exterior or vice versa, is the most important aspect of air flow control. While no building is perfect, the goal of a design should be near zero flow and

The primary plane of air flow control in a wall is generally called the *air barrier*. Because such a plane is in practise comprised of elements and joints, the term *air barrier system* (ABS) is preferred. In framed, low-rise residential buildings, the primary air barrier system is often comprised of an inner layer of drywall (sealed around the perimeter and at all penetrations) or sealed polyethylene. However, outer layers of sheathing, (such as gypsum, waferboard, fiberboard, EXPS) and housewrap or building paper provide additional resistance to out-of-plane air flow through the enclosure assembly. In many modern building assemblies, exterior sheathing is designed and detailed to be part of an outboard air barrier system. Note that the plane of airtightness labelled by the designer (and all building sections should indicate what is intended to be the air barrier) or builder as the air barrier system may not in fact act as the ABS.

4.1 Basic Requirements of Air Barrier Systems

Typically, several different materials, joints and assemblies are combined to provide an uninterrupted plane of primary airflow control. Regardless of how air control is achieved, the following five requirements must be met by the air barrier system (ABS):

1. Continuity. This is the most important and most difficult requirement. Enclosures are ***3-D systems***! ABS continuity must be ensured through doors, windows, penetrations, around corners, at floor lines, soffits, etc.

2. Strength. If the ABS is, as designed, much less air permeable than the remainder of the enclosure assembly, then it must also be designed to transfer the full design wind load (e.g., the 1-in-30 year gust) to the structural system. Fastenings can often be critical, especially for flexible non-adhered membrane systems.

3. Durability. The ABS must continue to perform for its service life. Therefore, the ease of repair and replacement, the imposed stresses and material resistance to movement, fatigue, temperature, etc. are all considerations.

4. Stiffness. The stiffness of the ABS (including fastening methods) must reduce or eliminate deflections to control air movement into the enclosure by pumping. The ABS must also be stiff enough that deformations do not change the air permeance (e.g., by stretching holes around fasteners) and/or distribute loads through unintentional load paths.

5. Impermeability. Naturally, the ABS must be impermeable to air. Typical recommended air permeability values are less than 1.3 x 10^{-6} $m^3/m^2/Pa$ or Q< 0.1 lps/m^2 @75 Pa. Although this is an easy property to measure it is not as important as might be thought. In practise, the ability to achieve other requirements (especially continuity) are more important to performance, and the air "permeance" of joints, cracks, and penetrations outweighs the air permeance of the solid materials that make up most of the area of the ABS.

As noted earlier, the secondary planes of air flow resistance fulfill several functions, either on their own or in conjunction with the other planes of air flow resistance. These secondary barriers not only add marginally to the overall airflow resistance of the assembly, they provide a level of redundancy if the primary air barrier is designed, built, or performs imperfectly. If the secondary barrier is of sufficient air tightness it may provide a great improvement to overall airtightness so long as compartmentalisation is provided . For example, research has shown that housewraps, sometimes called air infiltration retarders, can significantly reduce airflow through an imperfect primary air barrier even if they are not designed or built as an ABS. The satisfactory performance of many older wall systems can often be explained by the unintentional, and often synergistic, contribution to airtightness that layers such as building paper, board and panel sheathing, brickwork, etc. provide.

4.2 Air Barrier Systems vs Vapour Barriers

The fact that many vapour barriers also retard or eliminate air flow sometimes causes confusion. In fact, much of the older literature (and a disappointing proportion of current documents) confuse or combine the function of the ABS and vapour barriers, and the difference between the two is still one of the most common building science questions. Hence, the distinction will be presented here once again.

The function of a vapour barrier is simply the control of water vapour *diffusion* to reduce the occurrence or intensity of condensation. As such, it has one performance requirement: it must have the specified level of vapour permeance and be installed to cover most of the area of an enclosure.

Neither the Canadian National Building Code nor the Ontario Building Code requires the use of a vapour barrier in all enclosures. They also do not require the use of polyethylene as an air barrier or a vapour barrier. The codes (Part 5) wisely require that vapour diffusion be controlled when an assembly "would be adversely affected by condensation". The need for a specific vapour barrier layer can be assessed by simple calculations, and rarely is a layer with very low permeance like polyethylene sheet justified.

Air barrier systems control air flow and thereby control *convective* vapour flow. As can be seen from the previous sections, the control of air flow provides other benefits and has at least five performance requirements to meet.

Canadian building codes require an air barrier system in all enclosures that would be adversely affected by condensation. In practise, this means air barriers are required for almost all conceivable types of building enclosures, especially since they provide more than just control of condensation.

The vapour permeance of the air barrier must be considered in the same way as all other materials in an assembly should be. For example, in cold climates, a vapour barrier on the exterior is usually not acceptable (but can be designed for, as it is in an exposed membrane low-slope roof or a wall with metal cladding), whereas in hot humid climates, this location would be desirable. But the vapour permeance of the ABS is no more important than the vapour permeance of any other materials in an assembly, such as the cladding, sheathing, insulation, interior finish, etc.

4.3 Common Air Barrier Systems

A sheet of 6 mille (0.15 mm) thick polyethylene is often used as a vapour barrier. Poly is cheap to buy and install and has very low vapour permeance. However, it fails or barely meets most air barrier requirements other than impermeability. It is difficult and relatively expensive to achieve continuity, especially since it is pierced by services and enclosure penetrations at many locations. It is likely to fail structurally when exposed to wind gust loads, and can fail through fatigue if it flaps because of varying wind pressures. Hence, it is not very durable. It is so flexible that it can deform and transfer loads through unexpected paths, deform batt insulation, tear fastenings, pump air, etc. Nevertheless, for undemanding applications such as low-rise housing, poly may act as both the vapour barrier and the air barrier.

The airtight drywall approach (ADA) employs the interior layer of painted drywall as part of the ABS and poly (or an appropriate type of paint) as the vapour control layer. The drywall is stiff and strong enough for most applications and because it is visible, it is easy to inspect, repair, and to ensure continuity. Difficulty in achieving continuity are often encountered at service penetrations, wall-floor interfaces, intersection walls etc. Despite these difficulties, the ADA air barrier system is often more succesful than a poly system, and can be used in a wide-range of steel and wood framed roof and wall systems in both residential and commercial construction.

The vapour barrier and air barrier are often seperated in enclosures employing housewraps or exterior sheathing (e.g., sealed exterior gypsum, plywood, or OSB) as the primary air barrier. Poly, foil-backed drywall, or paint is installed near the interior and acts as the vapour barrier. The advantage of such exterior air barriers is that they are often easier to install in such a manner as to span over all service penetrations, plumbing, structural components, etc.

Another approach to exterior air barriers is the use of air impermeable, usually foam plastic or foil-faced, rigid insulation boards with sheathing tape and/or gaskets at joints. Such systems have the advantage of fewer penetrations, but the disadvantage that they are difficult to inspect and repair. The ability of these systems, including their joints, to transfer wind loads through connectors to the structural frame must be investigated for each application.

Reinforced concrete is often sufficiently airtight to form part of an ABS so long as the concrete is dense and crack size and spacing are controlled by the appropriate use of reinforcing. Blockwork is not generally sufficiently impermeable to act as an air barrier. Small shrinkage cracks further compromise its airtightness. The application of a thin layer of parging, preferably with fibres to limit crack sizes, renders them airtight.

In commercial applications, bitumen-based air barriers, in either liquid or reinforced membrane form, are often adhered to the exterior of blockwork, concrete, or exterior gypsum sheathing. To ensure continuity, compatible membranes are used to bridge cracks and tie the ABS to windows, etc. This type of air barrier tends to be very vapour impermeable and so also acts as a vapour barrier. Therefore, the majority of the insulation must be applied outside of such an ABS in cold climates. Cementitious, fibre-reinforced air barriers are also available. Basically polymer-modified and fibre-reinforced plasters, these systems require flexible joint details around penetrations, but are non-combustible and may be as vapour permeable or impermeable as specified. A variety of heavy duty elastomeric liquid-applied air barrier membranes are also available. These products can have a range of vapour permeance values (from very impermeable to very permeable). With the appropriate analysis, they can be placed anywhere in an enclosure and used in all climates.

In framed systems, two air barrier systems, one inside and one outside of the framing, are often desirable, with framing members consciously designed as in-plane compartment seperators to resist the internal lateral flows generated by wind pressures (Figure 7). Such redundancy is needed because of the susceptibility of these systems to wind washing, ABS failure, convective loops, and other air flow control problems.

5. Controlling Air Flow Within Enclosure Assemblies

Controlling airflow that passes through the enclosure is very important, but in some cases it may not be sufficient. Both thermal buoyancy (i.e., *natural convection* or stack effect) and differential wind pressures cause natural and forced convective air flows *within* building enclosures. These internal airflows can short-circuit thermal insulation and bypass air barriers with the attendant increase in heat transfer and risk of moisture deposition. Providing an excellent air barrier system will not necessarily control these problems, since no air flow need occur through an ABS for either of these phenomena to cause performance problems.

5.1 Natural Convection

An inspection of Equation 3 shows that the size of the pressure driving buoyancy-induced flow is primarily affected by two factors: the magnitude of the temperature difference and the difference in height. The amount of air flow that can be moved by this pressure is of course dependent on the geometry of the flow path or the air permeability of the material.

If a continuous air loop, even 1 mm in width, connects two sides of a layer of insulation a convective loop can form, robbing energy efficiency and causing moisture problems (Figure 5). Research [Lecompte 1990] has shown that significant heat losses and moisture transport can result from connected air gaps of only 1-2 mm width. To ensure no flow paths connect air spaces on the warm side of the insulation to the cold side, insulation should always be placed in tight contact along at least one surface. Semi-rigid cavity insulation must be firmly attached to one side of the air space in which it is installed to avoid such convection loops. Full bed or serpentine adhesive patterns are preferred to isolated daubs (which create continuous vertical gaps) for the same reasons.

Batt insulation is manufactured oversized so that when it is compressed (or friction fit) by the drywall gaps and wrinkles are minimised. If installation is not careful, and experience has shown that sufficiently careful installation is rare, small gaps will form and allow loops to form around the batt. Research at IRC [Brown et al 1993] has shown that small gaps, such as shown in Figure 6, can greatly impact heat flow (from 15% at $\Delta T=25$ to 35% at $\Delta T=55$ C).

Most batt insulation has such low density, however, that it does not restrict air loops even within its body when driven by large pressure differences (see Figure 5B), whereas semi-rigid or rigid insulation usually does. Flow within air permeable insulation usually occurs if large temperature differences act across a thin layer of insulation – the pressure difference is large if the temperature difference is large and the flow resistance is small if the thickness is small. This is often a concern in horizontal insulation (e.g., attics). One solution is the use of higher density blown-in insulation which reduces the air permeability of the material, and thus its propensity for convection losses. The use of multiple layers (i.e., in the form of insulating sheathing or layers of batts) reduces the temperature drop across each layer and thus the driving force for convection.

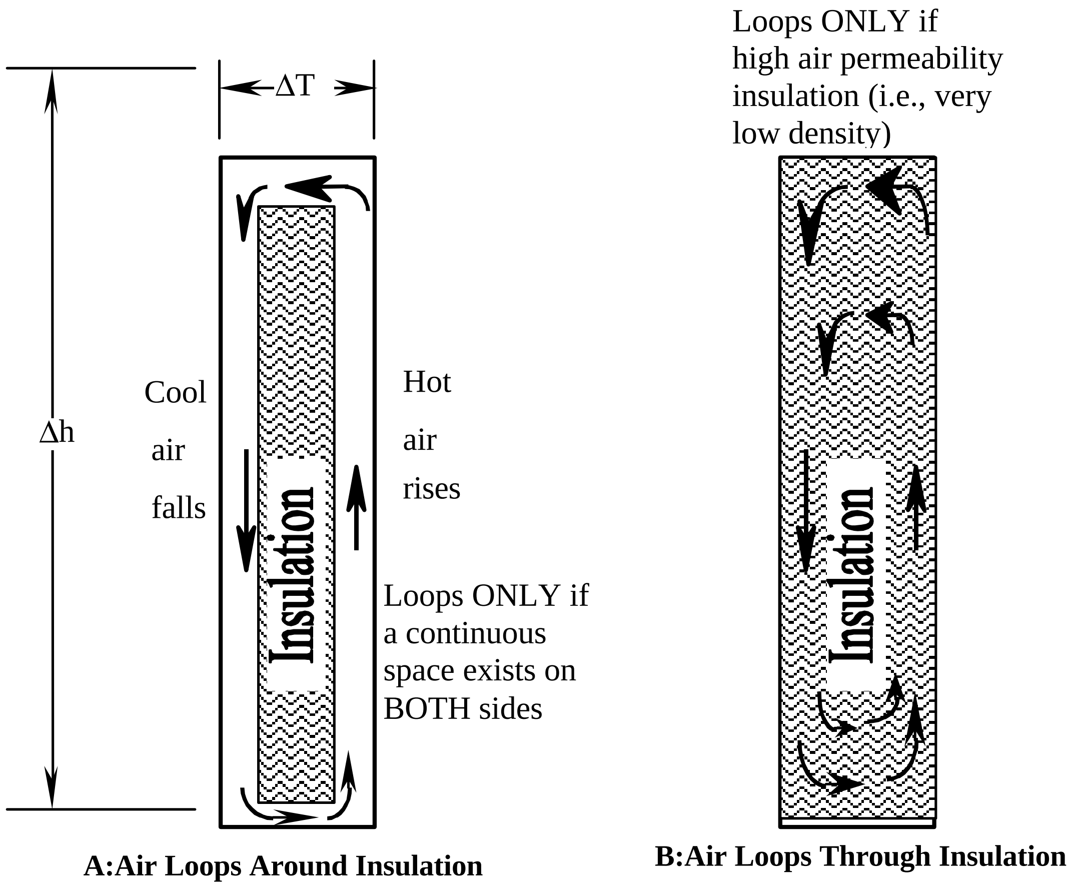

Figure 5: Natural Convection Air Flow Around and Through Insulation

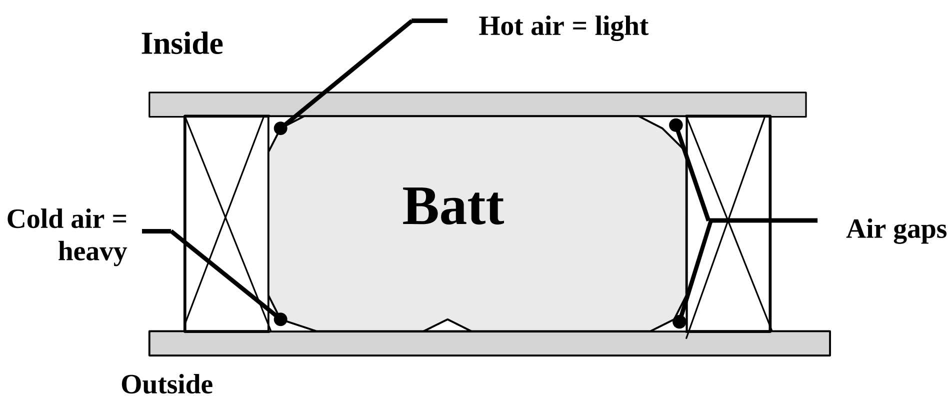

Figure 6: Natural Convection Around Batt Insulation

Multiple layers of insulation are often specified for low-slope roofs, partly to reduce or eliminate the convective loops that could occur in the small joints that inevitably form between boards. The driving pressure for flow in two independent 38 mm high gaps (a typical board thickness) is usually not large enough to cause significant looping in the typically small gaps (because Δh is small), but the pressures in a single 75 mm tap gap may be.

5.2 Wind Washing

High velocity air flowing behind the cladding or sheathing can also increase the amount of heat loss by penetrating the structure of low-density fibrous insulations (hence, batt insulation is very vulnerable). This phenomenon is often called wind washing, or *forced convection* and can cause surface condensation in outside corners, increased heat loss and other problems. Building corners and parapets are especially susceptible because the wind induces very steep pressure gradients in these areas (Figure 7). Pressure gradients of 100 Pa/m can form, and even small air flow paths can allow excessive air flows with such large pressures.

Air impermeable layers placed outside low-density fibrous insulation can control this form of heat loss. In Scandinavia and Europe, secondary, outer layers of airflow resistance are called wind barriers or convection barriers. To control wind-driven convective heat losses Finnish research [Uvslokk 1988, Ojanen 1995] has recommended limiting the maximum permeability of the wind barrier to between 10 and 25 x 10^{-6} $m^3/(m^2$ Pa s). Some high-density mineral fibre insulations, and rigid foam insulations, housewraps, building paper, and sheathing (all with taped or otherwise secured joints) can provide this level of control.

In-plane air flow resistors provide *compartmentalisation*, which helps to confines air leakage to limited areas of the enclosure, reduces wind washing effects, and can also improve pressure moderation performance. Compartmentalisation should be provided in all assemblies, either provided by tight separators at discrete intervals (e.g., sheet metal) or by the distributed resistance of low-permeance materials (e.g., dense-pack cellulose and foam). Corner seperators are often the most useful because of the high pressure gradients acting around corners.

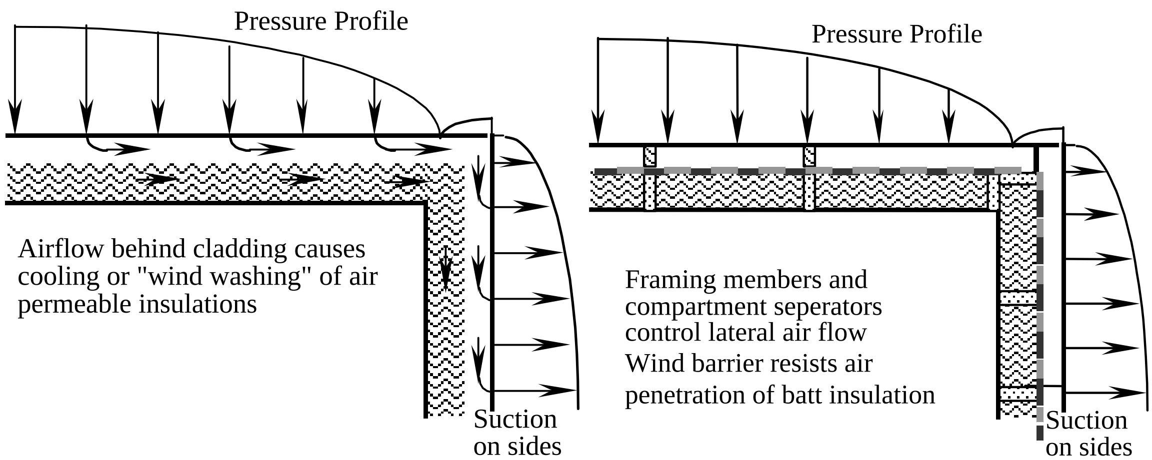

Figure 7: Forced Convection / "Wind Washing"

Framing members can also provide resistance to in-plane flow. Wood blocking, or draft stops, have long been used in wood framed construction to prevent the spread of fire and smoke. Wood framing may not be sufficiently airtight at corners because drying shrinkage causes small cracks between the framing and the siding (or drywall). Metal studs tend to have "knock outs" for services which allow unimpeded lateral air flow.

Vertical natural convection flow within the cores of hollow concrete block can be a very effective means of transporting heat and moisture. Figure 8 schematically shows a typical scenario in which a perfectly designed air barrier would not stop energy loss or condensation. Even if vertical insulation were used on the roof side of the parapet, condensation and heat loss would occur at the top of the blockwork cavity. Where this is a potential problem (namely at parapets and as basements project above grade), compartment separators in the form of mortar-filled courses, solid lintel blocks, filling with expanding foam, or similar should be provided.

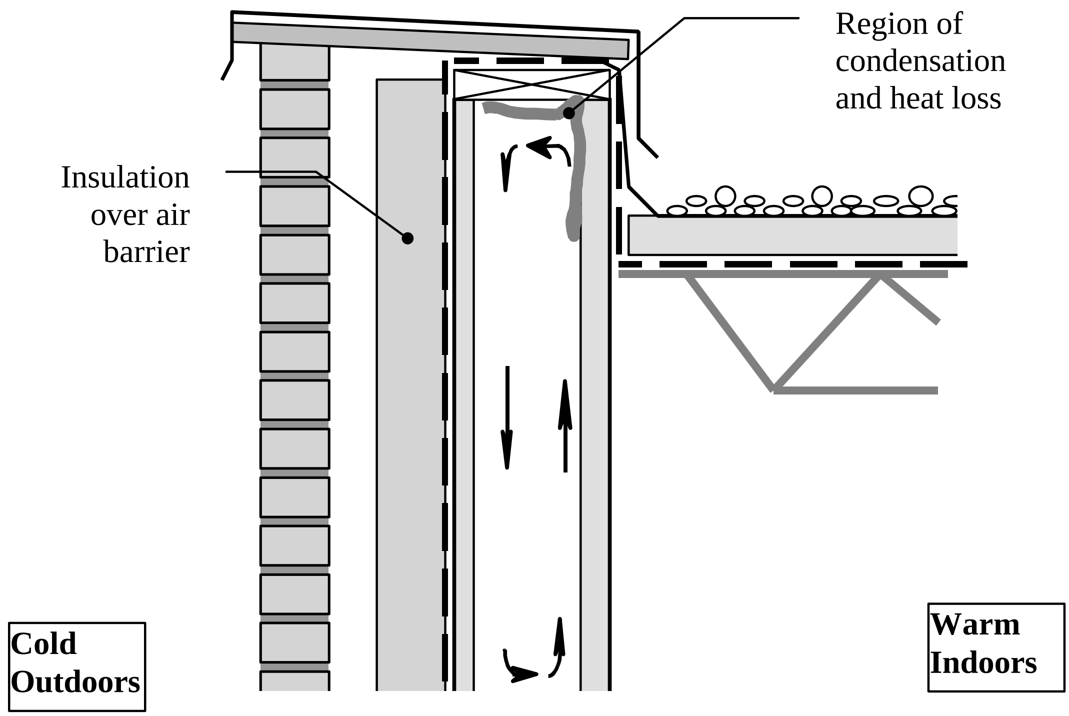

Figure 8: Convective Flow in Parapet of Hollow Blocks

5.3 Solutions To Forced and Natural Convective Flow

The primary means of controlling convective loops and windwashing effects are:

1. Insulation should be installed so that high density or closed-cell materials are fully in contact with one airtight surface. This may not control convection in low-density batt insulation which should completely fill the space into which it is installed (no gaps or wrinkles).
2. Good workmanship and inspection must be employed to avoid air gaps around both rigid, semi-rigid and batt insulation. Semi-rigid insulation offers the ability to be fitted or pressed to conform to rough surfaces like blockwork and concrete.

3. Some airtightness in the form of housewraps, taped sheathing etc., should be provided behind cladding to control wind washing.
4. Reduce the temperature difference across individual layers of insulation by using multiple layers of insulation with non-aligned joints (e.g., insulated sheathing over batt insulation).
5. Reduce the height of the connected space (Δh in Eq 3). Reduce the ability of lateral flow by providing air flow resistors around corners and other changes in plan. This can be achieved by compartmentalizing to limit vertical height and horizontal extent, and is especially important at corners and parapets. Compartmentalizing tall buildings has been shown to effectively limit stack effect [CMHC 1996], but requires care in design and detailing.

5.4 Pumping and Flexible Air Barrier Membranes

Many materials used as parts of an air barrier system are very flexible, and not fully adhered. Housewrap and polyethylene sheet are two common examples. These physical characteristics can cause performance problems that are often similar to a leaky air barrier system, even if the flexible material is part of an airtight system.

Wind pressures are highly variable, changing in magnitude from second to second and often changing direction at some times, especially in turbulent conditions or near corners and parapets. For a housewrap exposed on the exterior side of sheathing, the result can be a balloning outward under negative pressure conditions, drawing air from the studspace and from inside the building. When positive wind pressures are applied a few seconds later, the housewrap is pressed tight to the face of the sheathing pushing air out of the studspace into the building (Figure 9). The result of this "pumping" action can be interior air drawn into the studspace, allowing condensation in winter. Mould spores and material offgasing can then be pumped back into the building.

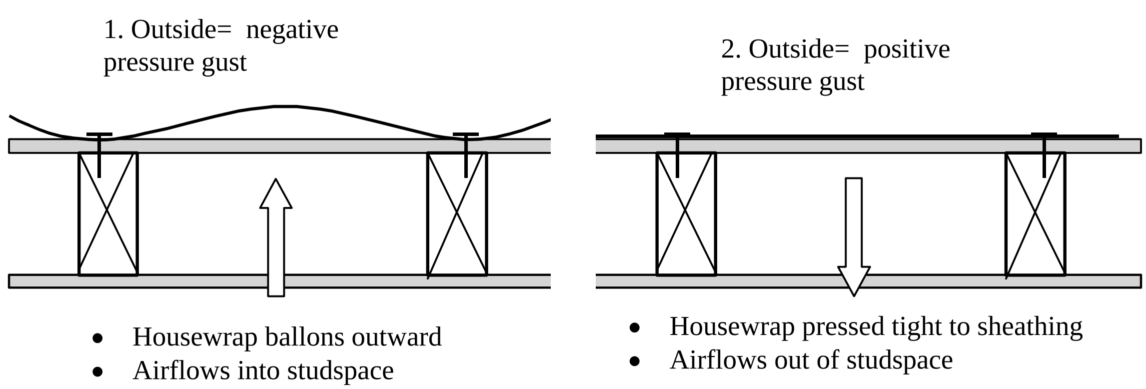

Figure 9: Pumping due to Flexible Exterior Air Barrier Membrane

If a functional air barrier system exists anywhere else in the enclosure assembly, the wind pressure will act across that layer, and the housewrap will not be able to pump. In advanced systems, an interior layer of airtight drywall is the primary air barrier system, the housewrap acts as an excellent wind barrier and drainage plane rather than as part of the air barrier system. This is an ideal system since the housewrap also provides a level of redundancy against minor penetrations of the interior ABS, and reduces the chance of convective loops forming.

To provide an effective air barrier, it is best to sandwich the housewrap between two stiff and strong layers of sheet material (e.g., fibreboard). A compromise solution, which limits pumping without stopping it, is to support the membrane at frequent intervals (e.g., by the use of siding, closely space furring strips, or, unintentionally, by mortar dams).

A polyethylene sheet between the interior drywall and batt insulation behaves in a somewhat similar manner to housewrap, except that the batt insulation provides some support. This support is rather limited, since it requires very little force to deflect batt insulation 15 to 20 mm. In situations where wind loads are expected to be high (tall buildings, windy locations, etc), the pumping action of poly will likely render it only partially effective as an air barrier system.

Loose-laid, non-adhered roof membranes are another example of the dangers of pumping. A fully-adhered roof membrane can be an excellent air barrier of properly detailed. A flexible mechanically attached membrane can pump large quantities of air into the roof, causing condensation problems in cold weather, and reducing energy efficiency in all weather. A stiff air barrier (e.g., a vapour barrier membrane supported by stiff insulation) can be provided on the inside of such systems to prevent air from being pumped into the roof from the interior of the building. However, pumping may still occur if the edges of the roof (especially the parapet) and penetrations are not sealed. In this situation, condensation problems in summer are likely.

6. Air Leakage Tolerant Designs

There is now a widely accepted rain control design philosophy that assumes some rain will pentrate cladding and thus that drainage, storage, or secondary water resistant layers should be provided to deal with the moisture that penetrates [Straube 1997]. In the same manner, prudent designers should acknoweldge that some air leakage could or even will occur and provide designs that either reduce the impact of air leakage on wall performance, include redundant layers of airtightness, or both.

6.1 Insulation as Moisture Control Strategy

One of the most powerful moisture control products that a designer of framed structures (wood or steel) has at their disposal is insulating sheathing. This has been known for some time [e.g., Timusk 1983], but seems little appreciated in practise. By providing a layer of relatively air impermeable insulation outside of batt insulation, numerous benefits accrue.

The most obvious benefit is condensation control. How? Air leaking through the enclosure wall in cold weather will contact the back of the sheathing within the studspace. In walls with sufficient exterior insulation, the dewpoint temperature of the interior air will be below the temperature of the back of sheathing and thus condensation due to air leakage and diffusion cannot occur within the studspace (Figure 10). Even if air leakage condensation does occur under extreme conditions (e.g., the 2.5% design condition), air leakage will quickly *dry* the wall when sheathing temperatures rise above the interior dewpoint.

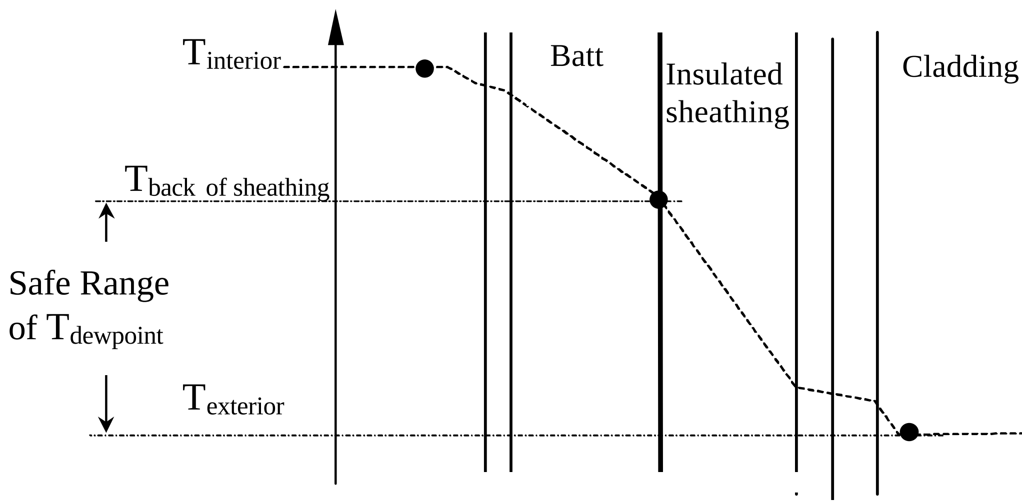

Figure 10: Insulating Sheathing Reducing Air Leakage Condensation

It is easy to decide on the level of insulation required to the exterior of the studspace to control air leakage condensation. If one assumes that interior finishes and exteror cladding have little thermal resistance (often a reasonable assumption) then the back of the sheathing temperature can be found from:

$$T_{back\ of\ sheathing} = T_{interior} - (T_{interior} - T_{exterior})\ R_{batt}/R_{total}$$

Table 2 provides some idea of the level of insulation (sheathing plus airspace and cladding) that should be provided outside of a batt-filled studspace to prevent cold-weather exfiltration condensation. It can be seen that mild temperatures and dry interior air require little exterior insulation to control condensation, whereas a museum in Yellowknife should have most of the insulation on the exterior.

It is not clear how to choose the exterior temperature to design for, since any level of protection can be chosen, from none to complete. Some judgement is therefore called for. The average January temperature, or the average less 5 Celsius, might be considered a reasonable value (and is readily available). For especially high performance systems, or walls that are highly sensitive to moisture damage, a lower value should be chosen, perhaps 10 °C less than average. A house in Toronto (January average temperature = -4 °C) with an interior RH of 40% and an R12 batt between 90 mm studs should therefore have about R6 (0.46 x R12) on the exterior to eliminate air leakage condensation for more than half the winter. Choosing a slightly higher value (R7.5) will increase the fraction of time during which condensation cannot occur. It should be clear that any insulated sheathing provided on the exterior of framed structures will provide better protection against air leakage condensation in cold weather than no insulation.

$T_{dewpoint}$	-3	3	7	10
	Indoor RH			
Outdoor T	**20**	**30**	**40**	**50**
0	none	0.14	0.33	0.48
-5	0.08	0.31	0.46	0.58
-10	0.23	0.42	0.55	0.65
-15	0.33	0.50	0.61	0.69
-20	0.41	0.56	0.66	0.73
-25	0.48	0.61	0.70	0.76
-30	0.53	0.65	0.73	0.78

Table 2: Ratio of Exterior-Interior Insulation to Control Air Leakage Condensation

For important projects or situations in which the design team has little historical experience, investigation using widely available no-cost computer models such as CMHC's easy-to-use EMPTIED and the more accurate and informative WUFI-ORNL would be prudent.

7. Conclusions

Air flow control is important for several reasons: to control moisture damage, reduce energy losses, and to ensure occupant comfort and health. Airflow across the building enclosure is driven by wind pressures, stack effect, and mechanical air handling equipment like fans and furnaces.

Design for air flow control involves much more than just providing a single plane of airtightness however -- internal convection, wind washing, and pumping are additional air flow mechanisms that can cause performance problems.

A continuous, strong, stiff, durable, and air impermeable air barrier system is required in all buildings to control airflow driven by these forces. This air barrier system should be clearly shown and labelled on all drawings. In addition, enclosure assemblies and buildings should be vertically and horizontally compartmentalized, may require secondary planes of airtightness (such as those provided by housewraps and sealed rigid sheathing) and may need appropriately air impermeable insulations or insulated sheathing.

It must be noted that increased airtightness must be matched by an appropriate ventilation system to dilute pollutants, provide fresh air, and control winter humidity levels. Good airflow control through and within the building enclosure will bring many benefits: reduce moisture damage, energy savings, and increased health and comfort. However, while airflow usually causes wetting in enclosures, it also can be a powerful drying mechanism. Therefore, enclosures with increased air flow control demand greater attention to other sources of drying (diffusion is the only practical mechanism available) and the reduction or elimination of other sources of wetting (built-in, rain and diffusion).

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